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Optimizing the Erbium-doped Fiber Amplifier (EDFA)'s Length and Location for Improved Free Space Optic (FSO) Range

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Abstract
Although free space optical (FSO) communication has a variety of advantages, such as license free, high bandwidth, and high security, its link distance is limited by weather conditions. Incorporating an optical amplifier within the FSO transmission path is one of the most promising methods to mitigate the aforementioned problem. The use of optical amplifiers not only improve signal to noise ratio (SNR), but also increase the link distance of the FSO system. In this paper, the erbium-doped fiber (EDFA)'s length and location were optimized to improve the FSO transmission range. The optimization process was conducted under clear air and light haze conditions using Optisystem. Decisions were taken in the optimization process based on Q-factor. Results confirmed that pre located EDFA with 2m length was the best choice as it gives better Q-factor value.

Keywords: Free space optical (FSO), Erbium-Doped Fiber Amplifier (EDFA), FSO link, post arrangement, pre arrangement.

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تحسين طول وموقع المضخم الضوئي المشبع بالاربيوم EDFA من اجل زيادة مدى الارسال لنظام الارسال الضوئي في الفضاء الحرFSO

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الملخص

على الرغم من أن الاتصالات الضوئية في الفضاء الحر (FSO) تتمتع بمجموعة متنوعة من المزايا، مثل عدم الترخيص وعرض النطاق الترددي العالي والأمان العالي، إلا أن مسافة الارسال الخاصة بها محدودة بسبب الظروف الجوية. يعد دمج مكبر الصوت البصري ضمن مسار إرسال FSO أحد أكثر الطرق الواعدة للتخفيف من المشكلة المذكورة أعلاه. لا يؤدي استخدام المضخمات الضوئية إلى تحسين نسبة الإشارة إلى الضوضاء (SNR) فحسب، بل يؤدي أيضًا إلى زيادة مسافة الارسال لنظام FSO. في هذا البحث، تم تحسين طول وموقع الألياف المشبعة بالإربيوم (EDFA) من اجل زيادة نطاق ارسال نظام FSO. تم إجراء عملية التحسين في ظل ظروف الهواء الصافي والضباب الخفيف باستخدام Optisystem. تم اتخاذ القرارات في عملية التحسين بناءً على عامل الجودة. أكدت النتائج أن EDFA المدمج قبل جهاز الاستقبال بطول 2 متر كان الخيار الأفضل لأنه يعطي قيمة أفضل لعامل Q.

الكلمات المفتاحية: نظام الاتصال الضوئي في الفضاء الحر (FSO)، مضخم الألياف المشبع بالإربيوم (EDFA)، مسافة ارسال نظام FSO، الدمج اللاحق، الدمج المسبق.

1. Introduction

1.1 Background and Motivation

FSO is a technology in which free-space traveling light signals are used to exchange data between two or more parties [1], [2]. It is characterized by its high capacity and low latency. The low latency feature comes from the fact that light can travel faster in free space compared with its speed when fiber optic cables are used [1]-[3]. FSO is an excellent means of communication in isolated areas as well as in areas undergoing post-disaster reconstruction [4]. FSO is

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also suitable for satellite communication as it enables much higher speed than the currently deployed radio frequency (RF) systems [5].In addition, FSO can come as an alternative that meets important requirements in the fifth generation (5G) and beyond, such as high capacity, high speed, low latency, and improved quality of service [6].However, the range that an FSO system can cover may be affected by some undesirable weather conditions, such as haze, fog, rain, and snow [1]-[3], [7]. In order to overcome the aforementioned limitation, it has been proposed to incorporate optical amplifiers within the FSO transmission path. Given the wireless structure of FSO systems, an optical amplifier can be incorporated using two different configurations. In the first configuration, an optical amplifier is used to boost the transmitted power. According to this configuration, the optical amplifier is called post-amplifier. In the second configuration, an optical amplified is assigned prior to the receiver to improve its sensitivity. According to this configuration, the optical amplifier is called pre-amplifier [8], [9].

