Multipurpose Quantum Network Simulators: A comparative study

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Abstract. *Quantum technology is transforming computing and communication, with quantum networks at the forefront. This paper evaluates multipurpose quantum network simulators, crucial for advancing these networks. Comparing 14 simulators, we highlight their adaptability across applications and configurations, aiding investigations into entanglement-based communication and quantum entanglement scenarios. By assisting researchers in selecting suitable simulators, our study facilitates practical implementation of quantum technology across multipurpose applications.*

1. Introduction

Quantum technology represents a transformative paradigm shift in the field of computation and communication. At the heart of quantum technology lies the concept of quantum networks, which enable the exchange of quantum information across distributed nodes. Quantum networks hold the promise for secure communication, quantum-enhanced sensing, and distributed quantum computing. They are poised to revolutionize industries ranging from finance to healthcare by providing capabilities beyond the reach of classical networks. However, research in this field is still in its nascent stages, and access to these networks remains scarce [Abelém et al. 2020].

Quantum simulators are indispensable tools in the field of quantum technology research. They serve as virtual laboratories for researchers to explore and experiment with quantum systems, providing insights into their behavior and potential applications. These simulators facilitate the study of quantum phenomena that may be challenging or impractical to observe in real-world quantum devices, due to the current technology available, including limitations in hardware precision, environmental control, and scalability. Their importance lies in their ability to accelerate research and development efforts, making quantum technology more accessible and enabling researchers to take advantage of its full potential.

There are several quantum network simulators available, some of which focus on quantum hardware platform or specific tasks such as QKD (Quantum Key Distribution). In this paper, we'll focus on multipurpose quantum simulators that can support various applications and network setups. Our study offers an comparison of multipurpose quantum simulators, providing insights into their capabilities and limitations. Additionally, we tackle the practical challenges inherent in quantum network simulators, emphasizing areas ripe for improvement and innovation. Furthermore, we delineate future directions in quantum network simulation, presenting researchers and developers with emerging trends and areas set for growth.

2. Quantum Simulators Network

2.1. Methodology for Comparing Quantum Simulators

Selecting an appropriate quantum simulator is a crucial decision for researchers and practitioners alike. We delve into the simulation capabilities from a network standpoint, focusing on features directly influencing the modeling and analysis of quantum networks. Firstly, we assess whether the simulators offer build-in implementations of different quantum network generations (1G, 2G, or 3G) [Abreu et al. 2022]. We examine the approach taken for quantum communication abstraction within the simulator, whether it involves qubits, directed photon transmission models, or EPR pairs. Additionally, we consider the availability of quantum network components such as repeaters, switches, or routers within the simulator. Furthermore, we investigate the inclusion of quantum protocols (such as routing, purification, entanglement swapping, network tomography, or others) and the incorporation of metrics such as fidelity, EPR/s, or throughput. We also analyze the presence of application protocols (such as QKD, teleportation or any application-layer protocol) for quantum networks. These network-oriented criteria aid researchers in selecting the simulator that best aligns with their specific quantum network simulation requirements and objectives.

2.2. Multipurpose Quantum Network Simulators

In this section, we compare various quantum simulators. Table 1 provides a comprehensive overview of the available quantum simulators, emphasizing their key features, supported platforms, and licensing details.

Table 1. Quantum Network Simulators.

Simulator	OpenSource	Focus	Gen	Type	Comp.	Prot.	Metric	App
Netsquid	No	Hard.	1G	Qubit	no	no	no	✓
NetQASM	No	App.	1G	EPR	no	no	✓	✓
QNE	No	App.	1G	EPR	no	no	✓	✓
SimulaQron	✓	Prot.	1G	EPR	no	no	no	no
QuNetSim	✓	Prot.	1G	EPR	✓	✓	✓	no
QuISP	✓	Prot.	1G	Photon	✓	✓	✓	✓
QNET	✓	Prot.	1G	EPR	✓	✓	✓	no
qSavory	✓	App.	1G	Qubit	no	no	no	✓
qNetVO	✓	Hard.	1G	Qubit	no	no	no	no
Sequence	✓	Prot.	1G	Photon	no	no	no	no
Squanch	✓	Hard.	1G	Qubit	no	no	no	no
AliroNet	No	Hard.	3G	Qubit	✓	✓	✓	✓
QKDNetSim	✓	App.	1G	Qubit	✓	✓	✓	✓
Qnet-lab	No	Prob	1G	Qubit	no	no	no	✓

Table 1 presents a comparison of various quantum network simulators based on several key features. As shown in Table 1, most of the simulators are open-source, with a few being proprietary. The focus of the simulators varies from being hardware-oriented (emphasizing physical components such as different EPR generators, various qubit technologies, and other aspects) to application-oriented simulators focusing on a higher level of abstraction that primarily considers the functioning of quantum network applications. Additionally, there are protocol-oriented simulators that focus on simulating specific protocol functionalities. In addition to this, it is noticed that only 1G generation network (based on heralded Entanglement Generation and purification) is build-in in the simulators, with native options to 2G and 3G networks with quantum error correction only appearing in AliroNet simulator. Following we present and comment on each simulator main features.

