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Performance evaluation of watermarked image transmission through atmospheric turbulence channels modeled by the Chi-square–inverse Gamma distribution

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Abstract

This paper presents an analysis of image transmission quality with embedded digital watermarking over an atmospheric turbulence channel. The channel is modeled using the Zero Borelight Chi-square–Inverse Gamma statistical model. Particular attention is devoted to the influence of two key parameters: the intensity of atmospheric turbulence and the Rician K-factor. Objective metrics, namely the Mean Square Error (MSE) and the Peak Signal-to-Noise Ratio (PSNR), are employed for quality evaluation. The results demonstrate that atmospheric turbulence considerably degrades transmission quality, whereas the Rician K-factor plays a crucial role in its enhancement. Furthermore, the effect of digital watermarking on preserving information integrity is verified. The findings provide valuable insights into the reliability of Free-Space Optical (FSO) communication systems and support the optimization of future system designs.

Keywords: FSO, mean square error, Chi-square-inverse Gamma distribution

1. Introduction

Free-Space Optical (FSO) communication represents a modern and efficient approach to information transmission, where data transfer between the transmitter and receiver is achieved through directed laser beams operating in the infrared spectrum (wavelengths 750–1550 nm). This approach eliminates the need for optical fiber deployment while still providing transmission rates comparable to fiber-optic systems, with the advantage of simpler implementation. Since FSO systems require a clear optical line-of-sight between the transmitter and receiver, they are most commonly applied in short-range communications, making them an excellent solution to the last-mile problem (Cordeiro et al., 2003). In this way, FSO technology effectively overcomes challenges posed by inaccessible terrain or regulatory and environmental constraints that render the installation of optical fibers impractical or impossible.

Nevertheless, FSO systems also have certain drawbacks that manifest through impairments in signal propagation. Even under clear-sky conditions, atmospheric turbulence may occur, leading to attenuation and fluctuations of the optical beam. In addition to turbulence, other factors such as atmospheric attenuation and pointing errors play an important role, further affecting the quality of the link. These phenomena may cause delays and errors in information transmission, which is why comprehensive analyses and calculations are necessary in the implementation of FSO systems in order to predict and minimize potential errors in advance.

Several studies in the literature have analyzed these effects. (Kappala et al., 2023) presented a work in which the impact of both atmospheric turbulence and pointing errors was simultaneously examined. The authors proposed a theoretical model for calculating the Bit Error Rate (BER) based on the Nakagami-m distribution and validated its applicability by comparing it with results obtained from experimental measurements. The study highlights the importance of employing analytical models for predicting the performance of FSO systems.

Abd El-Mottaleb et al. (2024) analyzed the impact of precipitation, specifically rain, on the performance of FSO links. System performance was evaluated using practical parameters and metrics such as MSE, PSNR, and SSIM. The results

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demonstrated that rain has a significant negative effect on optical signal propagation and further reduces the communication range.

Singh et al. (2025) investigated the application of Orbital Angular Momentum (OAM) multiplexing in FSO systems for image transmission under various weather conditions. The analysis showed that fog, rain, and strong turbulence significantly degrade the quality of transmitted images, as confirmed by the MSE, PSNR, and SSIM metrics. The use of median filtering resulted in considerable improvements in image quality, indicating the potential of combining adaptive signal processing algorithms with FSO technology.

In order to analyze the transmission characteristics of FSO systems, this paper investigates the transmission of images with embedded digital watermarks through a Zero Boresight Chi-square–Inverse Gamma turbulence channel, considering different atmospheric turbulence strengths and Rician K-factors. The impact of channel impairments on the quality of the reconstructed images was examined during the transmission of watermarked images through the Zero Boresight Chi-square–Inverse Gamma turbulence channel. Monochromatic test images, including Lenna, Pepper, Clock, and Cameraman, all with a resolution of 512×512 pixels, were used for performance evaluation. The watermark employed is a digital chessboard pattern with a resolution of 256×256 pixels, created using a matrix distribution of “1” and “0”, which is later embedded into the image via a binary mask. The watermark is embedded using the Discrete Cosine Transform (DCT) method (Stanojević et al., 2021) with an embedding coefficient K_u . Its role is to protect the image from unauthorized use and can also serve as an author identification. The refractive index structure parameter C_n^2 , which defines the turbulence strength, and the Rician K-factor were varied within ranges characteristic of the channel conditions. The quality of the reconstructed images after transmission through the Chi-square–Inverse Gamma turbulence channel was assessed using MSE and PSNR metrics. The results are presented in the form of tables and graphs.

