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Experimental Demonstration of Correlation between Copropagating Quantum and Classical Bits for Quantum Wrapper Networking

Sandeep Kumar Singh(1), Mehmet Berkay On(1), Roberto Proietti(2), Gregory S. Kanter(3), Prem Kumar(3), S. J. Ben Yoo(1)

(1) University of California, Davis, CA, 95616, USA {sansingh, mbon, sbyoo}@ucdavis.edu
(2) Politecnico di Torino, Turin, Italy roberto.proietti@polito.it
(3) Northwestern University, Evanston, IL 60208, USA, {gregory.kanter, kumarp}@northwestern.edu

Abstract *We demonstrate the correlation between co-propagating classical and quantum bits for a quantum wrapper networking. The preliminary experiment shows the visibility of >75% for the quantum bits and the bit error rate <5E-7 for the classical bits.*

Introduction

Quantum networks enable transmission of entangled (correlated) quantum bits (qubits) encoded into photonic degrees of freedom, e. g., polarization[1]–[5]. In addition, the security of qubits is enhanced compared to classical bits encrypted by theoretical algorithms thanks to properties such as qubits cannot be amplified, duplicated, or measured without altering them. However, future quantum networks need to imitate the functionality of the classical Internet, which is challenging due to the lack of quantum devices for buffering, amplification, routing, transport control, and network management protocols.

There has been some recent technological progress toward the development of quantum devices and protocols[6]–[11]. In particular, quantum memories[12]–[14] and entanglement swapping in repeaters[15]–[17], as well as quantum communication protocols[9],[18] inspired by the classical transport control protocol and Internet protocol (TCP/IP), are essential development toward realizing the quantum Internet.

Nevertheless, we need new architectures, protocols and technologies that does not require overhauling today's networks while transporting, monitoring and switching fragile qubits over coexisting quantum-classical network links. A recently proposed quantum wrapper networking (QWN)[19] technology can enable quantum networking on today's networking platform and facilitate seamless upgrade from the incumbent to the new with interoperability. In QWN, the quantum payload (qubits) is wrapped with classical bits as a header. The classical bits facilitate end-to-end transport of the quantum payload without having to read or alter the quantum data payload at intermediate switches and routers. Thus, finding the correlation between the co-propagated classical wrapper bits and quantum bits payload is the key for QWN to guarantee some level of Quality of Transmission (QoT) assurances.

In this paper, for the first time, we evaluate the correlation between QoT of classical bits and qubits for a QWN. First, we present an overview of the QWN protocol and system and highlight some associated challenges. Then, our preliminary experimental demonstration shows the possibility of copropagating classical bits and qubits with a visibility $> 75\%$ for a bit error rate below 5E-7.

Quantum Wrapper Networking

The basic concept of the quantum wrapper (QW) architecture is similar to optical label switching (OLS)[20],[21] designed for transparent and interoperable transport of optical datagrams using optical labels. As Fig. 1 illustrates, a quantum Internet protocol (IP) datagram consists of a QW Header with classical bits, QW Payload with qubits, and an optional QW Tail. The QW header consists of a preamble, circuit ID (or source-destination), priority, duration of the qubit payload, qubit entanglement state information, qubit multiplexing, experimental bits, quality of service, type of service (e.g., real or non-real time application), and additional bits for error estimates. The payload is typically short ($<$ 10,000 qubits) and bursty. Therefore, additional experimental bits are reserved for future optical packet switching in addition to bits for the class information.

The header is read by classical switches and routers to facilitate end-to-end transport of the quantum payload without reading or altering it. In Fig. 1, quantum nodes at the core forward

