Polarisation Based Entanglement Distribution Quantum Networking

M.J. Clark*, R. Wang†, S. Bahrani†, M. Peranić‡, O. Alia†, M. Loncaric‡, Ž. Samec‡,
A. Radman‡, M. Stipcevic‡, R. Nejabati†, D. Simeonidou†, J. Rarity*, S.K. Joshi*
* Quantum Engineering Technology Labs, University of Bristol, Bristol, United Kingdom
† High Performance Networking, University of Bristol, Bristol, United Kingdom
‡ Center of Excellence for Advanced Materials and Sensing Devices, Ruđer Bošković Institute, Zagreb, Croatia
mj.clark@bristol.ac.uk

***Abstract*—Quantum networks based on entanglement distribution have shown promise for building scalable and fully connected systems that support quantum key distribution. This work aims to go beyond simply implementing quantum key distribution and explore the potential of such networks for implementing quantum photonic interconnects. Our research demonstrates the passive polarization stability of these networks for over a week and highlights the benefits of dynamic reconfiguration to remove redundant resources. We discuss recent advancements in quantum frequency conversion and quantum memory-based networks, and argue that the development of scalable, long-distance interconnects is crucial for advancing quantum technology. Our findings have important implications for the future of quantum networking and highlight the need for entanglement based photonic interconnect networks, such that quantum technology can scale beyond monolithic systems.**

Keywords*—*quantum communication, quantum network, entanglement, entanglement distribution

I. INTRODUCTION

In the face of ever rapidly developing Quantum Technology (QT), a method of interconnecting QTs situated in separate locations[1] is required. The prevailing method is to connect QT nodes through photonic interconnects, such that quantum information is shared between locations, by building Quantum Networks (QNet). Recent demonstrations of QNets have been focused towards the single use case of Quantum Key Distribution (QKD) [1]–[3], and commercial implementations have been announced in recent years [4].

This focus on QNets for only a single QT application limits the future applications in Quantum Computation and Sensing [5]–[8]. Utilizing entanglement as a resource expands use cases of QNets into a regime of distributed QT [9], as shown in Fig. 1. One of the main obstacles to this approach is the variety of Quantum Memory (QM) platforms that are being developed. Each platform takes advantage of a different process to produce a quantum state, such as neutral atoms and trapped ions using atomic energy levels [10].

This produces a wide variation of the interaction wavelength by platform [11]–[14]. These photons are commonly produced in wavelength regimes that traditionally have not been used to transmit optical signals through fibre optic infrastructure, due to the high propagation loss [15]. Operating in this high loss regime prevents the separation of the clusters beyond a few hundred meters [11].

The technique of entanglement preserving Quantum Frequency Conversion (QFC) [17] can be used to overcome this limit. QFC is most commonly performed using the second order properties of non-linear crystals, through Difference Frequency Generation (DFG) and Sum-Frequency Generation (SFG) [18]–[21]. These processes allow photons in the $400-900\,\mathrm{nm}$ regime to be converted into the C-Band for efficient transmission through deployed fiber telecommunications infrastructure, or for photons in the C-Band to be converted into the correct frequency regime to interact with a QM. By

