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Towards Co-Existence of 100 Gbps Classical Channel Within a WDM Quantum Entanglement Network

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Abstract: We experimentally prove the feasibility of wavelength multiplexing bright 100 Gbps classical communication with multiple single-photon level entanglement channels over SMF-28e fibre in a quantum network. This minimises the resources needed for quantum networks.

1. Introduction

Quantum networking has mainly developed over the last two decades as relayed point-to-point quantum communication links [1], with primary application on quantum security and quantum key distribution (QKD) [2]. However, to address the Quantum Internet vision towards interconnecting seamlessly multiple quantum nodes and enable applications beyond QKD such as blind and distributed quantum computing [3], fully dynamic quantum networks [4] need to be deployed overcoming the relayed quantum links approach and allowing the co-existence of classical and quantum channels over the same fibre. Entanglement distribution has recently proved a very powerful technology for dynamic quantum networking, and demonstrations of static [5,6] and active [7] entanglement distribution concepts has opened the road for the deployment of fully functional quantum networks that allow simultaneous multi-point quantum nodes interconnection.

All quantum networks require quantum channels to distribute the quantum states, and classical channels to exchange measured information about these states, but these are normally deployed separately due to the very weak quantum signals (often single-photon level, i.e. ≈-160 dBm) and its low tolerance by the noise originated from the much stronger classical signals (typically a few dBm). However, the use of separate multiple fibres for quantum and classical data layers would be extremely impractical for large scale quantum entangled networks. Conditional co-existence of classical and quantum channels has been demonstrated for DV-QKD and CV-QKD quantum system [8–10]. For the entanglement distribution, such co-existence demonstrations have so far been limited for two users and in laboratory conditions [11] while significantly affecting the performance of the quantum entangled link. In the present communication, we first obtain an analytical expression to calculate the degradation of the Secret Key Rate (SKR) of the multi-wavelength quantum entangled link at the presence of classical communication channel. Following we experimentally assess the additional noise in terms of photon counts over a 0.8 km long deployed optical fibre that is part of our previously deployed 8-user quantum network testbed together with the collected data for the average secret key rates and photon counting statistics for the quantum entangled Bob-Feng link [6], to prove that co-existence of all 30 quantum entangled channels can be achieved with a minimum penalty of <3.8% in the SKR while sustaining an error-free 100 Gbps classical channel in the C-band.

2. Quantum entangled channels noise level tolerance calculation

When considering QKD as an application of quantum channels, all errors are assumed to provide the eavesdropper (Eve) with information about the key. As long as the quantum bit error rate (QBER) remains below 11%, it remains possible to extract a key with information theoretically perfect security [2]. A bright classical signal in the same optical fibre as the quantum signal(s) can, primarily due to Raman scattering, cause an increase in noise counts ($D \times Ch$, with D increased noise counts in each of the Ch wavelength channels) seen by the quantum detectors. The corresponding increase in the QBER is given by $\frac{\tau_c \times (S_A + (D \times Ch)) \times S_B}{P} - \frac{\tau_c \times S_A \times S_B}{P}$, where τ_c is the coincidence window, S_α is the photon count rate seen at user α, P is the total coincidence rate seen between the users. Further, the secure key rate is directly proportional to $\left[H\left(0.5 + \sqrt{QBER \times (1 - QBER)}\right) - H(QBER)\right]$, where $H(\varepsilon)$ is the Shannon Entropy of ε.

Adding classical channels to the same fibre as the quantum states has no effect on QKD other than this increased QBER and decreased key rate. Thus by measuring the noise caused by the classical transmission we can evaluate the feasibility of classical quantum co-existence.

3. Experimental Setup

To experimentally evaluate the excess noise created by the presence of a classical channel spectrally close to the quantum entangled channels, we added the classical equipment to the existing 8-user quantum network testbed

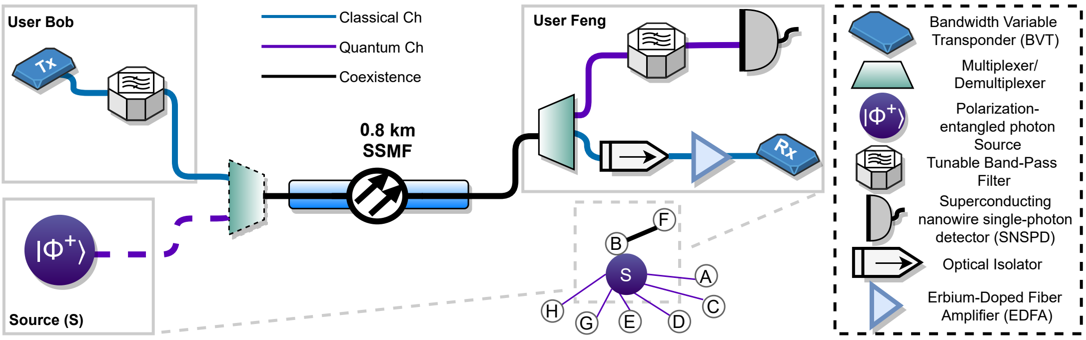

Fig. 1: Testbed design.