The purpose of these investigations is to analyze the characteristics of information transmitted under the influence of atmospheric turbulence modeled by the Zero Boresight Chi-square–Inverse Gamma channel and to evaluate the effect of channel-specific parameters on the quality of image transmission.

2. System model

The information carried by a portion of the signal can be modeled as:

$$x_T(t) = \frac{e\eta\pi}{2hf_c} \times AD^2 u_s(t) R_e\{a \exp(j2\pi f_{IF}t + Q_{IF}(t))\} \quad (1)$$

where $u_s(t)$ is the envelope of the desired signal, f_c is the optical carrier frequency, $f_{IF} = f_c - f_{LO}$ represents the equivalent signal frequency, a denotes the effective FSO fading fluctuation modeling the signal, e is the electron charge, h is Planck's constant, η is the photodetector quantum efficiency, D is the receiver aperture diameter, and A is the amplitude of the local oscillator (LO) field at the demodulator (Vučković et al., 2015).

The photodetector current at the receiver can be expressed as (Farid et al., 2007):

$$y_T(t) = hx_T(t) + n_T(t) \quad (2)$$

where n_T denotes the Additive White Gaussian Noise (AWGN) with zero mean and variance:

$$\sigma_n^2 = \frac{B_s e^2 \eta \pi}{2hf_c} A^2 D^2 \quad (3)$$

where B_s represents the signal bandwidth.

As mentioned, the transmission of an image with an embedded digital watermark is performed through a Zero Boresight Chi-square–Inverse Gamma turbulence channel (Stanojević et al., 2024):

$$f_I(I) = \sum_{q=0}^{\infty} \frac{\xi^2 K^p \Gamma(b + \xi^2 + 1) \exp(-K)}{I \Gamma(p+1) p! \Gamma(b) \Gamma(b + \xi^2)} \times G_{2,2}^{1,2} \left(\frac{1 - \xi^2}{b}, -p \middle| \frac{(b-1)\Omega A_0}{(K+1)I} \right) \quad (4)$$

where $\xi = w_{L_{eq}}/2\sigma_s$, $w_{L_{eq}}$ is the equivalent radius of the received beam, σ_s is the standard deviation of the pointing error (jitter) at the receiver, K is the Rician factor representing the power ratio between the dominant component and the scattered components, I denotes the received irradiance, and b is a distribution parameter that can be calculated from the expression $b = \frac{1}{\exp(\sigma_{Is}^2) - 1} + 2$, where σ_{Is}^2 is the log-variance of the irradiance (Peppas et al., 2019).

Additionally, $A_0 = [\text{erf}(v)]^2$, $v = \frac{\sqrt{\pi}a}{\sqrt{2}w_L}$ a $\text{erf}(\cdot)$ denotes the error function, and $G_{p,q}^{m,n} \left(\frac{a_p}{b_q} \middle| x \right)$ represents the Meijer G-function (Ansari et al., 2015; Amirabadi, 2017);

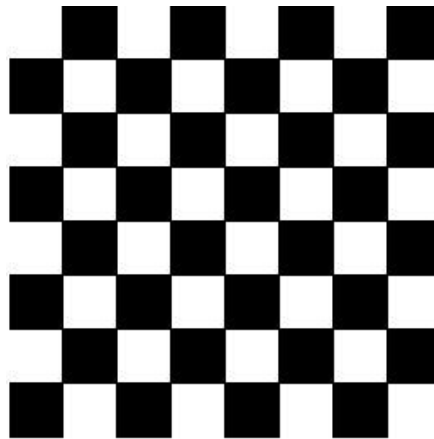
3. Determination of MSE and PSNR as image quality metrics

As previously mentioned, the transmission characteristics are tested using the test images Lenna, Cameraman, Pepper, and Clock (Figure 1), while a digital chessboard pattern is used as the watermark.

