Amplified Entanglement Assisted Communication Systems Operated in Desert Environment and Strong Atmospheric Turbulence Regime

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Abstract: In this paper we are presenting results that go against the common belief that entanglement is destroyed by the amplification using an EDFA. In this paper, we demonstrate the quantum advantage of entanglement-assisted communication at 10Gb/s, employing LDPC-coded BPSK, over classical laser communication even after the amplification of signal photons is performed by the EDFA in order to improve the reliability of entanglement-assisted (EA) communication operating in turbulent 1.5 km terrestrial FSO channels. To make EA system more robust against various atmospheric effects such as scattering, absorption, and turbulence effects we perform the optical phase-conjugation on idler photons rather than turbulence affected signal photons and use adaptive optics to make additional improvements in terms of the bit-error rate.

OCIS codes: (060.4510) Optical communications; (060.4250) Networks.

1. Introduction

The entanglement based quantum information technique in communication and sensing has a unique property that enables quantum sensing to reach Heisenberg limit [1,2] and the communication system to surpass the Shannon limit [3-5]. An entanglement assisted communication system benefits from quantum mechanics laws that opens possibilities for secure and reliable communication in a highly lossy and noisy environment [1]. In this paper we will discuss an additional feature where in contrast to common belief that EDFAs can destroy the entanglement between photon pairs we demonstrate contrary that entanglement enables quantum advantages even when the EDFA is used to amplify signal photons. The results from our experiments indicate that in the scenario when an entanglement assisted communication link is dominated by various types of atmospheric effects including diffraction, absorption, scattering, and turbulence effects rather than noise, we can amplify the signal photons without the loss of entanglement. An amplified entanglement assisted system is found to be superior to the corresponding classical laser communication counterparts in terms of the bit-error rate (BER).

The major challenges in a terrestrial free-space optical (FSO) communication system with lasers arises when the optical properties of the laser in a turbulent channel, such as in free-space, start to dominate [5,6,8-13], something that is not the case with fiber-optics communications. A terrestrial FSO communication link operating in a desert environment gets severely affected by absorption, diffraction, scattering, and turbulence effects [5]. An FSO communication link based on entanglement assisted concept, benefiting from quantum mechanical laws, can improve the reliability of an FSO system as we have demonstrated in our recent work on entanglement assisted communication where we have proposed to perform the optical phase-conjugation (OPC) [3]-[4], needed for the balanced homodyne detection, on idler photons against the popular convention of performing OPC on the signal photon at the receive side. In an FSO link, a beam carrying signal photons gets severely affected by atmospheric effects that makes them very unsuitable to perform a reliable OPC for homodyne detection. Moreover, it is extremely difficult to perform the OPC when the average number of received photons is smaller than 1. In our entanglement assisted system brighter signal photons are used to carry the information and OPC is performed on idler photons, which allows for implementing a multipurpose compact modular design that is easy to fabricate and at a much lower cost [3]-[4]. In this paper we are presenting results where we successfully demonstrate that the quantum advantage is preserved even after amplification of signal photons is performed by the EDFA. At the University of Arizona campus, we developed a 1.5 km long FSO link terrestrial FSO testbed by establishing an FSO link between Electrical and Computer Engineering department and Optical Sciences (Meinel) buildings, which is used to study the performance of entanglement assisted communications in a desert environment, which is characterized by rapid fluctuation in temperature and pressure, resulting in almost always present strong turbulence effects. We performed the amplified entanglement assisted LPDC-coded binary-phase shift keying (BPSK) communication system experiment that was operating at 10 Gb/s under strong turbulence regime and demonstrated that amplified EA system significantly outperforms amplified classical laser communication link that is operated in a weaker medium turbulence regime.

In the following section we will explain the motivation, followed by the details of the experiments including description of various modules, components, experimental procedure, and discussion of experimental results.

2. Motivation and experimental testbed for amplified entanglement assisted communication over a terrestrial FSO link

2.0 Motivation

Due to Mie scattering many signal photons do not reach the receive side. Due to diffraction the beam waste increases as the signal photons propagate towards the receiver and only a portion of signal photons can be collected by the compressing telescope. Turbulence effects introduce scintillation, beam wandering, and wavefront distortions. The scintillation affects the brightness of the received signal photons and for deep fades many signal photons are so weak that they do not contribute to the detection of the transmitted signal. Beam wandering effects influence the number of signal photons captured by the compressing telescope. The wavefront distortions affect the phase of the transmitted signal, in particular when the information is imposed on phases of the signal photons, like in this paper. The use of adaptive optics is essential to reduce the phase distortion on signal photons. The absorption effects absorb the photons by the atmosphere. The photons lost due to scattering, absorption, diffraction, and beam wandering effects do not reach the balanced detector and thus do not contribute to the detection process. The received signal photons, collected by the compressing telescope, are of low brightness because of various attenuation and turbulence effects, and as such are weakly correlated to the corresponding idler photons. By amplifying the signal photons by the EDFA we increase the brightness of the received signal photons thus improving the quantum phase-sensitive correlation on the receiver side. During stimulated amplification process EDFA also inserts new photons having the same properties as input photons but only classically correlated to the idler. Nevertheless, they still contribute to the homodyne detection process. Finally, EDFA adds spontaneous noise photons to the signal photons. Given that the optical beam on C- and L-bands transmitted over turbulent channels is dominated by various atmospheric effects rather than background radiation, the amplification of signal photons by the EDFA reduce the signal-to-noise ratio rather than destroying the quantum phase-sensitive correlation. On the other hand, the microwave signal photons, often considered for quantum sensing, quantum radar, and communication applications, experience much stronger turbulence effects and the background radiation is much stronger compared to the 1550 nm telecommunication window. Namely, the turbulence effects are slowly wavelength dependent. Longer wavelengths are less affected by the turbulence effects compared to shorter wavelengths [8]. On the other hand, the thermal background photons are also wavelength (frequency) dependent and follow the Bose-Einstein distribution:

$$\bar{n}_{\omega} = \frac{1}{e^{\frac{\hbar\omega}{k_B \mathcal{T}}} - 1}, \tag{1}$$

where k_B is the Boltzmann constant, $\mathcal{T}$ absolute temperature and $\hbar$ is reduced Plank constant. Given that the radial frequency ω of the microwave photons is significantly lower to the radial optical frequency (of the C-band), the average number of thermal photons is significantly higher. Therefore, the entanglement assistance in optical C- and L-bands is significantly more powerful compared to the microwave frequencies [16]. The background radiation noise is additive in nature, while the received signal photons experience the multiplicative noise introduced by the turbulence effects. The quantum phase-sensitive cross correlation is more tolerant to multiplicative noise compared to the additive noise as we have shown in [15]. The overall FSO channel performing the amplification of signal photons by the EDFA of gain G, for a single Bosonic mode, can be described as simultaneous attenuation and amplification channel, which is a Gaussian channel with symplectic matrix $\boldsymbol{S}$ and noise matrix $\boldsymbol{Z}$ as follows:

$$\boldsymbol{S} = T\sqrt{G}\boldsymbol{I}_2, \; \boldsymbol{Z} = \left[N_b + N_{EDFA} + \frac{1}{2}\left(1 - T^2 + G\right) \right] \boldsymbol{I}_2 \tag{2}$$

where T is time-varying transmissivity of the FSO channel, G is the EDFA power gain, N_b is the mean photon number of the background radiation, N_{EDFA} is the mean photon number of noise photons introduced by the EDFA. ($\boldsymbol{I}_2$ denotes the 2×2 identity matrix.) Therefore, the Gaussian nature of the channel is not affected by amplifying the signal photons. By amplifying the signal photons we can improve the entanglement assisted communication system performance and extend the transmission distance. For additional details on the Bosonic Gaussian channels an interested reader is referred to ref. [1,17]. By amplifying the orthogonal states we are not violating the no-cloning theorem, claiming that arbitrary (non-orthogonal) quantum states cannot be cloned. The orthogonal states can be cloned; otherwise, we will not be able to create the computational basis states.

2.1 Experiment overview

Our conventional laser-based communication system involves modulation of information employs an arbitrary waveform generator that imposes the information on the laser beam by performing either the phase or intensity modulation by a Mach–Zehnder type modulator. Information is often an encoded LDPC sequence, composed of data and parity bit that are imposed on an optical beam by modulation schemes such as BPSK, QPSK, QAM, *etc*. In the case of FSO communication this modulated output is first pre-amplified to the appropriate levels that can survive the losses associated with an FSO link. After the beam is received it is again amplified for detection purposes.

The optical beam propagating over the FSO link is affected by various atmospheric effects including absorption, scattering, and turbulence effects. In particular, the atmospheric turbulence effects distort the wavefront of the transmitted beam by introducing scintillation and beam wandering that makes the coupling into the optical fiber on receiver side quite challenging. The Figure 1 below, shows the block diagram representation of entire experiment.

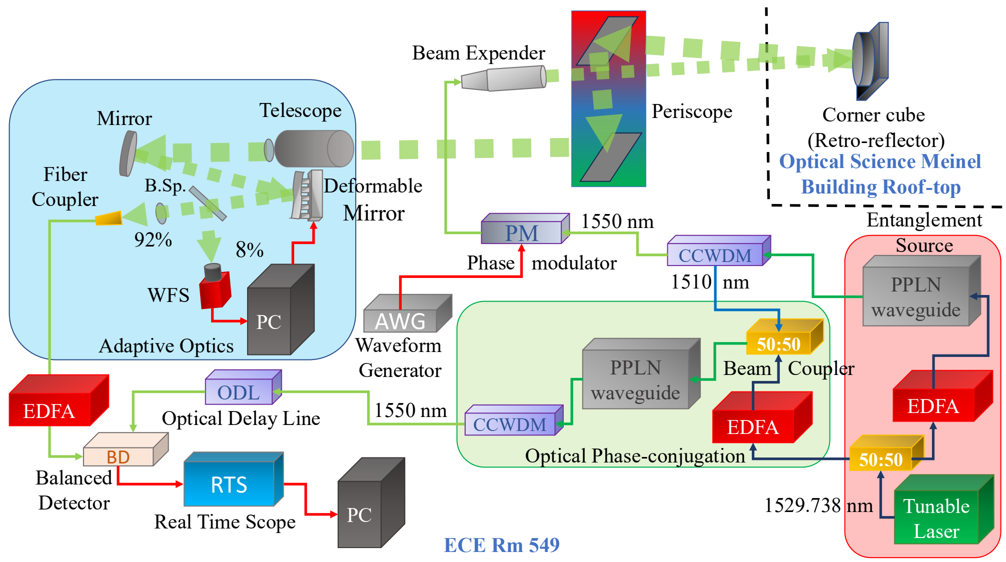

Fig. 1. Block diagram representation of the entanglement assisted FSO experimental testbed. PPLN: type-0 periodically poled lithium niobate waveguide, CCWDM: compact coarse wavelength-division multiplexing demultiplexer, PM: phase modulator, EDFA: Erbium-doped fiber amplifier, ODL: optical delay line, PC: personal computer, B.Sp.: beam splitter, WFS: wavefront sensor, AWG: arbitrary waveform generator.

