Co-propagation of Classical and Continuous-variable QKD Signals over a Turbulent Optical Channel with a Real-time QKD Receiver

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Abstract: We demonstrate classical and quantum signal co-propagation over a turbulent free-space channel with 3 Tbit/s throughput and record 2.7 Mbit/s secret-key rate. Our real-time GPU-based receiver assessed quantum signal integrity under different turbulence scenarios for the first time.

1. Introduction

Continuous-variable quantum key distribution (CV-QKD) provides an information-theoretic approach for securely distributing secret random keys. Leveraging weak coherent states, CV-QKD protocols utilize mature telecom technologies. Security relies on quantum mechanics for Gaussian and discrete modulation protocols where we apply the analytical bound for the asymptotic secret key ratio (SKR) under arbitrary modulation [1]. We consider realistic trusted noise and finite size effects [2]. Free-space optical (FSO) CV-QKD was first demonstrated under realistic atmospheric conditions in [3]. A 0.6 km free-space CV-QKD system operated in fog has been demonstrated in [4]. Compared to discrete-variable QKD, coexistence with classical channels has been less explored in CV-QKD. However, CV-QKD has the potential to be more tolerant to noise originating from wavelength-division multiplexing (WDM) channels [5]. Previous joint transmissions of CV-QKD with on-off keying signals [6,7] have been demonstrated. Recently, joint propagation of wideband fiber transmission of 100 coherent polarization multiplexed 16-ary quadrature amplitude modulation (QAM) WDM channels, and CV-QKD signals with an average secret key rate of 27.2 kbit/s was implemented in [8]. In this paper, we show a joint propagation of 15 coherent 64-QAM and CV-QKD signals, with a real-time receiver, over a turbulent optical channel achieving 3 Tbit/s of classical data rate and 2.7 Mbit/s of secret key rate.

2. Experimental Set-up

The experimental CV-QKD setup in Fig. 1 utilizes an offline transmitter (Alice) and real-time receiver (Bob) capable of operating in calibration and signal reception mode. Key system capabilities include <100 kHz linewidth external cavity lasers (ECLs), IQ optical modulation for probabilistically shaped 256-QAM signals [1], 250 Mbaud symbol rate with 50% pilot symbols, and 2 GS/s analog-to-digital converter (ADC) digitization at the receiver (Bob). With the help of a power meter and in a back-to-back configuration, Alice's average modulation variance

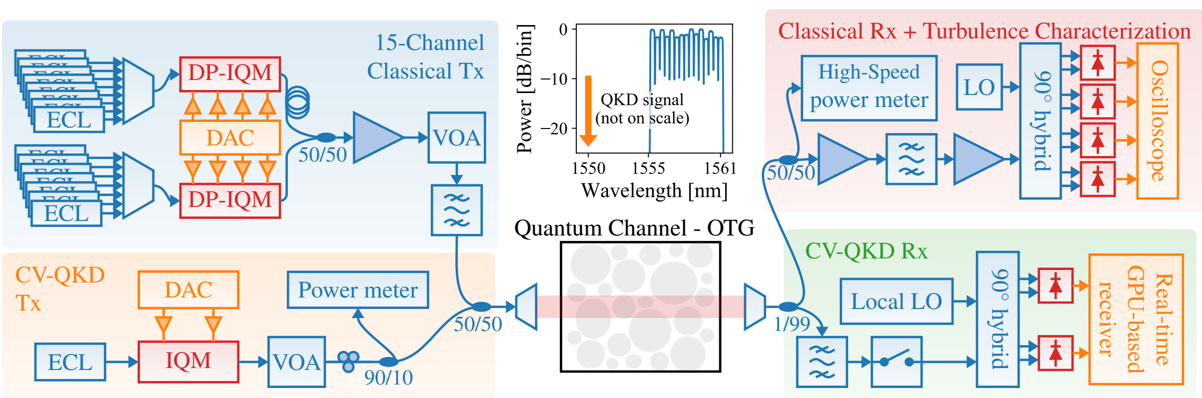

Fig. 1: Experimental set-up for co-propagation of classical and CV-QKD signals over a turbulent optical channel.

was 8 shot-noise units (SNUs). Bob uses a local ECL as a local oscillator into an optical hybrid, digitizes the outputs, and implements real-time digital signal processing (DSP) for calibration and quantum signal recovery.

