Quantum Wrapper Networking

S. J. Ben Yoo, Sandeep Kumar Singh, Mehmet Berkay On, Gamze Gül, Gregory S. Kanter, Roberto Proietti, and Prem Kumar

The authors propose Quantum Wrapper as a novel networking technology that enables simultaneous control, management, and operation of quantum networks that coexist with classical networks.

Abstract

We propose Quantum Wrapper as a novel networking technology that enables simultaneous control, management, and operation of quantum networks that coexist with classical networks. The quantum wrapper networks enable the transparent and interoperable transportation of quantum wrapper datagrams consisting of quantum payloads and, notably, classical headers, to facilitate the datagram switching without measuring or disturbing the qubits of the quantum payload. Furthermore, quantum wrapper networks can utilize the common network control and management for performance monitoring on the classical header, and infer the quantum channel quality.

Introduction

The quantum internet [1] opens up truly fascinating opportunities for connecting any places on the Earth's surface using quantum entanglement. Recent progress in quantum technologies, encompassing quantum sources, repeaters, processors, memory systems, detectors, and other components, shows great promise [2–4]. Once quantum computers become available, they will possess the capability to solve exponentially complex problems that classical computers struggle with. Consequently, the challenge arises of interconnecting quantum nodes and network devices that possess quantum state processing and storage capabilities, alongside effectively managing the infrastructure of a quantum network for secure communication and distributed computing.

Quantum Networks (QNs) could utilize existing fiber-optic infrastructure, as demonstrated in quantum key distribution and entanglement distribution networks [5–7], employing low-loss classical and quantum devices alongside communication protocols. However, despite advancements in quantum computing, networking, and related device technologies, the realization of a quantum internet remains distant. The delicate nature of quantum information, encompassing quantum bits and entanglement, poses challenges as the fundamental principles of quantum mechanics prohibit the necessary measurements for monitoring and management of networks. Nevertheless, the qubits need to be transported while preserving their integrity and transmission quality. Moreover, when quantum networking technology becomes available, our past experiences indicate the need for a carefully planned strategy to ensure successful transitions from classical networks to interoperable quantum networks. The development and deployment of quantum networks raise numerous new and challenging questions for consideration:

- How do you place a control plane on QNs?
- How do you manage QNs?
- How do you monitor the performance of QNs?
- How do you achieve transport in QNs?
- How do you switch and route in QNs?

Furthermore, even if we successfully address the aforementioned challenges, the prospect of dismantling existing classical networks to build a new quantum network seems unfeasible. Hence, it is imperative to develop a quantum network that can be deployed either independently or in conjunction with the existing classical network while maintaining backward compatibility.

Quantum Wrapper Networking Architecture And Protocols

We propose "Quantum Wrapper" (QW) as a networking technology, as discussed briefly in [8], that can enable quantum networking on existing networking infrastructure, backward compatibility, transparency, and interoperability while transporting the quantum information. Figure 1 depicts the Quantum Wrapper architecture, wherein the Quantum Wrapper Datagram is composed of the QW Header and the optional QW Tail in the form of classical bits. The classical headers and tail bits wrap the payloads (qubits). The header and tail help the transport of quantum payloads to their intended destinations. These payloads contain network control and management information such as routing, multiplexing, timing, formatting, and so on.

The fundamental concept of quantum wrapper technology is inspired by the architecture and protocols of the Optical Label Switching (OLS) [9]. OLS employs a standardized optical label format, such as a 40-bit label at a rate of 1 Gb/s, to transport and switch data payloads of various formats and protocols while offering switching at different granularity. The QW will utilize a similar header format, while the quantum payload can be in an arbitrary physical format like time-bin, frequency-bin, polarization-entangled, and so on. The QW supports both discrete-variable (DV) and continuous-variable (CV) qubits as the quantum payload. Further, the QW payload can also contain the low photon coherent states commonly used in QKD.