The atmospheric turbulence over urban areas in a horizontal FSO link can be far worse than that vertical FSO link. The heterogenous urban landscapes, various structures, surfaces, vents, and exhaust add to the variability in air temperature distribution over the optical path that in turn translate as variability in refractive indices over the entirety of this horizontal optical path resulting into far worse unpredictable turbulent atmospheric conditions.

2.2 Free-space optical link and terrestrial testbed at the University of Arizona

To explore the possibilities in FSO communication, we have developed an experimental testbed at the University of Arizona Campus shown in Fig. 1, that we used to demonstrate our amplified entanglement assisted experiment. The transmitter and receiver subsystems are located in the ECE Quantum Communication Lab (ECE Rm 549), while the FSO link is established between the ECE and Optical Sciences (Meinel) buildings, with the beam expender emitting the beam from the window of the ECE Rm 549 and a retroreflector on rooftop of Optical Sciences is used to reflect the beam back towards the ECE building to the receiving end with a round-trip link distance of 1.5 km. The diagram in Fig. 2 describes the major components and modules of the developed FSO testbed.

The way our FSO link is set up is that we transmit our information carrying beam from the ECE Lab 549 using a Thorlabs 20× beam expander toward the Meniel building's 2nd wing's rooftop, which is 750 m away. On the rooftop we have placed a 5" wide corner-cube retroreflector that returns the beam back toward ECE Rm 549 window, resulting in a link that is 1500 m long. In Figure 3 we provide the Google Earth image of the FSO link.

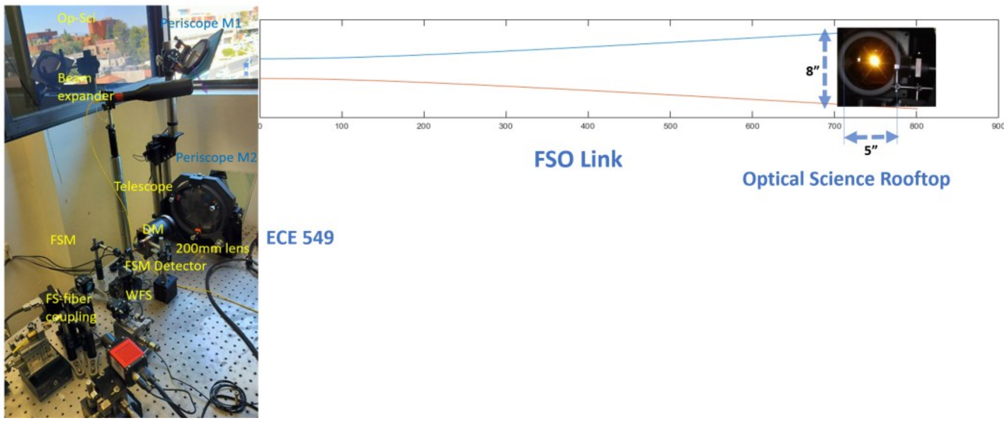

Fig 2. Components and modules of the developed FSO testbed: (*left*) the optical transceiver in the ECE lab 549 and (*right*) Meinel building rooftop. DM: deformable mirror, FSM: fast steering mirror, WFS: wavefront sensor, FS: fiber coupling stage.

Fig. 3. Image of the FSO link established at the University of Arizona campus, captured from Google Earth.

2.3 Entanglement generation source and transmitter subsystem

The experiment begins with the generation of entangled photon pairs by making use of a tunable laser, EDFAs, and a type-0 periodically polled lithium niobate (PPLN) waveguide [4, 5], with the entanglement generation source concept provided in Fig. 4. Type-0 PPLN waveguides, for which the entangled photons have the same polarizations, are selected over type I and type II PPLN waveguides because of much better nonlinear conversion efficiency [14]. This is our alternative to 780 nm pump-based solutions and represents a cost effective and efficient entanglement generation method by employing low-cost, mature telecom devices and modules.

We set the tunable laser source at 1529.738 nm and its output beam is split in two parts by a beam splitter for entangled photons pairs generation and for optical phase-conjugation. Both parts are first amplified by corresponding EDFAs, as shown in Fig. 1, to an appropriate level before providing pump signals to the Type-0 PPLN waveguides.

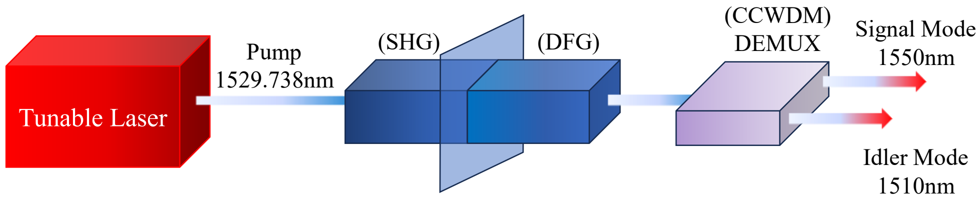

Fig. 4. Entanglement generation source based on Type-0 PPLN waveguide. SHG: second-harmonic generation, DFG: difference frequency generation.

