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RESEARCH ARTICLE **COMMUNICATION ENGINEERING**

Performance Evaluation of the Encrypted Image Transmission System Over Optical Fiber Using OptiSystem Under Varying Channel Conditions

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ABSTRACT

This paper presents the design, simulation, and performance analysis of an end-to-end optical communication link for encrypted grayscale-image transmission. Advanced Encryption Standard (AES) is applied to encrypt the image in MATLAB and then convert a 256 × 256 image into a binary sequence, which is then injected into OptiSystem. for optical modulation and fiber-optic transmission. Three operating wavelengths) 810 nm, 1550 nm, and 1625 nm(are investigated over distances of 50 km, 80 km, 100 km, and 150 km under different dispersion and attenuation conditions. Both a conventional Optical Amplifier (OA) and an Erbium-Doped Fiber Amplifier (EDFA) are considered. The performance of the system is assessed through various metrics in the electrical domain, such as the Q-Factor and Bit Error Rate (BER), alongside image quality indicators like Peak Signal-to-Noise Ratio (PSNR), Structural Similarity Index (SSIM), and Mean Squared Error (MSE). The results prove that the 1550 nm band yields error-free recovery (BER ≈ 10^{-176}, PSNR = 54 dB, SSIM = 1.0) under realistic single-mode-fiber parameters (α = 0.2 dB/km, D = 16 ps/nm/km). Conversely, heavy attenuation (α = 2.5 dB/km) and dispersion (D = 10 ps/nm/km) degrade performance severely, especially at 810 nm. The study highlights the importance of wavelength selection and dispersion management for secure image delivery and provides a reproducible methodology combining MATLAB and OptiSystem. Future research can extend this work by exploring adaptive dispersion compensation, forward error correction, and advanced modulation schemes

تقييم أداء نظام لنقل الصور المشفرة عبر الألياف الضوئية باستخدام OptiSystem تحت ظروف قناة مختلفة

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الكلمات المفتاحية

الاتصالات الضوئية.
تشفير الصور.
برنامج OptiSystem.
التشتت
ظروف التوهين

الملخص

تقدم هذه الورقة تصميمًا، ومحاكاة، وتحليلًا لأداء وصلة اتصال ضوئية من طرف إلى طرف لنقل صورة رمادية مشفَّرة. تم استخدام خوارزمية التشفير المتقدم (AES) في بيئة MATLAB لتحويل صورة بحجم 256 × 256 إلى تسلسل ثنائي، ثم تم حقنه في برنامج OPTISYSTEM من أجل إجراء التعديل البصري ونقل الإشارة عبر الألياف الضوئية. تم اختبار ثلاث أطوال موجية تشغيلية — 810 نانومتر، 1550 نانومتر، و1625 نانومتر — عبر مسافات 50كم، 80كم، 100كم، و150كم، وذلك تحت ظروف مختلفة من التوهين والتشتت. كما تم النظر في استخدام كل من المضخم البصري التقليدي (OA) والمضخم المعتمد على الإربيوم (EDFA). يتم تقييم أداء النظام من خلال مقاييس مختلفة في المجال الكهربائي، مثل معامل Q ومعدل خطأ البت (BER)، إلى جانب مؤشرات جودة الصورة مثل نسبة الإشارة إلى الضوضاء القصوى (PSNR)، ومؤشر التشابه الهيكلي (SSIM)، ومتوسط الخطأ التربيعي (MSE)، ومتوسط مربع الخطأ (MSE). وقد أظهرت النتائج أن النطاق 1550 نانومتر يحقق استعادة خالية من الأخطاء (BER ≈ 10^{-176}، PSNR = 54 ديسيبل، SSIM = 1.0) في ظل معلمات واقعية للألياف أحادية النمط (A = 0.2 ديسيبل/كم، D = 16 بيكوثانية/نانومتر/كم). بالمقابل، فإن التوهين العالي (A = 2.5 ديسيبل/كم) والتشتت (D = 10 بيكوثانية/نانومتر/كم) يؤديان إلى تدهور كبير في الأداء، وخصوصًا عند الطول الموجي 810نانومتر. تسلّط الدراسة الضوء على أهمية اختيار الطول الموجي المناسب وإدارة التشتت لضمان تسليم آمن للصور، كما توفر منهجية قابلة للتكرار تعتمد على الدمج بين MATLAB وOPTISYSTEM. البحث المستقبلي يمكن أن يوسع هذا العمل من خلال استكشاف تقنيات التعويض التكيفي للتشتت، و تصحيح الخطأ الأمامي (FEC)، و أنظمة التضمين المتقدمة

Introduction

In the era of high-speed multimedia communication, ensuring the security and integrity of transmitted image data has become a critical necessity. Sensitive images such as medical scans, biometric data, and remote sensing imagery must be protected from unauthorized access, interception, and

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degradation—especially when transmitted over public or long-range optical networks [1, 2].

