Multiverse: Quantum Optical Network Management

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***Abstract*—This paper presents the software-defined management system of DC-QNet, a quantum network testbed being deployed across multiple distant sites. The system uses a network management system (NMS) to manage the optical network, the classical IP network, and the quantum equipment involved in a quantum networking experiment. The NMS also implements a measurement plane that abstracts the heterogeneity of equipment and measurement complexity. The management system provides the ability to establish optical channels between quantum devices, control the devices, and support an extensible measurement plane that enables the automated setup and execution of experiments. The testbed and its management aim to simplify experiments and improve the efficient management of resources in the development of functional quantum networks.**

***Keywords*—quantum networks; optical networks; network management**

I. Introduction

Quantum networks will interconnect quantum devices by using phenomena resulting from quantum mechanical manipulations, such as entanglement and teleportation. Such networks enhance the power of quantum computing and build distributed applications with unprecedented security and computation capabilities. The devices involved in a quantum network may range from a single-photon source and detector to a fully functional quantum computer with quantum memory and routing capabilities. As quantum computing relies on physical concepts fundamentally different from binary classical computing, interconnecting quantum devices also requires rethinking network abstractions and protocols used so far to address unprecedented challenges for communication such as the destruction of the state of a qubit and any potential entanglement upon measuring it, and the impossibility of creating an identical copy of a given qubit (no-cloning). This makes designing a functional quantum network not simply an extrapolation of classical networks into the quantum world. Hence it requires a continuous effort of experimentation on quantum protocols, models, and devices, in which the collaboration of multiple agencies and companies is necessary. Quantum communications experiments are conducted with equipment that realizes networking operations such as entangled photon generation, single-photon detection, Bell State Measurements (BSM), polarization measurement, and single-qubit storage. Quantum devices are available at different participant sites and interconnected through optical fiber paths. In parallel to the optical/quantum setup, a classical network is required to configure devices, collect measurements, and deliver control messages. Automating such experiments through software helps save time and prevents configuration errors. Particularly, providing a Network Management System (NMS) which allows interconnecting distant devices (via optical fiber), controlling their interactions, and collecting measurements simplifies experiments. Automatically provisioning experiments based on a time schedule will further improve managing resources, as well as collecting and sharing results.

This paper describes DC-QNet, a Washington Metropolitan Quantum Network Research Consortium that will create, demonstrate and operate a quantum network as a regional testbed. This testbed hosts quantum networking experiments across several distant participating sites.

Multiverse is the NMS for DC-QNet that supports the management of a dynamic optical layer, a quantum layer, a classical IP network, and a measurement plane. The testbed and the management system provide an automated environment to set up and conduct quantum network experiments.

In the rest of this paper, Section II discusses the key requirement for the quantum network testbed. Section III presents the DC-QNet testbed design and its abstraction. Section IV presents the architecture of the Multiverse management system for DC-QNet. Section V describes some experiments implemented in DC-QNet using the Multiverse management system. Section VI reports on some related work that adopted a software-defined approach in quantum networks. Section VII concludes this paper and presents some perspectives.

II. Design Requirements

We introduce in the following the rationale behind the design adopted for the testbed network and its management. These design principles are meant to enable a realistic and extensible environment for quantum network experiments.

Quantum devices participating in the testbed provide different quantum capabilities which an experiment may require or not. Some experiments involve more than two devices, and quantum capabilities may not be available at all sites, or when it is needed. Trying to interconnect all sites with fiber in a mesh topology would be too costly and is not reasonable. The testbed architecture must offer a flexible optical layer that connects quantum sites and capabilities with a mix of predefined core paths as well as dynamically provisioned on-demand paths. To provide flexibility in connecting different sites with available equipment, sites are interconnected through a programmable optical network that acts as a physical optical layer of the quantum network to carry quantum information.

The main management task in the testbed is to provision and maintain fiber paths between designated sites as requested by experiments. These fiber paths are used by heterogeneous equipment to send and receive photons. Because of the lossy nature of optical channels and the probabilistic nature of quantum phenomena, path selection should consider multiple criteria such as fiber loss, path length, source power, detector efficiency, and resource availability. Once the paths are established, the quantum experiment that takes place between the nodes consists of a computation distributed among these nodes, which includes multiple attempts to create entanglements, driven by classical network communications and measurements. Therefore, coordinating experiments from fiber path provision to results need an entity that oversees testbed resources and protocols.