Inside the entanglement generation PPLN waveguide, in the first half the secondary harmonic generation dominates (SHG), while in the second half difference frequency generation (DFG) dominates, by employing the cascaded SHG-DFG nonlinear process we introduced in ref. [7]. The output of this PPLN is then fed to a compact coarse wavelength-division multiplexing (CCWDM) demultiplexer where we sperate the signal and idler photon pairs with signal photons located at 1550 nm wavelength and idler photons at 1510 nm, respectively. These CCWDM demuxes have high isolation of >40dB between adjacent wavelengths and >60dB for subsequent wavelengths. The signal photons are modulated by Mach-Zehnder-based I/Q modulator that we used as the phase modulator (PM). An arbitrary waveform generator (AWG) provides the RF information to this modulator. The AWG imposes LDPC encoded BPSK information at the data rate of 10 Gb/s, while operating at 120GSa/s, on the signal photons with forward error correction (FEC) frame rate of 0.6225 and the LDPC codeword length is 3992 bits. The information frame comprises of 2497 data bits and 1496 bits are the parity-check bits. The transmitted data is organized in packet of LDPC codewords with an additional 612 bits being used as the header of the packet. The purpose of this header is to identify the beginning of the FEC frames since in our experiment for the decoding step at the receiver end, we assume that the header is known to the receiver.

Traditionally, the OPC is performed on the received signal photons [1-5, 11]. In turbulent optical channel, however, many signal photons get lost due to scattering and diffraction effects or be absorbed by the atmospheric medium. The signal photons reaching the receive side are very weak in brightnesses as being affected by the turbulence effects. It is extremely difficult, or even impossible, to perform the OPC on received signal photons when the average number of signal photons is much smaller than 1. To solve this problem, we perform the OPC on bright idler photons instead, as shown in Fig. 1, so that the phase-conjugated idler photons and received signal photons wavelengths are matched and homodyne detection can be used. The OPC on idler photons is performed by interacting the idler photons with pump photons inside the OPC PPLN waveguide, as illustrated in Fig. 1. For additional details, an interested reader is referred to ref. [5, 11].

Figure 2 also shows the optical bench setup at ECE Rm 549. After the modulation, the information carrying signal photons are emitted into free-space using a Thorlabs 2” beam expender toward the Optical Science building rooftop. This summarizes the transmitter side of this experiment. The beam after traversing through the FSO channel get reflected back toward ECE Rm 549 by a retroreflector that is 750 m away from the beam expander, thus the returning beam makes a 1.5 km round-trip in the FSO channel over the densely located buildings at the University of Arizona campus.

2.4 Receiver: detection and decoding subsystem

The receiver side of this experiment comprises of a periscope, an adaptive optics setup on an optical bench, and the homodyne detector, followed by the offline digital signal processing and the LDPC decoding. The adaptive optics will be discussed in detail in the next subsection. The periscope allows for lowering the returning beam from the window height to the optical bench as it can be seen in Fig. 2. After the periscope, the incoming beam is compressed to a collimated beam using receiver telescope with a large diameter (200 mm) lens in the front and a doublet lens after it. The main purpose of this compression telescope is to provide a small cross section beam profile that is comparable to the aperture of the deformable mirror and other optical devices and also allow for an efficient coupling of this beam back into an optical fiber. This fiber is then fed to a low noise EDFA to amplify the beam to a level that is required for high-speed homodyne balanced detectors such as the ones that we use from the Optilab. This balanced detector is also provided with a reference 1550 nm that is prepared by performing optical phase-conjugation (OPC) on the idler photons. For this purpose, we first couple the idler photons (at 1510 nm) and the amplified second half of the tunable laser signal (at 1527.738 nm) by a beam combiner (coupler). The 2nd Type-0 PPLN waveguide is then fed with this mix from the beam combiner. The output of this PPLN is then given to the 2nd CCWDM to select OPC idler photons at 1550 nm. The output power of EDFA, used to amplify signal photons, is adjustable. We adjust it to make sure the overall average power of phase-conjugated photons is sufficiently larger than the average power of amplified signal photons. We chose the optimum ratio to minimize the BER. Because the signal photons take a 1.45km long journey in the free space, the idler OPC photons are passed through a 1km long optical delay line (ODL) in order to match the arrival time of signal photons at the balanced detector. This ODL in our experiment effectively serves as a quantum memory. The length of ODL is properly chosen to match the average propagation delay of the signal photons. Beam wondering effects cause the propagation time to be random around the average propagation time. To solve this problem, we organize transmitted data in FEC frames, with each frame having the header. The header information is used on the receiver side to detect the beginning of the FEC frame by cross-correlation method. The output power of EDFA, used to amplify signal photons, is adjustable. We adjust it to make sure the overall average power of phase-conjugated idler photons is sufficiently larger than the average power of amplified signal photons. We chose the optimum ratio to minimize the BER. After the balanced homodyne detector, the received signal is converted from optical domain to RF and is collected by a real-time scope. These sampled waveforms are then first tested for the beginning of the frame by performing cross-correlation analysis with the known header. Afterwards, the LDPC frames are analyzed for bit-error rate (BER) calculations and later the error correction is performed. In our experiment the strong LDPC code was able to correct all errors.

2.5 Atmospheric turbulence azimuthal phase compensation using adaptive optics

Our entanglement assisted communication system over the free-space optical link has an additional feature of the adaptive optics (AO). The main purpose of AO is to compensate for the wavefront distortion introduced by the atmospheric turbulent channel.