Fibre-optic systems offer several key advantages for image delivery, including large bandwidth, immunity to electromagnetic interference, and low latency. However, fiber links are not immune to physical impairments such as attenuation, chromatic dispersion, and nonlinear effects. These phenomena become more pronounced in long-haul links, leading to signal distortion and elevated bit error rates [3], [4].

To mitigate these vulnerabilities, image-level encryption methods such as the Advanced Encryption Standard (AES) have been widely adopted. AES is computationally efficient and ensures robust data confidentiality, making it suitable for real-time image protection. However, while numerous studies have evaluated optical link performance, few have examined how encrypted image transmission interacts with physical-layer parameters like wavelength, fiber length, and amplifier type [5-7].

In addition to encryption-based approaches, the choice of modulation techniques plays a critical role in determining the efficiency and robustness of optical communication systems. Orthogonal Frequency Division Multiplexing (OFDM), for instance, has gained significant attention due to its ability to combat chromatic dispersion and inter-symbol interference while supporting high spectral efficiency. The integration of OFDM with secure optical transmission frameworks can further enhance data rates and reliability, particularly in long-haul or bandwidth-constrained scenarios [8]. Although not the main focus of this study, modulation strategies such as OFDM represent a promising direction for future research in secure and high-capacity optical networks

This paper presents a complete design and simulation of an optical communication system for transmitting encrypted grayscale images using a hybrid MATLAB–OptiSystem platform. The encrypted image is converted into a binary sequence in MATLAB and injected into an optical transmitter in OptiSystem. Three telecom-relevant wavelengths—810 nm, 1550 nm, and 1625 nm—are tested across fiber spans of 50 km to 150 km, under both ideal and degraded conditions. The study evaluates system performance from both the electrical domain (Q-factor, BER) and the image domain (PSNR, SSIM, MSE).

Compared to previous research, this work contributes a novel cross-domain analysis that connects encryption-level metrics to optical signal degradation, highlighting the role of wavelength selection and optical amplification in achieving secure, error-free image transmission.

Related Work

Several studies have investigated the performance of optical communication systems under various channel conditions and modulation formats. However, most of this research has primarily focused on signal-domain metrics such as the Bit Error Rate (BER) and Q-factor, with limited attention to the secure transmission of images—particularly over long-haul fiber links—where both signal- and image-domain evaluations are essential.

More recently, Hasan (2023) evaluated optical signal degradation over varying fiber lengths and dispersion settings using OptiSystem. The study highlighted how increased distance and poor dispersion management negatively affect the Q-factor and BER. However, it did not explore data encryption or visual performance metrics such as PSNR or SSIM [1].

For instance, Jabbar et al. (2017) utilized OptiSystem to assess the performance of optical systems employing different transmission techniques. They examined the impact of laser versus LED sources, as well as NRZ versus RZ modulation schemes. Their findings showed that NRZ modulation combined with PIN photodiodes yielded superior signal integrity and reduced noise levels, supporting the design principles adopted in this study [4].

Kadhim et al. (2015) simulated a Free-Space Optical (FSO) system operating at wavelengths of 633, 850, and 1550 nm. Despite focusing on atmospheric channels, they found that the 1550 nm wavelength offered the best Q-factor and BER, reinforcing the importance of wavelength selection in optical system performance—even in fiber-based systems [5].

In summary, despite advancements in optical communication modeling, the existing studies tend to either focus on physical-layer metrics (like Q-factor and BER) or on image encryption algorithms in isolation. However, the combined influence of encryption schemes (e.g., AES), wavelength selection, amplifier type, and fiber channel conditions on both signal integrity and image quality (e.g., PSNR, SSIM) remains underexplored. This study addresses that gap by proposing a unified simulation-based framework that links cryptographic processing with realistic optical transmission parameters.

System Design and Methodology

This section describes the complete MATLAB–OptiSystem workflow used to encrypt, transmit, and recover grayscale images over a simulated single-mode-fibre (SMF) channel

System Overview and Architecture

This research implements the transmission of encrypted grayscale images over an optical fiber system. The design consist of two components: Pre-processing and encryption done in MATLAB, and optical transmission simulation done in OptiSystem. The full setup in Figure 1 illustrates combining image encryption with optical transmission and image post processing. The simulation analyzes image transmission through a fiber link while varying several parameters, including wavelength, amplifier type, and distance, and measures the performance with a combination of signal and image quality metrics.

