Real-time CV-QKD Reception Resilient to Urban Atmospheric Turbulence

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Abstract: We show a real-time CV-QKD receiver realization over a turbulent optical free-space channel with secret key rates up to 2.2 Mbit/s. The real-time GPU receiver evaluated quantum signal integrity under various turbulence scenarios, emulating an 800 m urban terrestrial FSO link.

1. Introduction

Continuous-variable quantum key distribution (CV-QKD) allows the distribution of secret random keys with information-theoretic security. The security proof of Gaussian and discrete modulation protocols rely on quantum mechanics. In this work, we use the analytical bound for the asymptotic secret key ratio (SKR) under arbitrary modulation [1], with trusted noise and finite size effects assumptions [2]. Leveraging weak coherent states, CV-QKD protocols utilize mature telecom technologies. First, free-space optical (FSO) CV-QKD was demonstrated under realistic atmospheric conditions in [3]. A 0.6 km free-space CV-QKD system operated in fog has been shown in [4]. Robust FSO implementations resistant to polarization drift were developed [5], along with an urban field trial [6] demonstration. In this paper, a free-space quantum channel characterization under different turbulence settings is analyzed. We showcase a real-time CV-QKD receiver implementation over a turbulent optical free-space channel with secret key rates of up to 2.2 Mbit/s.

2. Experimental Set-up

The implemented CV-QKD setup in Fig. 1 uses an offline transmitter (Alice) with system capabilities that include <100 kHz linewidth external cavity lasers (ECLs), IQ optical modulation for probabilistically shaped 256-ary quadrature amplitude modulation (QAM) signals [1] and 250 Mbaud symbol rate with 50% pilot symbols. On Bob's side, a real-time receiver is operated in calibration and signal reception mode. Bob uses a local ECL as a local oscillator into an optical hybrid, utilizes 2 GSa/s analog-to-digital converter (ADC) digitization, 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 [7], and parameter estimation. All receiver coupling losses are considered, resulting in a decrease from 67% to 40% quantum efficiency. Real-time post-processing on a graphics processing unit (GPU) evaluates security via excess noise and SKR estimations for each quantum data block. The CV-QKD signal with wavelength 1550.1 nm is combined with a continuous wave (CW) constant power tone with wavelength 1528.8 nm for channel monitoring before being collimated and directed through an optical turbulence generator (OTG) [8]. Through the forced mixing of two air flows with a temperature difference of up to 180 K, the OTG emulates a longer turbulent channel than the free space propagation distance of 0.8 meters. A power meter operating at 100 kSa/s monitors the received power. The normalized variance of the power fluctuations, which indicates turbulence strength in the channel, is calculated using $\sigma_P^2 = \left(\langle P^2 \rangle - \langle P \rangle^2\right) / \langle P \rangle^2$ where P represents the received optical power and $\langle \cdot \rangle$ the ensemble average [9].

3. Results

Figure 2a, top, shows the normalized irradiance for a 3-second trace and the probability density function (PDF) across different turbulence conditions. The measured power scintillation indexes corresponding to the turbulence settings A, B, C, D, and E are 3.0×10^{-6}, 2.6×10^{-3}, 7.6×10^{-3}, 1.8×10^{-2}, and 3.1×10^{-2}. These values

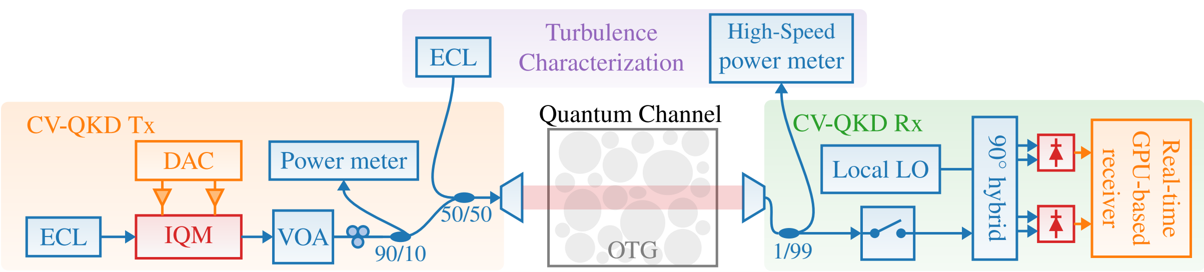

Fig. 1: Experimental set-up of CV-QKD over a turbulent free-space optical channel