Figure 5 depicts the AO setup that we implemented in our FSO link. In a lightwave line-of-sight based FSO communication link the beam travelling in free-space undergoes atmospheric turbulence effects. The atmospheric turbulence is mainly due to the temperature variations along the optical path in free space. This optical medium gets heated from the ground below, which can be anything such as ground that is covered or uncovered by vegetation, building’s rooftops, concrete parking lots, asphalt road, industrial vents, air conditioners vent, water body like river, lake, ocean, *etc*. All these release heat at different rates and at different times of the day and season. This situation is far worse in urban areas or areas with high daily temperature variations as in tropical, arid, and semi-arid regions. These temperature variations cause changes in refractive indices along the optical path. All these variations are responsible for distortion of azimuthal phase in the wavefront of our information carrying beam [6,8,9,12]. This causes the degradation of the optical beam wavefront, which exhibits the scintillation in the received power as well as the beam wandering effects. The common consequences are poor reception of power, loss of information, and possible outages.

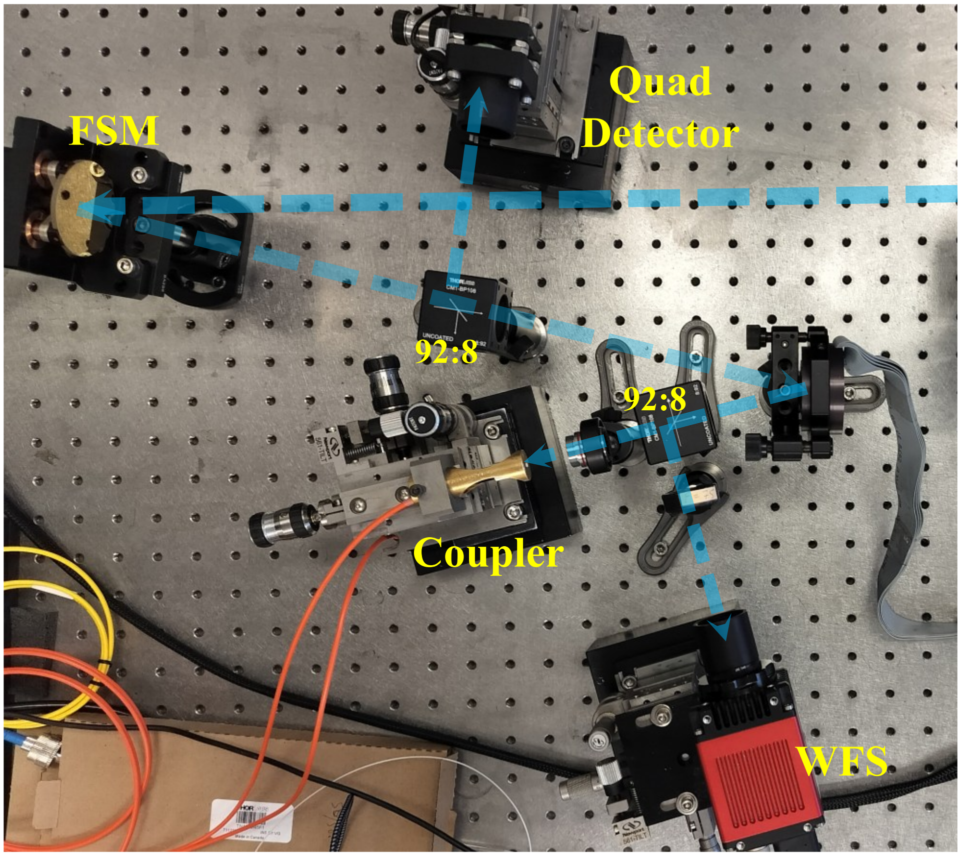

Fig. 5: Adaptive optics subsystem for turbulence effects compensation on our Optical table.

To counter the effects of atmospheric turbulence on our information carrying beam we implemented adaptive optics [12] as a solution, which is a technology used by earth-based telescopes to collect the light coming from celestial bodies. The light entering atmosphere from space undergoes similar phase distortions only differs in that it traverses the atmosphere vertically down whereas in FSO links, as in our case, is horizontal to the ground. In a typical adaptive optics system as shown in Figure 6, the beam first falls on a deformable mirror and then its wavefront is observed by passing it onto a Shack-Hartmann wavefront sensor (WFS). The sub-apertures of the WFS create a "spot field" onto the camera of the WFS from which the phase of each sub-aperture is determined by computation. This information is then broken down into Zernike polynomials with appropriate coefficient to each polynomial. Afterward, a fast computer performs calculations that are essential to create a phase-conjugate of the observed wavefront by converting the distorted image into control voltages to the actuator of the deformable mirror. The deformable mirror we are working with can be molded into various shapes by its 140 actuators arranged in square grid that can independently move the individual site on the mirror forward and backward.

This adaptive optics setup was built by our group with help from the Boston Micromachines Corporation (BMC). Our adaptive optics feature a 140 actuator Deformable mirror (DM) from the BMC and an 878 frames wavefront sensor from Applied Optical Systems (AOS). Then we send a collimated received beam onto the deformable mirror and after that we split 8% of that beam toward WFS, thus the WFS and DM operates in a feedback servo loop. This entire process is controlled by our software running on a fast personal computer for all the calculations and making adaptive optics corrections at a rate of 350+ frames/sec.