To develop a uniform management plane for the heterogeneous equipment that forms the testbed, the quantum network model needs to be technology agnostic and needs to work with quantum capabilities that are abstractions of the physical layer entities used to realize the physics of quantum mechanics concepts such as entanglement, teleportation, qubits, quantum memories, and so on.

III. Testbed Architecture

The DC-QNet quantum optical network testbed is built around an optical network layer which interconnects quantum nodes hosted by the participating sites. A generic quantum node architecture is defined which includes optical and classical connectivity, alongside a network operating system and a management agent (see Figure 1).

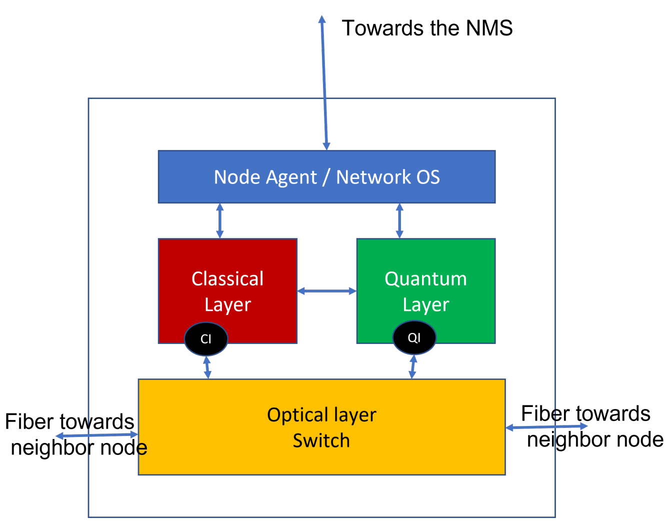

Fig. 1. Generic quantum node architecture

We introduce in the following the main components of the network architecture.

A. Optical network

The optical network is the physical layer of the network model adopted for the testbed architecture. The optical network is built with passive network elements (optical cross-connect switches) to provide fiber paths between quantum capabilities. The quantum capabilities are interconnected through optical paths dynamically established by the NMS. These interconnections form a circuit-switched network at the optical layer. The optical network supports the high-fidelity transmission of quantum states using photonic qubits and provides an environment where critical quantum resources are made accessible to network users and can be reallocated for various applications/experiments. The testbed includes 6 sites.

The distances between the sites and the quantum network layer sensitivity to optical loss made choosing a ring topology difficult despite its simplicity and ease of use. The geographic location of the different sites enabled the selection of a hub that includes two nodes and each site aims to lease 2 fiber pairs to end up with a star topology (or a hub-and-spoke). 8-port OXC (optical cross-connect) switches were selected to realize the desired optical topology that will enable the quantum network layer. This topology is shown in Figure 2.

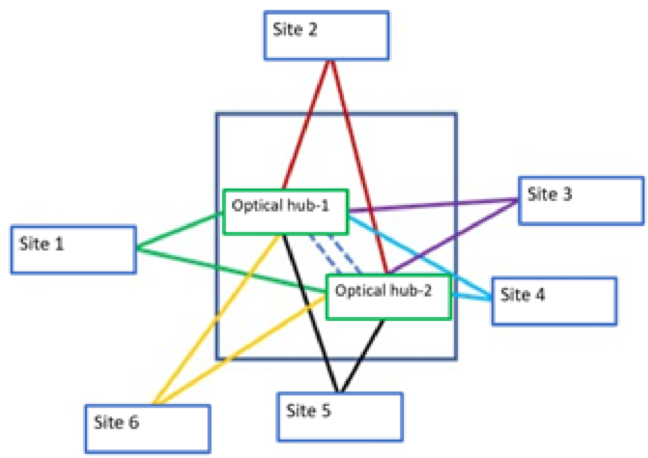

Fig. 2. Testbed logical quantum optical topology (classical not shown)

B. Quantum network

The quantum layer is formed of equipment providing quantum capabilities to the testbed including memories, sources, detectors, and Bell State Measurement (BSM) modules.

Quantum nodes are the equivalent of the network elements in a classical network. The management system assumes that these quantum nodes are equipped with quantum memories with a configurable number of qubits used to build quantum links described below. The management also assumes that these nodes can perform certain quantum operations such as entanglement and teleportation on their qubits. These nodes are also interconnected through a classical network and can exchange classical information. To build scalable and efficient topologies these nodes require multiple optical ports.

