FSO/CV-QKD/QBaudSK system based on 2PolSK-BPSK scheme considering dynamical atmospheric conditions

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ABSTRACT

In this paper, an FSO/CV-QKD/QBaudSK system using WCS and coherent detection for dynamical atmospheric conditions emulated by atmospheric turbulence box is presented. In particular, two systems (Alice and Bob) were designed and implemented in order to perform a conventional QKD algorithm using a unidirectional free space channel (private channel) and a bidirectional classical channel (public channel). The preliminary results obtained were related to the performance of the Degree of Polarization of the QWP and PolM considering and non-considering dynamical atmospheric conditions. The results showed the proposed method to be feasible for different weather conditions based on the BER using a 2PolSK-BPSK modulation.

Keywords: turbulence, free-space-optics, State of Polarization, quantum key distribution, Degree of Polarization, Phase-Shift Keying.

1. INTRODUCTION

In order to increase the efficiency of optical transmission systems is possible to use a multi-variable-levels and Continuous Wave (CW) modulation formats, such as Polarization Modulation (PolM) and Phase-Shift-Keying (PSK), among others [1,2]. In particular, the techniques used often are based on multi-symbol (Baud) transmission varying the optical phase using a single State of Polarization (either horizontal or vertical states, SOP-H or SOP-V, respectively) and coherent detection (homodyne, heterodyne, among others). However, the multi-symbol constellation can be transmitted using switched or simultaneous SOPs, which requires an extra or robust optical hybrid. Besides, the assumption of a constant atmospheric condition is widely used; however, the atmospheric condition is highly dependent on many factors which imposes a dynamic model communication channel, which has to researched in-depth. The latter is very important for Free Space Optics projects where the atmospheric conditions affect the performance, such as Free Space Optics /Continuous Variable Quantum Key Distribution systems (FSO/CV-QKD). Therefore, the challenges have to be analyzed in order to propose suitable and optimized mitigation techniques [3,4].

In addition, Quantum Key Distribution (QKD) systems are an important option to provide unconditional security for closed and open communication channel (optical fiber and free space links). Also, nowadays, the QKD systems implemented using FSO links permit to increase the security level over long distances, however, as mentioned, the dynamical atmospheric conditions also affect the overall performance and security level of QKD systems [5-8]. Thus, the analysis of novel modulation schemes, such as 2PolSK-BPSK with application in FSO/CV-QKD is an important issue, mainly considering the dynamical atmospheric conditions. The last in order to enhance the performance and security level. This paper is organized as follows: Section 2 provides a brief description of the experimental set-up and theoretical background. Section 3 presents some results and analysis, and finally, Section 4 provides conclusions and future work.

2. EXPERIMENTAL SET-UP AND THEORETICAL BACKGROUND

Our experimental set-up for emulation is shown in Figure 1, where the transmitter and receiver systems represent to Alice and Bob, respectively, considering the terms used in QKD context. Now, both Alice and Bob systems will be described. In particular, Alice uses a laser (λ=1550.1 nm) to generates Coherent States (CS) with diffused phase. A Phase Modulator (PM) modifies the optical phase based on a BPSK scheme and a PolM modifies the SOP related to the 2PolSK modulation scheme. The PM and PolM are drives by digital random electrical signals. In fact, both systems (Alice and Bob) are driven by True Random Number Generator (TRNG) in order to generate truly random digital sequences as a base of the secure link requirement [9,10]. In the QKD context, these random signal are highly important. After, Alice and Bob use an optical signal of 100nW and 2mW (necessary for reach the Standard Quantum Limit, SQL), respectively, where the maximum optical power is defined for a Local Oscillator (LO). In our case, only a laser was used, so the two optical signals mentioned are generated using fiber splitters and attenuators. At the Bob's side, a free space π/2 optical hybrid uses the SOPs of the two optical signals for the simultaneous detection of the conjugate variables of the Weak Coherent State (WCS) due to that performance depends of the degree of polarization (DOP).

