Receiver optimization of FSO system with MIMO technique over log-normal channels

MOHAMED B. EL MASHADE, AHMED H. TOEIMA, MOUSTAFA H. ALY[a,*]
Electrical Engineering Dept., Faculty of Engineering, Al Azhar University, Nasr City, Cairo, Egypt
[a]Electronics and Communication Engineering Department, College of Engineering and Technology, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt, Member of OSA

A major performance degrading factor in free space optical (FSO) communication systems is the atmospheric turbulence. Multiple input multiple output (MIMO) technique provides a promising approach to mitigate turbulence-induced fading. In this paper, MIMO technique with equal gain combining (EGC) is considered to enhance the data rate of the FSO communication system. Atmospheric turbulence impact is modeled as a log-normal channel and geometric losses are taken into account. Using non return to zero (NRZ) line code, FSO highly sensitive receiver using avalanche photodetector (APD) and PIN are designed and simulated for best system performance. The comparison is carried out with Bessel filter and Gaussian filters. We found that, the APD receiver using Gaussian filter is suitable for long range link with APD gain value of 3. Also, the selection of APD gain is critical to the system performance. The optimal value of APD gain required for best system performance decreases by increasing the size of MIMO.

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1. Introduction

FSO communication has become more and more interesting over the last two decades as an adjunct or alternative to radio frequency (RF) communication. This involves transmission between two buildings, between ground station and satellite, between end users and fiber optic backbone and as a backup link for optical fiber. Also, it is a license-free technology and offers much-enhanced channel bandwidth as compared to RF. It has low power consumption, reusability, it enables the use of same communication equipments and wavelengths by nearby systems, and it cannot be intercepted easily. Besides, the availability of cheap front-ends makes this technology cost effective when compared to optical fiber systems [1, 2].

The short wavelengths of the FSO system are easily attenuated by particulates such as fog, haze and rain droplets that are suspended in the air. One of the main problems facing a FSO system is the atmospheric turbulence. Optical turbulence arises as a result of random fluctuations in the refractive index of the atmosphere which are directly dependent on fluctuating atmospheric temperature and pressure [3]. The refractive-index fluctuations cause detrimental effects on the optical beam such as beam spreading, irradiance fluctuation, and loss of spatial coherence [4, 5].

Log-normal distribution is the most widely used model for the probability density function (pdf) of the irradiance because of its accuracy and simplicity [4, 6]. MIMO technology is most widely used in wireless communications. It utilizes the available different channel paths from the different transmit sources to enhance the spectral efficiency and link reliability. In addition, MIMO configurations can be used to achieve high diversity gains to combat channel fading without increasing power or bandwidth [7, 8].

The PIN diodes and APDs are the most commonly used photodiodes in FSO. PIN receivers are commonly used due to their low cost, high mitigation to wide temperature fluctuations and the ability to operate with cheap low bias voltage power supply. PIN receivers are less sensitive than the APD ones. The sensitivity of these receivers can be enhanced by increasing the transmitter power and using a larger receiver lens diameter. In case of APD, the increased power margin provides a more robust communication link than PIN receivers. This allows further reduction in transmitter power and the signal to noise ratio (SNR) can be increased through the internal gain of APDs. However, APD receivers are expensive and need high operating voltages which limit their practical usage [9- 11].

In this paper, we analyze an EGC MIMO technique in FSO communication systems with NRZ and PIN or APDs using Bessel and Gaussian filters for receiver optimization in the presence log-normal channel and geometric losses. Here, the number of MIMO varies from 1 to 4 and investigations are done on 1.25 Gbps system for all MIMO.

The remainder of this paper is organized as follows. The mathematical analysis and design model based on the FSO theory and the numerical analysis, and simulation of the FSO link in the presence of log-normal channel are presented in Sec. 2. Results and discussion are carried out in Sec. 3. This is followed by the conclusion in Sec. 4.