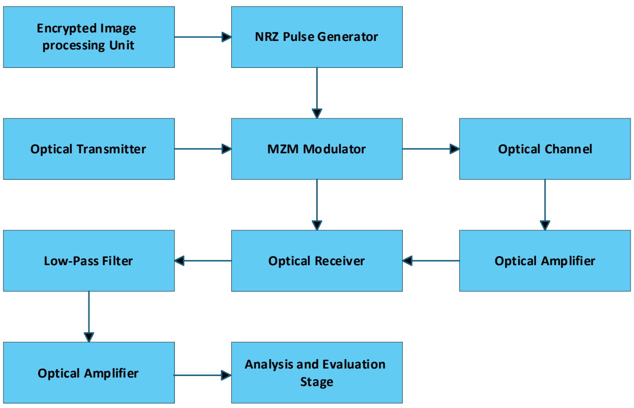


Fig. 1: System architecture for encrypted image transmission and analysis over optical fiber

OptiSystem Layout

The complete schematic layout of the proposed optical communication system, as implemented within the OptiSystem simulation environment is illustrated in Figure 2. The system architecture is designed to closely mimic the structure of a real-world long-haul optical transmission system and consists of several key components. It begins with a user-defined binary input, which represents the encrypted image and serves as the digital data source for the transmission. A continuous wave (CW) laser source provides the optical carrier signal required for data modulation. The digital signal is shaped using a Non-Return-to-Zero (NRZ) pulse generator, which converts the binary input into a suitable electrical pulse train. This pulse train is then fed into a Mach–Zehnder modulator, which impresses the data onto the optical carrier through intensity modulation. The modulated optical signal is transmitted over a single-mode fiber (SMF) channel, which emulates the physical transmission medium used in long-distance fiber-optic networks. An optical amplifier can optionally be inserted into the system to compensate for signal attenuation over extended distances. At the receiver end, a PIN photodiode detects the incoming optical signal and converts it back into an electrical signal for further processing and analysis.

This comprehensive layout forms the foundation for studying and evaluating the impact of various parameters such as transmission wavelength, fiber length, and the use of optical amplification on the overall performance of the optical communication system.

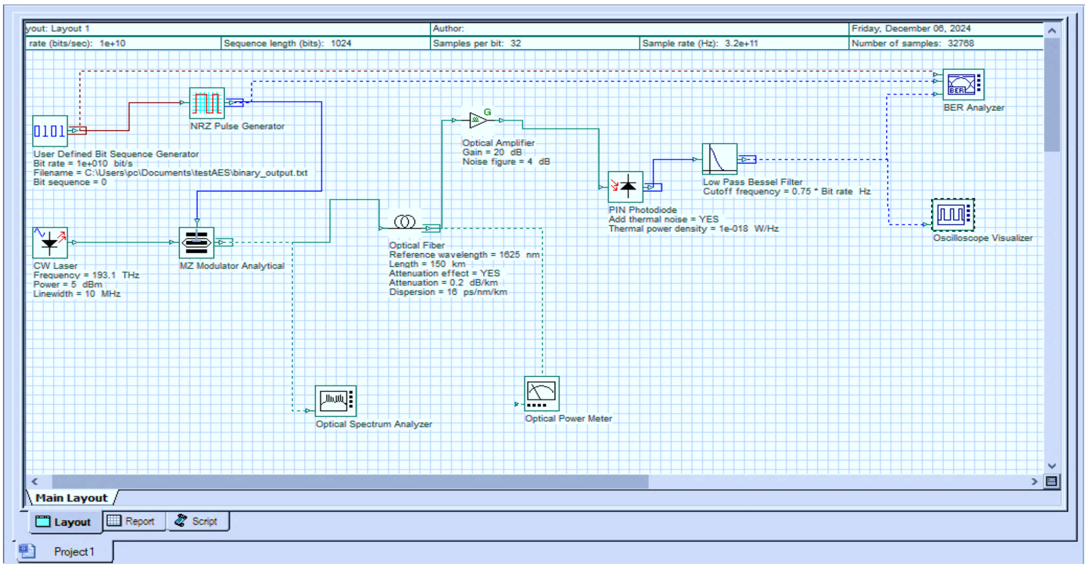


Fig. 2: Schematic layout of the proposed system in OptiSystem environment

MATLAB Pre-processing

A number of crucial pre-processing operations are carried out using MATLAB to get the input data ready before the optical transmission simulation starts. These steps include:

1. Image import and scaling : An 8-bit grayscale test image is loaded and resized to 256 × 256 pixels to standardise the payload.
2. AES-128 encryption: The pixel matrix is flattened into a byte stream and encrypted with AES-128 in CBC mode. A random 128-bit initialisation vector (IV) is generated for each simulation run.
3. Then the Cipher-text bytes are converted to a binary vector (MSB-first), yielding 256 × 256 × 8 = 524 288 bits.
4. Interface to OptiSystem: The binary vector is passed to OptiSystem via either a User Defined Bit Sequence component (text file), or a MATLAB Component socket for real-time sweeps.

OptiSystem Simulation and setup

This section presents the implementation of the proposed optical communication system on the OptiSystem simulation environment. The simulation aims to model and investigate the behavior of a long-distance fiber-optic transmission system with variable conditions. The main system elements at the transmission side are:

❖ Line coding The imported bit stream drives an NRZ pulse generator.
❖ Optical carrier. Three independent CW lasers are employed at 810 nm, 1550 nm (193.1 THz), and 1625 nm, each with a 10 MHz linewidth.
❖ External modulation Pulses modulate the carrier through a Mach–Zehnder Modulator (Vπ = 4 V, extinction ratio = 30 dB).
❖ Optical amplification An optional optical amplifier (OA) or erbium-doped fibre amplifier (EDFA) provides 20 dB small-signal gain with a 4 dB noise figure.