Thus, the output electrical current of Balanced Homodyne Detection (BHD) represents the information of the quadrature components of the quantum state transmitted. It is important to mention that the WCS is transmitted through a unidirectional free space channel and the dynamical atmospheric conditions are emulated by an atmosphere turbulence box. Both Alice and Bob systems use synchronization techniques, passive optics elements, digital processing and classical communication subsystems. Regarding the classical communication subsystem, it uses the bidirectional classical channel in order to perform the traditional QKD algorithm, i.e. BB84 protocol. In addition, Bob set-up uses an Optoelectronic Costas loop in order to minimize the phase error and maximize the overall performance.

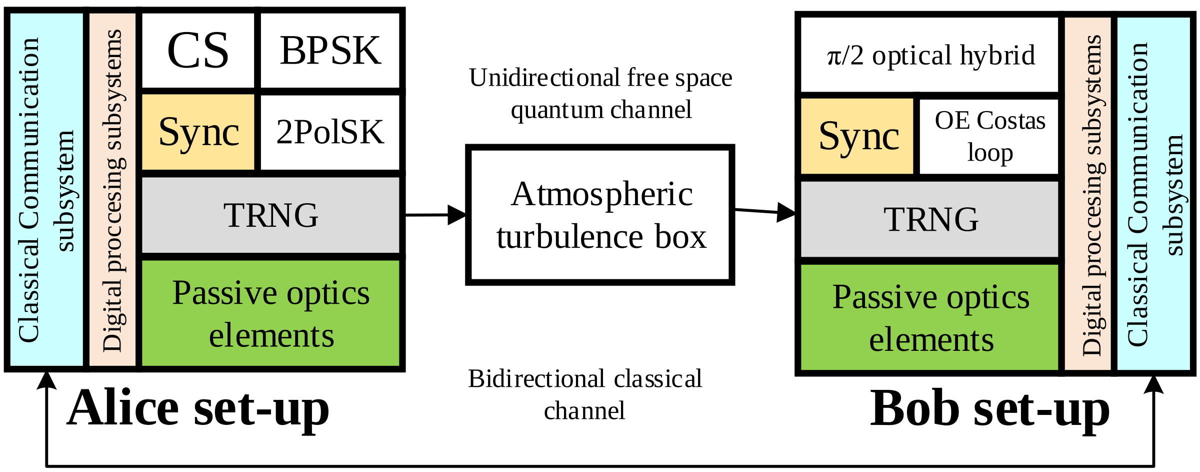

Figure 1. Alice-Bob experimental set-up.

Now, a general theoretical background will be presented. The photons number (N_{BHD1} (vertical SOP) and N_{BHD2} (horizontal SOP)) are measured according to Equations (1) and (2), respectively, considering the PolM using the creation ($\hat{a}_s^{+}$) and annihilation operators ($\hat{a}_S$) of the signal transmitted through the private channel , where the θ_{LO} and A_{LO} are the phase and amplitude of the LO, respectively. In particular, the optical power (related to the amplitude) of the data signal is not clearly considered as was the amplitude of the LO, because the operators were used due to the extreme reduced optical power. Next, a digital processing subsystem measure and calculate the electrical feedback in order to lock the phase of the LO using an optoelectronic (OE) loop.

$$N_{BHD1} = \frac{|A_{LO}|}{2}\begin{bmatrix}\exp(-j\theta_{LO} + \pi/2)\,\hat{a}_s + \\ \hat{a}_s^{+}\exp(j\theta_{LO} + \pi/2)\end{bmatrix} \tag{1}$$

$$N_{BHD2} = \frac{|A_{LO}|}{2}\begin{bmatrix}\exp(-j\theta_{LO})\,\hat{a}_s + \\ \hat{a}_s^{+}\exp(j\theta_{LO})\end{bmatrix} \tag{2}$$

Following, an emulated atmospheric turbulence box was used to represents the atmospheric effects. In particular, the Beer's law (see Equation 3) gives a mathematical expression considering a constant atmospheric attenuation based on specific coefficients, where β is the total attenuation coefficient and L is the distance (Km) between the Alice and Bob.

$$\tau = \exp(-\beta L) \tag{3}$$

In particular, β is defined as shown Equation (4):

$$\beta = \beta_{abs} + \beta_{scat} = \beta_{abs} + (\beta_m + \beta_a) \quad (4)$$

, which it is composed of the molecular-aerosol absorption and scattering, β_{abs} and β_{scat} , respectively. Specifically, β_{scat} depends on the Rayleigh and Mie scattering, β_m and β_a, respectively. However, some coefficients can be neglected considering a horizontal FSO link (but not for vertical FSO links).