2. Mathematical analysis and design

2.1 Background

Short range optical wireless communication links over log-normal channel with standard deviation σ = 0.1 and zero mean are considered throughout this paper. The pdf, $f_I(I)$ of log-normal fading channel is given by [12]

$$f_I(I) = \frac{1}{I\sqrt{8\pi\sigma^2}} e^{\left(-\frac{(\ln(I)-\ln(I_0))^2}{8\sigma^2}\right)} \quad (1)$$

where I_o is the average received signal light intensity without the considered log-normal channel and I is the received signal light intensity with turbulence. The optical intensity of a source is defined as the optical power emitted per solid angle in units of Watts per Steradian (W/sr) [13].

2.2 FSO channel

Atmospheric attenuation, free space path loss, transmitter and receiver gain, types of detectors, efficiencies and pointing loss factors are considered the main factors that highly affect the link budget calculations. Friis transmission formula is introducing the link budget model [14- 16]. The optical wireless channel is modeled by a mathematical equation. The optical received power, P_R, is [14]

$$P_R = P_T \eta_T \eta_R \left(\frac{\lambda}{4\pi Z}\right)^2 G_T G_R L_T L_R \quad (2)$$

where P_T is the transmitter optical power, η_R is the optical efficiency of the receiver, η_T is the optical efficiency of the transmitter, λ is the wavelength, Z is the distance between the transmitter and the receiver, G_T is the transmitter gain, G_R is the receiver gain, and L_T, L_R are the transmitter and the receiver pointing loss factor, respectively. The free space path loss is represented by the factor $(\lambda/4\pi z)^2$. The pointing loss factor L as a function of radial pointing error angle, θ, is given by [14]

$$L = e^{-G_T\theta^2}$$

This factor defines the attenuation of the received signal due to inaccurate pointing. When the transmitter is assumed to be uniformly illuminated from a circle aperture, the out beam cross section is considered as a Gaussian beam and the receiver antenna is a circular aperture. The transmitter and receiver gain expressions are, respectively, given by [14, 15]

$$G_T = (\pi D_T/\lambda)^2$$
$$G_R = (\pi D_R/\lambda)^2$$

where D_T and D_R are, respectively, the transmitter and receiver aperture diameters.

The geometric path loss for an FSO link depends on the beam width of the optical transmitter, φ, its path length, Z, and the area of the receiver aperture, A_r. Geometric loss is the ratio of the surface area of the receiver aperture to the surface area of the transmitter beam at the receiver. Since the transmit beams spread constantly with increasing range at a rate determined by the divergence, geometric loss depends primarily on the divergence as well as the range and can be determined by the formula stated as [13]

$$\text{geometric loss} = \frac{D_R^2}{[D_T+(Z\varphi)]^2} \quad (3)$$

where φ is the beam divergence, and Z is the link range. Geometric path loss is present for all FSO links and must always be taken into consideration in the planning of any link. This loss is a fixed value for a specific FSO deployment scenario; it does not vary with time, unlike the loss due to rain attenuation, fog, haze or scintillation.

2.3 MIMO FSO channel

The bit error rate, BER, of a MIMO system is obtained as [17]

$$BER = \int_{h_{mn}} f_{h_{mn}}(h_{mn}) Q\left(\frac{\sqrt{2}}{\sqrt{\sigma_n^2}MN}\sqrt{\sum_{n=1}^{N}\left(\sum_{m=1}^{M} R_d P_t h_{mn}\right)^2}\right) dh_{mn} \quad (4)$$

where $f_{h_{mn}}(h_{mn})$ is the joint pdf of vector $h = (h_{11}, h_{12}, \ldots, h_{MN})$ of length MN, Q(.) is the Gaussian Q function [11], the noise variance ($\sigma_n^2 = \sigma_{th}^2 + \sigma_{sh}^2$) is the summation of the shot noise and the thermal noise variances, σ_{th}^2 is the thermal noise variance, σ_{sh}^2 is the shot noise variance. R_p is the photodetector responsivity and P_t is the average transmitted optical power.