The modulated signal travels through The optical fiber channel. Different fiber parameters are systematically changed to simulate optical fiber link conditions in order to evaluate transmission performance. The parameters are:

❖ The modulated signal propagates through an SMF span whose parameters are swept to emulate benign and harsh links:
❖ Attenuation α = 0.2 dB km^{-1} (standard) or 2.5 dB km^{-1} (severe).
❖ Chromatic-dispersion coefficient D = 16 ps nm^{-1} km^{-1} (C-band) or 10 ps nm^{-1} km^{-1} (short-wave scenario).
❖ Span length L = 50, 80, 100, or 150 km.
❖ No dispersion-compensation fibre is inserted so that wavelength-dependent dispersion remains the dominant impairment.

At the receiver side, the system work as following steps:

❖ Opto-electronic conversion A PIN photodiode (responsivity = 1 A W^{-1}, dark current = 10 nA) detects the optical signal.
❖ Electrical filtering and decision The photocurrent passes through a 4th-order Bessel low-pass filter before bit slicing.

- ❖ Performance monitors Built-in Q-Factor and BER estimators quantify link integrity.
- ❖ Post-processing in MATLAB The recovered bit stream is re-imported, decrypted with the correct AES key/IV, and reshaped to reconstruct the image for PSNR, SSIM, and MSE evaluation.

Performance Evaluation Metrics

The system performance is assessed in both the signal domain and image domain. Signal performance is measured using Q-Factor and Bit Error Rate (BER). Image quality is evaluated using Peak Signal-to-Noise Ratio (PSNR), Structural Similarity Index (SSIM), and Mean Squared Error (MSE). These metrics help quantify the impact of optical transmission conditions on both signal integrity and visual quality of the transmitted image.

Below are the key mathematical formulas used to evaluate system performance in both the electrical and image domains.

(1) Q-Factor

The Q-factor is a widely used metric in optical communication systems to quantify signal quality at the physical layer. It reflects the signal-to-noise ratio in terms of decision threshold margins, directly linking to the probability of bit errors. Higher Q-factor values indicate cleaner eye diagrams and more reliable signal detection [9].

$$Q = \frac{\mu 1 - \mu 0}{\sigma 1 + \sigma 0} \qquad (1)$$

Where:

- $\mu 1, \mu 0$ are the mean voltage levels for logic '1' and '0'
- $\sigma 1, \sigma 0$ are their corresponding standard deviations.

(2) Bit Error Rate (BER)

BER measures the ratio of incorrectly received bits to the total transmitted bits, making it the most fundamental reliability indicator in digital communication systems. A low BER demonstrates the effectiveness of the system in preserving data integrity [9].

$$BER = \frac{1}{2} . erfc\left(\frac{Q}{\sqrt{2}}\right) \qquad (2)$$

Where erfc is the complementary error function.[9, 10]

(3) Mean Squared Error (MSE)

Although it is a simple mathematical measure, MSE is widely used due to its computational efficiency. Lower MSE values signify minimal distortion, while higher values indicate significant quality loss [10].

$$MSE = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}[I(i,j) - K(i,j)]^2 \qquad (3)$$

Where:

- I(i,j) = pixel value in the original image.
- K(i,j) = pixel value in the recovered image.
- M ×N = total number of pixels.

(4) Peak Signal-to-Noise Ratio (PSNR)

PSNR is an objective measure that compares the pixel-level similarity between the transmitted and received images. It expresses the ratio of the maximum possible signal power to the noise introduced during transmission, expressed in decibels[11][12].

$$PSNR = 10. log\left(\frac{MAX^2 I}{MSE}\right) \qquad (4)$$

Where MAX_I is the maximum pixel value (255 for 8-bit images).

(5) Structural Similarity Index (SSIM)

SSIM is a perceptual metric that evaluates image quality based on structural information, luminance, and contrast. Unlike PSNR, which is purely mathematical, SSIM correlates more closely with human visual perception. An SSIM value of 1.0 represents perfect structural similarity[11] [12].

$$SSIM(I, I_w) = \frac{(2\mu\mu_w + C_1)(2\sigma(I, I_w) + C_2)}{(\mu^2 + \mu_w^2 + C_1)(\sigma(I)^2 + \sigma(I_w)^2 + C_2)}, \qquad \textbf{(5)}$$

Where:

- μx, μy = local means
- σx, σy = standard deviations
- σxy = cross-variance
- C1, C2 = constants to stabilize the division

Results and Discussion

This section presents the simulation results of the proposed encrypted grayscale image transmission system using OptiSystem and MATLAB. The performance is analyzed in two domains. Frist one are the signal domain (Q-Factor, BER) and the second are the image quality parameters (PSNR, SSIM, MSE). The impact of wavelength, amplifier type, and fiber channel conditions is examined to identify optimal configurations for secure long-haul transmission.