In addition, the rain scattering coefficient have to be calculated and added to β using the Stroke Law by Equation (5) [11]:

$$\beta_{rs} = \pi a^2 N_a Q_s \quad (5)$$

, where a is the radius of raindrop (cm), N_a is the rain drop distribution (cm^{-1}) and Q_s is the scattering efficiency described as the ratio of the scattering cross section to the geometrical cross section. Thus, the parameter N_a can be calculated as Equation (6) shows:

$$N_a = R/(1.33 V_a \pi a^3) \quad (6)$$

, considering that R is the rainfall rate (cm/s) and V_a is the limit speed precipitation given by Equation (7):

$$V_a = (2a^2 g\rho)/9\eta \quad (7)$$

, ρ is water density (g/cm^3), g is gravitational constant, 980 $cm/s^2$and η is viscosity of air, $1.8x10^{-4}$ $g/(cmxs)$. Thus, the rain attenuation can be calculated by using Beer's law, and it is depending on the particular weather conditions where Alice and Bob are installed. Finally, the complete mathematical equation that represents the attenuation of a FSO link with particular dynamical features is described by Equation (8):

$$\tau(t) = \exp(-(\beta_{rs}(t) + \beta_{abs}(t) + \beta_{scat}(t))L) \quad (8)$$

Hence, $\tau(t)$ represents the time-dependent total attenuation coefficient [12,13]. It is important to clarify that the accurate time-dependent attenuation and scattering measurements are a relevant problem, therefore it is recommended uses weather data from recognized sources.

3. RESULTS AND ANALYSIS

Figures 2 and 3 show the experimental performance of the azimuth angle measured in the output port of the PolM and SOP in Alice and Bob, respectively, after a Quarter Wave Plate (QWP) to maximize the overall performance.

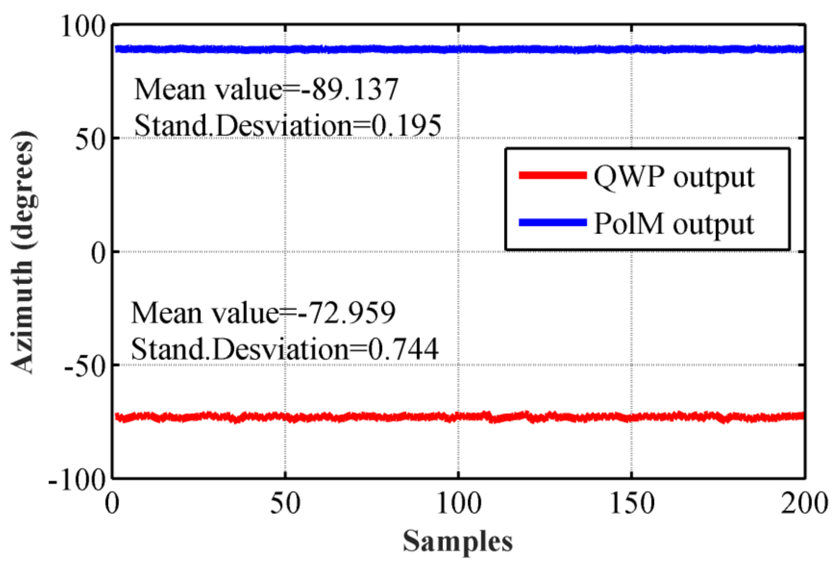

Figure 2. Performance of DOP of the output signal in the PolM and QWP.

The measurements consider that the value of R is within the limits ($1\ in/hr$-$4\ in/hr$) and the V_a value is the same upper limit value mentioned. In particular, the mean value of DOP for the output signal for the PolM is -89.137º (so close to the -90º as ideal value) degrees and a standard deviation value of 0.195º.

However, regarding the DOP of the output signal of the QWP, the mean value is -72.959º and the standard deviation value is 0.744º. After de turbulence box, the performance of the communication system related to the DOP for a particular atmospheric condition is showed in Figure 3, where the mean and standard deviations values for QWP and PolM are presented. The mean values for QWP and PolM are 98.075º and 97.307º, respectively. While that standard deviation values are 0.940º and 0.253º, respectively.