Quantum repeaters are special quantum nodes capable of performing long-distance entanglements via quantum swapping.

Quantum channels are the optical paths provided by the optical network layer to the quantum network layer to interconnect quantum nodes and exchange quantum information. These optical paths are called quantum channels in the quantum network layer. Quantum channels are inherently lossy and are subject to nonlinear effects of the fiber so that the success rate of each entanglement attempt decreases exponentially with the physical length of the quantum channel. Qubits are bound to quantum channels on each end uniquely before attempting entanglement. A qubit can be bound to a quantum channel at each end using the NMS. A quantum channel with assigned qubits on each end is called a bound quantum channel. To create a **Quantum link**, two nodes connected by a bound quantum channel make several entanglement attempts until success. Notice that we can have multiple quantum links between a pair of quantum nodes. The number of quantum links that can be built between two nodes connected by a quantum channel is limited by the number of qubit-pairs available on them. The functionality of the quantum link layer is to generate entanglements between neighboring quantum nodes, provide quantum gates that encode information in entangled states, and perform quantum error correction (QEC). The quantum network requires abstraction of the hardware to deal with heterogeneity of used equipment. For example, there are different equipment set up to create an entanglement; either spontaneous parametric down-conversion (SPDC) with one source, or atom-atom with a source at each endpoint and a BSM in the middle point. Even when the device type is the same, differences still exist. For example, two quantum receivers may use time taggers from different vendors that have different APIs and data formats. Therefore, the quantum layer model should be used without detailed knowledge of the physics of the devices. Whilst hiding physical details is necessary, it is also useful to allow enough flexibility for the experimenter in composing ephemeral devices (e.g., repeater) and set up (e.g., one hop entangle link) to (re-)use in experiments. This abstraction-composition requirement is addressed by the measurement capability platform, in which capability messages describe each measurement or action supported by a device, and how it should be requested. A specification message is derived from a capability, completed with parameters, and sent to the advertiser of the capability. The quantum network can host experiments for entanglement generation and distribution, swapping, and quantum state teleportation.

C. Time synchronization

Quantum communications require single-photon counting and time-tagging at a time scale of picoseconds. For example, an entanglement generation requires to be accurately coordinated between the two endpoints of a link. This requires a more accurate synchronization than is usually seen in classical networks with Network Time Protocol (NTP) and Precise Time Protocol (PTP). Detectors are connected to time taggers that record photon arrival at the picosecond level, time taggers are synchronized with White Rabbit (WR) technology. The WR protocol provides a pulse-per-second signal to time taggers. Time taggers are not designed to collect absolute time (TAI). Therefore, we systematically include a PTP synchronization in the agents that provide quantum capabilities, such as time taggers and detectors/analyzers. Time tagging is also a capability attached to a single-photon detector, through which one can ask for a time tags stream.

D. Classical management plane

Each quantum device and each optical switch is connected to a classical IP network, from which it is reachable from the NMS. The classical network represents the management and control plane of the testbed. Basic management capabilities of the classical network are included in the NMS.

Figure 3 illustrates the layered quantum node architecture including the time synchronization layer, the data plane, the management plane, the control plane, and the measurement plane.

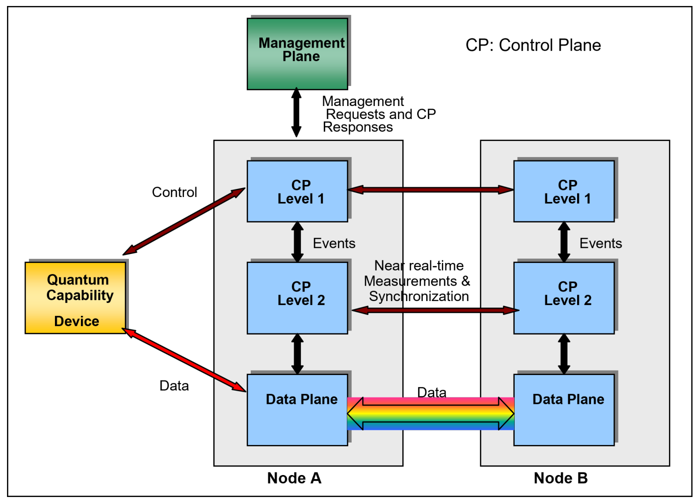

Fig. 3. Layered quantum node architecture

IV. Management System Architecture

An NMS has been developed to manage the testbed. The NMS includes a management plane for the classical network and the optical quantum network, and a measurement plane used for monitoring the network as well as collecting experiments measurements. Thanks to the capability platform, equipment details and the different APIs they use are hidden to the NMS, which only sees capabilities in a uniform message format, which describe the measurement or action and how it should be requested.