Netsquid[1] is a python-base quantum simulation library develop by QuTech[2]. It provides pre-defined network components like quantum qubits, channels (quantum and classical), and quantum memory, empowering users to implement fundamental quantum network protocols such as teleportation and entanglement swapping. Netsquid is one of the most used quantum network tool and has attracted an active community of developers. Moreover, Netsquid seamlessly integrates with Qiskit[3], an IBM quantum computing framework, facilitating hardware-level experiments. However, it's noteworthy that Netsquid's accessibility is limited as it's not open-source, with only restricted releases available to researchers. Additionally, while it excels in first-generation repeaters and hardware focus, it lacks advanced features like routing protocols, multiparty applications, and built-in quantum/classical network metrics such as fidelity, throughput, or bandwidth. QuTech also develops NetQASM[4], QNE-ADK[5], and SimulaQron [Dahlberg and Wehner 2018]. **NetQASM** offers a low-level instruction set architecture for quantum internet applications, emphasizing platform independence and extensibility for local quantum gates, classical logic, and remote entanglement generation. **QNE** serves as a quantum network application toolkit, facilitating experimentation via a web-based simulator, focusing on application development and network topology. **SimulaQron**, a distributed quantum network simulator, prioritizes application-oriented quantum computing, connecting processors through simulated quantum channels and classical communication. It enables precise simulation of quantum network behavior, supporting testing and evaluation of quantum computing applications in a distributed environment.

QuNetsim [DiAdamo et al. 2021] stands as another quantum network simulator, leveraging python as its foundational programming language to construct various network components. Distinguishing itself from Netsquid, QuNetsim comes equipped with a range of predefined network protocols, encompassing teleportation, entanglement swapping, distributed EPR pairs, superdense coding, and multiple tools for crafting routing protocols and QKD applications.

QuISP [Satoh et al. 2022], developed by Keio University, adopts a unique approach by utilizing the classical network simulation tool Omnet++[6] as its foundation to construct a quantum internet simulator. Leveraging the C++ programming language, QuISP enhances Omnet's classical internet components, integrating quantum capabilities like entanglement generation. With intuitive drag-and-drop features, users can effortlessly build scalable quantum networks comprising quantum nodes, repeaters, routers,

[1]https://netsquid.org/
[2]https://qutech.nl/
[3]https://www.ibm.com/quantum/qiskit
[4]https://github.com/QuTech-Delft/netqasm
[5]https://www.quantum-network.com/adk/
[6]https://omnetpp.org/

and auxiliary components. While QuISP implements teleportation, entanglement swapping is notably absent. However, it offers numerous purification protocols and quantum network tomography protocols, focusing on the creation of large-scale networks. Unlike Netsquid and QuNetsim, which process packets individually, QuISP boasts the capability to handle millions of packets simultaneously, performing a simulation based on describing accumulative errors instead of simulating each individual operation. **QNET** [7] is a python-based simulator created by the Institute for Quantum Computing at Baidu Research. This simulator uses discrete-event simulation framework, with includes features such as quantum satellite experiments, mobility nodes, and support for QKD applications. Moreover, QNET incorporates pre-implemented network nodes capable of serving as repeaters (only 1G) and routers.

Additionally, to enhance the scalability of the simulation, some simulators offer support for parallel simulation. **SeQUeNCe** [Wu et al. 2021] fully supports parallel simulation, utilizing a quantum state manager (QSM) to distribute shared quantum information across processes while minimizing overhead and synchronization. Its architecture comprises three stacked processes per network node, facilitating simulation of quantum registries, qubits, and virtual qubits. With five customized modules atop its simulation kernel - Hardware, Entanglement Management, Resource Management, Network Management, and Application - users can define additional functionality or test protocol schemes. On the other hand, **Squanch** also offers an open-source Python framework enabling high-performance, parallel simulations of distributed quantum information processing. Equipped with flexible modules for designing multiparty quantum networks and scalable error models, Squanch efficiently manipulates quantum information, providing researchers and developers with a robust tool for exploring complex quantum network protocols and applications. **QKDNetSim** [Soler et al. 2024] primarily focuses on Quantum Key Distribution (QKD) but is versatile enough to accommodate multiple applications. Developed using the NS-3 classical simulator, it offers potential for further development and integration with classical networks. The simulator boasts full QKD protocols, encryption schemes, key managers, and Quantum Random Number Generators (QRNG) simulation capabilities, making it possible to simulate real-world QKD topologies [Tavares et al. 2023].