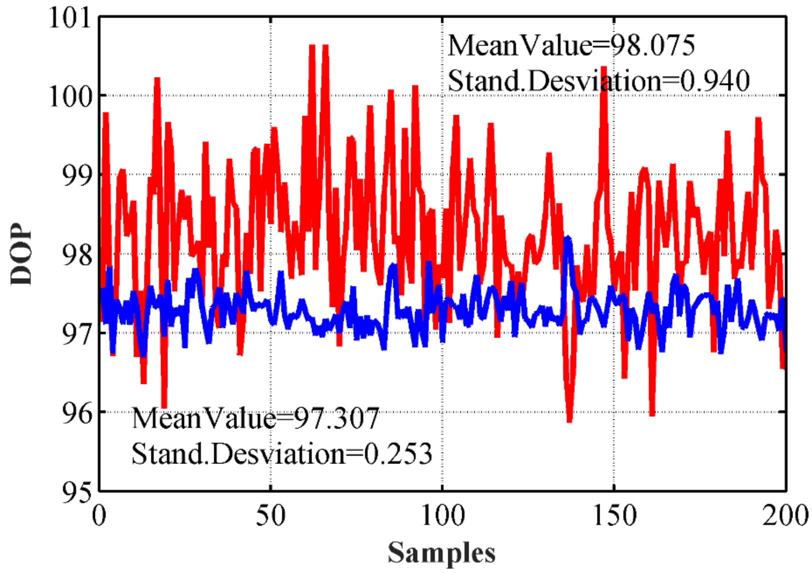

Figure 3. Performance of the Alice-Bob systems considering: $\rho = 1\ g/cm^3$ (general value of the water), although the water density change based on the salty level and temperature, $\eta = 1.8x10^{-4}\ g/(cmxs)$, $a = 1$, $R = 4\ in/hr$.

Next, considering the performance of the DOP showed in Figures 2 and 3, the performance of the communications link related to the erroneous bits received considering the dynamical atmospheric conditions is measured. Thus, the Bit Error Rate (BER) is determined using Equation (9):

$$\text{BER} = 0.5\ erfc\left(\sqrt{2N_S}\right) \tag{9}$$

, based on the photons number ($N_S = 0.25$ photons/pulse at 350 KHz) for each SOP (vertical and horizontal) considering a BPSK (Binary Phase-shift keying) scheme due to that the combination 2PolSK-BPSK can represent a QBaudSK (four baud shift keying) scheme used in CV- QKD systems. Finally, the BER was measured considering different atmospheric conditions using an atmospheric turbulence box, primarily, the dynamical attenuation parameter as shown in Figure 4. In particular, the figure shows the theoretical performance (black trace) of the FSO/CV-QKD/QBaudSK system considering both transmission polarization signals (SOP-H and SOP-V). While the experimental performance of both SOPs are representing using red circles and blue triangles. As can be seen, the BER measurements for both SOPs transmitted through a turbulent channel are so close to the theoretical performance. reaching a minimum and maximum values of BER of $10^{-2.5}$ and $10^{-0.9}$, respectively. It is important to clarify that the minimum BER value was obtained using 2 photons/pulse and the maximum BER value using 0.25 photons/pulse.