Figure 1. Monochromatic test images: Lenna, Cameraman, Pepper, and Clock



Figure 2. Digital chessboard watermark



Source: Result of the author's research, generated in MATLAB

Using the algorithms for embedding and extracting the digital watermark, as well as the image transmission algorithm through the turbulence channel (C. C. Chen et al., 2017; Stanojević N. et al., 2021), the digital watermark was first embedded into the image. Subsequently, the image was transmitted through the turbulence channel, followed by image detection at the receiver and extraction of the digital watermark. After the watermark extraction, the quality of the transmitted information (images) was assessed. To thoroughly evaluate the characteristics of images transmitted through the turbulence channel, measurement parameters such as MSE and PSNR were employed.

$$MSE = \frac{\sum_{i=1}^M \sum_{j=1}^N (x_{ij} - y_{ij})^2}{M \times N} \quad i=1 \dots M, j=1 \dots N \quad (5)$$

$$PSNR = 10 \log_{10} \frac{2^n - 1}{MSE} \quad (6)$$

where x_{ij} , and y_{ij} are the pixels of the original, transmitted, and reconstructed images, n is the number of bits, $M \times N$ is the image size.

MSE measures the average squared difference between the original and transmitted images, with a higher value indicating poorer quality of the transmitted information. PSNR represents the ratio between the maximum possible signal and the Mean Square Error (MSE) between the original and transmitted images. It is expressed in decibels (dB), and a higher value indicates better image quality.

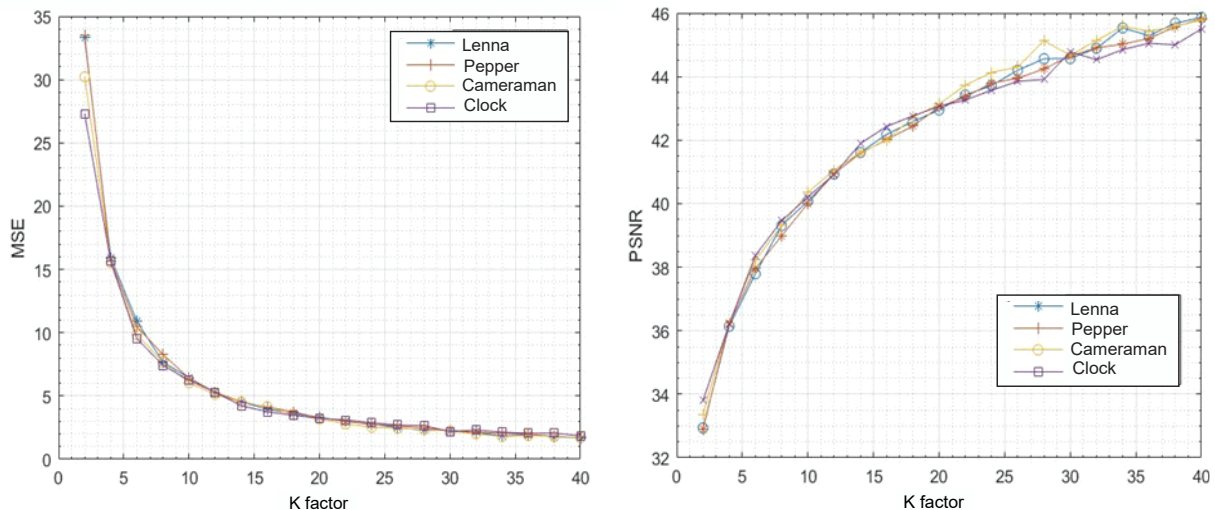
The MSE and PSNR results under weak, moderate, and strong turbulence conditions are presented in Tables 1, 2, and 3, while a detailed analysis of the results is illustrated through the accompanying graphs.