1.2 Literature Review

Several research proposals sought to improve the FSO performance using optical amplifiers. In this context, Sharma and Tharani [2] examined the FSO performance at 2.5 Gbps using hybrid optical amplifier configuration, (EDFA with semiconductor optical amplifier (SOA)). The configuration was examined under haze and rain conditions. A Transmission ranges of 40 km was reached under haze condition, whereas a transmission range of 45.5 km were reached under rain conditions. Malik et al. in [8] examined the performance of FSO using a variety of hybrid optical amplifier configurations (SOA-EDFA, EDFA-EDFA, and Raman-EDFA). The hybrid Raman-EDFA configuration shows the best performance when a transmission range of 20 to 100 km is considered, while the hybrid SOA-EDFA configuration shows the best performance when a transmission range longer than 100 km is considered. Researchers in [10] examined the FSO performance under fog condition with a range of up to 500 m using different amplifiers and an array of receivers. The results show that FSO exhibits a better performance when EDFA is employed compared with its performance with any other optical amplifiers. Researchers in [3] examined the performance of a 10 Gbps spectrum-sliced dense WDM FSO system using different optical amplifiers (EDFA, SOA, and Raman amplifier). Based on the results obtained, the SS-DWDM-FSO system showed the best performance with a maximum

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transmission range of about 10 km when using EDFA compared to its performance with any other optical amplifiers. Researchers in [11] proposed an FSO scheme using hybrid (EDFA-EDFA) configuration taking into account weak turbulence approximation. Based on the results obtained, enhanced performance was achieved over 5000 m. Researchers in [12] examined the FSO performance at 2.5 Gbps under rain conditions using pre EDFA configuration. An improved range of approximately 1675 m was achieved using the proposed solution. Researchers in [13] examined the performed of a 800 m FSO system under fog condition using several transmitter/ receiver pairs with pre-EDFA configuration. Based on the results obtained, an improved FSO performance was achieved using the proposed solution. Researchers in [14] proposed a novel relaying solution to improve the FSO performance in terms of bit-error rate (BER) and coverage distance. The solution is based on a combination of an optical amplify-and-forward (OAF) relaying technique, an EDFA, and an optical hard-limiter (OHL). The results obtained confirmed the superiority of the proposed solution compared to traditional ones.

1.3 Contribution

In this paper, the authors seek to improve the FSO performance in terms of its transmission distance. To achieve the aforementioned goal, they propose to integrate optical amplifiers within the FSO transmission path. In today's optical network, EDFAs are the most commonly used, due to its high gain, low polarization sensitivity, low crosstalk, and ability for multi-channel amplification [9], [15]. To come up with a satisfying results, the authors engaged in an optimization process in terms of the EDFA's length and location prior to the incorporating process. Two steps of optimization will be conducted. In the first step, the optimum EDFA length will be determined. In the second step, the optimum EDFA location will be determined. Decision will be taken based on Q factor indicator.

2. Materials and Method

Figure 1 shows the FSO system architecture that is simulated using Optisystem software.

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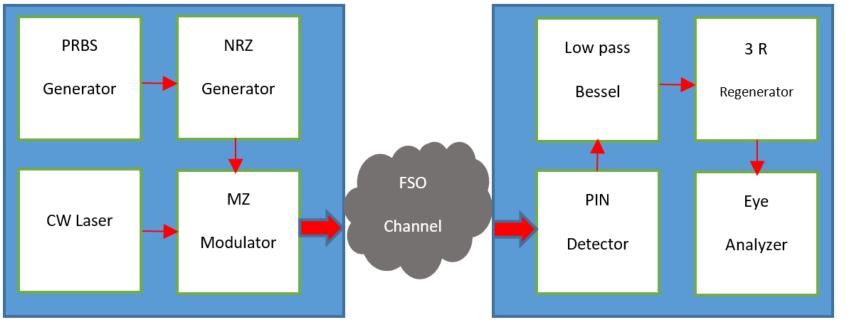

Figure 1. FSO system architecture.

The architecture is divided into three main parts, (the transmitter, the transmission medium, and the receiver). In the transmitter side, a pseudo random bit generator (PRBS), non-return to zero (NRZ) pulse generator, CW laser, and Mach Zehnder (MZ) were used to transmit the signals. Air or free space is the medium of transmission. In the receiver side, a PIN Photodetector, a low pass Bessel filter, and 3R Regenerator were employed to receive the signals. The 3R Regenerator is used to re shape, re time, and amplify the original bit sequence so that it can be analyzed using the eye diagram analyzer. Table 1 lists the key parameters used in the simulation. Two steps of optimization will be conducted in order to determine the appropriate EDFA length and location. Details on the optimization process is provided below.

