Performance Optimization of Hybrid ROFSO Link Using Hybrid Optical Amplifiers (RAMAN\EDFA) for Long-Haul Transmission with the C-band and L-band Comparison

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Abstract. In this paper, a hybrid system is proposed consisting of a radio-frequency (RF) over free space optic/fiber optic (ROFSO / FO). A free-space communication system is an alternative to optical fibers if it fails in performance or if it is difficult to propagate. This hybrid system is an effective solution for developing new generation networks, by transmitting the optical signal over long distances within the C-band, and L-band. The proposed system sends the radio frequency signal through the optical free-space link then extends to 80 km of optical fiber, of which 40 km is amplified by the Raman / EDFA hybrid optical amplifier. This paper aims to test the performance of the free space optic link under different weather conditions. The atmospheric attenuation, which reduces visibility, was considered as the main challenge. Several copies were sent in different paths in FSO to meet this challenge. The submitted system was implemented in the case of transmission in a wavelength within the C-band and also in L-band. The results of the hybrid system were compared by measuring the bit error rate (BER) and Q-factor under dust and fog conditions relative to Kim's standard model by using Optisystem. The results obtained showed an effective sensation at a long haul, in addition to not using an additional light source when transmitting for such long distances.

Keywords. Radio over free space optic, Fiber optic, Hybrid amplifier, RAMAN\EDFA amplifier, Multiple FSO channel, C-band and L-band.

1. Introduction

Free space optic communication is a line of sight technology that transmits information through the air. The optical signal is generated by the continuous laser or light-emitting diodes (LEDs) [1]. The FSO wireless communication system has been highlighted as one of the most important technologies that meet the requirements of the exponential growth of user requirements, mainly in the last mile, as it can overcome the bottleneck through its high transmitting capacity. This type of optical wireless communication is distinguished by its unlicensed transmission spectrum, high data rate transfer, easy to deploy, and low costs compared to radio frequency[2] [1]. Also, it is considered as a solution to increase
the bandwidth and portability [3]. It is used as an alternative to fiber optics according to its features. In many applications, a hybrid system consists of FSO: fiber optic [4]. This wireless technology is also able to overcome fiber deficiency [3]. However, atmospheric attenuation directly affects wireless communication. Therefore, absorption and dispersion are the most important challenges faced by Free-space optic communications [5]. To investigate reliable long-distance transmission using hybrid optical technologies under the influence of atmospheric changes on free space optic communication and to overcome the dispersion occurring in optical fibers by using the hybrid Raman EDFA amplifier. The sending of several copies for the same optical signals to achieve spatial diversity to overcome the transmission weakness or failure is caused by the atmospheric attenuation. Hence, several FSO transmission channels are used as shown in figure 1, [6][7]. Thus, it increases the power harvest of the wireless system [8].

![Multiple FSO channel](image)

**Figure 1.** Multiple FSO channel.

This paper aims to test the performance of the hybrid link between the transmitter and the receiver along with the wireless link under the influence of dust and fog, and to overcome the dispersion that occurs when increasing the transmission distances of optical fibers. It is verified that the system is operating efficiently and effectively within the L range. Therefore, the main purpose of this study is to demonstrate the possibility of directing the FSO directly to the fiber optic without the need for transformations from optical to electrical form and without adding another light source. In this paper, system configuration is presented in the second section, where it discusses the hybrid system ROFSO/FO and its components in addition to the effect of air attenuation on the FSO link. It also explains the optical amplifiers. The third part presents the design for the hybrid system, while the fourth section discusses the results of the proposed design. The conclusion is in the last part.

2. System configuration

2.1. ROFSO system

The free space optic communication system is an efficient system that compensates for the lack of optical fibers. It transmits a data rate of up to 2.5 Gbps. There, in the radio frequency systems, the maximum data rate transfer reaches hundreds of megabits per second. The ROFSO hybrid systems are a suitable and effective solution for reliable communications capable of adapting to changing weather conditions. Radiofrequency over free space optic (RFOFSO) communication possesses similar features to radio over fiber-optic (ROF) communication systems, except for laying fibers optic, where the carrier medium in RFOFSO is air. However, it has the same high portability in addition to its low cost of installation [3]. Therefore, combining the two systems in one hybrid system can solve many problems such as bottleneck,
last mile, and connection to remote areas and meet the user's requirements for fast data transfer at the lowest cost. Yet, diversity is one of the best solutions suggested [8]. In this hybrid system, the signal is not converted from electrical to optical form, where the optical signal is modulated by a radio frequency signal [3]. Due to the advantages of fiber optics in terms of large bandwidth, low losses in transmission, and electrical insulation, in addition to preventing electromagnetic interference compared to copper cables or wireless transmissions, it is widely spread in modern life. However, the color dispersion occurring in this type of transmission media is one of the most important challenges faced by optical fibers. The dispersion compensation fibers (DCF) are used to compensate for the dispersion caused by the refractive index and the velocity on the silica material, which then leads to an expansion of the pulse [9].

