Coexistence of Quantum/Classical Signals Over Converged Fiber/FSO links for Intra-Campus Networking

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Abstract A converged fiber/FSO QKD coexistence scheme over an installed intra-campus link is demonstrated. Both FSO/fiber and fiber/FSO transmission configurations exhibited robust performance and stability, with QBER values below 3.9% while the quantum pulses co-propagated with an SFP signal intensity of 0 dBm. ©2023 The Author(s)

Introduction

Quantum Key Distribution (QKD) has emerged as a promising solution for secure communication, leveraging the principles of quantum mechanics to exchange cryptographic keys with information theoretic security [1]. The straightforward way for integrating QKD systems in the existing network infrastructure relies on the use of optical fibers [2], which are continuously deployed to support the needs of modern classical networks and they offer low-loss transmission and high stability. The coexistence of both quantum and classical links on the same fiber core has been extensively studied [3], and advanced noise filtering techniques have been proposed to allow for a deployment-friendly approach without the need of dedicated fibers for the QKD links. In view of the future networks in metropolitan areas, the physical infrastructure of the network will rely on both wired and wireless access domain segments which can operate in a seamless way [4]. To assist in the security requirements of these networks, Free Space Optical (FSO)-QKD links have been successfully demonstrated in urban daylight scenarios [5], showing robustness against the strong background noise using effective noise filtering techniques in various domains [6]. In the context of hybrid fiber/FSO deployment paradigms, the quantum links will coexist with intense classical light in installed fiber topologies, and they will also co-propagate over wireless distances in metropolitan point-topoint links. In the above context, an FSO/fiber QKD link was demonstrated in Shanghai urban area [7] and its successful operation in daylight conditions was achieved based on adaptive optics for the FSO link and by using a 2 km underground fiber for connecting the measuring station with the optical telescope. Very recently, an impressive experimental campaign on intermodal QKD links in Vienna and Padova was demonstrated, based on sub-km FSO links and installed dark fiber links for the QKD transmission [8]. University of Bristol recently demonstrated an impressive classical/QKD coexistence scenario over a 2.5m wireless bridge for a fiber/FSO/fiber QKD link coexisting with Tbps-scale classical traffic [9]. While the above research milestones reveal the strong potential of QKD integration in converged fiber/FSO infrastructures, the next step requires the demonstration of quantum links over classical networks operating in real deployments.

We aim to contribute to the above direction by presenting experimental evidence of quantum/classical transmission over а converged fiber/FSO intra-campus link. Βv multiplexing a polarization-encoded singlephoton sender station with a signal carrying 1 Gbps of classical data from a Small Form Pluggable (SFP) transceiver which provides mobile X-haul connectivity to campus mobile stations [10], successful transmission of both classical/quantum signals in C-band was achieved over an installed 2.2 km intra-campus fiber infrastructure combined with a 40-m FSO link, emulating a building-to-building scenario. experimental measurement campaign Our focused on the Quantum Bit Error Rate (QBER) performance evaluation of the quantum link by considering the noise contributions from both Spontaneous Raman Scattering (SpRS) and background noise photons in the wireless link. We experimentally evaluated our classical/quantum link in both fiber/FSO and FSO/fiber transmission configurations. Both converged scenarios demonstrated robust performance when the Quantum Signal (QS) copropagated with a bit stream of 0 dBm, showing QBER values below 3.7% and 3.9% respectively, as well as calculated SKRs more than 200 bps.

Converged Fiber/FSO experimental setup

Fig. 1 shows the experimental coexistence setup. Quantum pulses were generated using a Continuous Wavelength (CW) laser source at 1550.12 nm, which was modulated at a repetition rate of 10 MHz using a Mach-Zehnder Modulator



Fig. 1: Converged Fiber/FSO coexistence experimental setup of quantum/classical signal (a) map of the 2.2 km IC fiber link, (b) indoor 40-m FSO link and (c) converged fiber/FSO setup.

