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A Testbed for Quantum Communication and Quantum Networks[1]

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ABSTRACT

We introduce the NIST Platform for Quantum Network Innovation (PQNI) – a new testbed on the NIST campus to accelerate the integration of quantum systems into a real life, active network in a controlled scientific setting. The testbed will be used to evaluate quantum scale devices and components such as single photon sources, detectors, memories and interfaces within various quantum network protocols and configurations for performance, optimization, synchronization, loss compensation, error correction, compatibility with conventional network traffic (often referred to as co-existence), continuity of operations and more.

Keywords: quantum communication; quantum network; field testbed

1. INTRODUCTION

Quantum communication has attracted significant, and growing, attention in the recent decades and has now become a very active research field. Quantum communication originated in the 1970's with Stephen Wiesner's idea of using quantum states to securely encode information for transmitting 'Quantum Money'. Following initial skepticism, the idea was finally published in 1983[1]. One year later, Charles Bennett and Gilles Brassard proposed a first Quantum Key Distribution (QKD) protocol, called BB84[2]. Since then, many new QKD protocols have been proposed such as simplified B92 [3], entangled photon source-based E91 [4], decoy state QKD [5], and measurement-device-independent (MDI) QKD [6]. The newly developed protocols overcame the security issues caused by imperfect devices, extended the limited communication distance caused by photon loss in the channel and greatly improved QKD security performance.

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1 The identification of any commercial product or trade name does not imply endorsement or recommendation by the National Institute of Standards and Technology.

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The first experimental laboratory demonstration of QKD was realized in 1989 in a free-space quantum channel that was only 30-cm-long. However, since then, QKD systems and networks have matured significantly to leave the confines of the laboratory and indeed, many have been extensively investigated in field environments. Current field testbeds of QKD systems have two directions, free-space and fiber-based. State of the art free-space systems mainly refers to satellite-to-ground communications. These systems have already been demonstrated successfully by several quantum communication research groups. In this paper, we focus on fiber-based quantum networks. So far, the main fiber-based quantum network field testbeds and typically QKD specific and include:

1) The DARPA Quantum Network, a project supported by the US Defense Advanced Research Projects Agency (DARPA) [7].
2) The Advanced Technology Demonstration Network (ATDNet) in the Washington D.C. area by Telcordia Technologies [8].
3) The Secure Communication using Quantum Cryptography (SECOQC) Network in Vienna, a project supported by the European FP6 project [9].
4) The Swiss Quantum Network (SwissQuatum) in Geneva operated by the University of Geneva [10, 11].
5) The QKD and Quantum teleportation field test in Calgary metropolitan fiber network [12].
6) The Tokyo QKD Network that consists of parts of the National Institute of Information and Communications Technology (NICT) open testbed network [13].
7) The Beijing-Shanghai quantum communication backbone in China [14, 15].
8) The Quantum City project in Durban, South Africa [16].

In addition to QKD systems, quantum communication has accelerated the development of quantum networks and, ultimately, the quantum Internet. However, building a quantum network is much more challenging than building a QKD network and the requirements are significantly different. Although today's commercial fiber optic infrastructure (primarily for classical communications) is widespread, the possibility for a quantum network to share the established classical network infrastructure is limited without purposeful consideration of the unique quantum requirements. Therefore, it is necessary to test new and existing quantum devices, new protocols and alternative network configurations using an active classical network infrastructure in a controlled scientific setting. The NIST Platform for Quantum Network Innovation (PQNI) is an extension of an existing classical network testbed (Platform for Network Innovation / PNI) established on the NIST Gaithersburg campus and will be used to field test new and existing quantum devices and components for performance, synchronization, loss compensation, error correction, compatibility with classical network traffic, continuity of operations and more. This paper will outline the quantum communication project at NIST and summarize the goals of the proposed PQNI testbed.

2. QUANTUM NETWORK RESEARCH IN NIST'S INFORMATION TECHNOLOGY LABORATORY

Beginning in 2004, the Quantum Communications Project in NISTs Information Technology Laboratory (ITL) has developed several QKD systems, including a free space QKD system [17], a Fiber-based QKD system with a record breaking sifted key rate [18], a long-distance QKD system with frequency up-conversion detectors [19], a cost-effective Detection-time-bin-shift QKD system [20] and a differential phase shift QKD system with a superconducting detector [21]. In addition to QKD systems, we also developed some key devices for quantum communication systems, such as entangled photon sources [22, 23] and upconversion single photon detectors and spectrometers [24-27].