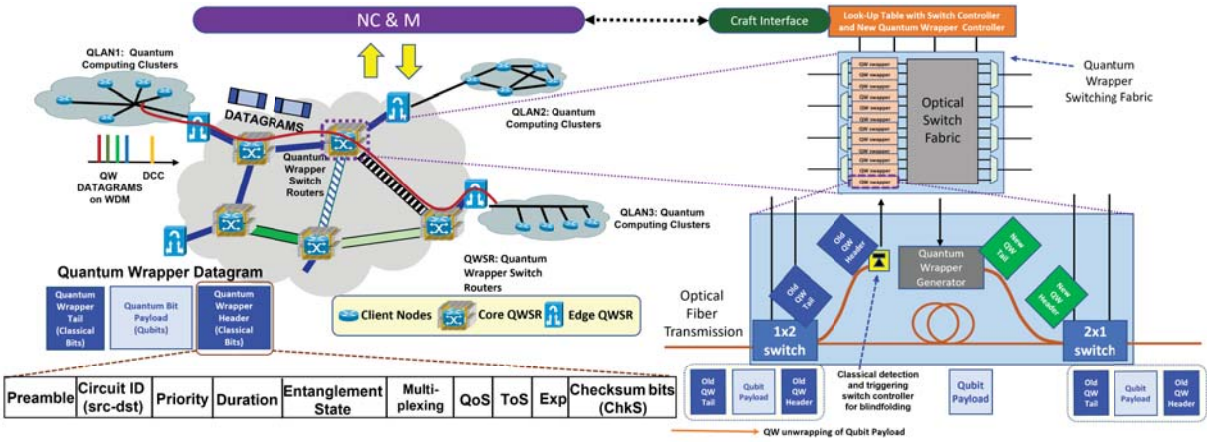

Fig. 1: (Left) A schematic of quantum wrapper network and protocol; (Right) A quantum wrapper switch interfaced with a software-defined network control and management (NC&M) agent and a quantum wrapper swapper controller that updates the lookup table based on the old header and tail information pertaining to routing, multiplexing, entanglement state, etc.

the datagrams, establish data flows, and setup/tear down circuits utilizing the quantum wrapper headers and data communication channel (DCC). The quantum edge nodes interface with quantum network clients and add quantum wrappers to the quantum payloads accordingly. The Quantum Wrapper Switches include Quantum Wrapper Swappers, which replace the old quantum wrapper with a new quantum wrapper while keeping the same qubit payload.

Quantum wrapper swapping is a key module of the QWN and quantum wrapper switch routers (QWSRs). The NC&M enables lookup table controllers and QW controllers to switch IP datagrams to their intended destination ports. A QWSR fabric consists of multiple QW swappers and an optical switch fabric. A QW swapper uses a 1×2 switch to send the header and tail to a classical detector to trigger the switch to route the payload to a destination port with a fiber delay line. In the meantime, the Quantum Wrapper Generator generates a new header and tail and append them to the QW payload by a 2×1 switch. Although Fig. 1 shows the QW header and payload as time-multiplexed, the QW datagrams can be on wavelength-division multiplexed (WDM) data channels, while a data communication channel (DCC) on a separate wavelength can support the NC&M plane communications for Software Defined Networking.

As QWN eliminates the need for qubits processing, it requires to accurately synchronize the clock for appending payload to the header, and to carefully control and monitor the effect of intra-channel and inter-channel noise on qubits and their quality of transmission. As demonstrated in Ref.[22] in the context of a classical OLS scenario[20],[21], the data payload bit error rates are strongly correlated with the label (supervisory channel) bit error rates. Taking a similar approach, it could be possible to infer the performance of the qubits payload without touching the qubits by conducting BER measurements on the QW classical bits. Thus, in the next section we conduct experiments to evaluate the correlation between the qubits and classical bits at different channels for emulating the payload and wrapper, respectively.

Preliminary Experimental Setup and Results

Crosstalk and reflection due to optical components on the link can significantly degrade the quantum channel's QoT as the quantum channel operates at very low power. Thus, we conducted a coexistence channel experiment and observed classical channel bit error rate (BER) as QoT of QW bits and the visibility of the quantum channel as QoT of qubits to demonstrate the feasibility of the QWN. The visibility is computed as the $v = \frac{C_{max} - C_{min}}{C_{max} + C_{min}}$, i.e., the ratio of the difference between the maximum and minimum coincidence counts, and the total coincidence counts[23]. The experimental setup is shown in Fig. 2.

We used a broadband polarization-entangled photon source (EPS-1000 from Oz Optics Limited) based on periodically-poled silica fiber. EPS is pumped at 782.86nm and generates entangled pairs centered around 1565.72nm. A Finisar Flex-Grid 4-ports wavelength selective switch (WSS) is used to demultiplex the *signal* and *idler*. We used a fiber-loop-based polarization controller (FPC), a polarization beam splitter (PBS), and LYNXEA-NIR InGaAs avalanche photodiodes (from Aurea Technology) as SPDs for qubits measurements. A time-to-digital converter (TDC) circuit calculates

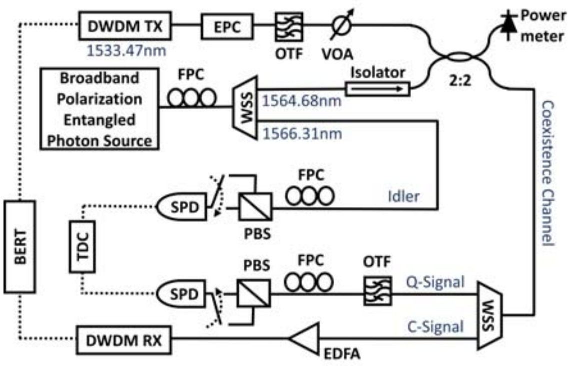

Fig. 2: A schematic diagram of an experimental setup.