presented in [6]. A bandwidth variable transponder (BVT) was deployed in nodes B and F (Bob and Feng, respectively), further enabling 0.8 *km* of co-existence. Fig. 1 shows the testbed.

Since Raman phenomena is the major source of noise contribution in our system, our theoretical analysis shows that anti-stokes shorter wavelengths close to the quantum channel are preferable. Given that, the quantum testbed employs 30 100 GHz entanglement-based quantum channels ranging from ITU-T CH19, i.e. $F_c = 191.9\ THz$ to ITU-T CH49, i.e. $F_c = 194.9\ THz$ (excluding CH34, i.e. $F_c = 193.4\ THz$ because no entanglement is produced at this channel by the quantum source used in our testbed.), we decided to apply the classical channels on the lower edge of the spectrum, i.e. ITU-T WDM CH17, i.e. $F_c = 191.7\ THz$, and CH18, i.e. $F_c = 191.8\ THz$ (one at a time). In both cases, the classical channel provides a $100 Gb/s$ 25 *Gbaud* PM-QPSK signal with a soft-decision forward error correction (SD-FEC) of 25% to enable a error-free transmission. A tuneable band-pass filter (TBPF) with $\approx$5 dB of insertion loss was used to suppress the noise from the BVT Tx on the quantum channels. We used a fixed WDM filter with a low insertion loss of 0.8 *dB* (represented by the multiplexer in Fig. 1) in which the quantum and classical channels are passed through the rejection and passing ports respectively resulting in co-existence in the common port.

After the multiplexer, the the classical data channel travels through 0.8 *km* of field-deployed standard single mode fibre (SSMF) to a similar WDM filter (represented by the demultiplexer in Fig. 1) that passes the classical channel while rejecting all other channels towards the Superconducting nanowire single-photon detector (SNSPD). This WDM filter provides a $\approx$10 dB of isolation from the excess noise of the classical channel to the rejection port. The classical channel is then connected to an optical isolator with insertion loss of $\approx$3 dB to prevent the tunable laser used by the BVT Rx as a local oscillator from travelling back to the SNSPD and altering the measurements. It also prevents the Amplified spontaneous emission (ASE) noise generated by the Erbium-doped fibre amplifier (EDFA) which is used to amplify the classical signal. Finally, the channels rejected on the WDM filter including the quantum channels, are sent towards a TBPF with sharp filter edges and then is received by the user's detector. This 100 *GHz* bandwidth TBPF provides $\approx$60 dB of isolation to the quantum channel from the excess noise generated by the classical channel, and was used to tune the rejected channels to the required wavelength of the quantum channel to measure the excess noise using the SNSPD. The SNSPD detection efficiencies ranging from $\approx$70 to 90%, a jitter of between $\approx$60 and 80 ps (including the measurement device), and dark counts of $\approx$1 kHz.

4. Results

Fig. 2 shows the experimental evaluation of excessive photon counts in the presence of a classical channel. Specifically, Fig. 2 a) presents the excess noise due to classical channel CH17 (191.7 *THz*) for launching power varying from -29 to -26 dBm. The excess noise is expressed in photon counts per second, and as detailed in Section 2 impacts negatively on the Quantum Bit Error Rate of the link, thus decreasing the SKR obtained.

Raman intensity simulations shown in Fig. 2 b) reveal that the peak of the scattering noise, highlighted within the appropriate range in both a) and b), is only affecting a limited number of the quantum entangled channels. It is also evident that the intensity of the anti-stokes (right side of Fig. 2 b) of the Raman noise is lower than the stokes (left side), hence supporting the choice of classical channels at the lower edge of the entangled source. Finally, it reveals that there is a region close to the classical channel with a dip to the scattering noise effect, further facilitating co-existence. In our case, according to the photon counts measurement Ch19 - Ch24 are the best candidates for co-existence next to channel 17, exhibiting less than 1000 counts. Fig. 2 c) repeats the previous experiment tuning the BVT Tx to CH18, for two power levels (-29 and -26 dBm), revealing that the noise peak is also shifted one channel to the right, thus confirming that the peak noise is a product of Raman phenomena.