We developed a complete 3-node, active QKD network controlled by MEMS optical switches [28]. As shown in Fig. 1, the QKD network operates at a 1.25 Gbps clock rate and can provide more than one Mbps sifted-key rate over 1 km of optical fiber. As part of the QKD network, we developed a high-level QKD network manager to provide QKD services to security applications. These services include managing the QKD network, and demultiplexing and synchronizing the secure key stream. To demonstrate the speed of our QKD system, we implemented a video surveillance application that is secured by a one-time pad cipher using keys generated by our QKD network and transmitted over public standard internet IP channels. The 3-node QKD network used 850 nm for the quantum channel and 1510 nm and 1590 nm for the classical channel. To connect our QKD nodes, a pair of MEMS optical switches were used, one for the quantum channel and the other for the bi-directional classical channel (1510 and 1590 nm).

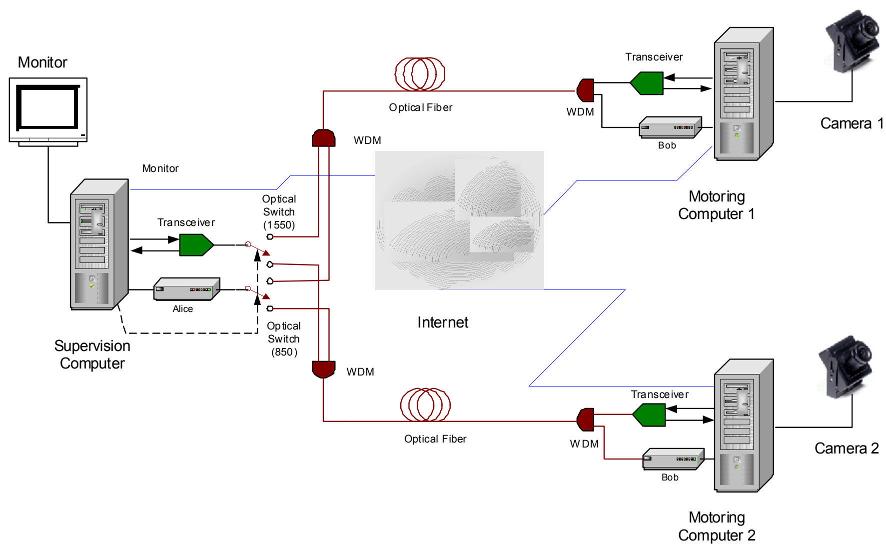

Fig.1. NIST 3-node QKD network.

A practical QKD network requires a utility program that coordinates the operations of all QKD nodes, such as switching, polarization recovery, timing alignment and protocol initialization, as well as provides services to upper layer security applications such as routing availability and secure key demultiplexing and synchronization. We developed a quantum network manager that performed these functions through various sub-managers.

In addition to the research on QKD and QKD networks, NIST quantum communication project is focusing on the implementation of a quantum network beyond QKD, which may lead to the development of a quantum computational network to connect quantum computers and ultimately, the future quantum Internet. Quantum repeaters are one of the most important technologies to realize a quantum network and the quantum Internet. Our project is now developing the critical building blocks for quantum repeaters, such as quantum memories[29, 30], quantum interfaces and compatible narrow bandwidth single photon pair source [31]. We also plan to test these new technologies and devices in field environments as part of the Platform for Quantum Network Innovation (PQNI).

The NIST Platform for Quantum Network Innovation (PQNI) is an extension of an existing 100 GHz (100-G) ring classical network testbed (Platform for Network Innovation / PNI) established on the NIST Gaithersburg campus. The system will be developed for field testing components, devices and systems related to quantum communications and for studying the feasibility and compatibility of multiplexing with conventional optical communication.

Quantum communication systems requires both quantum channels and classical channels. Photons carrying qubit information are transmitted through the quantum channel and require an all-optical link. Therefore, the quantum communication testbed requires an optically transparent network. A conventional optical communication network consists of some optical-electrical-optical (OEO) devices, such as optical switches. To implement a testbed for quantum communication, OEO devices should be bypassed with optical links or replaced by optical-optical-optical (OOO) devices.

Functionally, the architecture will include the capability to evaluate both quantum only networking and hybrid classical/quantum networking. In the hybrid network, the coexistence of the classical and quantum links will be implemented using a quantum adaptation layer.

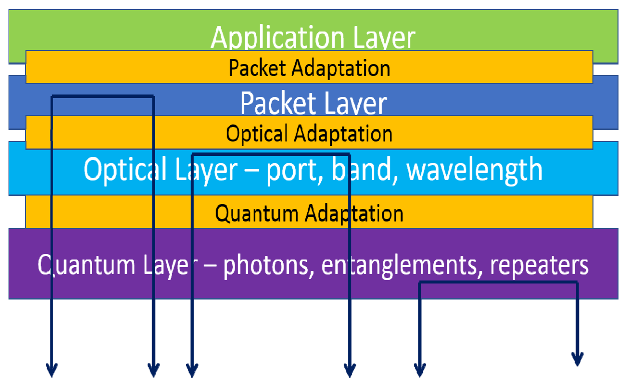

Fig. 2. Architectural aspects of the Quantum Network Innovation Platform.

