## SC23 Network Research Exhibition: Demonstration Abstract

# Quantum Networks a Reality

Muneer Alshowkan, Brian P. Williams, Alexander Miloshevsky, Nicholas A. Peters, Mariam Kiran, Joe M. Lukens

Oak Ridge National Laboratory

<(alshowkanm, williamsbp, miloshevskya, petersna, kiranm)@ornl.gov, Joseph.Lukens@asu.edu>

**Abstract**

Quantum networks will play a crucial role in maximizing the benefits of quantum technology, especially when scaling quantum sensor systems and quantum computers. Our key goal is to establish fault-tolerant quantum communications between localized as well as geographically distributed quantum resources. As the quantum network ecosystem expands, it facilitates interconnection of smaller networks, thus setting the stage for the ultimate realization of the Quantum Internet [1].

Within quantum networks, entanglement is a fundamental quantum resource that must be effectively distributed across multiple network nodes. To help overcome reduced entanglement throughput due to loss, multiplexing is often considered. Dense wavelength division multiplexing (DWDM) including flex-grid wavelength-selective switches (WSS) [2] are useful for multiplexing in quantum fiber optical networks. These technologies offer the means to carve and manage the entanglement resources. This capability not only enhances the efficiency of quantum information processing but also enables secure and high-capacity quantum communication between nodes, thus inspiring the advancement of quantum networking as a whole.

**Preliminary on Quantum Networks**

Quantum communications have demonstrated secure data transfer often using Quantum Key distribution (QKD). Quantum networks enable enhanced transmission and exchanging keys over fiber optic cable between geographically separated quantum processors or endpoints. A discrete variable (DV-QKD) sends photons through a channel where information is coded in the photon's polarization or other discrete encoding. In contrast, a continuous variable QKD (CV-QKD) encoding uses amplitude and phase similar to classical optical communications.

**Goals:** In this demo, we present some of our recent DV [7] and CV experimental systems [4]. The DV experiment centers on a carefully designed photon source tailored specifically for flex-grid quantum networks. Our experiment emphasizes the generation of photons that exhibit both frequency correlation and polarization entanglement, key attributes in advancing quantum network capabilities. This photon source is constructed using two WSSs, each tailored to either the C- or L-band. It consists of 150 pairs of channels - a total of 300 wavelengths - each with a bandwidth of 25 GHz, collectively spanning 7.5 THz and conforming to the ITU grid standards (ITU-T Rec. G.694.1). Performing local quantum state tomography for each channel and estimated by Bayesian state tomography [5], the experimental results in Fig. 1 reveals an average fidelity of 0.98. Furthermore, these findings establish a lower-bound for the total distillable entanglement at 181 kbits/s within existing configuration. These experimental results mark a significant step forward in enabling adaptable control over entanglement within quantum networks, particularly within the L-band, thereby contributing to advancement of quantum communication and networking technologies.

Photonic integrated circuits (PICs) offer an opportunity to reduce the size, weight, and power of optical devices. The Sagnac design previously outlined in [7] has inspired a silicon PIC design using a microring resonator (MRR) in place of the fiber loop for the generation of ultrabroadband polarization-entangled photons. An image of the circuit is shown in Fig. 2(a), where one can see the waveguides that guide the light through the circuit. A schematic of the circuit is shown in Fig. 2(b). Light is coupled into the silicon chip where a polarization rotator-splitter separates (PRS) the light into two paths, one for transverse electric (TE) and another for transverse magnetic (TM) polarized light. The TM polarization photons are rotated $90^0$ into TE polarization. The two paths are bidirectionally coupled into a MRR where polarization entangled photon pairs are produced through

spontaneous four-wave mixing in the matched signal and idler frequency bins (k) of the ring resonator. Finally, another PRS rotates one of the TE modes back to TM and recombines the two paths before outputting an entangled pair. Fig. 2(c) shows the state fidelity obtained from Bayesian quantum state tomography [5] of bins k ∈ [2, 50]. Due to elevated background noise from the laser, the first 10 bins have lower fidelity. Once we are substantially far away from the pump mode, the fidelity consistently remains around 90%-97%. We are investigating the potential application of our broadband, compact, and mass-producible source for a flex-grid network and its ability to tolerate link losses or meet the bandwidth requirements of individual end-users.

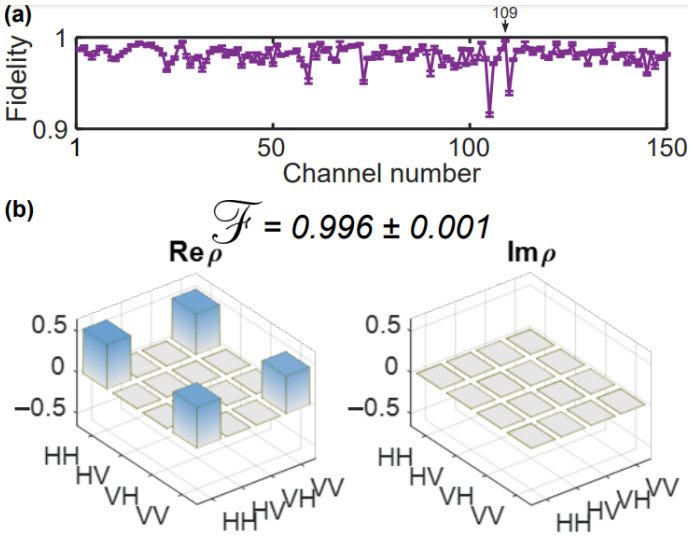



Fig. 1. (a) the fidelities of 150 channels and the arrow from the top points to the highest channel (109). (b) The density matrix of channel 109 estimated by Bayesian state tomography (see [3] for more details).

