Transmission of 128 Gb/s Optical QPSK Signal over FSO Channel under Different Weather Conditions and Pointing Errors

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Abstract. Free space optics (FSO) is a promising technology for high data rate transmission where data is transmitted wirelessly from one place to another. It has a variety of applications nowadays including indoor, outdoor, underwater, and deep space communications. However, the availability of link under various atmospheric conditions is a major concern. In this study, we evaluate the transmission of 128 Gb/s optical quadrature phase shift keying (QPSK) signal under different weather conditions and pointing errors. Simulation parameters such as FSO link range, atmospheric attenuation, pointing loss, and wavelength are taken into consideration. The system performance evaluation parameters including eye diagram, constellation, and received signal to noise ratio (SNR) are compared to find the best performance under different weather conditions. Numerical simulations show that the pointing errors up to 10 µrad and bad weather conditions up to 15 dB attenuation have severe effects on the system performance and we should use digital signal processing and equalization to enhance it.

1. INTRODUCTION
Free space optics (FSO) is a point-to-point communication technology that uses the visible and infrared bands to transfer high speed data in free space without guide such as fiber. The progress in this technology continued in terms of enhancing the system capacity and reach distance. Its applications cover different fields including military, civil and deep space applications that ranging from short range to ultra-range in thousands of kms [1]. Commercial products are available for a data rate of several hundreds of Mbps up to 10 Gbps. Moreover, FSO promises to offer rapid growth in data rates by using wavelength division multiplexing (WDM) by sharing the same space[2]. It is expected for each FSO transceiver to carry hundreds of wavelengths per FSO channel. Authors in [3] demonstrated the feasibility of up to hundred Tb/s using a WDM over FSO channel. In addition, as a result of the short installation time of FSO systems, there is a growing interest in military and civilian applications. However, the presence of aerosols in outdoor environment forms a real challenge especially when the particle size becomes close the signal wavelength. Such aerosols limit the link availability, reliability and decrease the reach distance down to hundreds of meters only. Therefore, such channel impairments are need to be understood and overcome in order to improve the transmission distance and link availability.

In this article we use the coherent optical quadrature phase shift keying (QPSK) over FSO channel with various channel conditions. The paper will be organized as follow. In Section II and
III, channel and system description is presented, Section IV describe the numerical simulation and results, finally we conclude the paper in Section V.

2. FSO CHANNEL MODEL

As the light propagates through the FSO channel, the optical signal are attenuated and distorted by two major impairment factors; attenuation and atmospheric turbulence [4]. The loss in the FSO link is due to absorption, scattering both (Rayleigh and Mie) are from rain, fog, snow, aerosols and dust as shown in Fig. 1., as well as beam divergence, and pointing loss [5, 6]. Due to propagation through the free space channel with air pockets of varying density, temperature, and index of refraction, light beam spreading and wandering will cause atmospheric turbulence [7] which results in random phase and amplitude variations of the received optical signal, results in increased bit error rate (BER) [8]. The irradiance fluctuation within the cross-section of the received beam is called as scintillation and it is quantified as scintillation index $\sigma_l^2$ and it is defined as [4]:

$$\sigma_l^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}$$

where $I$ indicate the irradiance at a particular point in the receiver plane. In this paper, we will focus on loss caused by atmospheric scattering and absorption and pointing loss.

Atmospheric conditions can be studied according to the size and concentration of particles comparative to the wavelength $\lambda$. Moreover, absorption and scattering coefficients from aerosols and molecular in the atmosphere add to the attenuation coefficient. The rain scattering coefficient can be obtained using Stokes law [9] as

$$\beta_{\text{rain}} = \pi a^2 N_a Q_{\text{scatt}}(\frac{\lambda}{a})$$

where $a$ is the radius of raindrops, $N_a$ is the distribution of raindrops, $Q_{\text{scatt}}$ is the scattering efficiency and $\lambda$ is the wavelength. The loss at various visibility levels has a high impact on the performance specially, when the particle size of fog is comparable with $\lambda$ and it will be calculated by the empirical model of Mie scattering as [4]:

$$\beta_{\text{fog}} = \frac{3.91}{V} \left( \frac{\lambda}{550} \right)^{-q}$$

where $V$ is the visibility in km and $q$ is constant related to distribution size and it is given as per Kim model as [4].

$$q = \begin{cases} 
1.6 & V > 50 \text{ km} \rightarrow \text{High visibility} \\
1.3 & 6 < V < 50 \text{ km} \rightarrow \text{Average visibility} \\
0.16V + 0.34 & 1 < V < 6 \text{ km} \rightarrow \text{Haze visibility} \\
V - 0.5 & 0.5 < V < 1 \text{ km} \rightarrow \text{Mist visibility} \\
0 & V < 0.5 \text{ km} \rightarrow \text{Fog visibility} 
\end{cases}$$