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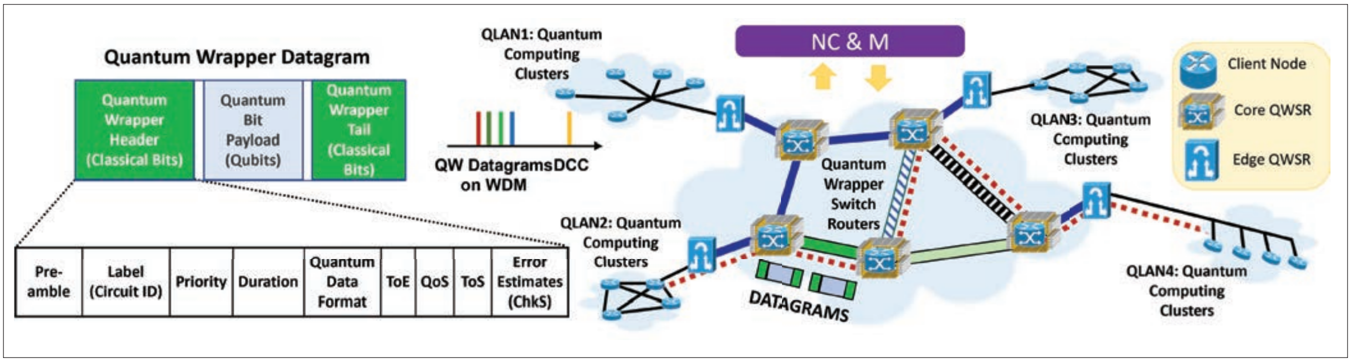

FIGURE 1. A schematic of quantum wrapper networking. The quantum information is transmitted using a structure called the Quantum Wrapper Datagram. Each datagram consists of three components: the Quantum Wrapper Header and Tail, which contain classical bits, and the Quantum Wrapper Payload, carrying the quantum bits. Quantum Wrapper Switches forward these datagrams while utilizing the quantum wrapper headers and the data communication channel (DCC). The edge nodes in the quantum wrapper network serve as interfaces for network clients and add Quantum Wrappers to the quantum payloads through time-multiplexing. A critical functionality of the Quantum Wrapper Switches is the ability to replace an old Quantum Wrapper with a new one while retaining the same qubit payload. The Quantum Wrapper Header comprises various fields required for reliable transportation of qubits.

Figure 1 presents an example of the header format. We expect QW to support various classes of services and data formats. Thus, the qubit payloads can be of variable size — from hundreds of kilo-qubits to giga-qubits. To incorporate the quantum payloads of variable size depending on the application, QW allows MPLS (Multi-Protocol Label Switching)-like switching and traffic engineering. We also reserve some experimental bits in QW for future optical packet switching. The QW can coexist with classical data communication channels by wavelength division multiplexing (WDM) and supports control and management plane communications for software-defined networks (SDN). We note that when high-rate unsynchronized WDM classical data channels coexist with quantum channels, issues, such as noise and crosstalk need to be considered [10]. While also classical, the QW header is temporally separated from the quantum payload, which helps to mitigate such noise issues.

As we will discuss further in more detail, QW networking has the following key approaches to address the challenging questions mentioned earlier:

- QW networking uses Classical Quantum Wrappers for transport, switching, and routing in the quantum network without reading the Quantum Data Payload (qubits) until the qubit receiver.
- QW networking uses classical bits in the Wrapper to conduct optical performance monitoring to infer Signal-to-Noise-Ratio (SNR), QoT, Dispersion, Polarization Mode Dispersion (PMD), and so on, without touching the qubits.
- QW networking supports data payload of any protocol and format.
- QW networking achieves full compatibility with Software Defined Networking (SDN).
- QW networking achieves interoperability and backward-compatibility with existing or legacy telecom protocols: Ethernet, OTN, MPLS, and so on.
- QW networking requires no strict synchronization of the network. QW can be used for timing synchronization or polarization stabilization.
- QW networking exploits much of the existing control plane protocols to allow backward compatibility and seamless upgrades from today's networks to the future quantum internet.

Next, we propose some key ideas and components — from devices to protocols — required for a full-blown quantum wrapper network and highlight some preliminary experimental progress to attain them.