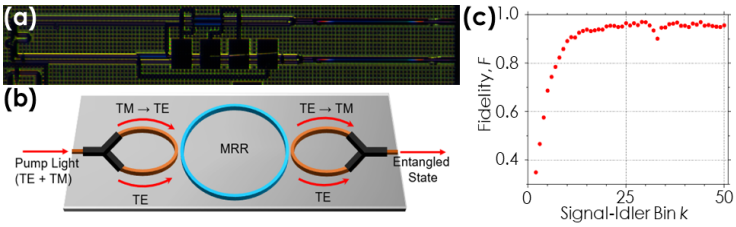



Fig. 2. (a) Image capture of the photonic integrated circuit. (b) Schematic of the chip design. (c) The polarization state fidelity with an ideal Bell state for matched frequency-bins $k \in [2, 50]$. [TE: transverse electric; TM: transverse magnetic; MRR: microring resonator].

For the CV demo, we feature a CV-QKD system with a true (LO). In contrast to discrete variable QKD, CV-QKD systems are built with what are currently more affordable 'off-the-shelf' components, that can operate at room temperature (no components require cryogenic cooling). Further, the CV-QKD light signals can coexist with classical signals (i.e. no dark fiber or nearly dark fiber is required). We demonstrate CV-QKD between Alice and Bob over a 10 km fiber link within ORNL's existing infrastructure, which includes aerial fiber as seen in Fig. 3. Our system generates both quantum and classical signals at different wavelengths and multiplexes them into a single optical fiber. The quantum-classical coexistence allows Alice and Bob to carry out CV-QKD over a single-optical link with an estimated secret key rate shown in Fig. 4. Our system demonstrates a true LO CV-QKD protocol [6] for the first time over real infrastructure. The true LO protocol removes potential security vulnerabilities and reduces cross-contamination of the quantum signal from the LO. Our system is compact, with all components for Alice's transmitter and Bob's receiver being housed in 19" rack units, (Fig. 5). Alice and Bob's units are deployable, and they can be physically separated. This is only possible due to our engineering solutions to timing synchronization, polarization correction, detector bias correction, and signal-reference relative phase correction.

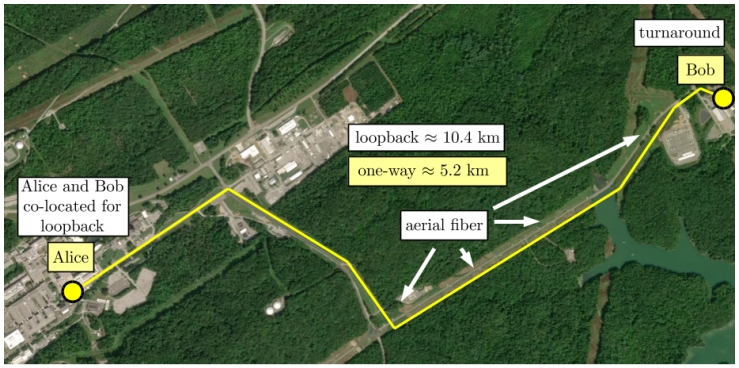



Fig. 3. (Aerial photo) Oak Ridge National Laboratory depicting the approximate optical fiber path from Alice to Bob in which quantum and classical communications coexist. We demonstrated operation of CV-QKD system over a 10.4 km loop-back link with Alice and Bob co-located in the same laboratory and also a point-to-point link in which Alice and Bob are separated spatially by 3 km and linked by 5.2 km of optical fiber.

**Future Work:** In the context of leveraging existing network infrastructure, through the coexistence of quantum and classical signals [7-9], wavelength division multiplexing (WDM) has emerged as a pivotal technology, enabling the simultaneous transmission of multiple communication carriers through a single optical fiber. This evolution has led to the development of advanced DWDM systems, which now support a multitude of channels [10, 11]. Currently, conventional and quantum technologies in the commercial domain operate within the optical C-band, covering the range from 1530 to 1565 nm.