The optical signal at the RX side is given by [4, 10, 11, 12]:

$$P_r = P_t \eta_t \eta_r G_t G_r L_t L_r L_{\text{atm}} L_{\text{pol}} L_{fs}$$

where $P_t$ is the TX optical power; $\eta_t$ and $\eta_r$ are the TX and RX optics efficiency respectively; $G_t = (\frac{\pi D_t}{\lambda})^2$ and $G_r = (\frac{\pi D_r}{\lambda})^2$ are the TX and RX telescope gain; $D_t$ and $D_r$ are the TX
and RX telescope diameter; $L_t$ and $L_r$, are the TX and RX pointing loss factor, respectively. $L_{atm} = e^{-(\beta_{rain} + \beta_{fog} + \ldots)R}$ is the atmospheric loss, $L_{pol}$ is the loss due to polarization mismatch, $L_{fs}$ is the free-space loss and is given by $L_{fs} = \left(\frac{\lambda}{4R}\right)^2$, where $\lambda$ is the wavelength; $R$ is the distance between the TX and the RX. Generally, in FSO link, the largest loss is the free space path loss. Most systems use a narrow-beam-divergence angle laser TX and narrow field of view RX; hence small mispointing can cause signal loss. The TX pointing loss factor will be given by $L_t = e^{-G_t \theta_t^2}$ where $\theta_t$ is TX azimuth pointing error angle. Similarly, the approximate RX pointing loss factor is given by $L_r = e^{-G_r \theta_r^2}$ where $\theta_r$ is RX azimuth pointing error angle.

To model the atmospheric fading, a Gamma-Gamma distribution is used. The probability of a given intensity is [13, 14, 15]:

$$P(I) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} I^{\alpha+\beta-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta I})$$

(4)

where $1/\alpha$ and $1/\beta$ are small and large scale variances, respectively [14]. The Gamma function and the modified Bessel function of the 2nd kind are given as $\Gamma(.)$ and $K_{\alpha-\beta}(.)$, respectively.

$$\alpha = e^{(1+1.11c_n^2)^{7/6}5/6 - 1}, \quad \beta = e^{(1+0.695c_n^2)^{7/6}5/6 - 1}$$

(5)

The Rytov variance can be obtained from: $\sigma_r^2 = 1.23C_n^2 k^{7/6} R^{11/6}$, where $C_n$ is the parameter of refractive index structure, $k$ is the wavenumber and $R$ is the link distance.

3. OPTICAL QPSK SYSTEM OVER FSO LINK

The quadrature phase shift keying (QPSK) is a multilevel modulation format that has been recently applied to optical communication and deployed in the field [16]. The QPSK modulator encodes 2 bits/symbol and each QPSK symbol is mapped by 1 of 4 possible phases of the optical signal. It transmits the four symbols at the half bit rate hence increasing the spectral efficiency by two. Figure 2 shows the Optical QPSK system over FSO link.

The optical QPSK transmitter is composed of a PRBS generator to generate a binary data with a bit rate 128 Gb/s followed by a quadrature amplitude modulation (QAM) mapper to map the the binary data to the inphase (I) and quataturae (Q) arms followed by two M-PAM pulse generators. In each arm, a Mach-Zehnder modulator (MZM) modulates the phase of the optical light generated by a laser diode source according to the value of the electrical input pulses. A phase modulator (PM) insert a phase shift of 90° over one of the arms to produce
the Q signal. The optical coupler combines I and Q signals to be transmitted through the FSO telescope. Thus, the QPSK optical signal will be represented as: [17]:

$$\vec{E}_{QPSK} = \left\{ \frac{1}{2} \cos(\frac{\Delta \phi_I(t)}{2}) + j \frac{1}{2} \cos(\frac{\Delta \phi_Q(t)}{2}) \right\}$$ (6)

where $\Delta \phi_I(t)$ and $\Delta \phi_Q(t)$ are the induced phase differences of the MZMs in the upper and lower arms: $\Delta \Phi_I(t) = \frac{V_{in 1}(t)}{V_x} \pi$ and $\Delta \Phi_Q(t) = \frac{V_{in 2}(t)}{V_x} \pi$ where $V_{in 1}(t)$ and $V_{in 2}(t)$ are the input voltage of M-PAM and $V_x$ is the voltage at the input of the MZM that introduces a phase shift of 180°.

The coherent detection using phase diversity receiver is used to detect both IQ components in homodyne receiver. As shown in Figure 2 this configuration adds a 90° optical hybrid network which can change the phase of the local oscillator by 90° to detect both I-Q components. The four output of the 90° optical hybrid network is as follows:

$$E_1 = \frac{1}{2}(E_s + E_{LO}), E_2 = \frac{1}{2}(E_s - E_{LO}), E_3 = \frac{1}{2}(E_s + jE_{LO}), E_4 = \frac{1}{2}(E_s - jE_{LO}).$$ (7)

Consequently the output current from the balanced photodetector circuits is given by:

$$I_I(t) = R \sqrt{P_S P_{LO}} \cos(\theta_S(t) - \theta_{LO}(t)), \quad I_Q(t) = R \sqrt{P_S P_{LO}} \sin(\theta_S(t) - \theta_{LO}(t))$$ (8)

where $R$ is the photodiode responsivity, $P_S$ and $P_{LO}$ are the power values related with the received and the LO signals respectively; $\theta_S(t)$ $\theta_{LO}(t)$ are the phases of the transmitted and LO signals respectively. Hence by this system we can restore the inphase and quadrature components of the complex amplitude optical signal. The ADCs digitize the electrical I and Q signals for the next step of signal processing using digital signal processor. It performs electronic equalization and compensation, bit detection, and measurement of the quality of the signal. The quality of the received signal is measured with various metrics such as the optical signal to noise ratio (OSNR), error vector magnitude (EVM) or bit error rate (BER). We used the OSNR, constellation diagram, and eye diagram to evaluate the performance of our proposed system.