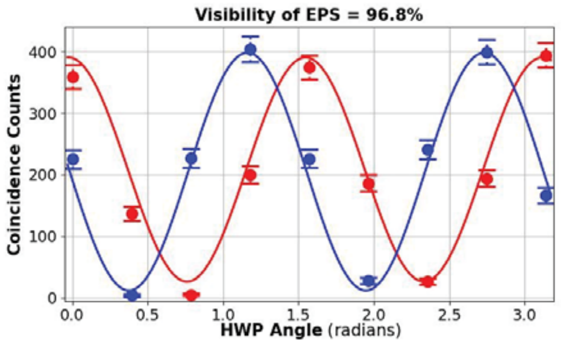

Fig. 3: Two-photon interference fringes with measurements in a H/V basis (in red) and a D/AD basis (in blue) in the absence of a classical channel.

the time difference between the received entangled photon-pair in the SPDs. The quantum efficiency of the SPDs is set to 20%, and the deadtime as 15μs. Before multiplexing the classical channel to the quantum channel, we measured two-photon interference fringes and visibility of the EPS of the quantum channels (signal and idler) for 100 seconds as illustrated in the Fig. 3.

We used a DWDM pluggable transceiver (TX) as a quantum wrapper source operating at 1533.47 nm wavelength with 10.313 Gb/s data rate. Pseudo-random bit sequence length of $2^{31}-1$ was used for BER testing. We placed an optical tunable filter (OTF) to attenuate the spontaneous emission of the TX's laser. Additionally, an isolator was used to suppress reflected classical channel photons in the *idler* measurements. We used a 2-by-2 power coupler/WSS to (de)multiplex classical bits and qubits. Although WSS's crosstalk is $>$40dB, we had to use another OTF before the *signal* qubit measurements. Furthermore, a variable optical attenuator (VOA) was used to vary the TX power of the coexistence channel. In order to average the effects of QW header crosstalk on the measurement of the polarization basis, we used an electronic polarization controller (EPC) and scrambled the polarization of the classical channel. At different TX power levels, we recorded BER and visibility with

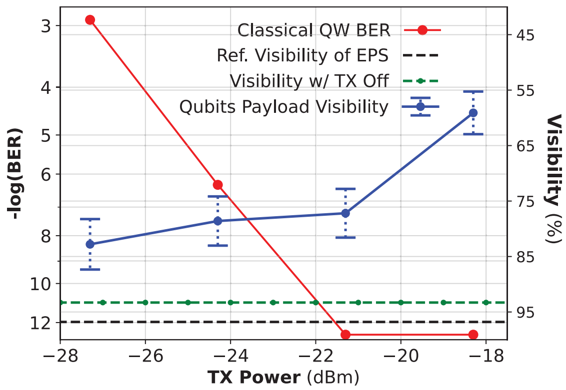

Fig. 4: Visibility (in blue) and BER (in red) verses transmitted power. The green dashed line is the visibility of qubits when TX is powered off. The black dashed line is the reference visibility of qubits without the classical channel.

a 0.6 ns coincidence window and recorded coincide counts for all four polarization axes for 500 seconds to measure visibility. Although the EPS visibility is measured as 96.8% in the absence of classical components for (de)multiplexing of the classical channel, due to background noise, insertion loss of the WSS, isolator, OTF, and power coupler, we measured the visibility as 93.3% when the TX is powered off. In the future, we will try to improve the performance measures by using low insertion loss, high crosstalk suppression, and low reflection (de)multiplexer devices.

We observed that at high TX power levels, QW classical bits are error-free; however, qubits' QoT degrades significantly. Besides, the quantum channel becomes more visible at the expense of a high QW header error rate at low TX power. There is a feasible TX power range to guarantee the integrity of both classical and qubits. In our experimental setup, this range is $[-24.3, -21.3]$ dBm, where the qubit's visibility is $>$75%, and the BER of classical bits is $<$5E-7. In the future, we plan to improve the visibility and consider time (and wavelength)-division multiplexed switching of quantum payload through classical wrapper bits as header.

Conclusion

We presented the correlation between quantum bits and classical bits over co-propagating channels in a fiber. Our experimental results show both a high visibility of quantum bits and low bit error rate of classical bits are achievable to realize a quantum wrapper networking.

Acknowledgements

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