Signal-Domain Performance

Optimal Fiber Conditions – OA Amplification

This section evaluates the transmission performance of encrypted grayscale images using a conventional optical amplifier (OA) under ideal fiber conditions. The test parameters were set as follows:

- Attenuation (α): 0.2 dB/km
- Dispersion (D): 16 ps/nm/km
- Distances: 50 km, 80 km, 100 km, 150 km
- Wavelengths: 810 nm, 1550 nm, 1625 nm
- Amplifier: Optical Amplifier (OA), gain = 20 dB

The encrypted image was serialized in MATLAB and injected into OptiSystem through a User Defined Bit Sequence component. The received signal was then decrypted and evaluated.

The results in the Tables 1a and 1b and Figure 3a and Figure 3b summarizes the Q-factor and bit error rate (BER) for the three wavelengths across increasing distances under ideal attenuation and dispersion conditions.

Table 1a Q-factor of encrypted image with OA (α = 0.2 dB/km, D = 16 ps/nm/km)

Q-factor (1625nm)	Q-factor (1550nm)	Q-factor (810nm)	Distance (km)
35.9683	27.1958	26.3947	50
20.7708	17.8084	17.1478	80
10.6326	10.2245	9.85539	100
0	0	0	150

Table 1b BER of encrypted image with OA (α = 0.2 dB/km, D = 16 ps/nm/km)

BER (1625nm)	BER (1550nm)	BER (810nm)	Distance (km)
1.00658e-283	2.75636e-163	6.17029e-154	50
2.57992e-96	2.10696e-71	2.25292e-66	80
5.3993e-27	4.20752e-25	1.80831e-23	100
1	1	1	150

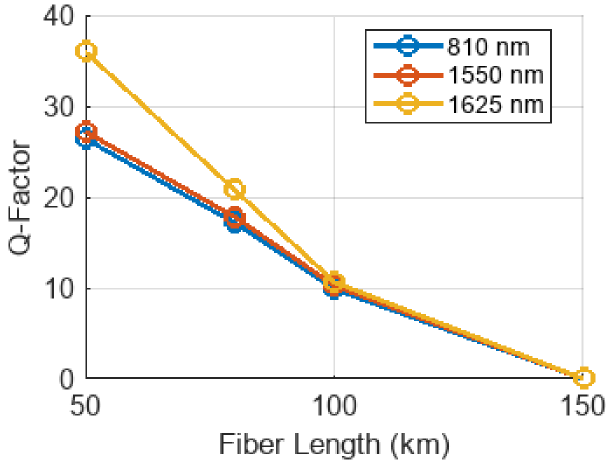


Fig. 3a: Q-factor of encrypted image with OA (α = 0.2 dB/km with different fiber length

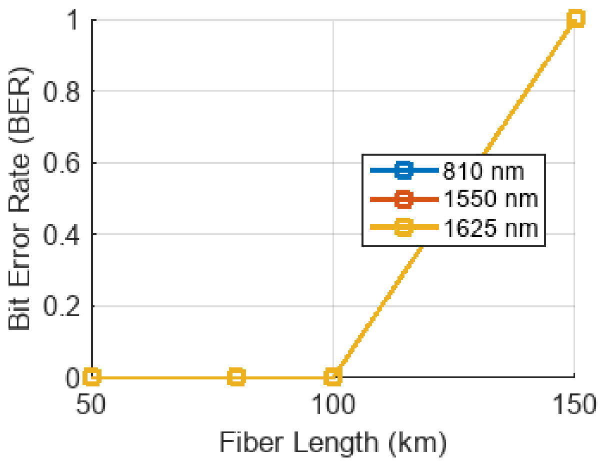


Fig. 3b: BER of encrypted image with OA (α = 0.2 dB/km with different fiber length

The simulation results show that all three wavelengths demonstrate robust and error-free transmission up to 100 km, with Q-factors remaining above 9 and BER values below 10^{-23}. Among them, the 1625 nm wavelength exhibits the highest resilience, maintaining a Q-factor of ≈ 10.6 and BER ≈ 5.39×10^{-27} at 100 km. However, at 150 km, signal quality collapses completely (Q = 0, BER = 1) for all wavelengths, indicating total link failure beyond this range without advanced compensation techniques.

Ideal Fiber Conditions – EDFA Amplification

To evaluate the impact of amplifier type on encrypted image transmission over long distances, the conventional optical amplifier (OA) was replaced with a 5-meter erbium-doped fiber amplifier (EDFA), inserted directly after the transmitter. The EDFA was configured with OptiSystem's default pump laser (980 nm, ~200 mW), yielding a reported small-signal gain of approximately 18 dB at 1550 nm.