The shot noise is caused by the background light while the thermal noise, σ_{th}^2, is a result of thermally induced random fluctuations in the charge carriers in the resistive element of the photodetector [12, 18]. The variance of the thermal noise, σ_{sh}^2, and the shot noise are given by [12]

$$\sigma_{th}^2 = \frac{4k_B T_K B_e}{R_L} \quad (5)$$

$$\sigma_{sh}^2 = 2q_e R_p (I + I_b) B_e \quad (6)$$

with k_B being the Boltzmann's constant, T_k is the absolute temperature, B_e is the equivalent bandwidth of the receiver, R_L is the load of the photodetector, q_e is the electron charge and I_b is the light intensity of the background light. The BER expression for APD and PIN is derived as following [19]

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) = \frac{exp(-Q^2/2)}{Q\sqrt{2\pi}} \quad (7)$$

The MIMO FSO design has been modeled and simulated for receiver performance characterization using MATLAB software and OptiSystem™ from Optiwave Corp. The components for log-normal channel conditions are not available in OptiSystem, so, we have written programs in MATLAB and linked them with OptiSystem. MIMO up to 4 systems is modeled. Moreover, the total collected noise is the same for both systems. The total transmitted power is the same for single input single output (SISO) and MIMO systems to ensure that in background noise-limited reception. The MIMO FSO design model over log-normal channel is illustrated in Fig. 1.

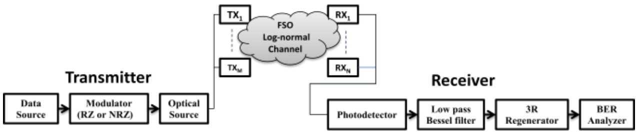

Fig. 1. Block diagram of MIMO FSO over log-normal channel

In the proposed design, the optical transmitter consists of three subsystems. The first subsystem is the User Defined Bit Sequence Generator (UDBS) which is the generator data source. This subsystem is to represent the information or data that needs to be transmitted. The output from a UDBS generator is a bit stream of pulses; a sequence of "1"s (ON) or "0"s (OFF), of a known and reproducible pattern. The second subsystem is the NRZ modulation format electrical pulse generator. This subsystem encodes the data from the UDBS generator by using the NRZ modulation format technique. The third subsystem in the optical transmitter is the direct modulated lasers.

Direct modulated lasers based on Mach-Zehnder modulator operating at wavelengths around 1550 nm are developed specifically for fiber optic communications systems because of the low attenuation characteristics of optical fiber in this wavelength range. The free space between transmitters and receivers is considered as FSO channel which is the propagation medium for the transmitted light. The optical receiver consists of APD or PIN followed by a low pass filter (Bessel or Gaussian). The receiver is used to regenerate electrical signal of the original bit sequence and the modulated electrical signal as in the optical transmitter to be used for BER analysis.

3. Results and discussion

In the proposed design, a highly sensitive receiver using APD and PIN is designed and tested for best system performance. A comparison is done using Bessel and Gaussian filters. A comparative study has been carried out for free space optical communication using NRZ modulation format, and by increasing the size of MIMO up to 4 systems. The results have been mentioned for FSO system at different values of receiver responsivity and gain. And by taking values of the various parameters like: data rate 1.25 Gbps, transmitter wavelength 1550 nm, transmitter aperture is 2.5 cm, receiver aperture is 8 cm, transmitted power is 10 dBm, transmitter and receiver optical efficiency (η_T, η_R) are 0.75 and 0.8 respectively, APD dark current is equal to10 nA, divergence angle is equal to 3 mrad, the operating temperature is 300 K (room temperature), Boltzmann constant is 1.38×10^{-23} W/K/Hz, electron charge is 1.6×10^{-19} C, and the receiver resistance load is 50 Ω. Also, an electrical bandwidth of 11.2 GHz is assumed, and the transmission distance is up to 1 km.