Figure 2 schematically shows a high-level quantum router. The lowest layer is the quantum hardware, which consists of a quantum router capable of storing and manipulating qubits. This quantum router has an optical interface over which it can generate entanglement with its adjacent nodes (directly over a fiber or logically over a wavelength component) and then exchange qubits with them. Sending and receiving qubits will depend on several implementations realized by first generating entanglement followed by quantum teleportation. The control, management, and measurement planes of this router will operate using a classical communication interface.

The PQNI will be used for a variety of research on quantum communication projects, which include:

1) To evaluate and optimize network performance. The biggest challenge for quantum communication systems in the field is to maintain the quantum state of photons during transmission. The fluctuations in the environment influences the quantum state of photons, resulting in high error-rate or even failure of the quantum communication link. The network performance and its stability, including loss, polarization and phase, will be evaluated and optimized for quantum communication.
2) To field test quantum components, devices and systems. Quantum components and devices, including single/entangled photon sources, single photon detectors, quantum memories and quantum interfaces will be

tested, and their performance will be evaluated in the testbed. The testbed will also be used for testing and evaluation of fully integrated quantum communication systems.

3) To study the multi-node configuration of quantum communication. A quantum network needs to connect many nodes and can dynamically configure and reconfigure the connections between these nodes. The study will include communication path routing, eavesdropper or fiber breakage detection and rerouting, and communication system restoration and synchronization. It will evaluate and test stability, name-based addressing schemes, and routing/forwarding mechanisms of point-to-point and point-to-multipoint quantum links.
4) To test the compatibility of quantum communication systems with conventional optical networks. Multiplexing with classical optical signals in the same networks will greatly reduce the cost of deployment of quantum communication systems. The testbed will be used to study the influence of the coexistence of a strong classical signal and a single photon signal as well as the compatibility of the quantum signal with a conventional optical network. We will develop a capability-based measurement plane that will operate in the classical network layer but with measurement probes for the quantum layer.
5) To evaluate security of the system. Evaluation of security architectures based on securing the physical quantum layer versus securing the information content exchanged and stored at different layers.

3. CONCLUSION

An acceleration of research efforts towards the development of quantum networks is underway and will ultimately lead to the quantum Internet. Significant developments in the technological, commercial and legislative arenas has occurred in recent years. Quantum scale devices and components such as single photon sources, detectors, memories and interfaces are ever readier to leave the confines of the laboratory. NIST quantum communication project plans to build a field testbed, PQNI, for testing components, devices and systems related to quantum network communications, and for studying the feasibility and compatibility of multiplexing with conventional optical communication networks.

REFERENCES

[1] S. Wiesner, "Conjugate coding," *ACM Sigact News,* vol. 15, no. 1, pp. 78-88, 1983.

[2] C. H. Bennet and G. Brassard, "Quantum cryptography: Public key distribution and coin tossing," in *Proc. of IEEE Int. Conf. on Comp., Syst. and Signal Proc., Bangalore, India, Dec. 10-12, 1984*, 1984.

[3] C. H. Bennett, "Quantum cryptography using any two nonorthogonal states," *Physical review letters,* vol. 68, no. 21, p. 3121, 1992.

[4] A. K. Ekert, "Quantum cryptography based on Bell’s theorem," *Physical review letters,* vol. 67, no. 6, p. 661, 1991.

[5] W. Y. Hwang, "Quantum key distribution with high loss: Toward global secure communication," (in English), *Physical Review Letters,* vol. 91, no. 5, Aug 1 2003.

[6] H. K. Lo, M. Curty, and B. Qi, "Measurement-Device-Independent Quantum Key Distribution," (in English), *Physical Review Letters,* vol. 108, no. 13, Mar 30 2012.

[7] C. Elliott, "The DARPA quantum network," in *Quantum Communications and cryptography*: CRC Press, 2005, pp. 91-110.

[8] T. Chapuran *et al.*, "Optical networking for quantum key distribution and quantum communications," *New Journal of Physics,* vol. 11, no. 10, p. 105001, 2009.

[9] M. Peev *et al.*, "The SECOQC quantum key distribution network in Vienna," *New Journal of Physics,* vol. 11, no. 7, p. 075001, 2009.

[10] D. Stucki *et al.*, "Long-term performance of the SwissQuantum quantum key distribution network in a field environment," *New Journal of Physics,* vol. 13, no. 12, p. 123001, 2011.