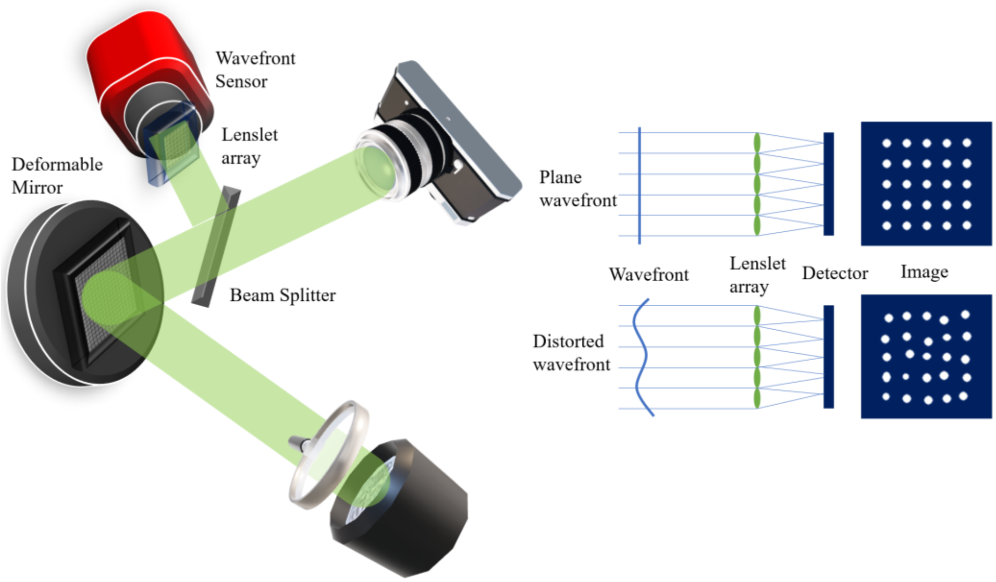

Fig. 6. The basic concept of our implementation of adaptive optics subsystem.

To improve the outdoor system stability, we make use of shock absorbing sorbothene vibration damping sheets under the aluminum breadboard upon which we have mounted the retroreflector. For beam wandering stability introduced by turbulence we have recently implemented a fast-steering mirror operated in a closed loop. The current system does not need alignment adjustment for several hours, which is sufficiently stable for proof-of-concept experiments.

3. Illustrative Experimental Results

To demonstrate the superiority of our amplified entanglement assisted communication system over the classical method we made a communication system setup with classical style laser communication system. As seen in Fig. 7, the fundamental difference in classical setup is that we replaced entanglement generation step with a simple tunable laser operating at 1550 nm, that is amplified appropriately before being fed to the modulator. On the other hand, on the receiver side we replaced the optical phase-conjugation step with another 1550 nm laser serving as the local oscillator for the purpose of balanced homodyne detection. We performed the experiment keeping all parameters similar to what we had while operating amplified entanglement assisted system, beside the atmospheric conditions for obvious reasons. To our advantage, while collecting the data for classical method the recorded turbulence was milder than what we recorded for the amplified entanglement assisted method.

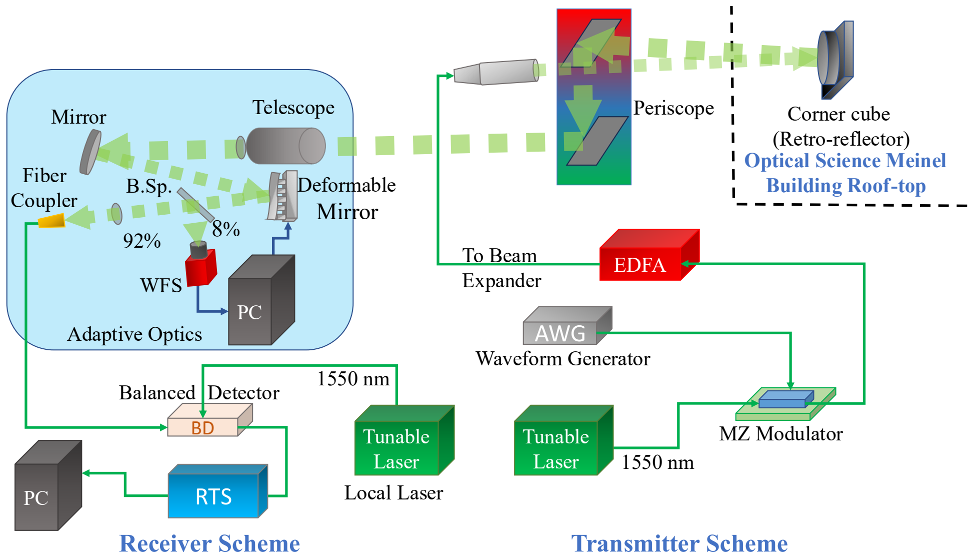

Fig. 7. Amplified classical communication system over the 1.5 km long FSO link.

Below in Figs. 8 and 9 we provide the experimental results showing the BER results for both amplified entanglements assisted method and the classical laser communication systems, for the launch power being 2.7 mW in both cases, with post reception amplifications, for Jan 4, 2024, and Jan 5, 2024. On both occasions the turbulence while working with the entanglement assisted case was stronger than the while running the classical style laser communication.

