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DV-QKD Coexistence With 1.6 Terabit/s Classical Channels in Free Space Using Fiber-Wireless-Fiber Terminals

O. Alia(1)*, A. Schreier(2), R. Wang(1), S. Bahrani(1), R. Singh(3), G. Faulkner(2), J. Rarity(4), D. O'Brien(2), G. T. Kanellos(1), R. Nejabati(1), D. Simeonidou(1)

(1) High Performance Networks Group, University of Bristol, Woodland Road, Bristol, UK
(2) Department of Engineering Science, Parks Road, University of Oxford, UK
(3) Formerly with (2), now with Cambridge Research Laboratory, Toshiba Europe Ltd., CB4 0GZ Cambridge, UK
(4) Quantum Engineering Technology Labs, H. H. Wills Physics Laboratory, University of Bristol, UK
**Corresponding author*: *obada.alia@bristol.ac.uk*

Abstract *We experimentally demonstrate for the first time the simultaneous transmission of a COW-based DV-QKD channel and an 8x200 Gpbs 16-QAM coherent optical channels, both operating in the C-band over 2.5 m of free space enabled by Fiber-Wireless-Fiber terminals. ©2022 The Author(s)*

Introduction

Quantum Key Distribution (QKD) technology is a key sharing protocol that depends on the laws of physics to generate information-secured symmetric keys[1]. QKD has been extensively demonstrated over optical fiber networks[2]–[5], and in free space with indoor handheld devices over 0.5 m[6]. Recently, the first experiment of a Coherent One Way (COW) lab-based QKD system transmission over free space was demonstrated[7]. The QKD system operates in the visible spectrum (852 nm) with a fixed channel loss of 16 dB over a transmission distance of 2 m. To facilitate free space transmission, Fiber-Wireless-Fiber (FWF) terminals have been utilised for high rate classical data transmission[8],[9]. However, FWF terminals have not been explored for QKD transmission or for the coexistence of QKD and classical channels. The coexistence of quantum and classical channels represents a challenge due to the high power of the classical channels (orders of magnitudes higher than the quantum channel)[10]. Nevertheless, coexistence has been demonstrated in single mode fiber[11], multicore fiber[12],[13] and hollow core fiber[14]. In this paper, we present a proof of concept demonstration of the first coexistence experiment between a quantum channel and 1.6 Tbps classical channels both operating in the C-band and transmitting over 2.5 m of free space using FWF terminals.

Fiber-Wireless-Fiber Terminals

Fig. 1 shows the system schematic of the FWF terminals[8]. Light from fibres is fed into the terminals and collimated (Col1 & Col2) before being actively steered using fast steering mirrors (M1 & M2). These gold-coated mirrors provide dual-axis beam steering with up to ±50° optical deflection per axis and a steering resolution less than 5μrad. The mirrors have a large angle step (20°) response time of 7.5 ms and a small angle step (0.1°) response time of 1.4 ms. The tracking system used to control M1 & M2 consists of IR Tags operating at 800 nm and 890 nm as well as a set of cameras. The infrared localisation beacons provided by IR tags are represented by red and blue lines in Fig. 1, respectively. Dichroic beam splitters (DF1 & DF2) are used to separate the communication signal and localisation beacon light. Cameras CAM1 & CAM3 have a wide field of view (FoV) which is used to locate the terminals, while the other cameras (CAM2 & CAM4) have a narrow FoV which allows for higher precision tracking to minimise the misalignment loss. Optical band-pass filters (BF1 & BF2) in front of each camera reject ambient light to enable reliable localisation and tracking of the terminals. The current latency of the tracking system allows for nomadic operations[8].

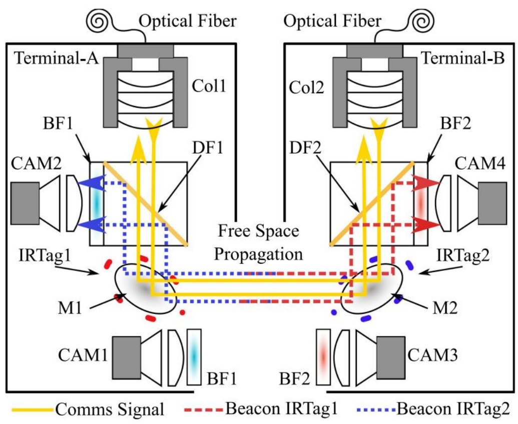

Fig. 1: Schematic of the FWF terminals[8].