DSP includes frequency offset compensation, filtering, equalization, pilot-based phase recovery [9], and parameter estimation. As Bob is assumed to be trusted, all the CV-QKD receiver losses due to coupling and the optical bandpass filter are taken into account in the quantum efficiency, resulting in a decrease from 67% to 35%. Real-time post-processing on a graphics processing unit (GPU) evaluates security via excess noise and SKR. Note that error correction and privacy amplification are implemented but not enabled because we have an offline transmitter. In addition to the CV-QKD signal, 15 classical 45 GBd polarization-multiplexed 64-QAM WDM channels, placed on a 50 GHz grid centered around 192.4 THz, are generated and transmitted, yielding a raw bit rate of 4.05 Tbit/s. With a channel normalized generalized mutual information (NGMI) of 0.83 and assuming an FEC of rate $R = \frac{4}{5}$, giving an overall rate of 0.75, the total data rate would be 3 Tbit/s [10]. The classical transmitter consists of 15 ECLs of which the outputs are multiplexed into odd and even channels and are modulated by two dual-polarization IQ-modulators (DP-IQMs) driven by a 4-channel 100 GSa/s digital-to-analog converter (DAC). The output is amplified using an erbium-doped fiber amplifier (EDFA) and band-pass filtered to minimize amplifier noise in the CV-QKD band. After combining with the CV-QKD signal, the light is collimated and directed through an optical turbulence generator (OTG) [11] before being collected back into a fiber. Although the free space propagation distance is 0.8 meters, the OTG uses the forced mixing of two air flows with a temperature difference of up to 150 K to emulate a turbulent channel with a longer distance. The strength of the turbulence is determined by monitoring the intensity fluctuations of the received power and fitting a combined log-normal pointing jitter distribution, described in [12]. The receiver for the classical channels comprises two EDFAs placed around a wavelength selective switch (WSS) to amplify and select the WDM channel under test, followed by a coherent receiver and 80 GSa/s oscilloscope. The digitized signal is processed using standard offline DSP.

3. Results

Figure 2a displays the normalized irradiance for a 1-second trace and the probability density function (PDF), across different turbulence conditions. From A to E, the scintillation indexes measured during these captures are 1.09×10^{-3}, 1.05×10^{-2}, 1.38×10^{-2}, 1.38×10^{-2}, and 1.70×10^{-2} Although all are within the weak fluctuations regime, the decreasing pointing jitter coefficient (123.58, 9.03, 3.14, 2.47, 1.74, respectively) indicates a greater variance of residual pointing error variance, resulting in a broadening received intensity PDF [12]. Consequently, fades approaching zero intensity become more probable versus the log-normal PDF, raising outage likelihood. This effect also appears in Fig. 2b, plotting the NGMI of the center WDM channel [10] across turbulence settings. The NGMI PDF comprises 10 µs long sequences, captured approximately every 3.75 seconds, with 48 captures for A, D, E and 32 for B, C.