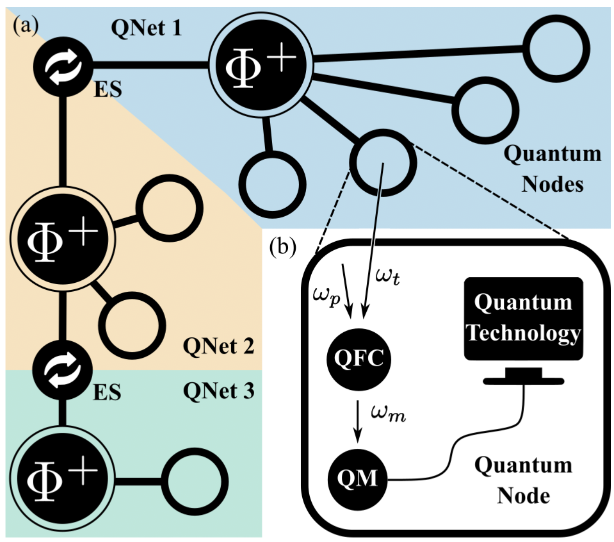

Fig. 1: Schematic of a Quantum Internet with Quantum Networks (QNet) providing photonic interconnects between Quantum Technologies (QT). Fig. **(a)** depicts the physical topology of QNets, and how they can be interconnected through Entanglement Swapping (ES). Fig. **(b)** shows the process of Quantum Frequency Confersion (QFC) into a Quantum Memory (QM), to connect QT with entanglement from the QNets. Here ω_p is the pump photon, ω_t is the entanglement transporting photon, and ω_m is the QM native photon.

[1]It is important to note that this does not mean exclusively space-like separated locations

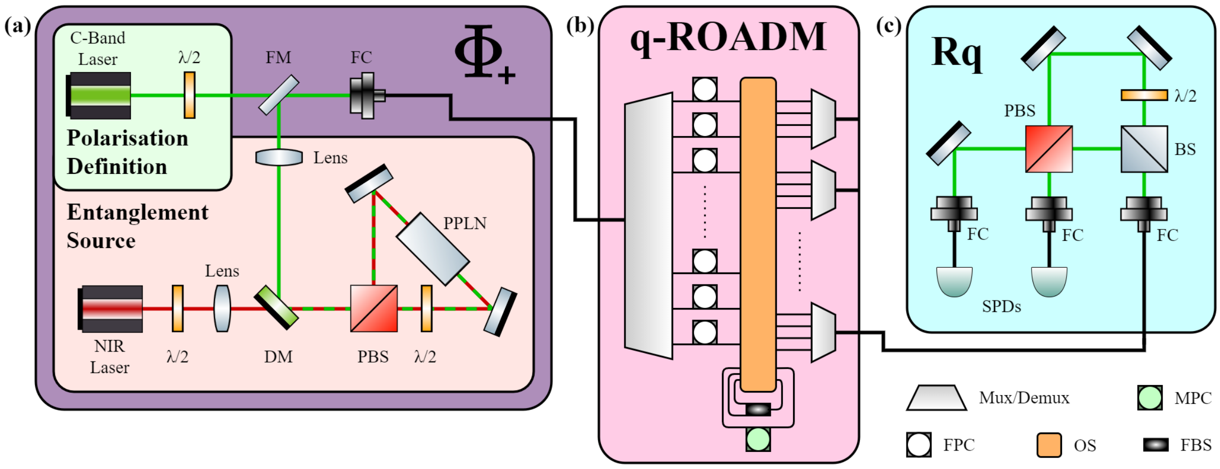

Fig. 2: The main components of the quantum network discussed [16]. Fig. **(a)** shows the photon pair source, comprised of a bulk optic entanglement source (ES) and the polarisation definition (PD). Fig. **(b)** is the quantum enabled Reconfigurable Optical Add Drop Multiplexer(q-ROADM). Fig. **(c)** is the quantum receiver (Rq). Here $\lambda/2$ is a half-wave plate, DM is a dichroic mirror, BS is a beam-splitter, PBS is a polarising beam-splitter, PPLN is a magnesium doped periodically poled lithium niobate crystal, FM is a motorised flip mirror, FC is a fibre collimater, SPD is a single-photon detector, FPC is a fibre polarisation controller, MPC is a motorised fibre polarisation controller, OS is an optical switch, FBS is a fibre beams splitter, and a (De)Mux is a wavelength (de)multiplexer.

careful selection of the pump wavelength in DFG and SFG, any desired wavelength within the C-Band can be achieved. If ω_p is the pump frequency, and ω_t is the frequency of the entanglement transporting photon, then the memory photon would have frequency $\omega_m = \omega_p + \omega_t$, as shown in Fig. 1 **(b)**. This process is reversible, so by performing the process on the memory(C-Band) photon the C-Band(memory) photon would be received out of the system. Development of these systems into high-efficiency processes is required for large scale QNets, where current systems reach an efficiency of about 30% [22].

