Free-Space Quantum Cryptography in a Turbulent Atmosphere

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Light traveling through the atmosphere is aberrated by turbulence; random fluctuations in the index of refraction of the atmosphere produce a spatially-varying random phase in the transmitted beam. These phases result in irradiance fluctuations ("scintillations") at the receiver, which, in turn, may result in signal degradation or complete loss. The use of larger apertures and multi-mode collection (aperture averaging) reduces these effects, but may introduce other sources of noise, such as solar background.

Adaptive optics (AO) may reduce these wavefront errors and improve coupling into a single mode; however, traditional AO using a wavefront sensor and phase modulator, such as a deformable mirror, is typically limited in bandwidth both in the spatial domain (e.g., number of deformable mirror actuators) and in frequency (e.g., feedback/feedforward lag and response time versus Greenwood frequency of the channel), especially over long channels with strong turbulence. Furthermore, the saturation limit of a single typical single-photon detector may limit the efficacy of single-mode operation for high-speed quantum key distribution (QKD) systems, which may make traditional AO unappealing in some high-rate circumstances.

As the secure key rate depends on the signal-to-noise ratio of a QKD channel, we expect that the fade statistics (typically modeled by a log-normal or gamma-gamma distribution) should directly impact the statistics of the maximum secure key rate for a free-space system. Fig. 1 shows how the received intensity at an aperture may fluctuate as a result of turbulence-induced fading. The maximum secure key rate is a function of the signal-to-noise ratio, which depends on the received intensity - lower intensities are less likely to result in a key due to background noise. Relying on a single aperture not only reduces the peak generatable key rate (due to detector saturation), but also increases variability. Increasing the size or number of apertures improves stability due to aperture averaging but increases background noise. Here we propose a new approach – "selective deactivation" – for postprocessing data from arrays of single-photon detectors to reduce the effects of turbulence on free-space quantum key distribution channels (Fig. 2) with many spatial modes. Alice combines the single-photon signal with a bright beacon at a nearby wavelength. The differences in irradiance fluctuations should largely be diffractive over the channel, so, provided the wavelength difference is small and the turbulence is not too strong, there should be a strong correlation between the irradiance fluctuations in the beacon and those in the signal-photon signal. Bob separates the beacon from the signal photons (using dichroic mirror elements) and determines its irradiance distribution with a camera. By mapping bright regions in the camera image to "pixels" in the single-photon detector array, Bob is able to determine where signal photons are likely to arrive within some time window. This allows him to omit detectors which are likely to produce only noise and thereby improve the signal-to-noise ratio of the channel without adaptive optics.

In our laboratory implementation, Alice uses degenerate spontaneous parametric downconversion (355 nm $\rightarrow$ 710 nm + 710 nm) to produce a heralded source of single photons. One of these photons is combined on a dichroic filter with a bright beacon at 670 nm. The beacon and photon signal are sent through a simulated turbulence channel to Bob, who images the beacon with a CCD and collects the single photons with lenslet array; each lenslet couples into a separate multi-mode fiber leading to individual silicon avalanche photodiodes. We simulate a free-space channel using two passes on a spatial light modulator (SLM) [3]. The SLM introduces a selectable phase retardance at each pixel in a 1920×1080 grid. Phase screens are generated using the von-Kármán spectrum for spherical wave propagation [1, 4] to produce the desired scintillation variance σ_I^2. We use two independently-generated phase screens for each pass on the SLM to simulate the index fluctuations in a realistic channel. For the two-phase screen (double pass) setup, we are able to accurately produce weak to moderate turbulence, or $\sigma_I^2 < 1$ [2]. Bob includes only detectors with CCD regions above some irradiance threshold in the QKD analysis.

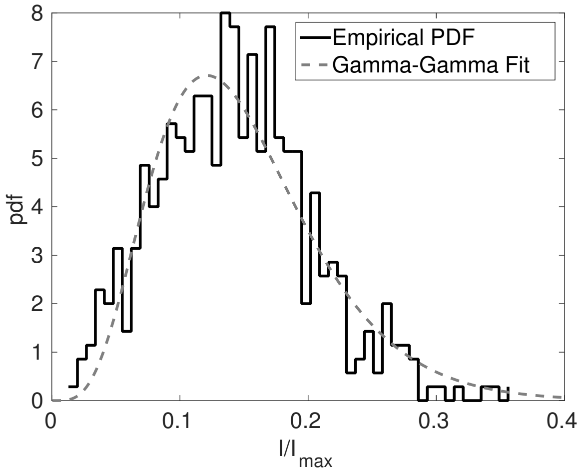


Figure 1: Sample received intensity distribution using our turbulence simulation system. The histogram represents an empirical probability density function for the intensity received from a 20 cm diameter beam into 6 cm aperture for $\sigma^2_{\text{Rytov}} = 0.01$ ($C_n^2 = 5 \times 10^{-17} m^{-2/3}, \lambda = 700$ nm, $L_{\text{channel}} = 3$ km). The simulated channel fading agrees well with a Gamma-Gamma distribution (expected for Kolmogorov turbulence-induced fading).