Table 1. Obtained MSE and PSNR results for different values of the Rician K-factor under weak turbulence conditions for the images: Lenna, Pepper, Cameraman, and Clock

K Factor	2	6	10	14	18	22	26	30	34	38
Lenna										
MSE	33.29	10.9	6.43	4.53	3.61	2.98	2.49	2.28	1.83	1.77
PSNR	32.94	37.79	40.08	41.61	42.58	43.42	44.2	44.57	45.53	45.68
Pepper										
MSE	33.59	10.48	6.4	4.55	3.74	3.02	2.64	2.24	2.06	1.82
PSNR	32.9	37.96	40.01	41.59	42.44	43.36	43.95	44.65	45.02	45.57
Cameraman										
MSE	30.22	9.84	6.04	4.52	3.51	2.78	2.44	2.23	1.79	1.81
PSNR	33.66	38.23	40.35	41.61	42.72	43.73	44.13	44.67	45.58	45.58
Clock										
MSE	27.3	9.54	6.24	4.23	3.47	3.1	2.7	2.18	2.14	2.07
PSNR	33.8	38.37	40.21	41.89	42.76	43.26	43.85	44.78	44.85	45

Source: Author's research

Figure 3. Graphical representation of the obtained MSE and PSNR for images transmitted through the turbulence channel under weak turbulence conditions



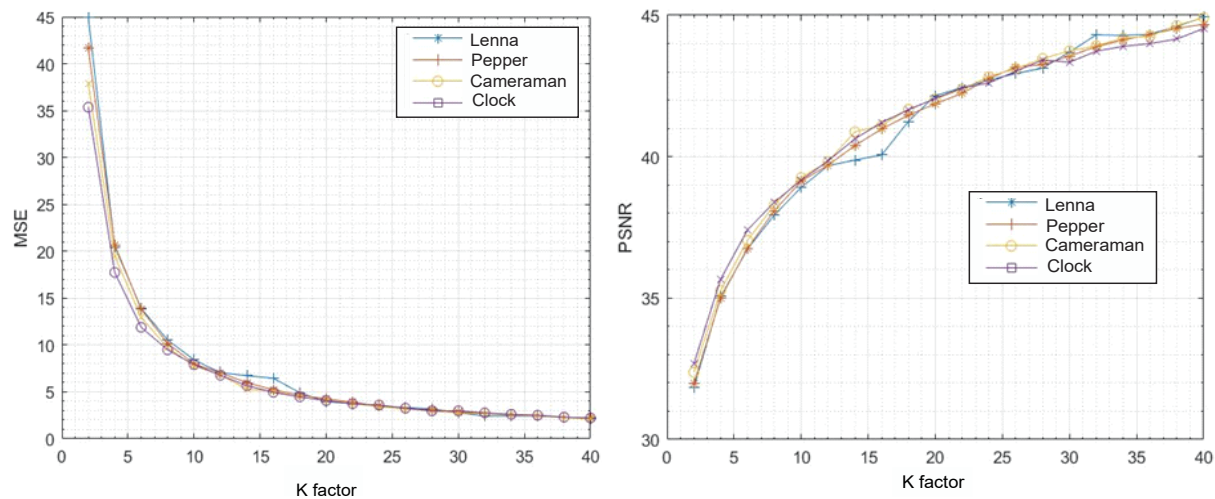
Source: result of the author's research, generated in MATLAB

Table 2. Obtained MSE and PSNR results for different values of the Rician K-factor under moderate turbulence conditions for the images: Lenna, Pepper, Cameraman, and Clock

K Factor	2	6	10	14	18	22	26	30	34	38
Lenna										
MSE	44.91	13.92	8.42	6.73	4.92	3.74	3.33	2.79	2.44	2.27
PSNR	31.84	36.73	38.91	39.88	41.25	42.44	42.94	43.70	44.29	44.61
Pepper										
MSE	41.64	13.82	8	5.99	4.67	3.91	3.16	2.88	2.53	2.3
PSNR	31.97	36.76	39.13	40.39	41.47	42.24	43.17	43.56	44.13	44.54
Cameraman										
MSE	37.86	12.04	7.78	5.30	5.09	3.78	3.20	2.77	2.5	2.25
PSNR	32.38	37.04	39.26	40.95	41.68	42.39	43.11	43.44	44.19	44.64
Clock										
MSE	35.36	11.89	7.92	5.66	4.47	3.74	3.27	2.99	2.52	2.22
PSNR	32.67	37.41	39.17	40.63	41.66	42.43	43.02	43.34	44.16	44.69