Based on the described system, the performance of MIMO FSO links for multiple size of MIMO over log-normal channel is generated in different operating conditions. Performance evaluation of the proposed link at 1550 nm and at a propagation distance up to 1km with NRZ line code and APD or PIN receiver and by using Bessel and Gaussian filters, simulation is analyzed.

Fig. 2 illustrates the effects of geometric loss on the performance of FSO system. The value of geometric loss is calculated using Eq. (3), assuming that the link range is up to 1 km at different values of beam divergence, which are considered as particular design specifications due to particular implementation. There are a number of parameters that control geometric loss: transmission range, the diameter of transmitter and receiver apertures, and laser beam divergence. These parameters also contribute to the design of FSO system, so that it is suitable during bad weather conditions.

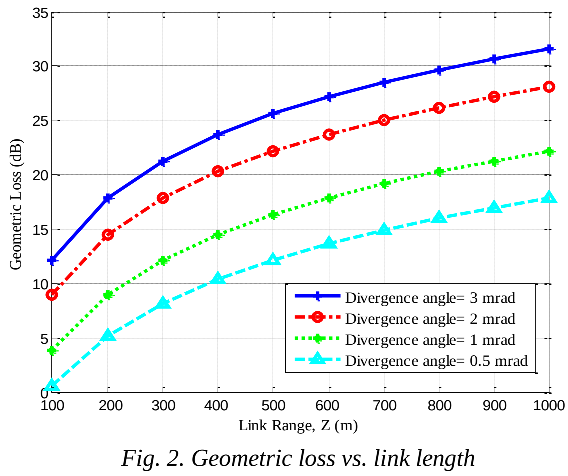

Fig. 2. Geometric loss vs. link length

From Fig. 2 it is clear that, geometric loss increases with link length. The geometric loss is 12.2 dB in link length of 100 m and increases to 31.6 in link length of 1000 m in case of 3 mrad divergence angle. As demonstrated in Fig. 2, geometric loss is proportional to divergence angle that for a 3 mrad divergence angle, the geometric loss is about 25.6 dB and for a 0.5 mrad divergence angle, the geometric loss is about 10.7 dB. This clarifies that using a small divergence angle of laser beam in FSO systems, the effect of geometric loss is minimized.

The Q-factor is the ratio of peak-to-peak signal to total noise. Fig. 3 shows the relation between the Q-factor and link range over log-normal channel using APD receiver has gain value of 3 with Bessel and Gaussian filters. From Fig. 3, it is clear that, in case of link range smaller than 240 m, APD receiver with Bessel filter gives a better performance, but in case of Z >250 m, APD receiver with Gaussian filter give better performance.

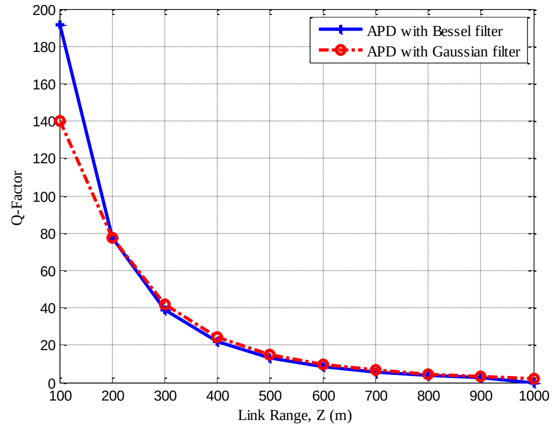

Fig. 3. The Q-factor vs. link range over log-normal channel using APD receiver with Bessel filter and Gaussian filters

Fig. 4 displays the achieved BER for different filters over log-normal channel using APD receiver of a gain value of 3 for link range ≥ 700 m. Results show that in case of APD receiver with Gaussian filter an improvement in BER is achieved as compared with the Bessel filter.