The NMS is an entity supporting manual user-driven management or semi-automated management. It is built with a flexible microservice architecture and is composed of the following components (see Figure 4):

Inventory Service stores network desired configuration, running state and topology. It includes a full model for optical networks that supports OXCs and a service to establish cross-connects for optical paths. It also includes an abstracted model for quantum nodes, quantum links, and qubits. It exposes an

API to create the testbed topology (optical layer, quantum layer, and classical network), and stores the status of the different network elements and resources (optical paths, quantum resources, etc.). Model objects in Inventory Service are protocol-agnostic representations of various network elements and concepts described below.

Optical Connection Service (OC) interacts with the optical switches to interconnect quantum nodes through optical paths. It exposes an API to create and delete optical paths for experiment setup and stores request specifications as the desired state for resources. The service supports the setup and the release of Permanent Optical Circuits (POCs). The user may establish an optical path manually by selecting cross-connects at each node on the path or having the NMS determine a suitable path between a source and a target quantum node. The Q-optical object model consists of OXC, Optical Link Termination Point (LTP) for fiber-based cross-connects and defines multiple Connection Termination Points (CTPs) over each LTP to support wavelength-based cross-connects if needed.

Quantum Network Configuration Service (QNC) interacts with the quantum nodes to manage quantum resources; namely enable/disable source, bind/unbind qubits, and create/destroy quantum links (attempt entanglements). The QNC service exposes an API to invoke these operations and stores request specifications. The QNC object model includes QSource, QReceiver, BSM, QMemory, Optical LTP, CTP, and Qubit. A Qubit can be used on an optical path (resp. wavelength) by binding it to the corresponding LTP (resp. CTP).

Classical Network Control Service (CNC) interacts with the classical IP switches which carry the control plane of the optical and quantum networks. This component exposes an API necessary for configuring and managing an IP network. The object model includes common IP network concepts such IP address configuration, VLANs, BGP, and static routes.

Measurement Service implements the measurement protocol over which the NMS interacts with quantum devices. This service allows the NMS to discover quantum capabilities advertised from quantum devices, then request measurements as needed, and collect the results. Some measurements, such as polarization measurement for entanglement, require alternating between measurements and actuation (but entanglement can be measured with BSM). Therefore, the capability platform can also be used to describe, discover, and request commands and configurations for equipment.

Experiment manager It interacts with all the above components to handle user-defined experiment scenarios. The experiment scenario includes start/end times, requested capabilities, resources to provision (fiber paths, qubits, etc.), and the measurement to perform.

Figure 5 shows a screenshot of the Multiverse UI.

V. Experiments Use Cases

This section describes the three main experiments deployed on the testbed: photon counts and coincidence detection, entanglement distribution, and fiber stabilization.