With these QFC systems, entanglement distribution QNets will distribute entangled photons between nodes, without the associated loss of memory native wavelengths. Different entanglement resources may provide additional constraints on the QFC implementation. For example, when polarization entanglement is utilized the process of QFC must not apply a polarisation projection or measurement that produces a mixed quantum state. As such polarization-insensitive QFC is needed [23], [24].

By utilizing bipartite entanglement QNets, Greenberger-Horne-Zeilinger (GHZ) states can be generated in QM [11], [25] to share entanglement beyond two-node entanglement. QNets can distribute entangled photon pairs between many locations in a dynamic way. This allows these GHZ-style memory networks to be connected in a scalable way, and by leveraging QFC, with low-loss C-Band interconnects across Metropolitan areas.

Here we discuss an approach to building entanglement distribution QNets [26], [27], that connects many nodes with fully connected topologies. These QNets are designed as photonic interconnects that can facilitate entanglement between QT, without limiting the systems to small set of use cases. Entanglement is measured using the Bennett-Brassard-Mermin (BBM92) [28] method of QKD, and networks are assessed using a weighted average Secret Key Rate (SKR) [16], [29]. The quantum measurements taken to preform BBM92 QKD also allow other protocols to be preformed, without changes being made to the system. These include preforming secure anonymous protocols [30] and exchanging secure digital signatures [31].

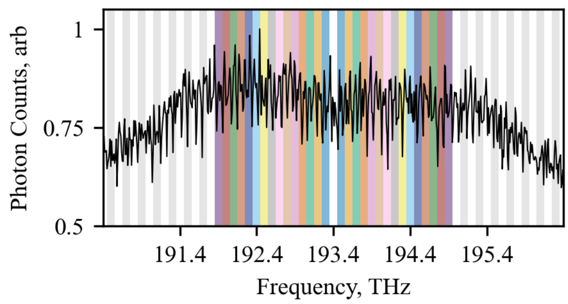

Fig. 3: The output spectrum of the entanglement source. Here the Photon counts are normalised to the maximum number seen in a frequency bin.

II. Polarisation Entanglement Networks

Polarization entangled photon pairs can readily be produced through Spontaneous Parametric Down Conversion (SPDC). The quantum source [16], as shown in Fig. 2 **(a)**, used a magnesium doped periodically poled lithium niobate non-linear crystal to produce frequency entangled C-Band photon pairs centred at 1550.12 nm (193.4 THz), as shown in Fig. 3. A Sagnac interferometer induces polarization entanglement on to the photon pairs, producing a hyper-entangled state in polarization and frequency.

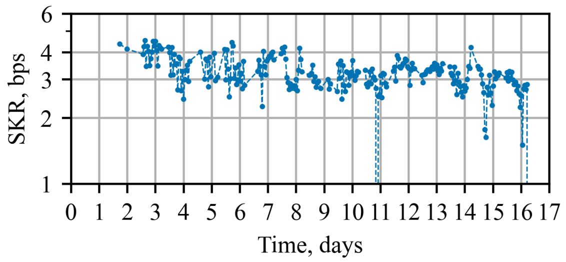

Fig. 4: Weighted average SKR of a 10-node fully connected entanglement based Quantum Networks [16].

Frequency entanglement is utilized to produce discrete bins of entanglement, through Dense Wavelength Division Multiplexing (DWDM) technology as shown in Fig. 2 **(b)**, in accordance to the telecommunications ITU grid. These 100 GHz bins are labeled communication channels (CC), where each CC shares entanglement with one other CC. This frequency splitting can be seen in Fig. 3, where the bars with matching color indicate the 15 CC pairs.