(MZM). Optical power was adjusted to achieve desired mean photon number of µ=0.5, which verified was through photon counting measurements. This value is typically used for such Decov-State protocols as BB84, representing the average photon number per pulse of the signal state [11]. Then, the QS was multiplexed with a data signal generated by an SFP, centered at 1551.8 nm, over three different transmission scenarios: i) a 2.2 km intra-campus (IC) fiber link, ii) a 40 m FSO and iii) a converged fiber/FSO link. The optical loss introduced by the installed fiber link was measured to be 4.5 dB (including the loss stemming from the multiple connection points) at 1550 nm. For the FSO link, Tx and Rx terminals comprised of commercial of the shelf air-spaced doublet collimators with an aperture of 25 mm. A coupling efficiency of 32% was achieved, which corresponds to 5 dB optical loss mainly due to SMF coupling efficiency. Collection efficiency is almost 100% due to the short distance of the link. Atmospheric absorption at 1550 nm is considered negligible for 40 m free space propagation [12]. Tip-tilt correction was used to account for any misalignment between the Tx and Rx terminals. An additional 2 dB optical loss was introduced by the fiber patches connecting the FC/PC terminated collimators with the multiplexing setup. In the last scenario, both IC fiber and FSO link were combined to deploy a converged scenario where both classical signal (CS) and QS coexisted in an intermodal fiber/FSO transmission with a total link loss of 11.5 dB. To effectively minimize the contribution of noise photons to the quantum passband, a triple stage notch filter with a narrow stopband of 0.8 nm and a total IL of 1.5 dB was utilized prior to transmitting the CS across the deployed scenarios. To isolate the quantum signal, a two-stage Band-Pass Filter (BPF), with 0.1 and 0.2 nm passband respectively with a total loss of 6 dB was used. Detailed information about the filtering stages can be found in [10]. To

evaluate the performance of the three transmission scenarios, we opted for Alice to prepare а single polarization encoding. Consequently, the polarization state after the filtering stage at the receiver end was adjusted to match the transmission axis of a Polarization Beam Splitter (PBS) (with Visibility > 99%) using a Polarization Controller (PC). Consequently, the quantum signal was directed exclusively to one of the two InGaAs Single Photon Avalanche Diodes (SPADs), allowing for photon counting QBER measurements to be conducted. The SPAD units (AUREA OEM NIR) operated at n=10% quantum efficiency in gated mode (6 ns gate) and dead time of 20 µs, thus limiting the SPADs after-pulsing effect to about 2%. The endto-end loss of the quantum channel was measured to be approximately 14 dB for the case where the transmission medium was the 2.2 km IC fiber, 17.5 dB for the case of the FSO link and 21 dB for the converged fiber/FSO scenario.

Results and Discussion

For the three scenarios described above, the performance of the quantum link was evaluated through photon counting QBER measurements, following the methodology reported in [13]. Specifically, а single-photon transmission scheme with a single biased basis choice was employed. Sender station's photons polarization axis was aligned with the PBS transmission axis using the PC, resulting in the quantum signal being directed only to SPAD 1 (Fig. 2a black squares). Therefore, any counts measured in SPAD 2 (Fig. 2a red circles) were considered erroneous. The QBER, which quantifies the ratio detectors, can be defined as follows [3]:

$$QBER (\%) = \frac{N_{false}}{N_{false} + N_{signal}} = \frac{1}{2} \frac{N_{ap} + N_{DCR1} + N_{DCR2} + N_{Noise} + N_{PBS}}{N_{total}}$$
(1)

of false detector clicks to the total clicks in both where N_{DCR1} and N_{DCR2} corresponds to the Dark Count Rate (DCR) of each detector, which were measured to be 17 and 19 counts per second N_{Noise} refers to the respectively. (cps), background noise photons arising from the transmission of the CS in both detectors, N_{PBS} are the counts detected at SPAD 2 due to the imperfect visibility of the PBS, and N_{ap} is the afterpulsing contribution counts which divided by N_{total} results in the afterpulsing probability p_{ap} (%). The factor $\frac{1}{2}$ is inserted in the Eq. (1) since each noise photon has a probability of 50 % to be registered an erroneous as count. Α representative example is presented in Fig. 2(a) for the case of the fiber/FSO transmission. As the launch power increases, the erroneous counts increase exponentially resulting in increased QBER values according to Eq. (1).

Fig. 2(b) provides the calculated photon counting QBER values under varying launched optical power levels for the three transmission scenarios. It is observed that, for the case of the converged fiber/FSO and vice versa, similar performance is obtained, reaching QBER values lower than 3.5% for SFP launch power of 0 dBm. For the 40 m FSO link, QBER values lower than 1.7%, for launched optical power up to +5 dBm were obtained. This is due to the absence of the SpRS noise photons in contrast to when the propagation medium is the IC fiber link where QBER values start increasing exponentially when the launched power levels exceeded -10 dBm. In Fig. 2(c), the photon counts generated by the SpRS for different classical wavelengths in the quantum passband (1550.12 nm) are displayed. The count rate shown is normalized based on the count rate measured for the SFP's wavelength of 1551.8 nm. It was validated, that the allocation of the CS 2-3 nm apart from the QS results in lower SpRS noise count rates [3], [13] justifying our choice for the QS at 1550.12 nm. By accounting the Raman noise generated in the IC fiber link, expected SKRs values of 210 bps were calculated, for the DS-BB84 protocol, according to [11], when the quantum signal was co-



Fig. 3: QBER measurement over time for the converged Fiber/FSO link

propagating with a SFP signal with launch power of 0 dBm.