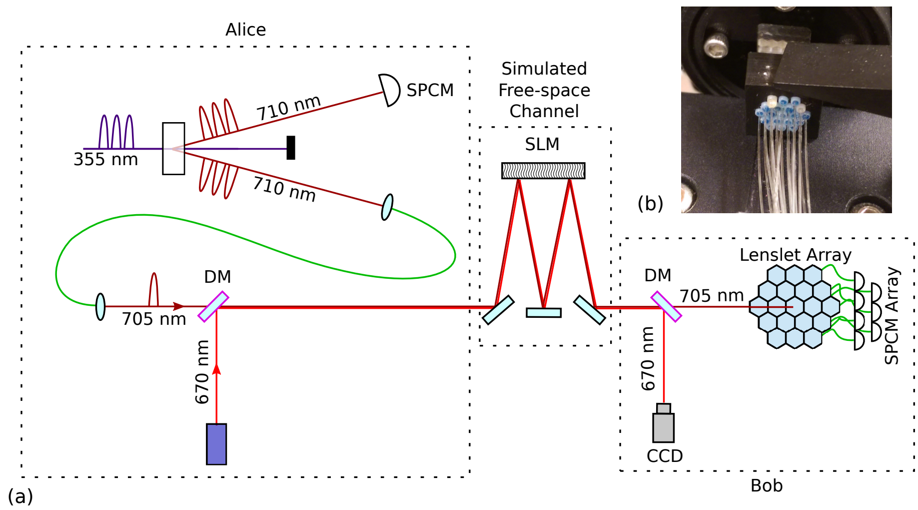
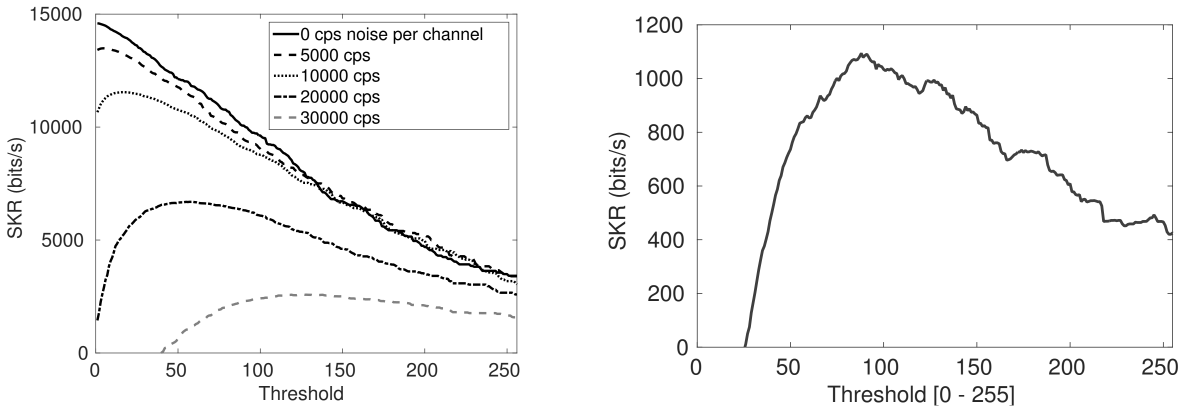


Figure 2: Experimental setup for selective deactivation. (a) Alice generates 710-nm photon pairs through spontaneous parametric downconversion of a 4-W pulsed 355-nm pump and transmits one photon of each pair to Bob, along with a bright 670-nm beacon. Both the signal and beacon travel through a scaled-down 30-km simulated turbulence path. The beacon is then separated from the signal via a dichroic mirror and imaged with a CCD. Subapertures associated with low intensity regions in the CCD image are consequently omitted from the QKD analysis to improve the signal-to-noise ratio. (b) Image of lenslet and fiber array leading to single-photon detectors. Each lenslet/fiber represents one subaperture for selective deactivation.



(a) (b)

Figure 3: Estimated SKR assuming BB84 using selective deactivation. (a) Numerical simulations of selective deactivation for 19 detectors collecting from a turbulent free-space QKD channel with irradiance variance $\sigma_I^2 = 0.2$ (laser repetition rate 120 MHz, 100 kcps coincidence rate for no turbulence). (b) Experimental results of the selective deactivation technique with noise rates of about 20 kcps per detector. We simulate a turbulent channel with scintillation index $\sigma_I^2 = 0.2$ (moderate turbulence) using two reflections from a phase-only spatial light modulator. Presented here is the average estimated secure key rate from 100 independent turbulence scenarios generated using this setup. Retaining all 19 detectors (threshold = 0) results in no generated key because the total background level is too high; retaining some balance of detectors (threshold $\approx$ 90) results in an optimal key rate for this setup, better even than the single-detector case (threshold = 255). There is a good qualitative agreement in experimental versus simulated behavior, though there are additional fluctuations in the experimental data due to an uneven distribution of detector noise and efficiency among the 19 single-photon detectors.

Figs. 3(a)-(b) show the results of simulations and laboratory experiments of the selective deactivation technique, respectively. For a system with no noise, simulations confirm that there is no benefit to deactivating any subaperture (an intuitive result, as removing detectors with no noise does not improve the overall signal-to-noise ratio), while for noise encountered with realistic silicon avalanche photodiodes ($\sim$20 kcps) there is a regime where selecting some subset of multiple subapertures produces the optimal key rate. This subset is determined by thresholding by the intensity measured on a CCD by Bob. Experimental results (Fig. 3(b)) also show an enhancement in the generated key rate for a particular threshold value. The fluctuations in this data are due to unevenly distributed noise among the 19 detectors analyzed for this experiment - detectors with a superior signal-to-noise ratio may be discarded prematurely, as we currently select detectors corresponding to regions of high CCD intensity alone without regard to the detectors' individual noise characteristics. Future refinements of this technique will generate the optimal subset of detectors taking into account individual backgrounds.

References

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