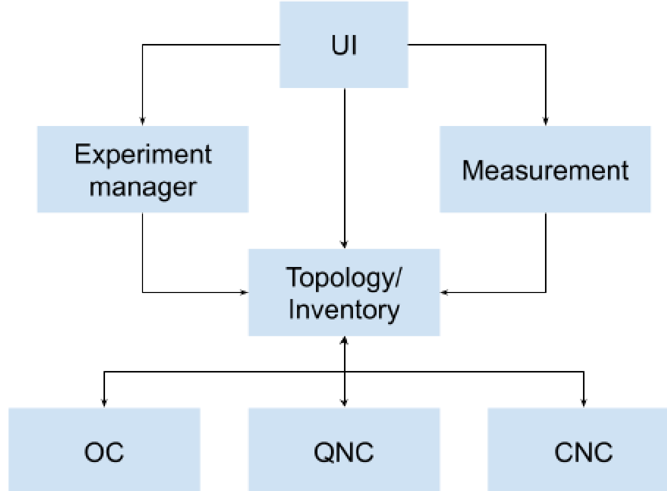

Fig. 4. Management system architecture

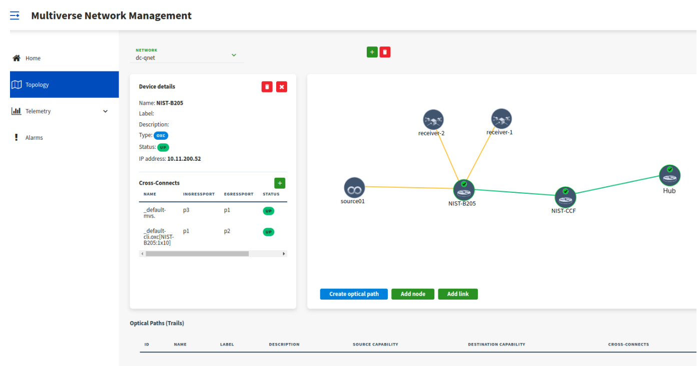

Fig. 5. Multiverse UI

A. Coincidence detection

This experiment involves the optical layer and is fundamental for entanglement distribution. The experiment consists of a quantum node, Alice, which holds the source, one detector unit, and one time tagger. Two other nodes, Bob and Charlie, are in separate locations from Alice and each other with their detector and time tagger. Alice and Bob are connected through a fiber link, as well as Alice and Charlie. The three nodes are time-synchronized and are capable of reporting photon detection events. The experiment's objective is to recover coincident photon detection events between Alice-Bob and Alice-Charlie alternatively. The optical paths between Alice and Bob (resp. Alice and Charlie) are dynamically created through the OC service. Measurements are obtained through the measurement plane. Each node has a probe agent which interfaces with its time-tagger to read photon-counting events. The coincidence detection processing is based on time-tagged photon detections reported by each Alice, Bob, and Charlie. This processing is provided by an analyzer (coordinator agent) on which the scientists define their analysis scripts and parameters. Figure 6 illustrates the experiment setup.

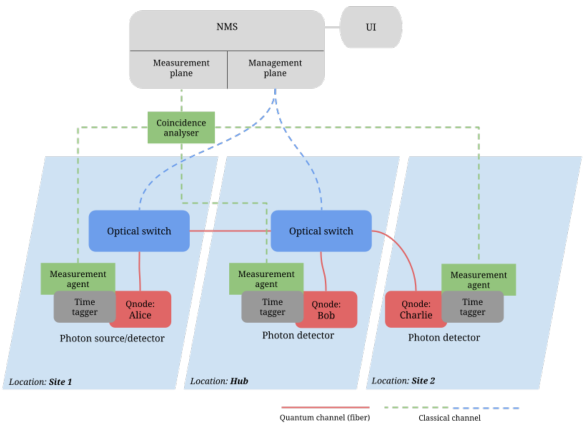

Fig. 6. Coincidence detection experiment

B. Entanglement distribution

Using the photon detection and coincidence analysis capabilities used in the first experiment, the entanglement distribution can be demonstrated by adding an additional capability: polarization plate rotation control which allows measuring the polarization of the quantum state of a received photon. In this experiment, the source (Alice) sends pairs of polarization-entangled photons, each on a wavelength. The output signal is demultiplexed and the two-output links are connected to the optical network. Additionally, each of Bob and Charlie includes a polarization rotation plate, and two optical paths are created in parallel: one from Alice (the source) to Bob and the other from Alice to Charlie. The analyzer collects photon coincidence from Bob and Charlie for different polarization plate degrees. Figure 7 illustrates the experimental setup.

C. Optical fiber stabilization

Optical fiber polarization state compensation is an important aspect of optical fiber quantum communications to ensure the stability and purity of the polarization state of the light signal. Fiber polarization state compensation is achieved by monitoring and adjusting the polarization of the light signal in near real time. In this experiment, a source node Alice produces entangled photon pairs. The signal and idler photons are sent to two receivers, Alice receives the idler photons locally while the signal photons are transmitted through an optical fiber path to Bob. The two receivers randomly measure the polarization of each photon. The polarization state of the photons is adjusted using the polarization controller to a desired value and then sent through the optical fiber. The polarization state of the light at the output is measured, and changes in the polarization state are induced by varying environmental conditions such as temperature or mechanical stress. The stabilization process