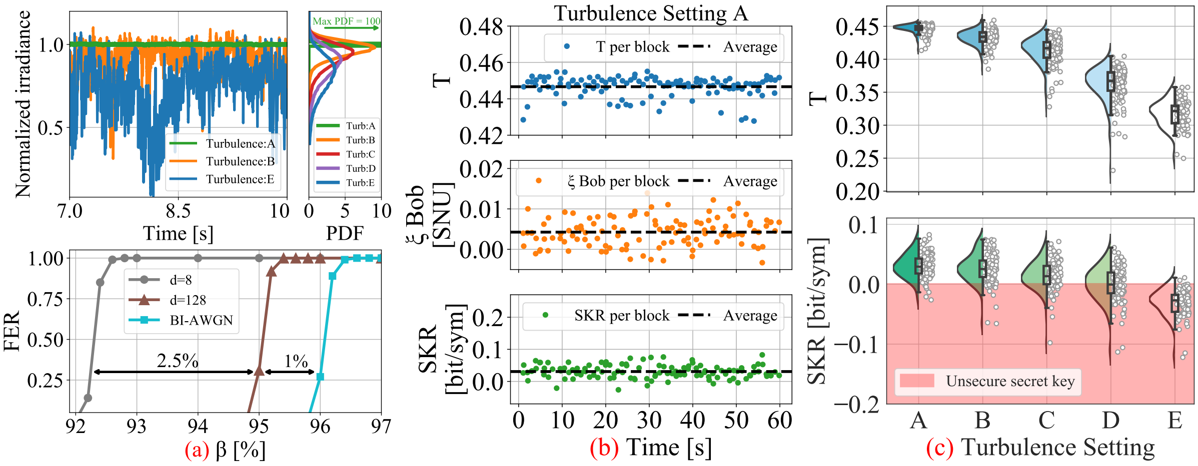

Fig. 2: (a) Top - Normalized irradiance over time for A, B, and E turbulence settings and PDF for all. Bottom - β and FER curve for different dimensionalities (b) Real-time capture with no turbulence (setting A) for transmittance T, ξ_{Bob} and SKR (c) Data distribution of T and SKR for different turbulence settings

correspond to measurements from an 800 m urban terrestrial FSO communication link [10]. Extreme fading approaching zero received optical power occurs with a high probability. This indicates that the turbulent channel is dominated by beam wander, resulting in increased outage likelihood. Secret key ratio calculations used system parameters of: modulation variance $Va = 7.4$ shot-noise units (SNUs) for settings A, B, C, D and $Va = 9.6$ SNU for E, 40% quantum efficiency, 10 dB clearance and 6.8×10^6 quantum block length. A multi-dimensional reconciliation protocol with a dimensionality of $d = 128$ is used for error correction. Figure 2a, bottom, shows the reconciliation efficiency (β) and frame-error-rate (FER) curves for $d = 8$, commonly used in literature, $d = 128$, and a binary input additive white Gaussian noise (BI-AWGN) channel. With higher dimensionality, 2.5% gains in β with 30% frame-error-rate (FER) help to increase the number of positive secret key blocks. Figure 2b shows the CV-QKD GPU receiver output over 60 seconds under setting A, with average transmittance $T = 0.45$, excess noise $\xi_B = 0.0043$ SNU and $SKR = 0.031$ bit/symbol, corresponding to 2.2 Mbit/s. The average excess noise for settings A, B, C, and D remains constant. However, setting E's average excess noise was 0.0081 SNU due to the increased excess phase noise behavior with higher modulation variance (Va). Figure 2c evaluates the performance of T and SKR for different turbulence settings. With stronger turbulence and deep fading, the median transmittance gets significantly lower to a minimum of $T = 0.32$. The attenuation in channel transmittance from turbulence setting A to E is equivalent to the additional losses incurred by propagating through an extra 8 km of standard single-mode fiber with an attenuation coefficient of 0.2 dB/km. Quantum key blocks are secured if the $SKR > 0$ and discarded when $SKR < 0$. From settings A through C, more than 50% of the quantum key blocks remain secured, though the median SKR exhibits a 54.3% reduction. Under the severe turbulence setting E, minimal cryptographic key material can be extracted, as the strong scintillation and beam wandering effects dominate.

4. Conclusion

This work demonstrates a real-time CV-QKD receiver implementation that assesses quantum signal integrity through security parameters like excess noise and secret key ratio. Secret keys at rates up to 2.2Mbit/s are obtained over a turbulent 800m free-space optical channel, emulated under different atmospheric turbulence conditions. By evaluating performance under varied turbulence, this work provides insights into overcoming practical limitations and advancing next-generation high-rate QKD systems deployed over free-space optical links.

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