Using data from our quantum network testbed [6] we collected the average secret key rates and photon counting statistics for the Bob-Feng link over 18.4 hours. When this data is combined with the excessive photon count measurements of Fig. 2 a) and fed into the analytical expression obtained in Section 2 we obtain the impact of excessive noise from the classical channel to the secret key rate of the WDM entangled links. With a classical

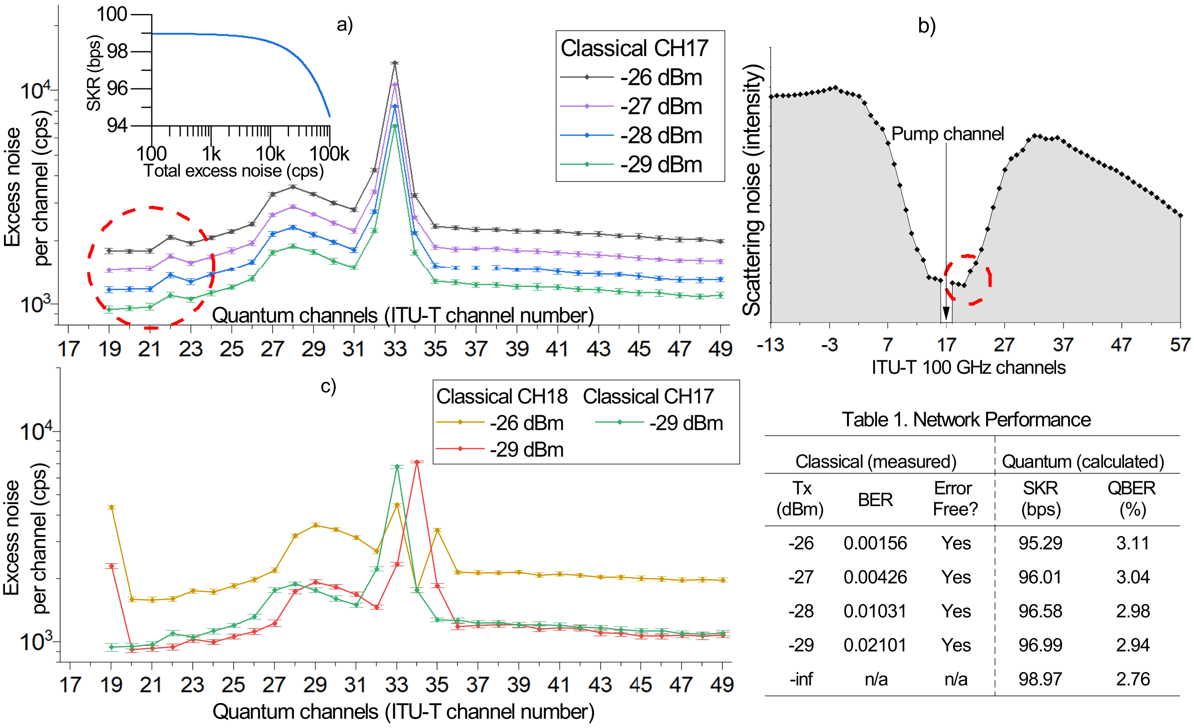

Table 1. Network Performance

Classical (measured)			Quantum (calculated)	
Tx (dBm)	BER	Error Free?	SKR (bps)	QBER (%)
-26	0.00156	Yes	95.29	3.11
-27	0.00426	Yes	96.01	3.04
-28	0.01031	Yes	96.58	2.98
-29	0.02101	Yes	96.99	2.94
-inf	n/a	n/a	98.97	2.76

Fig. 2: a) Excess noise due to classical CH17 on different quantum channels. b) Stokes and anti-stokes of the Raman intensity centred on CH17. c) Excess noise due to classical CH17 and CH18 on different quantum channels.

launch power of -26 dBm, we predict QBER will increase by 0.35% and the SKR with co-existence will be 95.3 bits per second – a decrease of <3.8%. At this point we should note that we consider the cumulative effect of the noise photon counts generated across the all 30 channels of the spectrum of the WDM entangled links.

5. Conclusion

We demonstrated a viability study of quantum-classical co-existence on a 0.8 km deployed fibre part of our previously deployed 8-user quantum network testbed and proved in the form of excess noise measurements that co-existence is feasible on 30 channels on the C-band with a classical channel launcing at -26 dBm at $F_c = 191.7\ THz$.

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