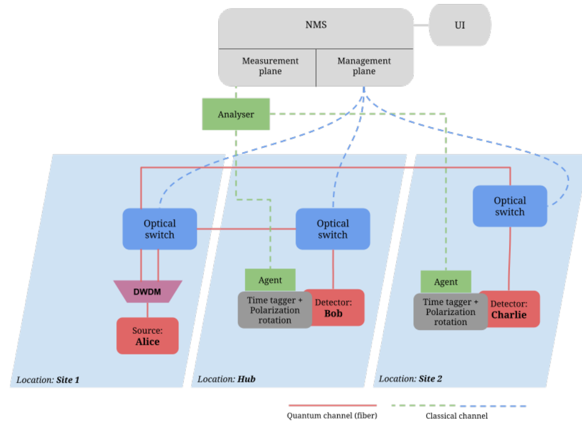

Fig. 7. Entanglement distribution experiment

is then performed using the polarization controller, and the polarization state of the light is measured again at the output. Figure 8 illustrates the experimental setup.

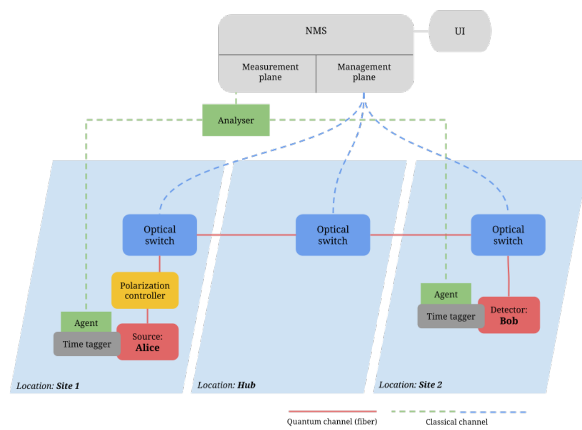

Fig. 8. Fiber stabilization experiment

VI. Related Work

Quantum communication studies such as routing assume that a communication always involves two quantum nodes directly connected with an optical fiber link. This is not the common case in a testbed when different participating sites in geographically distant areas need to be interconnected on-demand over the optical infrastructure. Therefore, a management and control software is necessary for the experimental quantum communications.

Software-defined quantum networks are considered by many studies. Authors in[1] consider using popular SDN control protocols such as OpenFlow to carry quantum metadata such as quantum channel identifier, equipment parameters. The controller instructs devices about how metadata should be forwarded. Work in[2] extends the approach into the control of quantum communications. Unlike the DC-Qnet testbed, these designs consider networks with monolithic and fully-fledged devices. Hence, they do not deal with equipment heterogeneity and the necessity of their composition, required in experiments.

The SDN paradigm is adopted to manage a QKD network in[3] and[4] with a practical deployment. Researchers in[5] designed an architecture based on wavelength-selective switching (WSS) to efficiently connect different equipment, like our approach with OXCs.

VII. Conclusion and Perspectives

The development of quantum networks is a complex task that requires a continuous effort of experimentation on quantum protocols and devices. A management system has been developed to automate quantum networking experiments in the DC-QNet testbed across several distant participating sites. The current design supports a basic testbed infrastructure, but several improvements are possible.

Wavelength-selective switching (WSS) will further increase optical layer connectivity by allowing cross-connect wavelengths within a fiber link. This will also prevent deploying DWDM for multiplexing and demultiplexing wavelengths. Our network model already supports wavelength cross-connects, and the deployment of WSS is planned in future versions of the testbed. Currently, fiber optical interconnections form a circuit-switched network, but a packet-switched approach is also possible in theory. The packet-switched architecture will combine a classical header encoded using bits with a quantum state encoded using qubits to form a quantum datagram at the optical transmitter. This quantum datagram is forwarded from switch to switch with the classical header read and re-written at each switch to accommodate the route until it reaches the destination receiver that will process the classical header and deliver the quantum state to a quantum memory or a quantum detector element. The quantum datagram architecture requires the most integration between the optical and the quantum layers.

Some design decisions such as a detailed network stack model require experimenting with quantum equipment that is either not available or difficult to manage. Therefore, quantum simulations/emulations are being developed as part of the management system to evaluate the advanced aspects of the quantum network.

Disclaimer

Certain equipment, instruments, software, or materials, commercial or non-commercial, are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement of any product or service by NIST, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

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