Performance Analysis of WDM-hybrid RFoFSO\FO System Under Different Weather Conditions Utilizing A Hybrid Optical Amplifier

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Abstract. The hybrid system WDM Radiofrequency over free space optics\fiber optic (RoFSO\FO) is one of the modern technologies that support developing the 5th generation for the communication network. The WDM RoFSO\FO system is designed to transmit high data rates over a long distance under variable weather conditions (fog, dust, and rain). Where the attenuation caused by atmospheric changes is one of the most important obstacles faced the FSO channel. The spatial diversity technique is used by sending multiple copies across the free space to improve system performance. The hybrid design tested the performance of 16 channels optical transmission, each channel transmits 2.5Gbps data rate modulated by PSK modulator on a 20GHz radio frequency signal. Where 40 gigabits per second was transmitted via 4000m multi-channels FSO extending to 120 km optical fiber as a total distance, 80 km of which was amplified by Raman / EDFA hybrid optical amplifier. The bit error rate BER and the Q-factor monitored and compared with the standard Kim model. From the results obtained by using the OptiSystem simulation, an improvement in the system was found significantly by increasing the transmission capacity when using WDM technology and long-distance transmission under variable weather conditions without adding a light source.

Keywords. RoFSO, WDM, Optical amplifier, hybrid optical amplifier, RoF, PSK, QPSK, Raman/EDFA.

1.Introduction

Due to the increasing demand for high-bandwidth communication networks and large data rate transmission to meet the user requirements, which led to the combination of free space optic communications with the infrastructure of the communication network to provide the high bandwidth, fast data transmission[1][2]. FSO technology has been highlighted for its high security, unlicensed spectrum, and ease of installation .It is considered an alternative to radiofrequency, ease of deployment, and low cost it provides[3]. Wavelength Division Multiplexing (WDM) technology has been implemented to expand the bandwidth and increase the system capacity, which consistent with the evolution of modern life[2].

The RoFSO hybrid system is considered one of the most suitable communication technologies for new generation networks. Where it modulating the radio frequency signal over the optical carriers and transmitting it through an optical channel without conversion from an electrical to an optical signal and vice versa[4]. The use of the FSO link to transmit the radio frequency signal has improved the communication system by increasing the bandwidth compared to the radio frequency bandwidth[5].
Considered as an effective alternative to Rof systems, which have transmission capacity similar to the optical fiber in addition to its low cost[1].

Despite the efficacy of optical fibers, it diffusion difficult or impossible sometimes and costly due to drilling and installation[6]. However, color dispersion is one of the most important challenges that fiber optic face when traveling over long distances, which are overcome by using Dispersion Compensating Fiber (DCF) to compensate for the dispersion[7]. The chromatic dispersion leads to the expansion of the pulse that occurs due to the velocity group on the silica material and the refractive index[8].

The FSO signal uses the atmosphere as a medium for transmitting the optical signal. As with any wireless communication system, atmospheric turbulence changes the intensity of the optical signal due to the attenuation resulting from absorption and dispersion[9]. Therefore, several copies of the optical signal are sent along different paths in parallel, leading to exposure to different atmospheric turbulence, thus improving the performance of the system when achieving the principle of spatial diversity[10][11].

This paper aims to test the WDM RoFSO/FO hybrid system’s performance under different weather conditions associated with a long-distance fiber-optic with Raman / EDFA hybrid optical amplifier.

This paper was divided as follows: In the second section, calculating atmospheric attenuation methods are presented in addition to showing the importance of using a hybrid optical amplifier. While the third section shows the proposed design to provide the best performance for the hybrid link under variable weather conditions. The fourth section discusses the results obtained for this design, and finally, the most important conclusions of the design are discussed.

2. Principle

2.1 Free Space Optic Atmospheric influence

The FSO system requires a continuous clear line without interruption to maintain contact between the sender and the receiver. Atmospheric influence is one of the most important obstacles faced by the optical signal, which leads to the attenuation of the transmitted signal, such as fog and dust. The rate of attenuation varies according to the weather conditions from 0.5 to 350 dB / km, Respectively, from clear weather to dense fog[5]. The attenuation of the signal is overcome by choosing the appropriate transmission power and wavelength, as the higher wavelengths have the ability to penetrate particles of dust and fog, which is the main obstacle to scattering and absorption of the optical beam. The weather conditions change from one place to another, so the intensity of the laser beam changes accordingly. From this principle, the spatial diversity method was applied as one of the effective solutions to obtain a clearer light signal[12]. The attenuation can be calculated by the equation for crossover:

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

Where \( \beta \) expresses the scattering coefficient, \( \lambda \) represents the length of the wavelength and is measured by nm, also \( v \) visibility and it measured in km, at last \( q \) Represents the diffusion of the scattering particles. \( q \) Is calculated by the equation below to obtain the attenuation of the signal:
\[
q = \begin{cases} 
  1.6 & v > 50 \text{km} \\
  1.3 & 60 \text{km} < v < 50 < \text{km} \\
  0.16v + 0.34 & 1 \text{km} < v < 6 \text{km} \\
  v - 0.5 & 0.5 \text{km} < v < 1 \text{km} \\
  0 & v < 0.5 
\end{cases}
\] (2)

2.2 wavelength division multiplexing (WDM)

The goal of developing communication systems is to increase the transmission capacity and the data rate transfer. This is achieved by using the wavelength division multiplexing (WDM) in an optical communication system, it's an efficient technique used with long-distance[13]. Transmits a multi-optical carrier of different wavelengths over a single optical link as shown in Figure1. The transmission capacity can be increased by adding extra channels. On the receiving side, the received optical signal is preferred and returned to the original carriers' wavelengths by a de-multiplexer[14].

![Figure 1. The wavelength division multiplexing (WDM) system](image)

2.3 Optical Amplifiers

As its name indicates, it amplifies the optical signal without the need for transformations from optical to electrical form[15]. It is used with long-distance communication between two points to compensate for losses in the fiber optic. These devices have a high capacity and are used for a long time beside it is operated efficiently with WDM systems. There are several types of optical amplifiers, including EDFA and Raman used in this paper. They are combined with working in sequential; this is known as hybrid optical amplifiers (HOA).

The Erbium-Doped Fiber Amplifier is the first type of optical amplifier that has widespread until it became one of the basic components in optical communication systems due to its low noise ratio compared to the amplification effectiveness provided[16]. This type of amplifier adopts the laser pump, the doped fiber length, and the coupler which is used to combine the wavelength of the signal and the pump. EDFA amplifier operates in the C-band and L-band as it has two windows with a wavelength of 1530 to 1560 nm.

The second type is the Raman amplifier which is used with long distances according to the Raman dispersion principle. It is used widely with WDM technology[17]. This type of amplifier can provide gain at any wavelength by choosing the appropriate wavelengths and the pump's power. The Raman amplifier is more suitable for applications in the L-band than EDFA[18].
Fiber Bragg Grating is used with Raman / EDFA Hybrid Amplifier at long-distance transmission to compensate for dispersion in amplified optical fiber[19]. It is a small device that works in environments with high temperatures and has high sensitivity despite its small size[20].

### 3. System and channel methodology

#### 3.1 The transmitter and receiver

The WDM RoFSO/FO hybrid system consists of 16 channels at the transmitter and receiver sides. The first component of the transmitter is a pseudo-random bit sequence generator that generated 2.5 Gbps data rate placed on a 20 GHz RF signal via a PSK modulator. The electrical modulation output of PSK has constant capacitance and variable phase, modulated optically with an optical carrier by MZM for each channel separately. CW continuous laser source used to generate light carriers with a 160mW transmission power. The channel wavelengths were extending from 1567.8 to 1579.8 nm with a channel space between them 0.8 nm, the transmitter and receiver components of the RoFSO/FO hybrid system. MZM's optical signals are combined by a WDM to send them as a single optical signal transmitted over an optical transmission link. WDM transmit 40 gigabits per second (2.5 gigabits * 16), Table 1 shows the transmitter and receiver parameters for the hybrid system.

| Parameter                  | Measurement |
|----------------------------|-------------|
| Transmit Power             | 160 mW      |
| Channel spacing            | 100 Gb      |
| Samples bit rate           | 64          |
| Transmitter aperture diameter | 2.5          |
| Bit rate generation        | 2.5 Gbps    |
| PSK frequency              | 20 GHz      |
| Phase offset               | 45 deg      |

On the receive side, wavelength division de-multiplexing (De-WDM) is used to separate optical signals. The receive side consists of a Gaussian Optical Filter used to isolate the two optical signal according to the specified wavelength connected to Photodetector APD that sense a light signal and converts it into an electrical signal. Band Pass Gaussian Filter filters the radio frequency signal transmitted through an optical transmission line by allowing certain frequencies to pass, thus obtaining a signal with the same transmitted frequencies. To retrieve the input data, a Quadrature Demodulator is used. To measure the Q-factor and bit error rate, a 3R regenerator is used with a BER analyzer.
3.2 Hybrid Optical Channel

In the design of a hybrid system, the output WDM signal is transmitted in several copies that travel in different paths to ensure that the signal arrives in high quality after passing through an atmospheric attenuation of 34 dB / km. The 4-channels FSO are collected by a power combiner and then passed over a 40
km fiber optic, as shown in Figure 3. With 3.2 Dispersion Compensating Fiber (DCF) on both ends of the optical fiber is used to compensate for the dispersion occurring when the optical signal is transmitted over long distances.