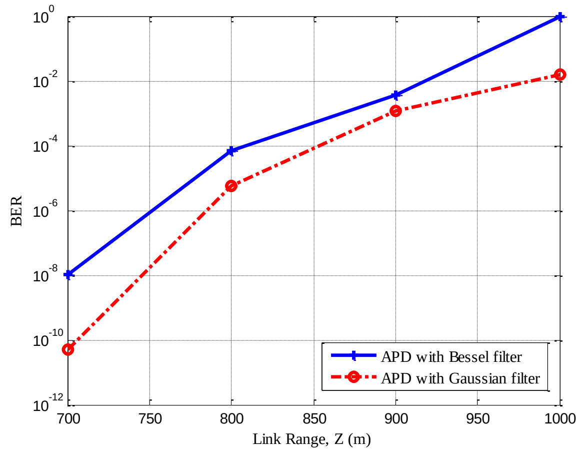

Fig. 4. Bit error rate vs. link range over log-normal channel using APD receiver with Bessel filter and Gaussian filters

Fig. 5 displays the relation between the Q-factor and number of MIMO for 500 m link range over log-normal channel using APD receiver with Bessel filter by increasing the APD receiver responsivity from 0.7 to 1 A/W.

It is observed that in case of SISO and by increasing the APD receiver responsivity from 0.7 to 1 A/W, the system performance is enhanced by approximately 37%. In case of using APD receiver responsivity 0.7 A/W and by increasing the size of MIMO to (2×2), the system performance is increased by approximately 545%. One gets a large value of the Q-factor of 114.3 by using MIMO (4×4) in case of 1 A/W APD receiver responsivity, and yielding a value of 91 of the Q-factor in case of using 0.7 A/W APD receiver responsivity.

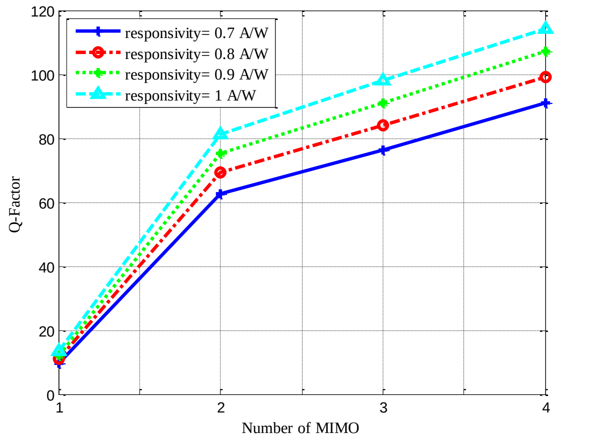

Fig. 5. The Q-factor vs. number of MIMO over log-normal channel at different values of APD responsivity for 500 m link range using Bessel filter

The relation between the Q-factor and number of MIMO for 500 m link range over log-normal channel using PIN receiver with Bessel filter, and by increasing the PIN receiver responsivity from 0.7 to 1 A/W is shown in Fig. 6.

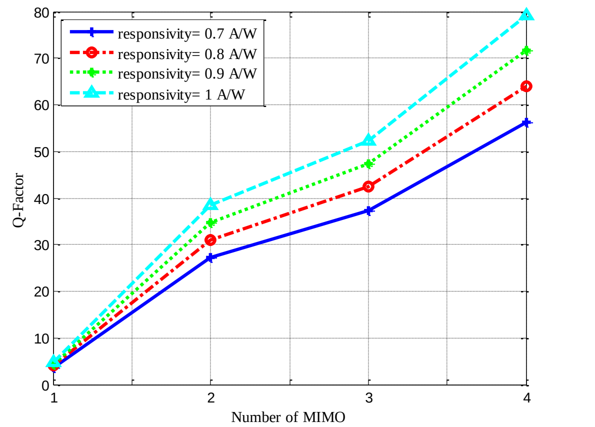

Fig. 6. The Q-factor vs. number of MIMO in log-normal channel at different values of PIN responsivity for 500 m link range using Bessel filter

From Fig. 6, it is noted that in case of SISO and by increasing the PIN receiver responsivity from 0.7 to 1 A/W, the system performance is enhanced by approximately 38.5%. In case of using PIN receiver responsivity 0.7 A/W and by increasing the size of MIMO to (2×2), the system performance is increased by approximately 176%. One gets a large value of the Q-factor of 79.2 by using MIMO (4×4) in case of 1 A/W PIN receiver responsivity, and yields a value of 56.2 of the Q-factor in case of using 0.7 A/W PIN receiver responsivity.