- Optimizing the EDFA Length

Two EDFA lengths were included in this process (2m and 5m). The length that gives higher Q factor will be chosen. This process will be conducted under clear air and light haze conditions using post and pre EDFA configuration.

- B. Optimizing the EDFA Location

As mentioned above, an optical amplifier can be incorporated with the FSO transmission path using either post or pre configuration. This process will be conducted under clear air and light haze conditions. The EDFA configuration that gives maximum link range will be selected
Figures 2 and 3 are the Optisystem layouts that illustrate post and pre EDFA configurations, respectively.

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Table 1. Key parameters used in the simulation.

Parameters	Value
Data Rate (in Gbps)	2.5
Wavelength (in nm)	1550
Output Power (in dBm)	10
Beam Divergence angle(in mrad)	0.5
Transmitter Aperture (in cm)	2.5
Receiver Aperture (in cm)	37.5
Transmitter Loss (in dB)	1.8
Receiver Loss (in dB)	1.8
Additional Loss (in dB)	1

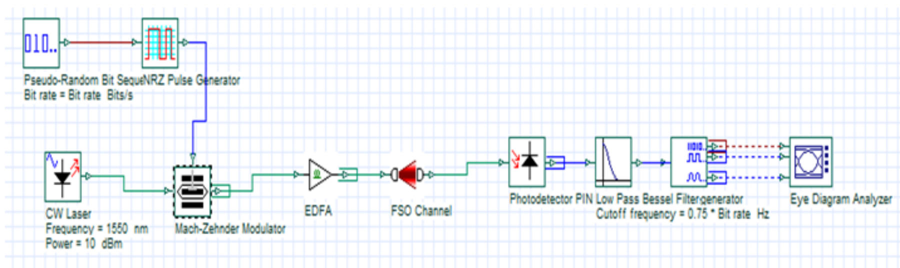

Figure 2. Post EDFA configuration.

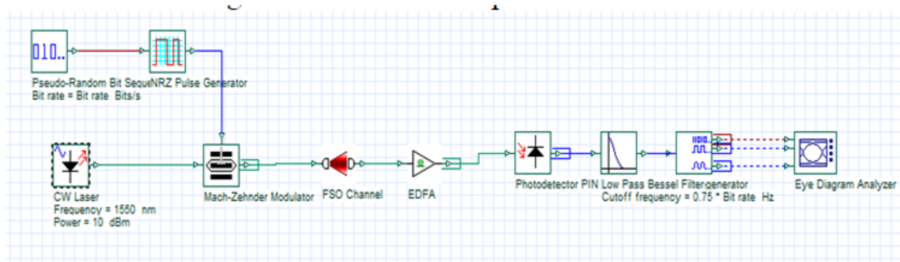

Figure 3. Pre EDFA configuration.

For a successful FSO system, the attenuation must be estimated before installation according to the weather condition of the intended area. The work of this paper focused on Al-Bayda city, Libya. Visibility data were collected three times daily over a period of three months (January, February and March) in 2021. Equation (1) is called the Beer-Lambert law. It has been used to calculate the attenuation for FSO systems.

$$\alpha_{fog} = \frac{3.219}{\mathrm{V}\ (Km)} \left(\frac{\lambda}{550}\right)^{-q} \tag{1}$$

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Where: V is the visibility in km, λ is the wavelength of the signal, and q is the size distribution coefficient of scattering. Data on V parameter were collected three times daily over a period of three months (January, February and March) in 2021. KIM's model has been used to calculate q as follows:

$$q = \begin{cases} 0 & for\ V < 0.5\ Km \\ V - 5 & for\ 0.5 < V < 1\ Km \\ 0.16\,V + 0.34 & for\ 1 < V < 6\ Km \\ 1.3 & for\ 6 < V < 50\ Km \\ 1.6 & for\ V > 50\ Km \end{cases} \quad (2)$$

Table 2 lists the visibility and attenuation for clear air and light haze environments.

Table 2. Visibility and attenuation for clear air and light haze environments.

No of events recurs	Weather condition	Visibility (Km)	q	Attenuation (dB/Km)
6	Clear air	6.44	1.3	0.1580
1	Light haze	4.83	1.1128	0.2557

3. Results and Discussions

In this part, the results will be presented in the form of curves and then discussed and analyzed in order to come up with targeted recommendations.