Once frequency demultiplexed, selected CCs are time multiplexed into 4 logical channels (LC), and the remaining CCs are relabelled as LCs. Taking advantage of time multiplexing and frequency multiplexing simultaneously, larger networks of nodes can be connected with a single source with a limited set of CCs. Each LC is connected to a port of an optical switch via a fibre polarisation controller. A series of frequency multiplexers are connected to the outputs of the optical switch, allowing many LCs to be combined into a single fiber, each of which is connected to a separate node. In such a setup, LCs can be assigned to any frequency multiplexer, allowing for a dynamically connected network of entanglement sharing [32].

Here we have shown how a quantum-enabled Reconfigurable Optical Add Drop Multiplexer (q-ROADM), as shown in Fig. 2 **(b)**, can be utilized to allow active switching between different topologies [32]. Changing the topology in a QNet allows for many different scenarios, beyond changing which nodes generate a secret key in a QKD network at that point in time. Reducing the number of simultaneous LCs reduces the perceived noise counts when measuring only a single LC [29], [32]. Due to the required switching between topologies required to produce a fully-connected QNet in this manner, this reduces the total time in which each LC can be measured. We have noted a trade-off between the quality of network components and the advantage that active switching gives. Notably, when the detector Jitter increases a dynamically switched set of non-fully connected network topologies see a reduced Quantum Bit Error Rate (QBER) and gain a boost in SKR across the combined fully-connected QNet [29].

With a set of 5 LCs per node, a QNet with 10 nodes can be constructed, as shown in Fig. 5 [16]. Using both time and frequency multiplexing creates duplicated connections in the system. These connections can be distributed to nodes that require a higher bandwidth of entanglement sharing or can be utilised for different applications, by demultiplexing the channels at the node.

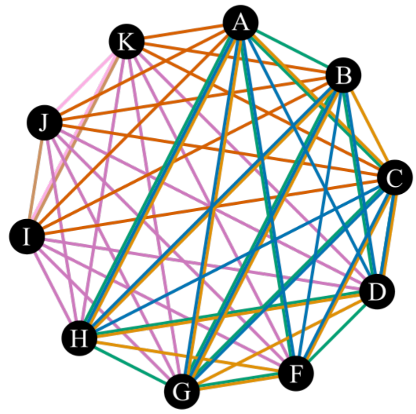

Fig. 5: Topology of the entanglement distribution Quantum Networks. Here color represents a frequency channels received by nodes.

We demonstrated such a QNet, with deployed telecommunications fiber, and showed polarization stability upto 11 days of continuous operation with a weighted average SKR of 3.4 bps, improving on the previous record of 1 day [27]. In this QNet, all LCs were birefringence compensated before up-time began, such that the definition of polarization at the node matched that of the source location [33]. No further compensation was completed for the duration of data collection, showcasing that current fiber infrastructure has sufficiently low birefringence induced polarization rotation that a network is stable within expected poissonian fluctuation of the QBER for BBM92 QKD.

In the set of 10 nodes, 3 were connected through metropolitan scale deployed fiber with propagation loss ranging from 1.5 to 3.2 dB, and the remaining nodes had local connections. A further 2 nodes were connected, but failed in the network initialisation stage. This shows that such QNets are resilient to node downtime, and that extra nodes can be connected with no change to the current resource distribution.

III. Conclusion

Entanglement-based QNets have shown promise in connecting nodes for both QKD and QM entanglement [11], [16], [27]. While previous research has focused on either long-distance QKD networks [16], [26], [27] or small-scale QM networks [11], [13], [14], [25] , a critical challenge remains: developing low loss C-Band QNets to interconnect QMs across metropolitan areas. To address this challenge, we recommend focusing on the incorporation of bidirectional QFC [18] and developing new technologies to interface photons in the C-Band with current QM systems. By doing so, we can unlock the potential for QT to develop beyond single monolithic systems [5]–[8].

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