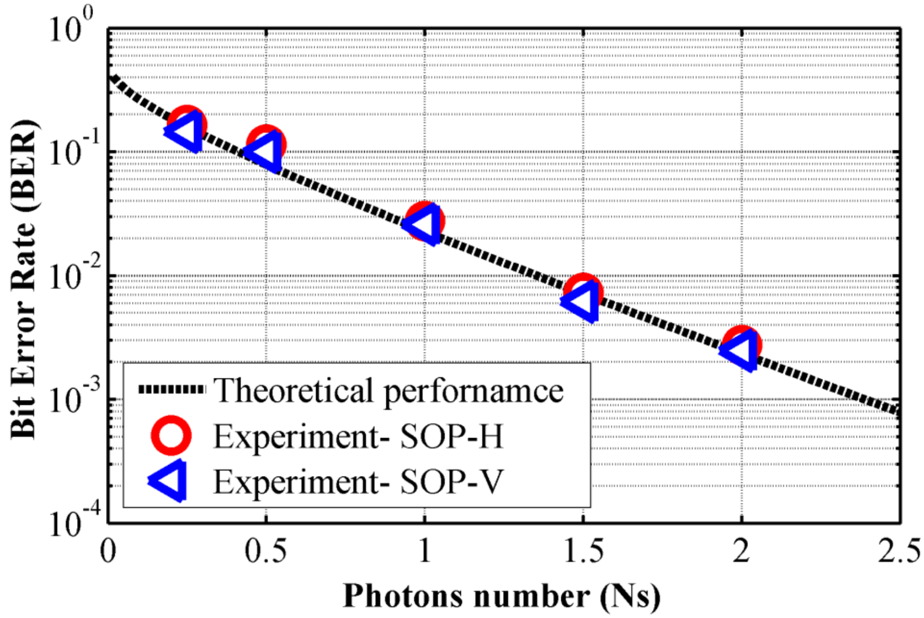

Figure 4. Bit error rate for different photons number with the same atmospheric conditions.

4. CONCLUSION

The paper presents the emulated performance of an FSO/CV-QKD systems using a 2PolSK-BPSK considering dynamical atmospheric conditions. Some results regarding the state and degree of polarization are shown in order to determine the Bit Error Rate for different photons number. It is crucial the understanding of the atmospheric channel in order to improve the communications systems and thus, enhance the existing communications systems and research novel communications systems that support a lot of information.

REFERENCES

[1] Liu W. and Yao J., “Photonic Generation of Microwave Waveforms Based on a Polarization Modulator in a Sagnac Loop”, Jour. of Light. Tech, 32, 3637 – 3644 (2014).

[2] Pointurier Y., de Valicourt G., Simsarian J. E., Gripp J. and Vacondio, F. “High data rate coherent optical slot switched networks: a practical and technological perspective”, Comm. Mag., 53, 124 - 129 (2015).

[3] Kaushal H. and Kaddoum G., “Optical Communication in Space: Challenges and Mitigation Techniques”, Comm. Surv. & Tut., 19, 57 - 96 (2017).

[4] Peppas K. P. and Mathiopoulos P.T., “Free-Space Optical Communication with Spatial Modulation and Coherent Detection Over H-K Atmospheric Turbulence Channels”, Jour. of Light. Tech., 33, 4221 – 4232 (2015).

[5] Qu Z. and Djordjevic I. B., "High-Speed Free-Space Optical Continuous Variable-Quantum Key Distribution Based on Kramers–Kronig Scheme," Photonics Journal, 10, 1-7 (2018).

[6] Trinh P. V., Pham T. V., Dang N. T., Nguyen H. V., Ng S. X. and Pham A. T., "Design and Security Analysis of Quantum Key Distribution Protocol Over Free-Space Optics Using Dual-Threshold Direct-Detection Receiver," Access, 6, 4159-4175 (2018).

[7] Qu Z. and Djordjevic I. B., "Four-Dimensionally Multiplexed Eight-State Continuous-Variable Quantum Key Distribution Over Turbulent Channels," Photonics Journal, 9, 1-8, (2017).

[8] L. Anthony and G. Philippe, “Unconditional Security Proof of Long-Distance Continuous-Variable Quantum Key Distribution with Discrete Modulation”, Phys. Rev. Lett. 102, 180504 (2011).

[9] Lopez J. and Arvizu, A., “Simultaneous dual true random numbers generator”, DYNA, 83, 93-98 (2016).

[10] Vatajelu E. I. and Di Natale G., "High-Entropy STT-MTJ-Based TRNG," Transactions on Very Large Scale Integration (VLSI) Systems, 27, 491-495 (2019).
[11] Malik A., Kumar S., Singh P., and Kaur P. [Intelligent Communication, Control and Devices. Advances in Intelligent Systems and Computing], Springer, Singapore, 623-631 (2018).
[12] Grabner M. and Kvicera V., "Multiple Scattering in Rain and Fog on Free-Space Optical Links", Jour. of Light. Tech., 32, 513-520 (2014).
[13] Sandalidis H. G, Tsiftsis T. A., Karagiannidis G. K. and Uysal M., "BER Performance of FSO Links over Strong Atmospheric Turbulence Channels with Pointing Errors," Communications Letters, 12, 44-46 (2008).