Quantum Wrapper Switching Routers

QW Switching Routers (QWSRs) are interface devices that employ quantum-aware optical frontend and QW network interface card (QWNIC) electronics. QWSRs at the edge transmit and receive the QW datagrams. A QWNIC is equipped with optical transceivers to generate and analyze the headers. Additionally, it communicates with the quantum local area network (QLAN) clients. Either individual QLAN clients can generate the quantum payloads or request from QWSR. A QWSR can employ quantum sources such as attenuated coherent light-based or entangled photon pair-based sources. On the other hand, QWSR at the core performs packet switching for QW datagrams as shown in Fig. 2a. QWSRs in Fig. 1 may consist of a lookup table with controllers that interface with network control and management (NC&M), an optical switch fabric, and QW swapping modules each of which consists of 1 × 2 switches, fiber delay line(s), and a QW generator. Figure 2b shows an example of a time-multiplexed packetized transmission of the QW header and tail with qubit payload. The QW datagrams utilize guard time between the header(tail) and the payload to account for 1 × 2 optical switch rise (fall) time. The QW swapping mechanism of the qubit payload is also shown. The QW header swapping module replaces the old header and wraps the delayed quantum payload again with a new header. As in multi-purpose label switching networks, this type of QW header swapping mechanism can offer the scalability of a label-switched network (e.g., MPLS and OTN). Further, QWSR can employ single photon detectors and necessary optical devices for Bell state measurements. Therefore, entanglement between the quantum payloads can be swapped. QWSR exploits much of the control plane and data plane technologies already demonstrated in Optical Label Switching Routers [9], where AWGR-based wavelength routing switching fabric will be replaced by transparent switches.

The Quantum Wrapper based quantum networking is especially exciting not only because it offers a rich set of attribute-based networking encoded on the wrapper frame bits (labels), but because it also offers a means to conduct real-time optical performance monitoring.

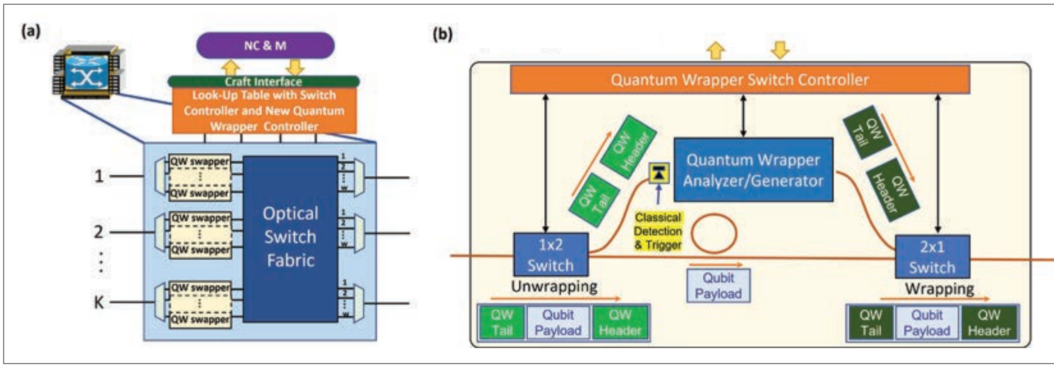

FIGURE 2. a) quantum Wrapper Switching Router consists of QW swapping modules with an optical switch fabric; b) a QW swapping module consists of a lookup table with controllers that interface with NC&M, 1 × 2 and 2 × 1 switches, fiber delay line(s), and a QW generator. A 1 × 2 switch unwraps the header and tail for classical detection and triggers for switching and new wrapper generation. Meanwhile, the polarization-entangled Qubits payload is delayed. Again, a 2 × 1 switch wraps the Qubit payload with a new QW header and tail and directs the new datagram to the optical switching fabric.

Control Plane for QW Networks

To create a software-controlled quantum wrapper network, an out-of-band data communication channel can be utilized for control information exchange between Quantum Nodes and the control and management system. Additionally, an in-band signaling can be used within the Quantum Wrapper for datagram communication and datagram forwarding. It can help manage network communication, forward table updates, and reconfigure programmable network elements. The management system can collaborate with the network control plane for QW label distribution and forwarding table updates.

Monitoring in QW Networks

Networks require a service plane, a management plane, a control plane, and a data plane. The management plane governs the devices in the network and the state of those devices, for example, power, configuration, operational readiness, and so on. The management plane has five main roles [4]: performance management, fault management, configuration management, security management, and accounting management. Monitoring is an essential function for the proper management and operation of any network. In the classical hardware-defined networks, nearly all the monitoring functions took place in the electronics such as linecards, electronic switches, routers, terminals, etc. These network interface elements check the signal integrity, framing errors, bit errors, address errors, and feed such information to the management plane for conducting the five roles mentioned above.