Dispersion compensation fiber is an effective way to improve fiber-optic link performance. The positive dispersion in the fiber link is compensated for by the high negative dispersion possessed by the DCF. This type of fiber is used before and after the long span fiber to provide pre- and post-compensation [10].

2.2. Free space optic attenuation

In recent years, the transmission of radio frequency over the free space optic communication has appeared. In comparison with the radio frequencies, free space optic communication is affected by dust and fog more than snow and rain. Consequently, it leads to deterioration and attenuation of the optical signal at the receive side, in addition to a change in the intensity of the laser beam. In the FSO link of 1 km, transmission rate disturbances due to atmospheric attenuation are evident[11]. On the other hand, choosing the wavelength is important. The higher wavelength has the ability to penetrate fog and dust [12]. The average attenuation varies according to weather conditions, with an attenuation rate of 0.5 dB / km for clear weather to 350 dB / km in the case of dense fog. The visibility is the main factor affecting attenuation[13]. Attenuation can be calculated through the equation below for the experimental model:

\[
\beta = \frac{3.91}{v} \left( \frac{\lambda}{550 \text{nm}} \right)^{-q}
\]

Where; \( v \) is visibility range measured by (Km), and \( \lambda \) is the wavelength in nanometers, while \( q \) is a division of scattering particle volume calculated according to the standard Kim model depending on the extent of vision through:

\[
q = \begin{cases} 
1.6 & v > 50 \text{km} \\
1.3 & 60 \text{km} < v < 50 < \text{km} \\
0.16v + 0.34 & 1\text{km} < v < 6\text{km} \\
v - 0.5 & 0.5\text{km} < v < 1\text{km} \\
0 & v < 0.5
\end{cases}
\]

2.3. Optical amplifiers

Lots of experiments are aimed to provide high-efficiency communication networks to meet the requirements of modern life. To address the attenuation in optical communications, optical amplifiers are often utilized to overcome this challenge in long-distance propagation attenuation. Erbium-doped fiber (EDFA) and Raman amplifiers are used to amplify the optical signal along with the optical transmission link[14]. The function of optical amplifiers is to directly amplify the optical signal without the need for optical-to-electrical conversions. Optical amplifiers can be used after the transmitter, before entering the optical fiber to avoid the weakening of the signal that occurs during the long-distance travel and using it at the end of the optical link to increase the receiver’s ability to sense the received optical signal, and finally can use it inside the fiber to restore the optical energy to the required level and regenerate the optical signal [15].
One of the most widespread and oldest types is EDFA. It gained this diffusion through its effective low-noise amplification at a wavelength of about 1550 nm. It can be used over long distances due to the flat gain it provides in rare earth materials[16]. This type of gain can be obtained by using a hybrid amplifier consisting of EDFA / RAMAN operated at the C-band and L-bands, in addition to the wide amplification range and low noise level of the types of amplifiers they provide. Pump wavelength and pump power are the main factors on which the gain spectrum of a Raman amplifier depends. Carefully choosing the wavelength is very important to obtain a flat gain profile[17]. Through the effect of stimulated Raman dispersion, the Raman gain can be obtained. This occurs through the interaction of the intrinsic vibrations of the particles with the incident light wave as it travels through the optical channel. In this case, the scattering that produces a photon occurs through the vibration of the molecule. The combination of more than one optical amplifier is called a hybrid optical amplifier. The combination of EDFA and Raman is the best choice for hybrid optical amplifiers, in addition to its ability to reduce the variations in gain[16]. Despite the amplification provided by the hybrid amplifiers, the distortion encountered especially in long distances causes weakness in the optical signal. Therefore, a realistic fiber grating component is used to compensate for the dispersion [18]. Fiber Bragg grating (FBG) is small, high-precision, high-sensitivity, reusable, and resistant to electromagnetic interference. In addition it is used in a high-temperature region, because it is effective with sensors and amplifiers[19].