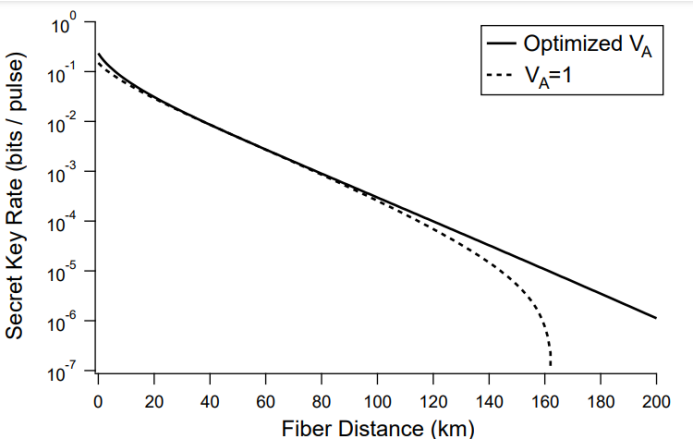



Fig 4. Secret key rate for a trusted receiver given measured and estimated system parameters for optimized (constant) modulation variance $V_A$ ($V_A$ = 1) (see [4] for more details).

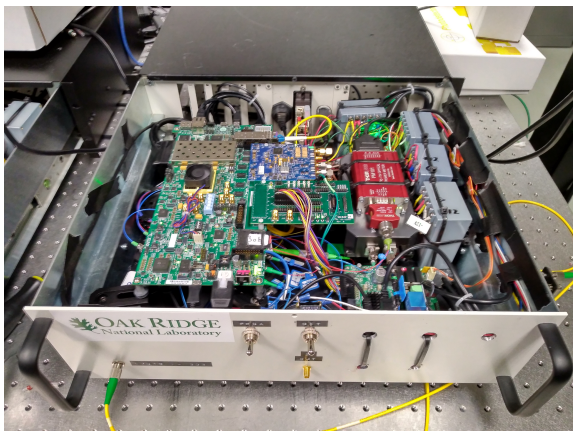



Fig. 5. Bob's CV-QKD receiver (shown) and Alice's transmitter are rack-mountable units. We will demo this at Booth.

However, expanding networking capabilities is becoming increasingly attractive with advancements in critical communications components. In particular, the adjacent L-band (1565–1625 nm), characterized by its low-loss properties, presents a compelling avenue for increasing the number of channels and overall WDM capacity.

With these developments, broadband polarization-entangled photon sources, which also naturally have frequency correlations due to energy conservation, are well suited for flex-grid DV quantum networks [13]. Harnessing the C and L telecommunications bands expands the amount of entanglement that can be transmitted and when combined with flex-grid technology, enhances network flexibility and adaptability. While previous entanglement distribution experiments have reached the L-band, realizing full control of the fiber bandwidth remains a challenge.

**Resources**

- We need a booth for demonstration. The demo will be done on a laptop and would need a large monitor to display to a wider audience.
- We will need a network connection to set up our network circuits (linked to ORNL quantum networking lab).

**Acknowledgements:**This work was funded by the U.S. DOE under contract no. DE-AC05-00OR22725. Funding for the DV systems was provided by DOE Office of Science, Advanced Scientific Computing Research (Field work Proposals ERKJ381, ERKJ378, ERKJ353). Funding for the CV system was provided by the U.S. Department of Energy, Office of Cybersecurity Energy Security and Emergency Response (CESER) through the Risk Management Tools and Technologies (RMT) Program.

**Involved Parties:** Nagi Rao (ORNL)

**References**

[1] H. J. Kimble, Nature 453, 1023 (2008).
[2] Y. Ma, L. Stewart, J. Armstrong, I. G. Clarke, andG. Baxter, J. Lightwave Technol. 39, 896 (2021).
[3] M. Alshowkan, J. M. Lukens, H.-H. Lu, B. T. Kirby, B. Williams, W. P. Grice, N. A. Peters, Opt. Lett.47, 6480 (2022).
[4] B. P. Williams, B. Qi, M. Alshowkan, P. G. Evans, and N. A. Peters, arXiv (2023), 2309.03959 [quant-ph].
[5] J. M. Lukens, K. J. H. Law, A. Jasra, and P. Lougovski, New J. Phys.22, 063038 (2020).
[6] B. Qi, P. Lougovski, R. Pooser, W. Grice, and M. Bobrek, Phys. Rev. X5, 041009 (2015).
[7] P. Townsend, Electronics Letters 33, 188 (1997).
[8] N. A. Peters, P. Toliver, T. E. Chapuran, R. J. Runser, S. R. McNown, C. G. Peterson, D. Rosenberg, N. Dallmann, R. J. Hughes, K. P. McCabe, J. E. Nordholt, and K. T. Tyagi, New Journal of Physics 11, 045012 (2009).
[9] T. E. Chapuran, et al., New Journal of Physics 11, 105001 (2009).
[10] O. Gerstel, M. Jinno, A. Lord, and S. B. Yoo, IEEE Commun. Mag. 50, S12 (2012).
[11] Q. Cheng, M. Bahadori, M. Glick, S. Rumley, and K. Bergman, Optica 5, 1354 (2018).
[12] N. B. Lingaraju, H.-H. Lu, S. Seshadri, D. E. Leaird, A. M. Weiner, and J. M. Lukens, Optica 8, 329 (2021).
[13] F. Appas, F. Baboux, M. I. Amanti, A. Lema ́ıtre, F. Boitier, E. Diamanti, and S. Ducci, npj Quantum Information 7, 118 (2021).