3.1. Optimizing the EDFA Length using post configuration

Figures 4 and 5 show Q factor versus link range at the clear air and light haze conditions, respectively.

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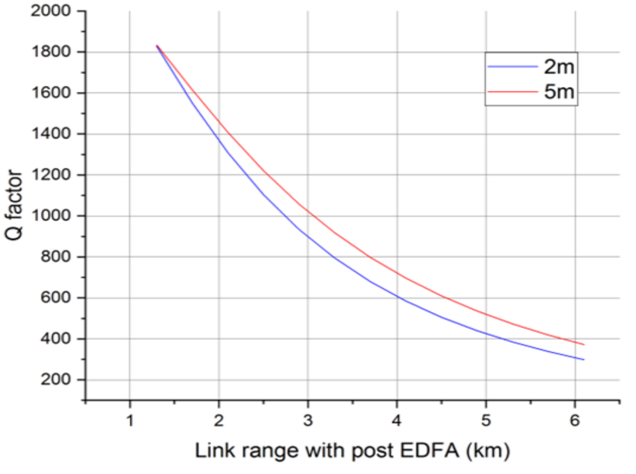

Figure 4. EDFA length versus Q-factor at clear air condition, post EDFA configuration is considered.

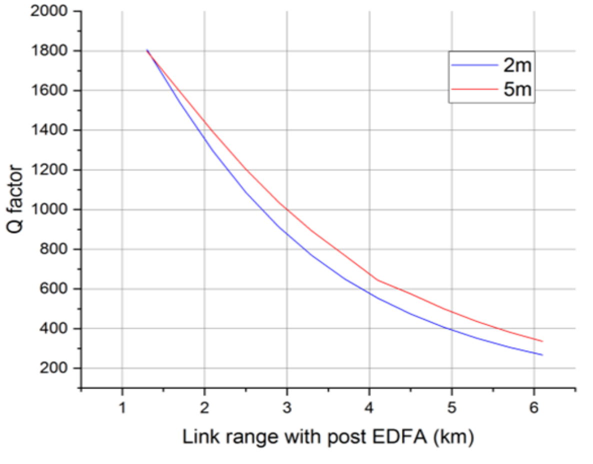

Figure 5. EDFA length versus Q-factor at light haze condition, post EDFA configuration is considered.

It can be obviously seen that the post EDFA configuration with 5 m is the best choice as it gives higher Q factor value.

3.2. Optimizing the EDFA Length using pre configuration

Figures 6 and 7 show Q factor versus link range at the clear air and light haze conditions, respectively. From the graph, it is clear that both lengths lead to almost the same result. Based on cost considerations, the pre EDFA configuration with 2 m will be chosen.

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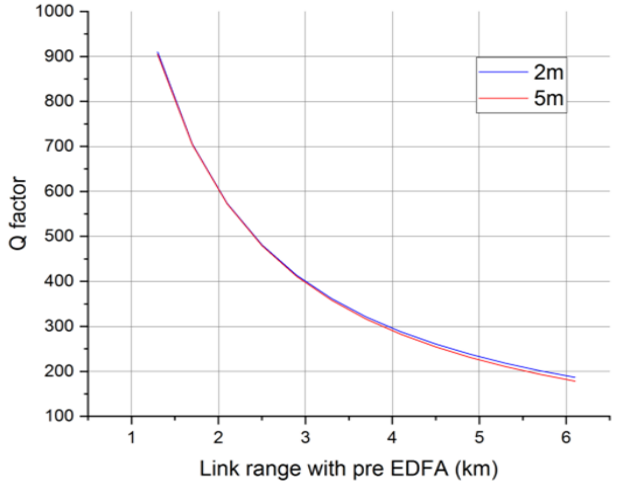

Figure 6. EDFA length versus Q-factor at clear air condition, pre EDFA configuration is considered.