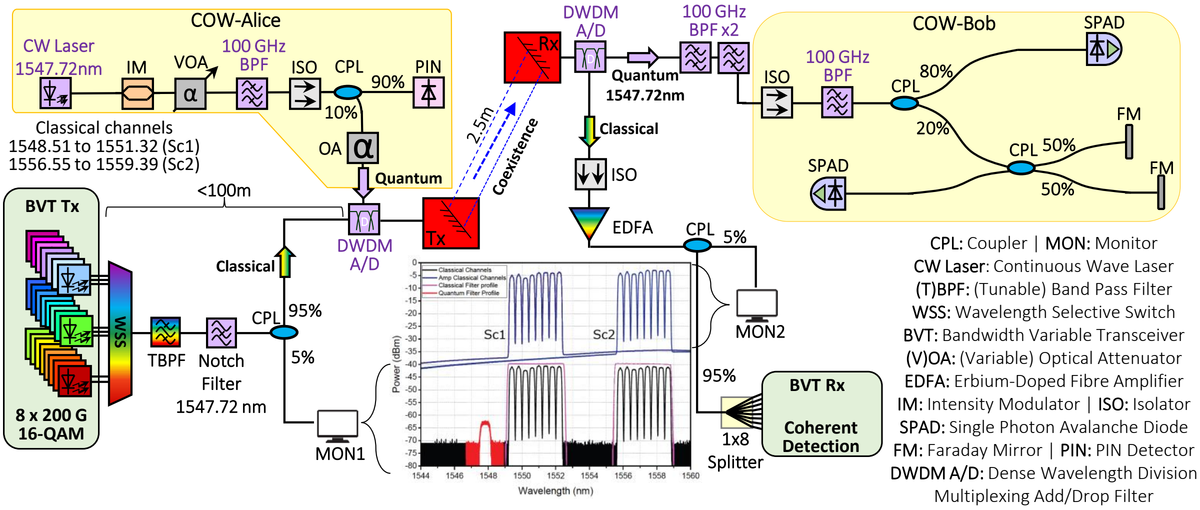

Fig. 2: Experimental testbed for the coexistence of 1.6 Tbps classical channels and QKD channel over 2.5 m of free space. Inset: Spectrum of the combined transmission of quantum and classical channels with optical filter profiles of both scenarios.

Experimental Testbed

Fig. 2 illustrates the experimental system setup. For the classical channels, two optical-packet DWDM platforms are used with bandwidth-variable transponders (BVTs). All 8 ports of the BVT were configured to use 16-QAM modulation for a maximum capacity of 200 Gbps per channel resulting in 1.6 Tbps of transmission overall with a detector sensitivity of -26 dBm. The adaptable soft-decision forward error correction is configured with a 15% overhead to enable error-free transmission. Furthermore, all 8 ports were configured to the highest possible transmission power resulting in a total power of 0 dBm at the input of the FWF Tx terminal. An average BER of 2.376×10^{-7} was measured throughout all experiments. For the quantum channel, an IDQuantique Clavis3 DV-QKD system[15] is used which implements the COW protocol[1]. The DV-QKD system has a fixed frequency for the quantum channel of 193.70 THz (1547.72 nm).

As shown in Fig. 2, the eight coherent output ports of the BVT are multiplexed using a wavelength selective switch (WSS) which performs as a multiplexer and a band pass filter (BPF) with an extinction ratio of 30 dB. The WSS output is then connected to a tunable band pass filter (TBPF) with a flat-top and sharp filter edges (lower trace in the inset Fig. 2) with a high extinction ratio of 60 dB. The classical channels are then connected to a passive DWDM notch filter to further suppress the noise level at the quantum channel wavelength (1547.72 nm) followed by a 95/5 coupler where the 5% port is connected to a monitor to observe the classical channel profile (black channels in the inset Fig. 2). The 95% port is connected to the reflect port of a DWDM add/-drop (A/D) filter which passes the quantum channel wavelength and reflects all other wavelengths (the classical channels). The quantum channel is connected to the pass port of the same DWDM A/D filter. This DWDM A/D filter is used as a multiplexer to combine the quantum and classical channels in a coexistence configuration which is fed to the FWF Tx terminal with a 0 dBm total power. Both the quantum and classical channels are transmitted through 2.5 m of free space to the FWF Rx terminal. The Rx terminal is followed by a similar DWDM add/drop filter which passes the quantum channel through double stage filtering using two fixed WDM band-pass filters (red profile in the inset Fig. 2) centred at the quantum channel wavelength (1547.72 nm), to eliminate any crosstalk generated by the classical channels. The transmission port of the DWDM A/D is connected to the Bob-QKD unit. The quantum channel has a measured back-to-back loss of 11.5 dB. The output of the reflection port of the DWDN A/D filter is connected to an optical isolator to prevent the tunable laser used by the BVT Rx as a local oscillator from propagating back to the Bob-QKD unit and interfering with the QKD measurements. It also prevents the Amplified Spontaneous Emission noise generated by the Erbium-doped fiber amplifier (EDFA) which is used to amplify the classical signals. The output of the EDFA is also connected to a 95/5 coupler where the 5% port is used to observe the amplified classical channel profile (blue channels in the inset Fig. 2). The 95% port is connected to a 1x8 splitter which is used to separate the eight classical channels for coherent detection.