From Figs. 5 and 6, it is clear that the system performance when using PIN receiver with Bessel filter in case of high receiver responsivity of 1 A/W by using MIMO (4×4), is equivalent to MIMO (2×2) system using APD receiver.

Fig. 7 shows the comparison between using APD receiver with Bessel filter and Gaussian filters of SISO FSO system over log-normal channel by varying the values of APD receiver gain of 500 m link range. Using APD receiver gain value of 3, one gets the same system performance for two cases. By increasing the value of APD receiver gain, APD receiver with Bessel filter gives a better performance until the system goes to saturation greater than APD receiver gain value of 6.

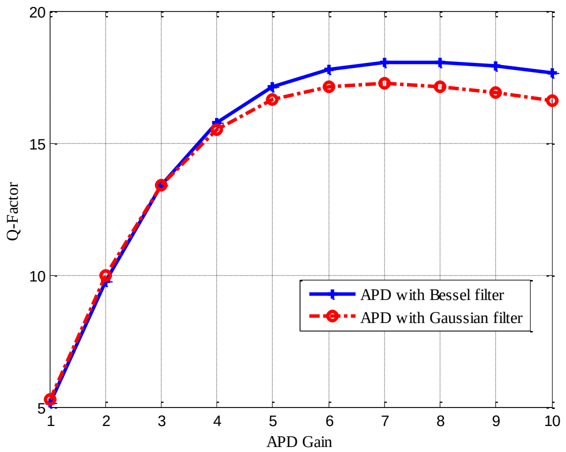

Fig. 7. The Q-factor vs. APD gain for SISO over log-normal channel with Bessel and Gaussian filters for 500 m link range

In Fig. 8, the Q-factor is drawn with the APD gain using Bessel and Gaussian filters over log-normal and channel link range of 500 m for FSO MIMO (2×2). There is no much difference in the optimum gain of value of 4 for different filter types. The link performance is highly improved and yields a high value of 85.6 for the Q-factor in case of Bessel filter and value of 77.3 in case of Gaussian filter. In the two cases, by using APD receiver gain value greater than 4, the same system performance for two cases is degrading.

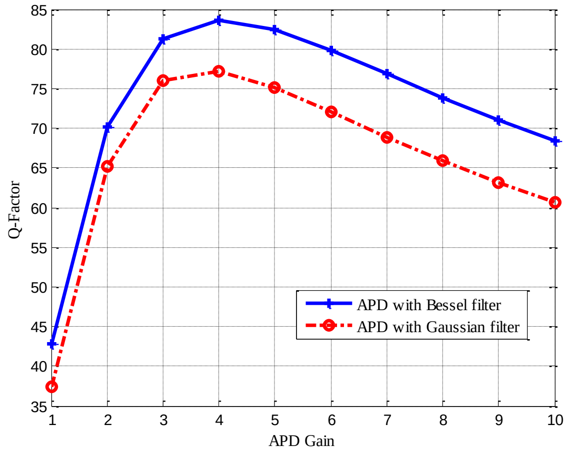

Fig. 8. The Q-factor vs. APD gain for MIMO (2×2) over log-normal channel with Bessel and Gaussian filters for 500 m link range

The Q-factor with different APD gain is shown in Fig. 9 using Bessel and Gaussian filters for FSO MIMO (3×3) over log-normal channel and link range of 500 m. The increasing the value of APD gain improves the system performance until a gain of 3 in case of using Bessel filter and value of 4 in case of using Gaussian filter. At greater values, there is a significant decrease in Q-factor which deteriorates the system performance. From Fig. 9, it is observed in all values of APD gain, using Bessel filter gives better performance compared to using Gaussian filter.