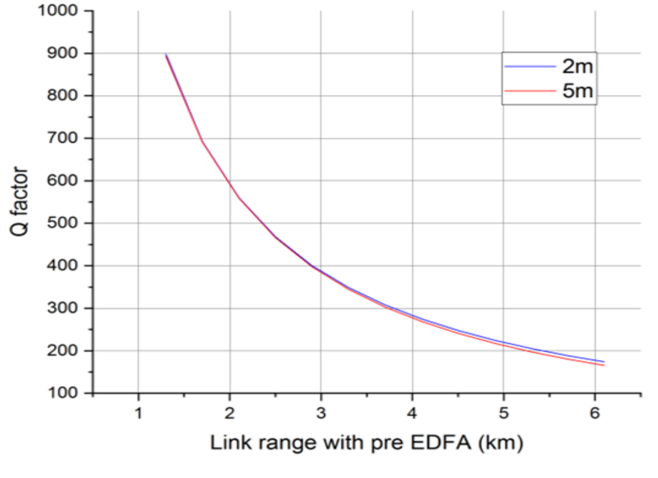

Figure 7. EDFA length versus Q-factor at light haze condition, pre EDFA configuration is considered.

3.3. Optimizing the EDFA location

Based on the EDFA length optimization, provided above, the post EDFA configuration with 5 m and pre EDFA configuration with 2 m will be engaged in this process as they represent the optimum lengths.

In this process, the EDFA configuration that gives maximum range will be chosen. The maximum transmission range is obtained when

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Q factor = 6. Figure 8 and 9 show Q factor versus link range at the clear air and light haze conditions, respectively.

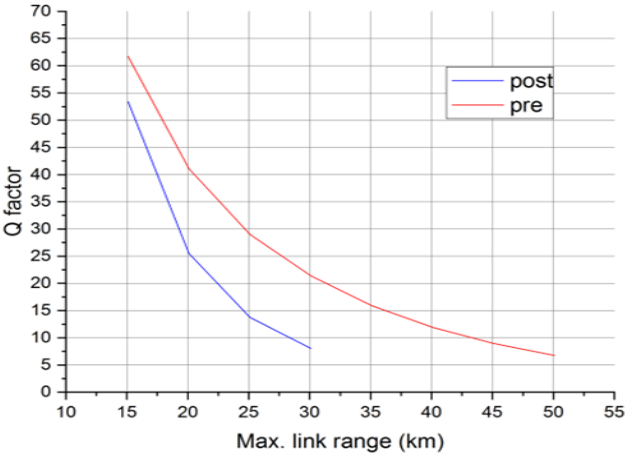

Figure 8. FSO range versus Q-factor at clear air condition, post and pre EDFA configurations are considered.

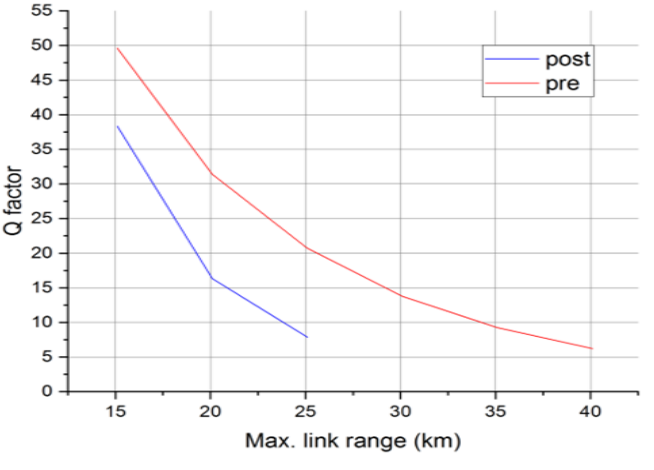

Figure 9. FSO range versus Q-factor at light haze condition, post and pre EDFA configurations are considered.

It is clearly seen from the graph that the pre EDFA configuration is the best choice as it gives the longer link ranges, 50.1 km and 40.1 km at clear air and light haze conditions, respectively, compared with the shorter rangers achieved with the post EDFA configuration, 30.1 km and 25.1 km.

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4. Conclusions

In this paper, the EDFA's length and location were optimized in order to improve the FSO transmission range. Two steps of optimization were conducted in order to determine the appropriate EDFA length and location. Two EDFA lengths were included in first step (2m and 5m). The process in the second step was devoted in order to compare and choose the best EDFA configuration (post or pre EDFA configuration). All the steps were conducted at the clear air and light haze conditions. The results confirmed that the post EDFA configuration with 5 m is the best choice as it gives higher Q factor value. The results also confirmed that the pre EDFA configuration is the best choice as it gives the longer link ranges, 50.1 km and 40.1 km at clear air and light haze conditions, respectively, compared with the shorter rangers achieved with the post EDFA configuration, 30.1 km and 25.1 km.

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