3. Simulation setup

The hybrid system consists of a transmitter, an optical transmission channel, and a receiver. On the transmitter side, a pseudo-random bit sequence generator that generates a 2.5 Gbps data rate connected with a non-return to zero (NRZ) pulse generator linked to a Mach-Zehnder, is used to modulate the signal generated with the optical carrier. The optical signal was set at the wavelength in the C-band at 1550 nm and 1620 nm with an L-band emitted by a CW continuous laser source with a transmission power of 160 mW. The optical signal relied on the use of 4-channels FSO sent parallel in free space subjected to atmospheric attenuation, which calculates the visibility through the previous equations and according to Kim's standard model as shown in Table 1.

### Table 1. Attenuation coefficient for free space optic channel.

| Weather   | Atmospheric Attenuation dB/km | Visibility Km |
|-----------|-------------------------------|---------------|
| Heavy dust| 242                           | 0.07          |
| Moderate  | 85                            | 0.2           |
| Dust-fog  | 34                            | 0.5           |
| Rain      | 10                            | 1             |
| Haze      | 4                             | 2             |
| Clear     | 0.4                           | 10            |
|           | 0.2                           | 23            |

This study is dedicated to the attenuation of 34 dB / km for dust and fog for each FSO channel. The transmission process is done by using lenses with 5 cm diameter that transmit the light signal and 25 cm for the receiver lenses, each signal with a different path from the other. Hence, the attenuation experienced by the scattered signals is different for the free-space optic channel. The optical link extending over a distance of 40 km fiber optic with an attenuation of 0.2 dB / km. The dispersion compensation is accomplished by using 3.2 km of scattering. The erbium-doped fiber amplifier EDFA
with a length of 3 meters and a pumping power of 40 mW is used to overcome the attenuation in the optical fiber connection. Also, an amplified 40 km signal is transmitted by the Raman / EDFA hybrid amplifier to obtain a total distance of 80 km of fibers optic as shown in figure 2. At the receiving side, it consists of an avalanche photodetector (APD) in the first stage to detect the optical signal and convert it into an electrical signal. Then the signal is passed to the Bessel low pass filter. The 3R regenerator with a BER analyzer is used to measure the Q-factor and bit error rate (BER).

![Figure 2](image-url)
4. Results
The results are discussed and presented in this section by indicating the numerical values of the Q-factor and bit error rate (BER) for the hybrid RF/FSO/FO system mentioned before. An Optisystem v7 simulation system was used to implement the proposed design and to display the eye diagram, BER, and Q-factor. According to the Kim standard models, the lowest permissible bit error rate in telecommunications is $10^{-9}$, and approximately 6 of the Q-factor [20].

Under ideal weather conditions, the FSO communication system works well and similar to fibers optic. However, when changing the weather conditions to which the FSO communication is exposed. Thus, the visibility decreases and this leads to a decrease in the performance of the system. The performance of the free-space optics communication link is verified by comparing the results of the proposed design with the standard of the Kim model measurements.

Initially, to prove the effectiveness of hybrid system 4-FSO channels under the influence of high attenuation, they were compared with a 2-FSO channels hybrid system as shown in Figure 3, which represents a 1 km 2-FSO channel at 34 dB/km attenuation with a 40 km optical fiber connected to a hybrid optical amplifier Raman/EDFA that amplified 40 km, thus bringing the total fiber length up to 80 km within the C-band of 1550 nm wavelength.

![Figure 3](image)

Figure 3. 2-Channels FSO at 40 km optical fibers in C-band.