Finally. Fig. 3 presents а stability measurement over 70 minutes for the converged fiber/FSO link. The spikes in the QBER represent obscuration/blockage of the FSO link. Our fiber/FSO intermodal setup exhibited several minutes of stability when no CS signal was present maintaining an intrinsic QBER lower than 5%, without applying any real time corrections. The QBER fluctuations is mainly attributed to polarization drifts arrising from fiber-based components and the IC transmission.

Conclusions

In this work, a converged fiber/FSO coexistence QKD scheme was demonstrated over an installed intra-campus network. Our fiber/FSO intermodal setup exhibited robust performance when the QS co-propagated with high intensity SFP data showing acceptable QBER values below 3.5% with calculated SKRs more than 200 bps.

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Fig. 2: (a) cps of both SPDs for the converged scenario, (b) Normalized SpRS noise counts (c)QBER (%) vs Optical Power

References

- E. Diamanti, H.-K. Lo, B. Qi, and Z. Yuan, "Practical challenges in quantum key distribution," *Npj Quantum Inf.*, vol. 2, no. 1, Art. no. 1, Nov. 2016, doi: 10.1038/npjqi.2016.25.
- [2] H.-L. Yin *et al.*, "Measurement-Device-Independent Quantum Key Distribution Over a 404 km Optical Fiber," *Phys. Rev. Lett.*, vol. 117, no. 19, p. 190501, Nov. 2016, doi: 10.1103/PhysRevLett.117.190501.
- P. Eraerds, N. Walenta, M. Legré, N. Gisin, and H. Zbinden, "Quantum key distribution and 1 Gbps data encryption over a single fibre," *New J. Phys.*, vol. 12, no. 6, p. 063027, Mar. 2010, doi: 10.1088/1367-2630/12/6/063027.
- [4] A. Bekkali, H. Fujita, and M. Hattori, "Free-Space Optical Communication Systems for B5G/6G Networks," in 26th Optoelectronics and Communications Conference (2021), paper W1A.1, Optica Publishing Group, Jul. 2021, p. W1A.1. doi: 10.1364/OECC.2021.W1A.1.
- [5] M. Avesani *et al.*, "Full daylight quantum-key-distribution at 1550 nm enabled by integrated silicon photonics," *Npj Quantum Inf.*, vol. 7, no. 1, Art. no. 1, Jun. 2021, doi: 10.1038/s41534-021-00421-2.
- [6] H. Ko et al., "Daylight Operation of a High-Speed Free-Space Quantum Key Distribution using Silica-Based Integration Chip and Micro-Optics-Based Module," in 2019 Optical Fiber Communications Conference and Exhibition (OFC), Mar. 2019, pp. 1–3.
- [7] Y.-H. Gong *et al.*, "Free-space quantum key distribution in urban daylight with the SPGD algorithm control of a deformable mirror," *Opt. Express*, vol. 26, no. 15, pp. 18897–18905, Jul. 2018, doi: 10.1364/OE.26.018897.
- [8] F. Vedovato *et al.*, "Realization of intermodal fiber/freespace quantum key distribution networks," in *Quantum Computing, Communication, and Simulation III*, P. R. Hemmer and A. L. Migdall, Eds., San Francisco, United States: SPIE, Mar. 2023, p. 96. doi: 10.1117/12.2668341.
- [9] A. Schreier *et al.*, "Coexistence of Quantum and 1.6 Tbit/s Classical Data Over Fibre-Wireless-Fibre Terminals," *J. Light. Technol.*, pp. 1–7, 2023, doi: 10.1109/JLT.2023.3258146.
- [10] D. Zavitsanos et al., "Coexistence Studies for DV-QKD Integration in Deployed RAN Infrastructure," in 2022 International Workshop on Fiber Optics in Access Networks (FOAN), Jul. 2022, pp. 6–9. doi: 10.1109/FOAN56774.2022.9939691.
- H.-K. Lo, X. Ma, and K. Chen, "Decoy State Quantum Key Distribution," *Phys. Rev. Lett.*, vol. 94, no. 23, p. 230504, Jun. 2005, doi: 10.1103/PhysRevLett.94.230504.
- [12] L. C. Andrews and R. L. Phillips, Laser beam propagation through random media, 2nd ed. Bellingham, Wash: SPIE Press, 2005.
- [13] A. Ntanos, D. Zavitsanos, A. Stathis, G. Giannoulis, and
 H. Avramopoulos, "Deployment-Oriented
 Classical/Quantum Coexistence in X-Haul Fiber Link for
 B5G Networks," in *Conference on Lasers and Electro-*

Optics (2023), paper AM3N.5, Optica Publishing Group,May2023,p.AW3N.5.doi:XXXX/CLEO_AT.2023.AW3N.5.