Figure 3a shows the CV-QKD GPU receiver output over 60 seconds under setting A. Secret key rates (SKRs) used system parameters of: Va = 8 shot-noise units (SNUs), 35% quantum efficiency, 10 dB clearance, 107 quantum block length, 10% frame error rate, and β = 0.95 with error correction codes from [13]. Average results per quantum block were: transmittance of 0.444, excess noise of 0.0048 SNUs, and SKR of 0.037 bits/symbol. Negative excess noise arose from random thermal and shot noise fluctuations. Since the average excess noise was 0.0043 SNUs across all settings, it is omitted for other conditions. Added free-space classical signals negligibly impacted excess noise due to low Raman scattering, power, and Bob's band filtering. Figure 3b shows the transmittance and SKR probability distributions and medians across turbulence settings. Stronger turbulence increased variance, creating more outliers. Settings C and D shared approximately equal scintillation index, PDF,

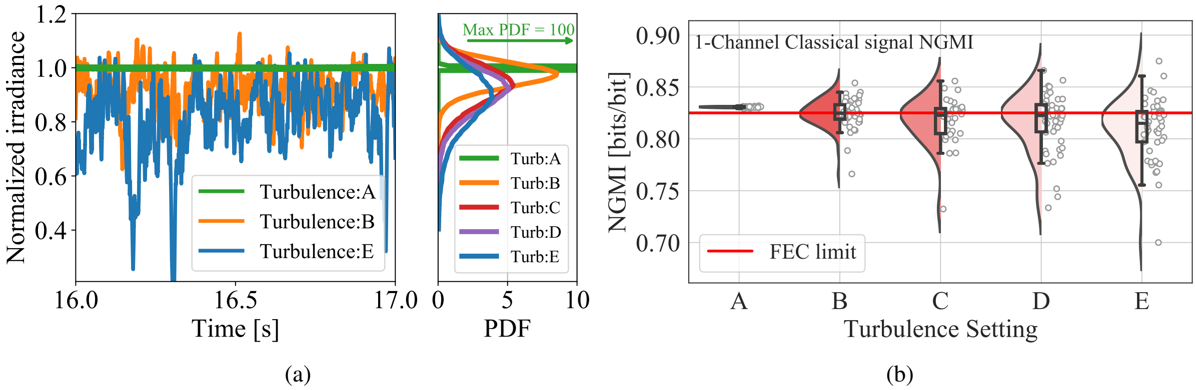

Fig. 2: (a) Normalized irradiance over time for A, B, E turbulence settings and PDF for all (b) NGMI data distributions in all turbulence settings, for the measured 1-channel classical signal

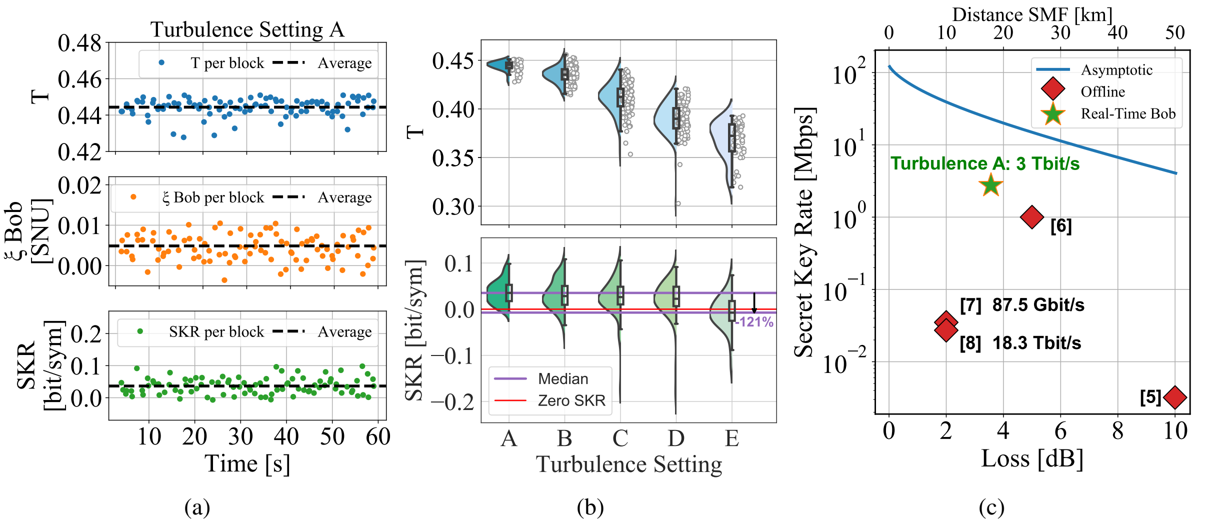

Fig. 3: (a) CV-QKD real-time capture with no turbulence for transmittance T, ξ_{Bob} and SKR (b) Data distribution of transmittance and SKR for different turbulence settings (c) Secret key rate and classical rate comparison with state-of-the-art experimental demonstrations