In a classical optical software-defined network (SDN), the optical monitoring functions become very difficult if transparent end-to-end connections are desired. For the proposed quantum optical networks with SDN control planes, we expect to find even more significant challenges due to the quantum nature of the qubits. One solution to this challenge is to employ the Quantum Wrapper protocol discussed above. The proposed method differs from previous publication [11] in that it offers interoperability with packet, burst, flow, and circuit switching while engaging a centralized control plane like SDNs as well as distributed control planes as in IP networks. Additionally, monitoring with QW's allows for the link health to be estimated using classical signals, as opposed to the use of quantum-parameters like qBER.

Monitoring the classical bits in the framing bits of a Quantum Wrapper can allow inferred monitoring of the qubit payload. For instance, the framing bits can include source, destination, traffic engineering, check-sum, and so on, and offer information pertaining to *what type of packets are going from where to where with what type of service (ToS), class-of-service (CoS), and quality-of-service (QoS)*, and detecting these framing bits electrically and optically will offer optical wavelength monitoring, optical signal-to-noise monitoring, and bit-error-rate (BER) estimations.

The Quantum Wrapper based quantum networking is especially exciting not only because it offers a rich set of attribute-based networking encoded on the wrapper frame bits (labels), but because it also offers a means to conduct real-time optical performance monitoring. This allows maintaining the required quality of service (QoS) and high level of performance even for signals that experience time-varying physical layer impairments (QoS-aware and impairment-responsive networking) [12]. Here, we can encode supervisory channel information at low speed (e.g., 1.25 Gb/s) in the Wrapper that precedes in time relative to the qubit data payload. Since the data and the supervisory channel signal follow that same path, many characteristics of the quantum and classical channels would be the same or highly correlated, for example, loss, PMD (under time-multiplexing of header and payload on the same wavelength), chromatic dispersion, and polarization-dependent loss. This affords the opportunity to use the classical channel to monitor such properties, giving insight into the quantum channel integrity. Thus, by incorporating the supervisory channel BER measurement in the control plane distributed over the network, one can map the link state condition across the network and adjust the physical layer parameters.

There are, however, many things that can affect the fidelity of the qubits may not manifest themselves in the supervisory channel. For example, 10^{-2} noise photons/ns will not show up in the classical channel but they can destroy most of the quantum channels. Nevertheless, the ability to periodically send an empty "supervisory" packet containing attenuated coherent-state (including vacuum state) light would allow the actual quan-

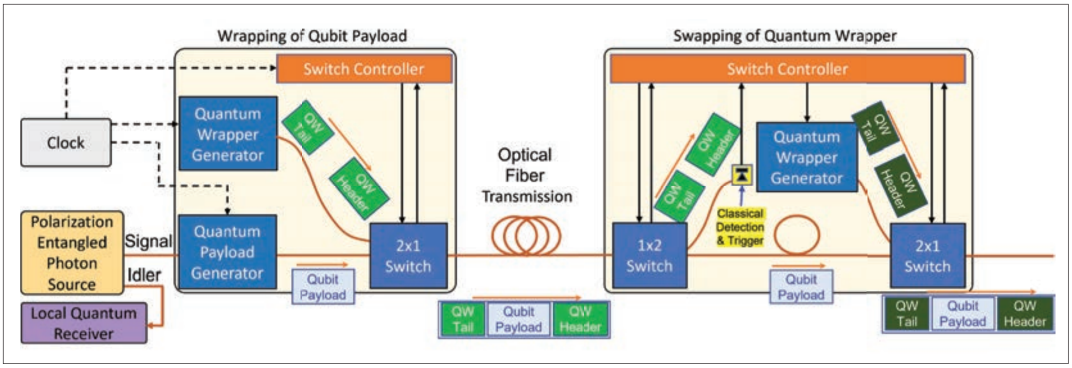

FIGURE 3. A schematic of the transmission of quantum wrapper datagrams on a point-to-point optical fiber link. An Entangled Photon Pair Transmitter generates signal and idler pair photons. A Qubit payload consists of packetized entangled signal photons. A Quantum Wrapper Generator generates classical Header and Tail bits. A 2 × 1 Switch wraps the payload with the help of a switch controller by a synchronized clock. At the reception, a 1 × 2 Switch unwraps QW header and tail from the received Qubit payload with the help of a recovered clock.