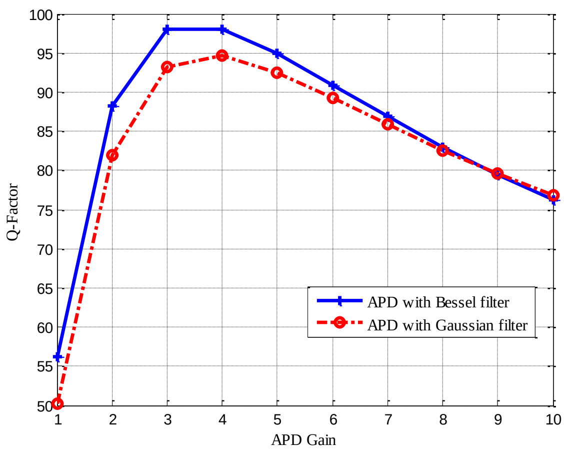

Fig. 9. The Q-factor vs. APD gain for MIMO (3×3) over log-normal channel with Bessel and Gaussian filters for 500 m link range

Repeating for MIMO (4×4), Fig. 10, it is observed that by using optimum gain of 3 for different filter types. The link performance is highly improved and yields 114.3 Q-factor in case of Bessel filter and 111.2 in case of Gaussian filter. In the two cases, by using APD receiver gain value greater than 3, the system performance for the two cases is degrading.

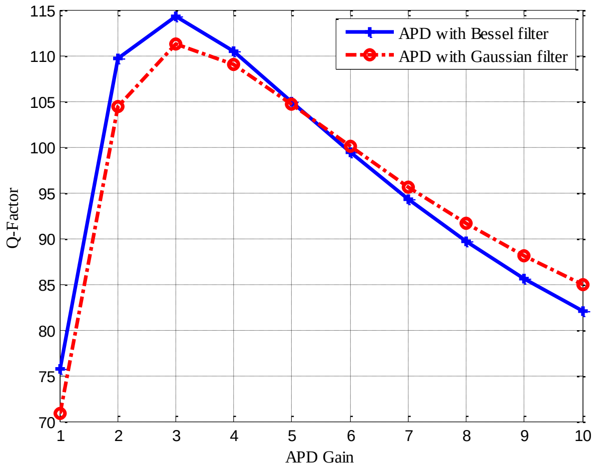

Fig. 10. The Q-factor vs. APD gain for MIMO (4×4) over log-normal channel with Bessel and Gaussian filters for 500 m link range

4. Conclusion

MIMO with EGC is employed to increase FSO communications system performance in log-normal channel by receiver optimization. NRZ line code with 1550 nm operating wavelength utilizing APD and PIN receiver is analyzed and the comparison is done using Bessel and Gaussian filters. The impact of the responsivity of the APD and PIN receiver on the overall system performance is investigated as well. The simulation results have demonstrated that APD or PIN receiver with Gaussian filter gives a better performance in case of link range greater than 250 m. The performance of APD receiver is much better than that of corresponding PIN receiver. Obtained results demonstrate that APD gain is critical to the system performance.

Increasing the value of responsivity improves the BER performance, but increasing the size of MIMO significantly improves the system performance compared with increasing the APD or PIN receiver responsivity.

In addition, the study may be utilized in the receiver design for enhancing performance, where it is found that using APD high receiver gain of value of 6 with Bessel filter gives a better system performance than using the Gaussian filter. The optimum gain of APD receiver does not change substantially for different receiver designs in case of SISO. The optimum gain for high system performance for different receiver designs decreases by increasing the size of MIMO.

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*Corresponding author: drmosaly@gmail.com