Figure 4 shows the results of the RFOFSO / FO hybrid system when transmitting the optical signal through four different paths in the free space at a distance of 1 km under the influence of dust that causes attenuation of 34 dB/km, with fiber optic of 40 km length connected to extra 40 km amplified by a hybrid...
optical amplifier. The 2-FSO and 4-FSO channels have the same configuration for the hybrid system except for the number of FSO channels. By comparing the BER of the results for the two-hybrid systems, an improvement was found in performance when increasing the number of the channels; a less BER was obtained for the same distance and attenuation at 4-FSO channels, which leads to obtaining a clearer signal and more efficient system performing. The hybrid RFOFSO/FO system with Hybrid Optical Amplifier Raman/EDFA has been tried in the C-band and L-band to demonstrate performance efficiency at L-band in comparison to C-band. Figure 5 displays the test results of a hybrid system at a 10 GHz radiofrequency modulated by an optical carrier traveling through a 4-FSO channel at a distance of 1 km and an attenuation of dust and fog 34 dB / km connected to a 40 km fiber-optic followed by a 40 km amplified fiber with Raman / EDFA hybrid. By observing the Q-factor for the wavelengths of the C-band extending from 1550 to 1565nm followed by the wavelengths of the L-band until 1620 nm, it was found that the system operated with high efficiency and good performance within the standard except for the wavelength of 1605 nm, with 3.8 Q-factor and 10^-5 BER, which is less than the standard acceptable value of 5.4 Q-factor and 10^-9 for BER. To prove the effectiveness of the system, it was tested under 10 dB / km rain attenuation.

Figure 4. 4-Channels FSO at 40 km optical fibers in C-band.
The results shown in Figure 6 were obtained by implementation of the hybrid system consisting of transmitting a 10 GHz radio-frequency signal modulated with an optical carrier at 1620 nm wavelength and 160 mW transmission power. It is sent through an optical link which consists of 4-FSO channels under a light attenuation of 10 dB/km for the rain associated with 40 km of optical fiber, whose output is connected to the hybrid optical amplifier. At 3000 m, acceptable results were obtained with BER up to $10^{-11}$. The BER reduced as the distance or attenuation decreased. So, it shows $10^{-291}$ BER at 1200 m when testing the hybrid system at a distance from 1200 m to 3000 m with 10 db/km.

Figure 6. 4-Channels FSO at 40 km fiber link in L-band.
Figure 7 shows the RF spectrum from the visualizer after implementing the hybrid system in the Optisystem. The radio frequency spectrum can be observed in addition to the maximum power on the transmitter and receiver side. Figure 7 (a) presents the RF spectrum analyzer for the transmitter at a wavelength of 1620 nm with a distance of 3000 m under an attenuation of 10 dB / km in 4-FSO channels connected with 40 km of fiber optic followed by the use of a 40 km Raman / EDFA hybrid optical amplifier. On the other hand, figure 7 (b) shows a receive-side radio frequency spectrum analyzer after transmitting over the optical link. Figure 8 (a) shows the optical spectrum before transmission over the optical link at the wavelength 1620 nm which consists of 4-FSO channels and 40 km fiber optic with 40 km hybrid optical amplifier. Meanwhile, figure 8 (b) shows the optical spectrum after transmitting through an optical link of the hybrid RFOFSO/FO system. Thus, it proves the efficiency of the system at this point compared with the transmitter power.

**Figure 7.** RF Input and output power for 1620 nm.

**Figure 8.** Optical input and output power for 1620 nm.
5. Conclusion
In this paper, the performance of the hybrid RFOFSO/FO system is evaluated by examining the bit error rate (BER) and the Q-factor by using Optisystem simulation. The system transmits a 10 GHz radio frequency signal modulated by an optical carrier. The optical beam is transmitted over multi-FSO channels at a distance of 1 km under the influence of dust and fog attenuation connected to a 40 km fiber optic attached with a hybrid optical amplifier Raman/EDFA with a length of 40 km. The total distance of the optical fibers used in the proposed hybrid system is 80 km. To prove the effective performance of the system, it was tested in the case of sending the optical signal through two different paths compared with the 4-channel FSO system under strong dust and fog conditions within the C-band. The system has proven its efficiency when increasing the number of FSO channels, as the visibility raise when the number of channels increases, and the bit error rate (BER) decreases. It was found that it reaches 1000 m when transmitting over 2-channel FSO, while a wireless connection of 1400 m was obtained when transmitting via the 4-channel FSO. The results proved the efficiency of the hybrid system despite the high attenuation that the FSO link was exposed to. Then, the results of the hybrid system in the L-band was generally operating at high efficiency under the attenuation of 34 dB / km according to Kim's model. To prove the efficiency of the hybrid system for different weather conditions, the system was tested at a wavelength of 1620 nm transmitted through 4-FSO channels under attenuation of 10 dB / km connected to a 40 km fiber-optic linked with Raman / EDFA hybrid amplifier for 40 km, thus making the total distance of the fiber 80 km. The hybrid system proved its efficiency to operate in the L-band under different weather conditions.

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