Most advanced quantum networks will rely at least in part on the distribution of quantum entanglement, as entangled states are a critical requirement for functions like teleportation, quantum-enhanced long baseline interferometers, distributed sensing, and distributed computing.

tum equipment (single photon detector, quantum memory, etc.) to make quality measurements pertinent to the qubit system. This kind of measurement can reveal details of the quantum channel and the quantum component performance relatively quickly and in a controlled way.

TCP/IP for QW Networks

The Transport Control Protocol over Internet Protocol (TCP/IP) has been used in classical Internet to facilitate the reliable end-to-end transmission of data. In quantum wrapper networks, the TCP/IP can be implemented by incorporating windowing technique, congestion control mechanism, and header fields such as synchronization (SYN), acknowledgment (ACK) or negative acknowledgment (NACK), and time-to-live (TTL), among other functions in the Quantum Wrapper. QW allows the header monitoring to send the ACK/NACK upon receiving the QW header or time out. Again, these functionalities are accomplished without reading the qubit payload.

Quantum Entanglement Distribution

Most advanced quantum networks will rely at least in part on the distribution of quantum entanglement, as entangled states are a critical requirement for functions like teleportation, quantum-enhanced long baseline interferometers, distributed sensing, and distributed computing. Despite some advances in quantum entanglement distribution technology [13], the deployment is limited by the stringent coherence times requirements, among others. With the use of the quantum wrapper, the distribution of quantum payloads with either CV or DV entanglement is possible between a pair of quantum nodes. The quantum wrapper could be utilized to assure entanglement distribution between the requesting node pairs with the highest entanglement fidelity possible.

Quantum Repeaters

Distributing quantum information, including entanglement, over a long distance is challenging due to fiber channel loss. Furthermore, the fundamental properties of quantum mechanics forbid qubits to be copied and duplicated (amplified), which has hindered the development of so-called quantum optical amplifiers, popularly known as quantum repeaters. While the transportation or teleportation of photonic qubits, which contain quantum information, across network nodes poses challenges, recent progress in quantum repeater concepts shows promise [14]. As the repeaters can extend the utility and distribution of the entangled light, QW can employ the repeaters for these benefits. The information in the QW can furthermore potentially be used to help control the repeater, for instance including the option to bypass the repeater if the quantum signal (e.g., wavelength) is not compatible with it.

Preliminary Experiments For Quantum Wrapper Networking

We performed preliminary point-to-point QW datagram transmission experiments to gain insight into the feasibility of QW networking [15]. Further, we extended the testbed to a three-node network with a single source node connected to two distinct destination nodes via a QWSR node. In the preliminary experiments, classical headers and quantum payloads occupy different wavelength channels and passive wavelength-division (de)multiplexing devices (un)wrap QW datagrams instead of the low-loss nanosecond switches in Fig. 3. Commercial DWDM small-form-factor pluggables transmit and receive the QW headers, which are 58.85 ms long at 1561.42 nm for 10 Gb/s data rate. The QW payloads are 149.12 ms long at 1574 nm. The experimental QW header consists of a clock-data recovery pilot sequence, a payload destination ID, a payload duration, a pseudo-random bit sequence for bit-error-rate testing and header start (stop) identifier sequences.

To realize the Qubit payload transmitter, we used a polarization-entangled photon pair source that generates signal photons in the L-band and *idler* photons in the C-band at the quantum state of

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|HV\rangle + |VH\rangle).$$

We recorded QW header BER and the coincidence-to-accidental ratio (CAR) at each destination node. CAR represents the quality of the quantum channel, as the ratio of coincidence counts to accidental counts. A single-photon avalanche diode receives the QW payloads and a time-to-digital converter circuit digitizes the photon arrival time for coincidence counts (CC) measurements.