Other simulators are still in early development stages. **qNetVO**[8], an approach to circuit-based Quantum Network Variational Optimizer, represents a hardware-oriented quantum simulator that models quantum communication networks using differentiable quantum circuits. Leveraging automatic differentiation and gradient descent, it optimizes circuit parameters with respect to a cost function. Supported by Xanadu and the University of Illinois Urbana-Champaign, this Python-based tool offers promising potential. On the other hand, **qSavory**[9], a Julia-based full-stack simulator of quantum hardware, spans from low-level analog physics to high-level network dynamics. Developed by researchers at UMASS Amherst, it includes a discrete event simulator and symbolic representations for quantum objects, compatible with various backend simulators. Moreover, **SimQN** [Chen et al. 2023], from the University of Science and Technology of China (USTC), presents a full network stack simulator focusing on network attributes rather than physical

[7]https://github.com/baidu/QCompute/tree/master/Extensions/QuantumNetwork
[8]https://github.com/ChitambarLab/qNetVO
[9]https://github.com/QuantumSavory

ones. With modularized network-layer utilities enhancing protocol reusability and simplifying simulation environment construction, SimQN offers significant utility for studying quantum componets .

Various proprietary simulations also offer innovative solutions. **AliroNet**, from Aliro company, for instance, includes an emulator capable of utilizing quantum hardware when available. Its comprehensive simulator implements discrete event simulation, multiple quantum state computation backends, generic quantum and classical device components, optical components, noise models, networking concept abstractions, and support classes. Aliro provides emulation, pilot, and deployment modes, facilitating scalability from single-photon experiments to large networks. **Qnetlab**, from Cisco, offers a no-code approach to quantum network simulation, allowing users to construct network topologies and protocol instruction sets through a simple drag-and-drop interface. With its protocol builder tool, it aims to ease the development of quantum network applications by minimizing the learning curve. Despite being proprietary, Qnetlab aspires to become open-source and serve as a platform aggregating multiple quantum simulators.

2.3. Open Challenges and Main Outcomes

Quantum network simulators have gain significant advancement in recent years, yet several challenges persist, crucial for furthering their development and practical application. Among these challenges is the imperative to accurately model quantum physics, errors, and noise, along with the precise timing of operations, considering variations between discrete and continuous approaches. Moreover, ensuring flexibility and modularity in these simulators is essential to enable efficient interaction and configuration, particularly in the context of scaling up to accommodate networks with numerous nodes. In our analysis, only QuISP has shown scalability to create larges networks (more than 100 nodes). Furthermore, the predominant reliance on first-generation quantum network models, lacking error correction or purification implementations, underscores the necessity for advancing to second and third-generation simulators. These iterations would incorporate more sophisticated quantum communication strategies, potentially unlocking new insights and breakthroughs within the field.

Despite these challenges, quantum network simulators have already yielded several noteworthy outcomes. The emergence of open-source platforms like has democratized access to quantum simulation tools, empowering researchers and enthusiasts to explore quantum networking concepts with greater ease. The push towards open-source solutions with comprehensive documentation, exemplified by Cisco's Qnetlab proposal, holds promise in addressing these requirements. Moreover, the inclusion of built-in network components and protocols in simulators such as QuNetSim and QuISP streamlines the simulation process and accelerates the development of quantum communication protocols. These outcomes signal a promising trajectory for quantum network simulation, with ongoing efforts poised to address existing challenges and unlock new possibilities in quantum communication and networking

3. Conclusion and Future Works

In this paper, we have presented a comprehensive overview of various quantum network simulators, discussing their key features, software and network perspectives, and comparing them based on several criteria. These simulators play a crucial role in advancing the field of quantum networking by enabling researchers to simulate and test various quantum network protocols, algorithms, and applications. These criteria help researchers choose the most suitable simulator for their specific needs and research objectives.

For future works, we anticipate the continued evolution and improvement of existing simulators, as well as the development of new simulators that address the emerging challenges and requirements of quantum networking research. Moreover, collaboration between simulator developers, quantum hardware manufacturers, and quantum network researchers is crucial to ensure that simulators remain aligned with the latest advancements in quantum technology.

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