[11] A. Rubenok, J. A. Slater, P. Chan, I. Lucio-Martinez, and W. Tittel, "Real-world two-photon interference and proof-of-principle quantum key distribution immune to detector attacks," *Physical review letters,* vol. 111, no. 13, p. 130501, 2013.

[12] R. Valivarthi *et al.*, "Quantum teleportation across a metropolitan fibre network," *Nature Photonics,* vol. 10, no. 10, p. 676, 2016.

[13] M. Sasaki *et al.*, "Field test of quantum key distribution in the Tokyo QKD Network," *Optics express,* vol. 19, no. 11, pp. 10387-10409, 2011.

[14] R. Courtland, "China's 2,000-km quantum link is almost complete [News]," *IEEE Spectrum,* vol. 53, no. 11, pp. 11-12, 2016.

[15] T.-Y. Chen *et al.*, "Metropolitan all-pass and inter-city quantum communication network," *Optics express,* vol. 18, no. 26, pp. 27217-27225, 2010.

[16] A. Mirza and F. Petruccione, "Realizing long-term quantum cryptography," *JOSA B,* vol. 27, no. 6, pp. A185-A188, 2010.

[17] J. C. Bienfang *et al.*, "Quantum key distribution with 1.25 Gbps clock synchronization," *Optics Express,* vol. 12, no. 9, pp. 2011-2016, 2004.

[18] X. Tang *et al.*, "Experimental study of high speed polarization-coding quantum key distribution with sifted-key rates over Mbit/s," *Optics Express,* vol. 14, no. 6, pp. 2062-2070, 2006.

[19] H. Xu, L. Ma, A. Mink, B. Hershman, and X. Tang, "1310-nm quantum key distribution system with up-conversion pump wavelength at 1550 nm," *Opt. Express,* vol. 15, no. 12, pp. 7247-7260, 2007.

[20] L. J. Ma, T. J. Chang, A. Mink, O. Slattery, B. Hershman, and X. Tang, "Experimental demonstration of a detection-time-bin-shift polarization encoding quantum key distribution system," (in English), *Ieee Communications Letters,* vol. 12, no. 6, pp. 459-461, Jun 2008.

[21] L. J. Ma *et al.*, "1310 nm differential-phase-shift QKD system using superconducting single-photon detectors," (in English), *New Journal of Physics,* vol. 11, Apr 2009.

[22] L. Yan, L. J. Ma, and X. Tang, "Bragg-grating-enhanced narrowband spontaneous parametric downconversion," (in English), *Optics Express,* vol. 18, no. 6, pp. 5957-5963, Mar 15 2010.

[23] O. Slattery, L. Ma, P. Kuo, and X. Tang, "Narrow-linewidth source of greatly non-degenerate photon pairs for quantum repeaters from a short singly resonant cavity," *Applied Physics B,* no. 121, pp. 413-419, 2015.

[24] L. J. Ma, J. C. Bienfang, O. Slattery, and X. A. Tang, "Up-conversion single-photon detector using multi-wavelength sampling techniques," (in English), *Optics Express,* vol. 19, no. 6, pp. 5470-5479, Mar 14 2011.

[25] L. J. Ma, O. Slattery, and X. Tang, "Single photon frequency up-conversion and its applications," (in English), *Physics Reports-Review Section of Physics Letters,* vol. 521, no. 2, pp. 69-94, Dec 2012.

[26] L. Ma, O. Slattery, and X. Tang, "Detection and Spectral Measurement of Single Photons in Communication Bands Using Up-Conversion Technology," (in English), *Laser Physics,* vol. 20, no. 5, pp. 1244-1250, May 2010.
[27] O. Slattery, L. Ma, P. Kuo, Y.-S. Kim, and X. J. L. P. L. Tang, "Frequency correlated biphoton spectroscopy using tunable upconversion detector," vol. 10, no. 7, p. 075201, 2013.
[28] L. Ma, A. Mink, H. Xu, O. Slattery, and X. Tang, "Experimental demonstration of an active quantum key distribution network with over Gbps clock synchronization," (in English), *Ieee Communications Letters,* vol. 11, no. 12, pp. 1019-1021, Dec 2007.
[29] L. Ma, O. Slattery, and X. Tang, "Optical quantum memory based on electromagnetically induced transparency," *Journal of Optics,* vol. 19, no. 4, p. 043001, 2017.
[30] L. Ma, O. Slattery, and X. Tang, "Noise reduction in optically controlled quantum memory," *J Modern Physics Letters B,* vol. 32, no. 14, p. 1830001, 2018.
[31] O. Slattery, L. Ma, P. Kuo, and X. Tang, "Narrow-linewidth source of greatly non-degenerate photon pairs for quantum repeaters from a short singly resonant cavity," *Applied Physics B,* vol. 121, no. 4, pp. 413-419, 2015.