![Figure 3. Optical transmission link for the hybrid system](image)

The optical fiber has a low attenuation of 0.2 dB/km which is compensated by using a 3 m EDFA optical amplifier with a power pump of 40 mW. Then it is connected with a hybrid optical amplifier Raman-EDFA with 40 km fiber. The optical link parameters are mentioned in Table 2.

**Table 2. Hybrid optical link FSO/FO component measurement**

| Parameter                           | Measurement |
|-------------------------------------|-------------|
| FSO range                           | 1500m       |
| Attenuation                         | 34 dB/Km    |
| Receiver aperture diameter          | 30 cm       |
| Beam divergence                     | 1 mrad      |
| Gain of an optical amplifier        | 20 dB       |
| Fiber optic range                   | 40 km       |
| Bidirectional Optical Fiber Length 1 | 3.2 km      |
|                                    | 2           |
| Erbium-Doped Fiber Length           | 3 m         |
4. Result
OptiSystem simulation software was used to design and implement the WDM RoFSO/FO hybrid system. The results were discussed by referring to the bit error rate BER and the eye diagram to demonstrate the system’s effectiveness in variable environments and at different distances. Figure 4 displays the BER for the result transmission of 40 Gbps by ideal WDM (16 * 2.5Gbps) with a 20 GHz radiofrequency signal modulated on an optical carrier for each channel in the L-band range. The optical signal is transmitted through 4-channels FSO over 1500 meters under the influence of atmospheric dust and fog. The FSO output is connected with 40 km of optical fiber. The fiber is extended for 80 km that amplified by Raman / EDFA Hybrid Optical Amplifier.

![Radio frequency nm vs BER](image)

**Figur4.** BER of transporting 40 Gbps by 16-channel WDM Ro-FSO

To prove that the WDM RoFSO/FO hybrid system works with different weather conditions in L-band, the FSO link was tested at rain attenuation. Figure 5 shows the BER results of 40 Gbps WDM transmission through 4-channels FSO with a distance of 4000 m for attenuation of 10 dB / km connected to an optical fiber of 40 km length hybrid optical amplifier with 80 km respectively. Figure 6 shows the optical spectrum for a 16-channels before and after transmission over the hybrid optical link attenuated by 10 db/km over a distance of 4000 meters through 4-FSO channels extending to 120 km of optical fiber, of which 80 km is amplified by a RAMAN / EDFA hybrid optical amplifier.
**Figure 5.** BER of transporting 16-channel WDM Ro-FSO 4000m at rain attenuation

**Figure 6.** Optical spectrum analyzer of 16-channel Ro-FSO (a) before and (b) after 4000 m.
Figure 7 shows the eye diagram for the optical signal of the first, eighth, and last channels of the 16 channels to illustrate the efficiency of the proposed hybrid system performance. It was found that the signal is transmitted clearly and with the largest bit error rate of $10^{-37}$ at the eighth channel and reaches the lowest bit error rate at the first channel $10^{-79}$ after its transmission over a distance of 4000 meters FSO under the influence of attenuation of 10 dB/km extended for 40 km of fibers Optical connected with 80 km fiber amplified by RAMAN/EDFA hybrid optical amplifier.

Figure 8 shows the output of the Optical Signal to Noise Ratio (OSNR). It is used with systems that contain optical amplifiers, as it indicates the degree of weakness of the signal after its transmission through the optical system consisting of 16 channels that travel 4000 m through 4-channels FSO at attenuation of 10 dB/km linked with 40 Optical fiber followed by 80 km fiber amplified by the hybrid optical amplifier.
5. Conclusion
In this paper, the Optisystem simulation was used to implement the proposed hybrid design by monitoring the bit error rate (BER) and Q-factor readings of each channel for the WDM hybrid system after transmitting the optical signal over multiple FSO channels extended to the optical fibers for a long distance. Initially, the hybrid system was tested by transmitting a signal at a data rate of 40 Gbps through a WDM Ro FSO / FO hybrid optical system under different weather conditions (dust, fog, and rain) within the L range. To increase the system capacity by sending a wavelength division multiplier with the data rate High (WDM), 16 channels (2.5Gbps * 16) were transmitted, 2.5 was put over a 20GHz radio frequency signal by PSK modulator. Each signal was modulated by optical carriers (1567.8 - 1579.8) nm. The system has proven its efficiency when transmitting an optical signal via 4 FSO channels of 4000 m with attenuation of 10 dB / km associated with a 40 km optical fiber followed by an 80 km hybrid optical amplifier Raman / EDFA. A significant improvement was found for the proposed system by increasing the distance to more than 120 km of the optical path under different weather conditions without using another optical source where it was found that the use of WDM and FSO multiplexers in addition to hybrid optical amplifiers.

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