Studying the Effects of Atmospheric Propagation on QKD using a Scintillation Playback System

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Quantum key distribution (QKD) using free space optical (FSO) systems will, in most applications, involve atmospheric propagation[1,2]. As is well known from classical FSO communication links, turbulence can cause large power variation in the link strength[3,4]. Optical scintillation can cause fades below and surges above the mean power that last tens of milliseconds. Fades can be as deep as 20-30 dB. For classical links, a significant amount of effort has gone into optimizing components to deal with large signal dynamic range, and designing communication protocols that can accommodate errors that arise from these effects. QKD systems will also need to deal with these effects [5,6].

Scintillation is inherently a stochastic effect, and is highly sensitive to environmental factors such as solar fluence, wind speed and humidity. This makes studying its effects during field tests difficult, because in comparing different protocols, or receiver hardware, conditions are not the same from one run to the next. Recently, a new approach to experimental studies of scintillation has been demonstrated for classical FSO links [7]: scintillation-induced fluctuations in power are recorded in the field using a high dynamic range photodetector and analog-to-digital converter. The recorded files can then be played back in the lab to simulate the effects of scintillation in a repeatable way. A key feature of this approach is that field recordings of scintillation are taken with the same optical systems, and over the same range and conditions, as the actual FSO link. In addition, the modems, detectors and modulators used in the laboratory playback system are identical to those used in the FSO terminals. The result is a laboratory experiment that reproduces, with high fidelity, the field conditions and component performance of the actual link. The ability to repeat the same scintillation conditions while varying system settings or protocol selection allows optimization that would not be possible in the field.

We have applied this same technique to studying scintillation effects on a QKD link. Scintillation was recorded at the US Naval Research Laboratory's Maritime Lasercom Testbed [8]. This facility has sites on both sides of Chesapeake Bay separated by 16 km. One end is 30 meters above the water, and the other end is 5 meters above the water. The scintillation recording system consisted of a transmitter operating at a wavelength of 1550 nm and emitting a beam with a divergence of about 150 microradians. A 4-inch diameter receiver at the other end of the link recorded power fluctuations with a low noise photodetector that had a 40 dB dynamic range. The power fluctuations were digitized with a 10 KHz 16 bit analog-to-digital converter. The scintillation recording link is classical. Large power levels were used to accurately record the atmospheric fluctuations. Scintillation files were recorded over a period of months under a variety of weather conditions and times of day. This range has been shown to accurately model atmospheric conditions that might be expected for a ship-to-ship link. In addition the lower turbulence over water than over land means that the link can also serve as a stand-in for a low elevation angle ground-to-space link.

This scintillation playback system is shown below. It is designed to implement a BB84 protocol, but other QKD protocols could also be used. The experimental systems are conveniently displayed in three component parts: i: the overall timing diagram that encompasses the complete system (Fig. 1); ii: the free-space optics where the four polarization-controlled beams are formed into a spatially overlapping bit stream (Fig. 2) and iii: the analyzer optics where the received single photons are counted (Fig. 3).

A cw tunable laser with a polarized fiber output is passed through an acousto-optic (AO) modulator. The purpose of the AO modulator is to impose a known atmospheric turbulence irradiance profile onto the beam. After the AO modulation, the laser encounters the first LiNiO3 modulator that produces a 5ns duration pulse at a 5MHz repetition rate. A tree of three 1x2 fiber splitters is then used to produce four outputs. Each beam is either transmitted or attenuated depending upon the state of a subsequent in-line LiNiO3 modulator. This array of four modulators can be operated with i) any one modulator selectively open ii) all modulators open, or iii) with a randomized 32K sequence. In the latter configuration the modulators are randomly activated over 2^{15} operations over a 6.55ms period. In this way a known key is generated that can be validated by subsequent analysis.

The four fiber outputs are then used as inputs to the polarization selecting optics shown in Fig. 2. The beams are collimated to a few mm in diameter and then half wave plates are used to control the orthogonal polarizations (H and V) of each pair of beams (Sources 1 and 2 and Sources 3 and 4). Polarizing beam splitters are used to combine each pair and then another half wave plate converts Sources 1 and 2 to ±45° polarization components. From that point on near normal mirrors are used to spatially overlap all four beams. NIR optical density filters are inserted at this location.

The analyzer optics of Fig. 3 reverse the process, unfolding the polarization components, and the outputs are transmitted by way of 50µm MMF to Aurea single photon detectors (SPD). There are narrow band optical filters in front of each receiver. The SPDs are gated at 5MHz with variable gate durations, but nominally they are operated with a 10ns gate width. The efficiency was set at 10% for consistency amongst the receivers. The dead time was usually set at 10µs although experiments were carried out to find the useful range of operation limited by after-pulsing contributing to the background counts.