The system was tested under ideal fiber conditions:

• Attenuation (α): 0.2 dB/km.
• Dispersion (D): 16 ps/nm/km.
• Wavelengths: 810 nm, 1550 nm, 1625 nm.
• Distances: 50 km, 80 km, 100 km, 150 km.

No image recovery or decryption was performed in this stage. Instead, the analysis focused on Q-Factor and BER to assess how EDFA improves signal quality compared to OA. Tables 2a and 2b also Figure 4a and Figure 4b summarizes the Q-Factor and BER values across all wavelengths and distances using EDFA.

Table 2a. Q-Factor values using EDFA (α = 0.2 dB/km, D = 16 ps/nm/km)

Q-factor (1625nm)	Q-factor (1550nm)	Q-factor (810nm)	Distance (km)
39.2782	26.8997	28.9666	50
27.7952	21.2247	21.1749	80
23.3112	18.4029	18.5707	100
13.5561	11.804	11.7811	150

Table 2b. BER values using EDFA (α = 0.2 dB/km, D = 16 ps/nm/km)

BER (1625nm)	BER (1550nm)	BER (810nm)	Distance (km)
0	8.44e-160	7.03e-185	50
1.91e-170	2.25e-100	6.48e-100	80
1.30e-120	4.84e-76	2.29e-77	100
2.79e-42	1.53e-32	1.89e-32	150

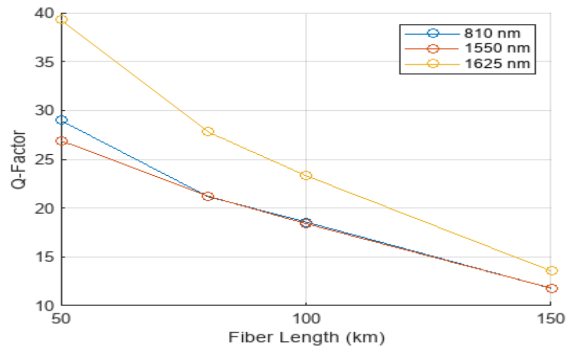


Fig. 4a: Q-Factor vs. Distance using EDFA

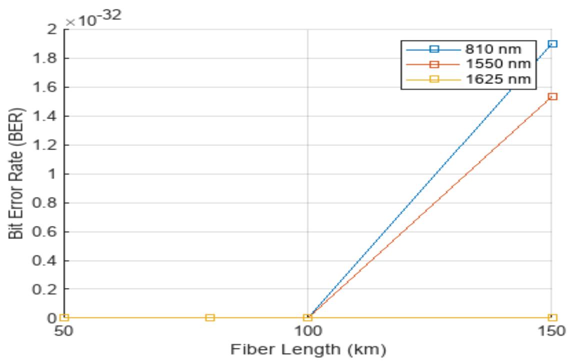


Fig. 4b:BER vs. Distance using EDFA

In addition, Figure 5a and Figure 5b highlights the best-performing combination (1625 nm at 50–150 km) and compares it with 1550 nm, showing how EDFA maximizes signal robustness at long distances.

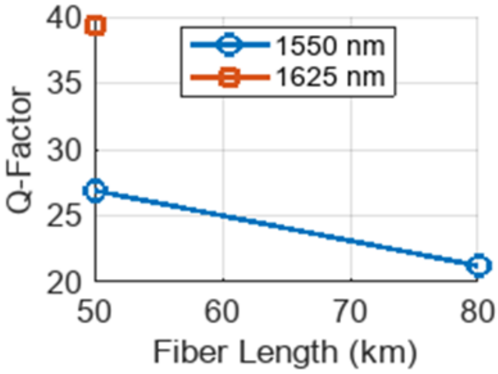


Fig. 5a: Comparative performance of Q-Factor between 1625 nm and 1550 nm under EDFA amplification

Replacing the conventional optical amplifier (OA) with an EDFA significantly improved transmission range. With EDFA, Q > 6 was sustained up to 150 km for all wavelengths. The 1625 nm channel achieved the best results (Q ≈ 13.56, BER ≈ 10^{-42} at 150 km), followed by 1550 nm and 810 nm. These findings confirm that EDFA is essential for extending reach in encrypted optical links.

Harsh Fiber Conditions – OA Amplification

This section presents a focused analysis of encrypted image transmission under degraded fiber conditions, specifically high attenuation and dispersion. Due to time and processing constraints, the evaluation was limited to the 810 nm and 1550 nm wavelengths at 50 km, which were the only channels decrypted for image quality comparison.

- Attenuation (α): 2.5 dB/km (only applied at 810 nm and 1550 nm)
- Dispersion (D): 10 ps/nm/km
- Wavelengths analyzed: 810 nm, 1550 nm
- Distance: 50 km
- Amplifier: Optical Amplifier (OA)

Table 3 reports the Q-factor and BER for 810 nm and 1550 nm at 50 km under harsh fiber conditions.