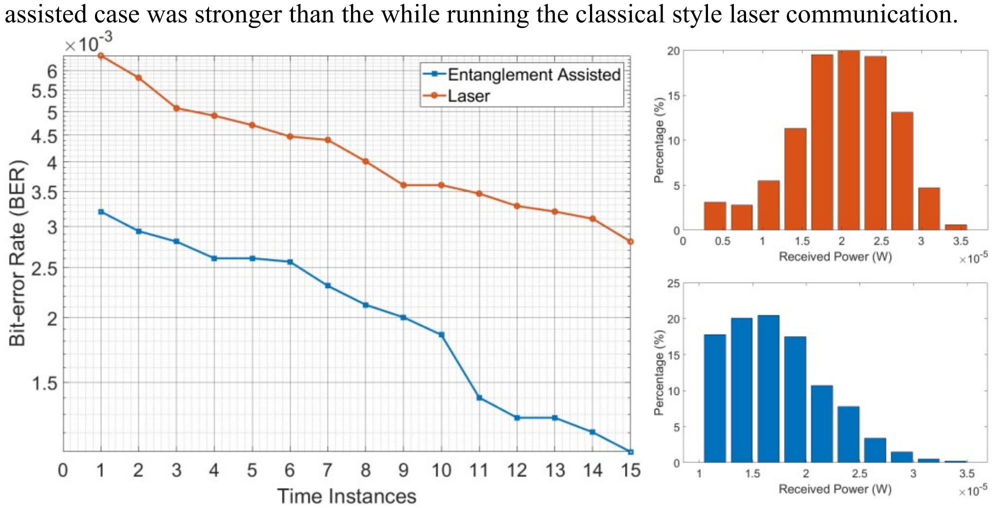

Fig. 8. Amplified entanglement assisted communication vs. classical laser communication system over the FSO link on January 4, 2024. Comparison is performed in terms of uncoded BER for different FSO channel realizations. (After ref. [18]; © IEEE 2024; reprinted with permission)

From the Jan. 4th results shown in Fig. 8 we conclude that the amplified entanglement assisted BER plot, denoted by the blue curve, performs significantly better than the classical laser communication, denoted by red curve. While working with the entanglement case, the signal photons were propagated though strong turbulence which is illustrated by the blue histogram bar plot for the received power which shows a Rayliegh distribution. In contrast, the classical style laser system, the signal beam was propagating in much milder turbulence as the red histogram for received power that shows a right skewed plot. The classical laser communication system was not operational at all in strong turbulence regime for this launch power.

The traditional entanglement assisted receiver performs the OPC on receive side [3,9] and as such requires coupling the optical beam affected by strong turbulence into the core of SMF, which is extremely difficult to do with a low-cost design advocated in this paper. Namely, to perform the OPC on signal photons, based on PPLN waveguide, the turbulence affected optical beam needs to be coupled to the SMF to avoid exciting higher order nonlinear spatial modes in the PPLN waveguide. This is the reason why we introduced the scheme in which we perform the OPC on idler photons instead, so that we can use the MMF to couple the beam and free-space based balanced detectors as an entanglement assisted detector, which represents a low-cost solution for future FSO applications.

Another realization for the purpose of comparison was made on the next day, Jan 5, 2024, as seen in Fig 9, with same launch powers. This time around the atmospheric turbulence condition for amplified entanglement assisted case and the classical style communication were surprisingly similar to the previous realization of Jan. 4 as can be inferred from the bar plot of receiver power for respective case. The blue histogram for amplified entanglement assisted case exhibits a Rayliegh distribution, indicating strong turbulence regime, while the red histogram for the classical laser case is right skewed histogram indicating medium-to-low turbulence. Similarly to Fig. 8, the classical lightwave communication system was not operational at all in strong turbulence regime for this launch power.

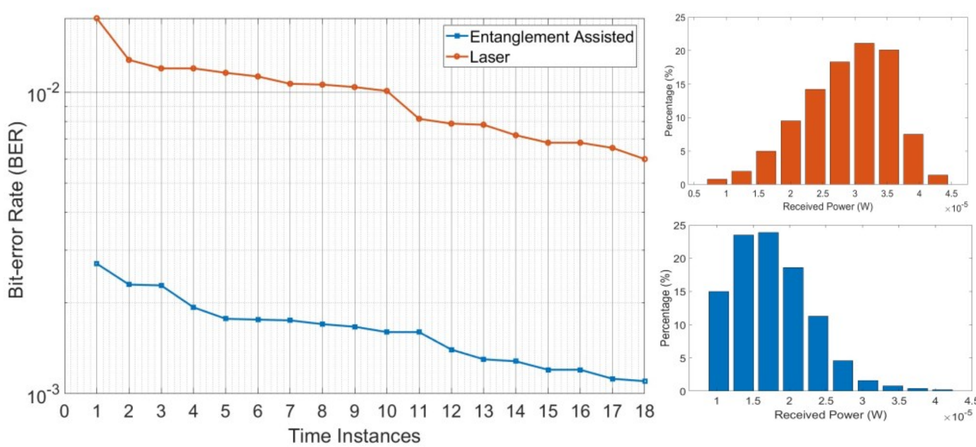

Fig. 9. Amplified entanglement assisted communication vs. classical laser communication system over FSO link on January 5, 2024. Comparison is performed in terms of uncoded BER for different FSO channel realizations. (After ref. [18]; © IEEE 2024; reprinted with permission)

To further explore the capabilities of our amplified entanglement assisted system we put our system to test in harsh summer of Tucson Arizona, when summer is in its full glory with daily average peak temperature being above 100 degrees Fahrenheit. We performed the experiment on May 2nd, 2024. Corresponding experimental BER results that are summarized in Fig. 10. As can be clearly seen from the plots that under the infamous, road melting, extreme summer weather conditions of semi-arid suburban environment of Tucson at University of Arizona our amplified entanglement assisted communication system, operated in strong turbulence regime, outperformed the classical style laser communication, operated in medium turbulence, for the same launch power of 4.6 mW.