Finally, a time-to-digital converter records all four SPDs signals as well as the random sequence start of scan pulse and the start of the scintillation irradiance playback file. Each count of the digital converter corresponds to a nominal 81ps. The typical scintillation file runs for 10s and is continuously repeated.

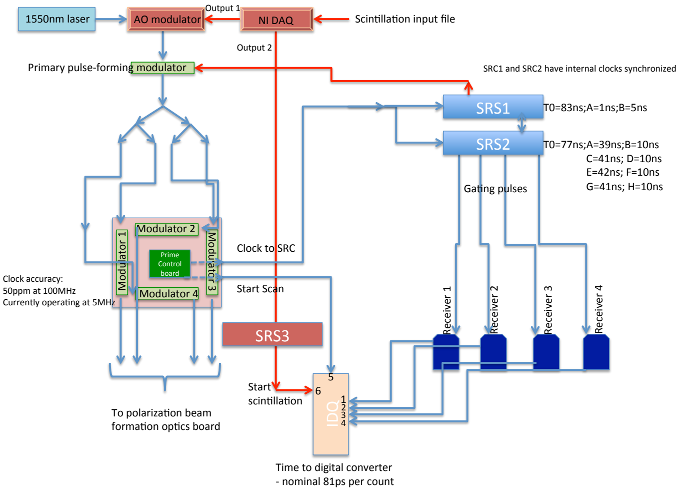

Figure 1. Timing diagram for QKD measurement system.

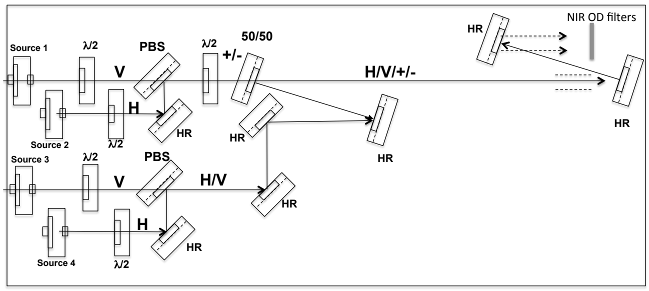

Figure 2. Polarization beam formation optics.

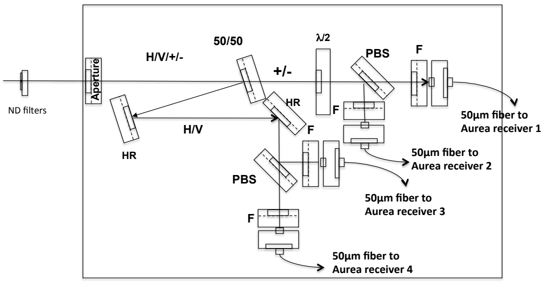

Figure 3. Polarization analyzer optics. F- designates a 1550nm bandpass filter in addition to ND filters.

Figure 4 below shows an example of the counts (in a 5 millisecond period) recorded on the QKD scintillation playback system in the lab and the scintillation file recorded at the test range and a graph of detector

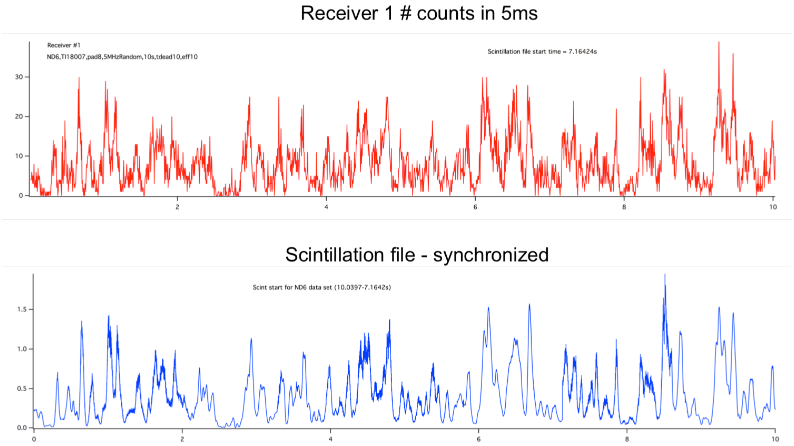

Figure 4. Results of a QKD experiment using the scintillation play back system and recorded scintillation

After the playback experiment the data can be analyzed to determine key length, error rate and other parameters. The set up can be used to study a variety of protocols for QKD in scintillation, for example the thresholding approach proposed by Vallone et. al [9]. Application to studies such as this will be presented.

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