Table 3 Q-factor and BER at 50 km (encrypted image, α = 2.5 dB/km, D = 10 ps/nm/km)

BER	Q-factor	Wavelength
1	0	810nm
1	0	1550nm

When attenuation was increased to α = 2.5 dB/km and dispersion reduced to D = 10 ps/nm/km, severe performance degradation occurred. At 50 km, both 810 nm and 1550 nm wavelengths dropped to Q = 0 and BER = 1, indicating total signal failure. The results highlight the sensitivity of long-haul links to combined high-loss and high-dispersion environments.

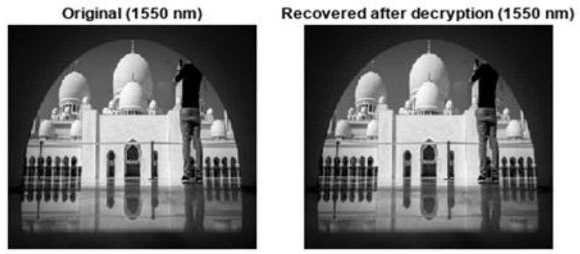
Image-Domain Performance

Ideal Fiber Conditions – OA Amplification

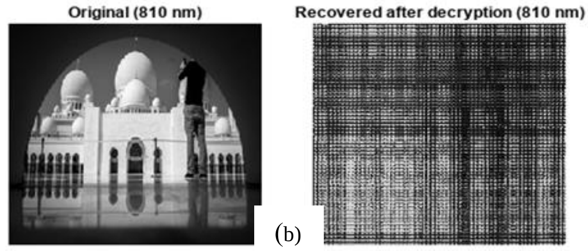
Due to time constraints, image reconstruction was performed at 50 km only, for 810 nm and 1550 nm. The images were decrypted in MATLAB and compared to the original image. the image quality performance as shown in Table 4 and Figure 6.

Table 4 Image quality metrics at 50 km (OA, α = 0.2 dB/km)

MSE	SSIM	PSNR	Wavelength
9634.151	0.0159	8.2927 dB	810nm
0.00	1.000	54dB	1550nm



(a)



(b)

Fig.6: Snapshots of test image used in simulation (a) original image & recovered images at 50 km(1550 nm) , (b) original image and recovered images at 50 km (810 nm)

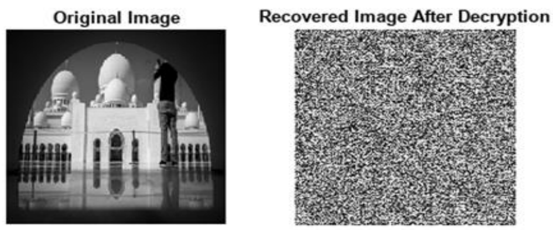
The results showed that due to time constraints, At 50 km, decrypted images demonstrated a stark difference between wavelengths. The 1550 nm channel achieved perfect recovery (PSNR = 54, SSIM = 1.0, MSE = 0.00), while the 810 nm channel suffered severe degradation (PSNR ≈ 8.29 dB, SSIM = 0.0159, MSE ≈ 9634), indicating heavy distortion.

Harsh Fiber Conditions – OA Amplification

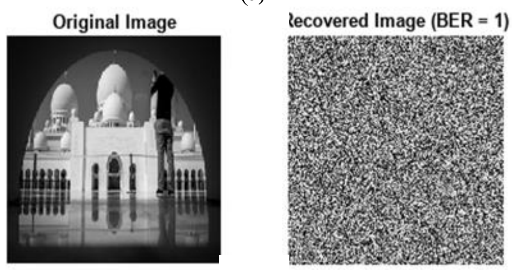
The results of decrypted images at 50 km were assessed using PSNR, SSIM, and MSE to quantify the visual impact of fibre impairments as shown in Table 5 and Figure. 7.

Table 5. Image quality metrics at 50 km (encrypted image, α = 2.5 dB/km, D = 10 ps/nm/km)

MSE	SSIM	PSNR	Wavelength
11962.2970	0.0075	7.3527 dB	810nm
12594.4781	0.0059	7.1290 dB	1550nm



(a)



(b)

Fig.7: Visual comparison of decrypted images at 50 km under harsh fiber conditions: (a) 1550 nm (b) 810 nm

The results show that at 50 km under α = 2.5 dB/km and D = 10 ps/nm/km, both 810 nm and 1550 nm channels failed to preserve acceptable visual quality. PSNR dropped below 7.4 dB, SSIM values were under 0.008, and MSE exceeded 11,000 for both cases. Interestingly, 810 nm slightly outperformed 1550 nm in this scenario, possibly due to simulated receiver sensitivity variations.

These findings indicate that under extreme attenuation and dispersion, neither channel was able to preserve acceptable visual quality. The unexpected result—810 nm slightly outperforming 1550 nm—may be attributed to sensitivity variations in the simulated receiver or channel nonlinearities at short distances under harsh settings.