4. NUMERICAL SIMULATION AND RESULTS
We used the Optisystem tools to design and simulate the optical QPSK-FSO system based on the following parameters shown in Table 1.

Table 1: Optical QPSK FSO system parameters for various weather conditions [5]

| Symbol | Value               | Bit Rate 128 Gb/s | Link Range 0-100 km | Transmitted power $P_t$ -10 dBm | Wavelength $\lambda$ 1550nm | TX & RX aperture diameter $D_t$ & $D_r$ 15 cm | Laser line width $\nu$ 100MHz | TX & RX radiation efficiency $\eta_t$ & $\eta_r$ 0.85 & 0.75 | Photodiode responsivity $R$ 0.85 | MZM Extinction ratio $ER$ 25 dB | TX and RX Pointing Error $PE_t$ & $PE_r$ 0-10 $\mu$rad |
|--------|-------------------|------------------|---------------------|-------------------------------|-----------------------------|---------------------------------|-----------------------------|--------------------------------|-----------------------------|-------------------------------|--------------------------------|
| Weather Att. (dB/km) Visibility | Clear 0.11 dB/km 40 km | Clear 0.19 dB/km 23 km | Haze 1.5 dB/km 4 km | Fog 15.55 dB/km 0.8 km |

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Due to, imperfect alignment of FSO TX and RX telescopes, there is a loss error. Typically, these pointing errors are seen for distances in excess of 3 km, at which an additional power should be considered in the link budget. Moreover, a geometric losses result from beam divergence should be considered. A typical FSO transponder has optical beam divergence in the range of 210 mrad. According to the channel model presented previously. finally, different weather conditions are shown in Table 1, where the attenuation factor for clear air is 0.155 dB/km and increased for heavy fog to 84.904 dB/km.

4.1. Effects of FSO link range on the system performance

The Fist metrics that we would like to use are two curves showing received optical signal to noise ratio (OSNR) versus link range and optical spectrum of the received signal as presented in Fig. 3(a and b). The first curve depicted in Fig. 3a shows how much bandwidth is needed and how much power will be received at a given link range of 15 km. The second curve shown in Fig. 3b is derived from the first and shows the average received optical signal to noise ratio in which FSO system will operate for a given atmospheric attenuation. As shown in Fig. 3b, the receive OSNR will decrease by increasing link range due to the different losses in FSO link. The other metric is the eye diagram performance. Figure 4 shows the effects of different link range on the eye opening and time jitter. For short link range the eye opening will increase with reduction in time jitter as well. In addition the received signal power will be higher. As the link range increases the eye will close with higher time jitter and lower received power.

Figure 3: Effects of FSO link range on the system performance with no pointing errors and clear weather, attenuation = 0.19 dB.

Figure 4: Eye diagram for optical QPSK Signal at various link range with no pointing errors and clear weather, attenuation = 0.19 dB
4.2. Effects of pointing error on the system performance

As most systems use a narrow-beam-divergence angle laser TX and narrow field of view RX; hence small mispointing can cause signal loss. In this section we study the effects of mispointing of FSO transmitter and receiver. Figure 5 shows the signal at the receiver in the same weather condition under different pointing errors. Similarly, as point error increase the performance goes worse and the eye will close with higher time jitter. Next, we evaluate the performance in terms of constellation diagram. As the pointing error increases the error increased and error vector magnitude (EVM) will increase with increasing BER. so for higher pointing error we should use electronic compensation or equalization to improve the performance to acceptable levels.
4.3. Effects of different weather conditions on the system performance

Finally, we studied the system performance at different weather conditions with attenuation and visibility values listed in Table 1. Fig. 6 depicts the measured eye diagram under clear, haze, and fog weather. Under clear weather the visibility reaches up to 50 km and the height of eye opening is higher with small time jitter. In Fog weather where attenuation reaches 15.5 dB/km, the performance will be worse as shown in Fig. 6d. In addition, Figure 5 and 6 shows the constellation diagram at different weather conditions and pointing error.

5. CONCLUSIONS

In this paper, we study the transmission of 128 Gb/s optical quadrature phase shift keying (QPSK) signal under different weather conditions and pointing error. The FSO link range, atmospheric attenuation and pointing error have been studied. The system performance in terms of eye diagram, signal constellation, and received OSNR are compared to find the best performance under different weather conditions such as clear, haze and fog weather.

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