and median NGMI per Figs. 2a and 2b. However, differing pointing jitter coefficients noticeably decreased median transmittance by 9% and SKR by 14% in C vs D. Per Figure 2a, deep fades in setting E caused insufficient received power for real-time DSP, discarding those blocks. From A to E, median transmittance fell 16% and median SKR 121%. Currently, setting E represents the limit for positive key rates with stable DSP on our setup, needing further analysis to mitigate dead times during deep fading. Figure 3c compares our performance against state-of-the-art fiber CV-QKD co-propagating classical channels. Under turbulence A, we attained 3 Tbit/s classical data rate and 2.7 Mbit/s SKR, considering 50% pilot data, 50% calibration data, and 50% parameter estimation.

4. Conclusion

The co-propagation of classical and continuous-variable quantum key distribution (CV-QKD) signals through a turbulent free-space optical channel was studied. Across proposed turbulence levels, quantum and classical parameters offered insight into real-world quantum channel behaviors. Considering system practicality via a real-time QKD receiver in signal and calibration modes, a realistic secret key rate of 2.7 Mbit/s was attained alongside a 3 Tbit/s total classical data rate.

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References

1. A. Denys *et al.*, “Explicit asymptotic secret key rate of continuous-variable quantum key distribution with an arbitrary modulation,” Quantum **5**, 540 (2021).
2. P. Jouguet *et al.*, “Analysis of imperfections in practical continuous-variable quantum key distribution,” Phys. Rev. A **86**, 032309 (2012).
3. D. Elser *et al.*, “Feasibility of free space quantum key distribution with coherent polarization states,” New J. Phys. **11**, 045014 (2009).
4. S. Wang *et al.*, “Feasibility of continuous-variable quantum key distribution through fog,” Opt. Lett. **46** (2021).
5. R. Kumar *et al.*, “Coexistence of continuous variable qkd with intense dwdm classical channels,” New J. Phys. **17** (2015).
6. D. Huang *et al.*, “Field demonstration of a continuous-variable quantum key distribution network,” Opt. Lett. **41** (2016).
7. T. A. Eriksson *et al.*, “Coexistence of continuous variable quantum key distribution and 7×12.5 gbit/s classical channels,” in *2018 IEEE Photonics Society Summer Topical Meeting Series (SUM),* (IEEE, 2018).
8. T. A. Eriksson *et al.*, “Wavelength division multiplexing of continuous variable quantum key distribution and 18.3 tbit/s data channels,” Commun. Phys. **2**, 9 (2019).
9. S. van der Heide *et al.*, “Receiver noise stability calibration for cv-qkd,” in *2023 Optical Fiber Communications Conference and Exhibition (OFC),* (2023), pp. 1–3.
10. A. Alvarado *et al.*, “Replacing the soft-decision FEC limit paradigm in the design of optical communication systems,” J. Light. Technol. **34**, 707–721 (2016).
11. V. van Vliet, “Optical turbulence generator for lab-based experimental studies of atmospheric turbulence in vertical optical communication links,” Master’s thesis, TU/e (2022).
12. K. Kiasaleh, “On the probability density function of signal intensity in free-space optical communications systems impaired by pointing jitter and turbulence,” Opt. Eng. **33**, 3748 – 3757 (1994).
13. K. Gümüş and L. Schmalen, “Low rate protograph-based LDPC codes for continuous variable quantum key distribution,” Proc. ISWCS 2021 (2021).