Unencrypted Transmission Comparison

Since encryption was not applied, the visual comparison focuses solely on transmission distortion caused by channel impairments.

Table 6 and Figure 8 8a and 8b show the results under harsh fiber conditions (α = 2.5 dB/km, D = 10 ps/nm/km), both the 810 nm and 1550 nm channels experienced a complete failure to preserve visual image quality. Despite the absence of encryption, the received images at 50 km showed severe distortion, with a PSNR of only 3.97 dB and an SSIM of –0.1889 for both wavelengths. The high MSE values (above 26,000) further confirm substantial pixel-level degradation and a total loss of structural integrity.

Table 6 PSNR, SSIM, and MSE at 50 km (original image, OA, α = 2.5 dB/km, D = 10 ps/nm/km)

MSE	SSIM	PSNR	Wavelength
26088.5966	0.1889	3.9663 dB	810nm
26088.5966	0.1889	3.9663 dB	1550nm

(a)

(b)

Fig. 8: Output of unencrypted image transmission under harsh fiber conditions at 50 km: (a) Received image and difference image at 1550 nm (b) Received image at 810 nm

These results suggest that under extreme attenuation and dispersion, neither wavelength can support reliable image transmission—even without encryption. The visual difference images illustrate the high error content and inversion effects introduced by the harsh channel.

To enable acceptable image recovery in such conditions, future systems must employ robust error correction codes, dispersion compensation modules, or consider upgrading to more advanced amplifiers such as EDFA. Without such enhancements, transmission in long-distance, lossy links remains impractical for image-based communication

Comparative Analysis and Key Insights

This section synthesizes the findings from all experimental stages and highlights the core insights derived from both signal- and image-domain analyses. The goal is to distill performance trends, clarify the influence of physical parameters, and establish guidelines for optimizing encrypted image transmission over optical fibers.

Key Comparative Findings:

1. Effect of Wavelength:

• 1625 nm consistently achieved the highest Q-factor and lowest BER across all conditions, especially with EDFA, proving it to be the most robust against dispersion and attenuation.

• 1550 nm provided near-lossless image recovery under ideal conditions and remained relatively strong even under moderate impairments.

• 810 nm performed adequately under ideal settings but degraded rapidly under harsh conditions due to its susceptibility to bending and modal losses.

2. Impact of Amplifier Type:

• Replacing OA with EDFA led to substantial performance improvements across all wavelengths.

• EDFA extended the transmission distance with acceptable signal quality (Q > 6) from 100 km (OA) to 150 km, particularly at 1550 nm and 1625 nm.

3. Decryption Feasibility and Image Quality:

• Decrypted images at 50 km revealed that encryption overhead did not significantly degrade image quality under ideal conditions.

• Under harsh settings (α = 2.5 dB/km, D = 10 ps/nm/km), image recovery quality dropped sharply, especially for 810 nm.

4. Comparison Between Encrypted and Unencrypted Transmission:

• Without encryption, PSNR and SSIM values remained high under ideal conditions.

• Under the same harsh parameters, however, even the original images suffered severe distortion, confirming that encryption was not the cause of signal degradation—fiber conditions were.

As Conclusion, the results demonstrate that secure optical image transmission is feasible over distances up to 150 km when:

• Longer wavelengths (1550 or 1625 nm) are used,

• An EDFA is applied for amplification,

• And fiber conditions are well managed or compensated.

Conclusion

This paper presented the complete design and simulation of a secure optical communication system for transmitting grayscale images, combining AES encryption with OptiSystem-based modeling. The system was evaluated across three telecom-relevant wavelengths—810 nm, 1550 nm, and 1625 nm—under varying fiber conditions and amplifier types. The results highlight several important findings: wavelength selection plays a critical role, with the 1550 nm channel enabling lossless image recovery (PSNR = ∞, SSIM = 1.00) under ideal single-mode fiber parameters and outperforming 810 nm at longer distances due to its lower attenuation and dispersion. Channel impairments were found to be the dominant limiting factor over extended fiber spans; for instance, at 1625 nm, reliable performance ($Q > 6$, $BER < 10^{-9}$) was sustained up to 100 km but declined without amplification or dispersion compensation. Furthermore, replacing a conventional optical amplifier with an EDFA significantly extended the transmission reach, particularly at 1550 and 1625 nm, with the $Q > 6$ threshold stretching from 100 km to 150 km. Finally, the study confirmed that image-domain metrics such as PSNR and SSIM closely correlate with signal quality, as a Q-factor drop below approximately 6 coincided with PSNR values under 30 dB and SSIM below 0.9, underscoring their utility in assessing the performance of encrypted image transmission over optical links. Based on the experimental findings, several directions are suggested for future research and practical implementation. These include adopting adaptive dispersion compensation and forward error correction to enhance performance over long spans and harsh channels, as well as exploring quality estimation for predicting image degradation

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