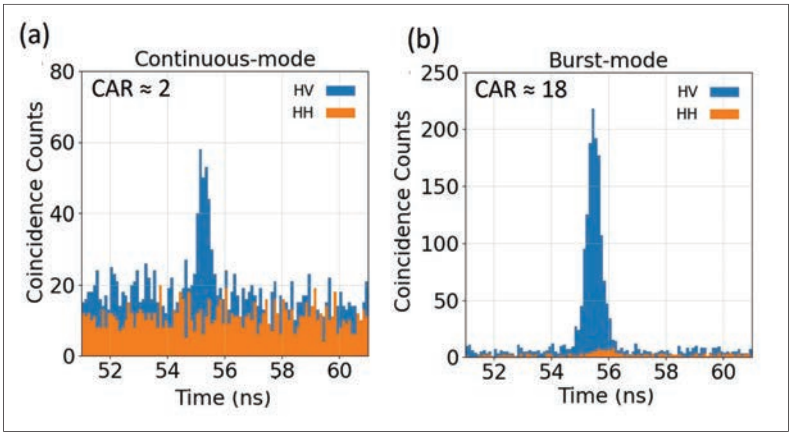

FIGURE 4. a) Coincidence counts with WDM continuos-mode headers; b) Coincidence counts with WDM burst-mode headers [15]. H anv V stand for horizontal and vertical polarization axes.

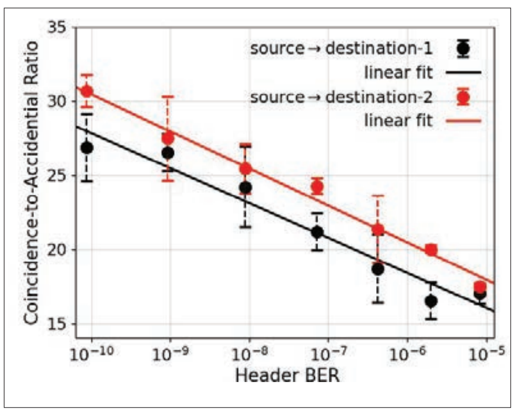

FIGURE 5. Correlation of quantum payload CAR and Header BER measured at the QWSR.

Figure 4 shows CC aggregated in 100 seconds for continuous and burst mode QW headers with ~ 10 m fiber link. We observed that the CAR of the quantum channel degrades significantly to 2, if we utilize continuous headers due to the limited channel isolation of the demultiplexing WDM device. However, by time-division multiplexing the burst-mode headers and packetized quantum payloads, the CAR recovers to 18 [15]. Further, with a three-node experiment, we also performed a relatively long-distance transmission of 20 km, for two distinct destinations. We observed a CAR of 15 and 20 for destination-1 and destination-2 respectively. Finally, Fig. 5 depicts the relation between the QW header BER and the QW payload CAR. To this end, we replaced the fiber spools with variable optical attenuators and altered the source-to-QWSR link loss by 0.5 dB at each step. Intuitively, increasing the attenuation in the channel degrades the QW header's SNR and causes higher BER; similarly, the CAR as *Quantum SNR* decreases with increasing channel attenuation. We conclude that the QW header's BER can infer QW payload CAR under wavelength-independent link losses. Therefore, quantum channel quality can be monitored by QW headers without directly measuring the qubits.

Conclusions and Future Directions

We introduced a new concept of Quantum Wrapper Networking, which facilitates quantum networks to co-exist with classical networks. Furthermore, a common network control, management, and performance monitoring framework can be used for both classical and quantum networks. Through some preliminary experiments, we demonstrated packetized transmission of the quantum wrapper datagrams. We observed that it is possible to monitor the quantum channel quality without measuring qubits with the help of quantum wrapper bits.

As this article highlighted, there are many challenges in realizing quantum networks — from the application layer to the physical layer. Thus, we need to come up with innovative solutions. Especially in quantum wrapper networks, the development of a software-control and management switching the quantum payloads when a specific quantum wrapper header is detected is key. Although using quantum wrapper headers to monitor quantum channels is interesting, the qubit entanglement fidelity depends on many factors, including quantum noise, which will not be detected by the quantum wrapper bits. Furthermore, developing timing synchronization and polarization stabilization techniques using quantum wrapper bits would facilitate the deployment of quantum wrapper networks paving the way toward the future quantum internet.

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