Results

The testbed was connected without the FWF terminals to investigate the effect of the Raman scattering generated by the fiber on the quantum channel performance. As shown in Fig. 3, the secret key rate (SKR) drops significantly when the spacing between the quantum and the classical channels is 8.8 nm (Sc2) comparing to 0.8 nm (Sc1) using the same launch powers. A spectral spacing of 0.8 nm means the quantum channel is placed in a Raman spectrum dip, whereas the spacing of 8.8 nm means the quantum channel is placed at the Raman spectrum peak causing additional crosstalk within the BPF filter bandwidth. Although the fiber length is short < 100 m, Raman scattering degrades the quantum channel performance due to the high spectral density of the communication channels.

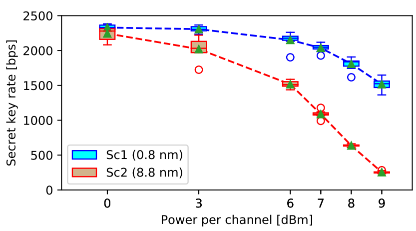

Fig. 3: Back-to-Back measurement of the SKR with different spacing between the quantum and classical channels.

Fig. 4 shows the experimental evaluation of the SKR of the quantum channel when coexisting with 8 classical channels via 2.5 m of free space at a coexistence power of 0 dBm with different spectral spacing between the quantum and classical channels. At a spectral spacing of 0.8 nm (Sc1), the mean SKR drops by 13% from ≈ 2300 bps to 2000 bps. For the spacing of 8.8 nm (Sc2), the mean SKR drops by 45% from ≈ 2300 bps to 1250 bps. Both observations are in good agreement with Fig. 3 at 7 dBm launch power indicating no additional Raman noise being generated in the free space path. Moreover, the QKD link demonstrated long term stability within a 200 lux lab environment indicating a lack of significant ambient light penalty.

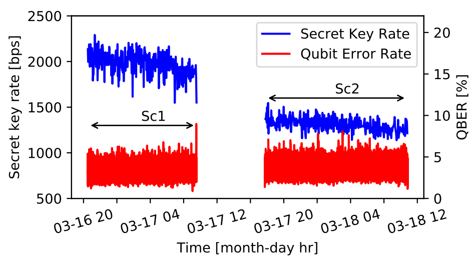

Fig. 4: Long term measurements of the QKD link operating in coexistence with 1.6 Tbps classical channels.

Fig. 5a) shows the experimental evaluation of the SKR and quantum bit error rate (QBER) with the IR Tag of the FWF terminals turned on and off. As shown in Fig. 5a) the IR Tag has no impact on the quantum channel performance with the average SKR of ≈ 2300 bps and an average QBER of ≈ 3%. Fig. 5b) shows the mean SKR with deliberate off-axis steering applied to the Rx terminal. As illustrated in Fig. 5b), the SKR decreases abruptly with increasing angular link misalignment and reaches zero bps when the angular link misalignment is bigger than 0.025°. This behaviour is mainly due to the additional fiber coupling losses induced by angular misalignment.

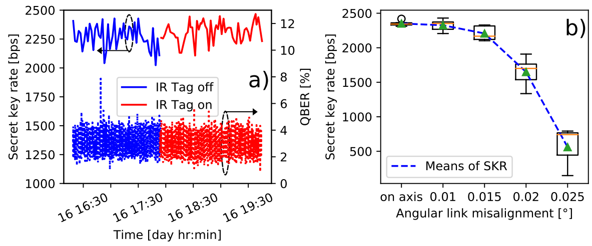

Fig. 5: Quantum channel performance at a distance of 2.5 m. a) SKR and QBER of the terminals with the LED ring turned on (Red) and off (Blue). b) SKR plotted against the angular link misalignment of the terminals.

Conclusions

We experimentally demonstrated the transmission of a COW-based DV-QKD channel when coexisting with eight classical channels at 0 dBm total power over 2.5 m of free space. The FWF terminals enable a free space transmission, which is free of ambient light penalties and additional Raman effects. The insertion loss of the FWF terminals is supported by conventional QKD systems. However, tracking accuracy is key as the SKR is shown to decrease abruptly with increasing the angular link misalignment. It is worth noting that, the FWF terminals do not discriminate between photons associated with QKD, classical channels or photonic noise. Future work will include an upgraded FWF terminal system allowing for integration into access networks distributing QKD and classical channels pushing towards all-optical network architectures.

Acknowledgements

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