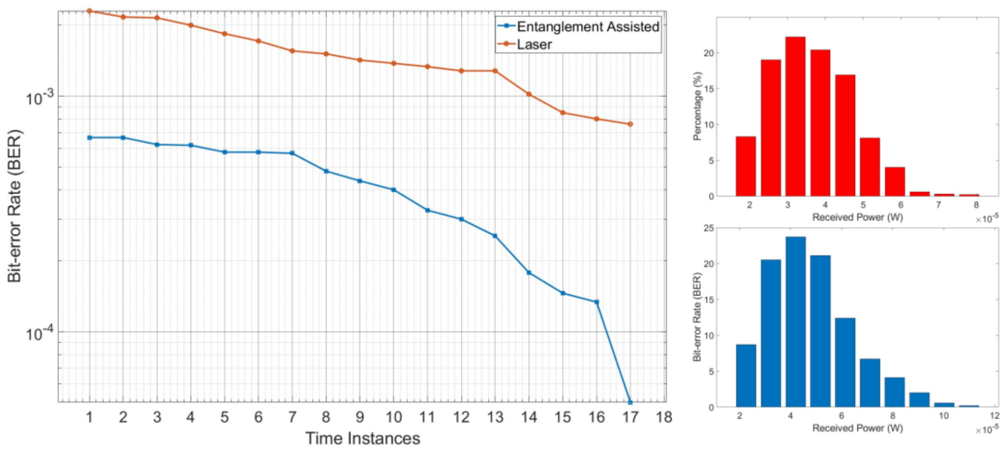

Fig. 10. Summer comparison of the amplified entanglement assisted communication against classical laser communication system over FSO link on May 2, 2024.

We made another realization for amplified entanglement assisted system by making further improvements by introducing azimuthal phase correction for the wavefront distortion due to atmospheric turbulence by adaptive optics. The curves in Fig. 11 show the results of applying adaptive optics by the red curve while the blue curve is when no adaptive optics was applied. The results demonstrate the clear improvement by adaptive optics. Both the red histogram for the adaptive optics case and blue histogram for without AO case have a Rayleigh distribution indicating presence of strong turbulence throughout the course of performing the experiment. In all cases shown in Figs. 8-10 the LDPC decoder was able to correct all errors.

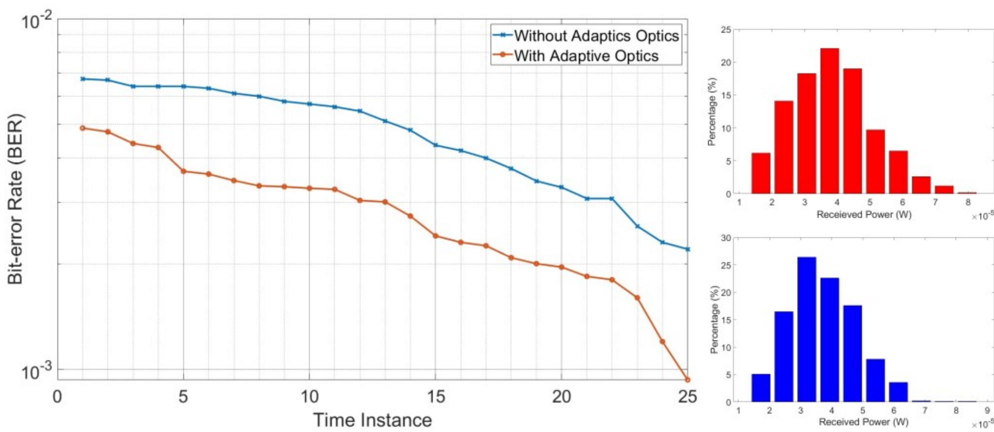

Fig. 11. Amplified entanglement assisted communication system performance with experiments performed on March 27, 2024, in comparison to improvements from adaptive optics communication system over FSO link. Comparison is made in terms of BER for different FSO channel realizations for the cases with (red curve) and without (blue curve) application of adaptive optics.

4. Concluding remarks

In conclusion, in contrast to the common understanding to not use EDFA as it can destroy the entanglement, we have made use of EDFA only to amplify the received signal photons that are extremely attenuated while the modulated signal photons make their journey under strong turbulent condition in the FSO link. Even though many signal photons may be lost due to scattering and absorption effects, while those reaching destination are severely affected by turbulence effects, the background noise in C- and L-bands is not the main issue so that the signal photons can be amplified without destroying the entanglement between signal and idler photons. Our experiments conducted over terrestrial FSO link in a desert environment indicate that the amplified entanglement assisted communication system significantly outperforms the corresponding amplified classical laser communication system in strong turbulence regime. Given that for the launch powers used in experiments the classical system is not operational in strong turbulence regime while the amplified entanglement assisted communication system is operational, we demonstrated the clear quantum advantage. The classical communication system was operational in medium turbulence, but still inferior to the amplified entanglement assisted system operated in strong turbulence.

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Disclosures. The authors declare no conflicts of interest.

Data availability. Experimental results presented in this paper are not publicly available but can be obtained from the authors upon a reasonable request.

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