Source: Author's research

Figure 4. Graphical representation of the obtained MSE and PSNR for images transmitted through the turbulence channel under strong turbulence conditions



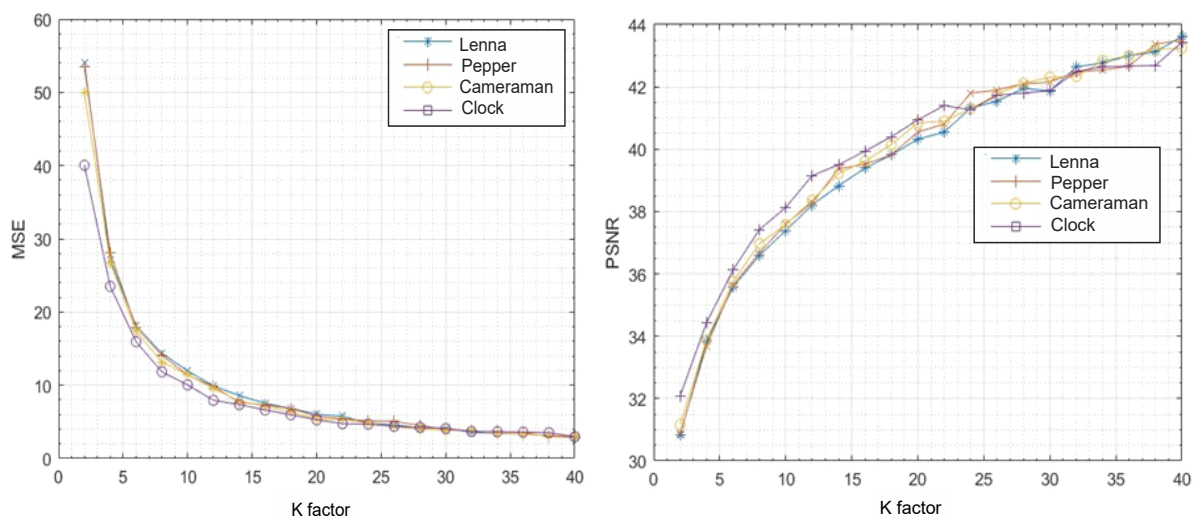
Source: Result of the author's research, generated in MATLAB

Table 3. Obtained MSE and PSNR results for different values of the Rician K-factor under strong turbulence conditions for the images: Lenna, Pepper, Cameraman, and Clock

K Factor	2	6	10	14	18	22	26	30	34	38
Lenna										
MSE	54.07	18.16	11.95	8.59	6.83	5.77	4.59	4.26	3.47	3.2
PSNR	30.83	35.57	37.39	38.83	39.82	40.55	41.54	41.87	42.77	43.12
Pepper										
MSE	53.51	17.86	11.39	7.67	6.82	5.43	5.06	3.99	3.65	3.01
PSNR	30.88	35.64	37.6	39.31	39.82	40.81	41.12	42.15	42.54	43.37
Cameraman										
MSE	50.04	17.4	11.43	7.85	6.33	5.3	4.37	3.85	3.41	3.14
PSNR	31.16	35.75	37.58	39.22	40.15	40.9	41.76	42.31	42.84	43.12
Clock										
MSE	40.04	15.95	10.05	7.36	5.97	4.75	4.38	4.25	3.65	3.53
PSNR	32.08	36.12	38.13	39.5	40.4	41.4	41.73	41.88	42.65	42.69

Source: Author's research

Figure 5. Graphical representation of the obtained MSE and PSNR for images transmitted through the turbulence channel under strong turbulence conditions



Source: result of the author's research, generated in MATLAB

Analysis of the results from the tables and graphs shows that for $K=6$ under weak, moderate, and strong turbulence conditions, the MSE values are 10.90, 13.92, and 18.16, respectively, while for $K=10$ the corresponding MSE values are 6.43, 8.42, and 11.95. Before transmission, immediately after embedding the digital watermark, the MSE value was 1.64.

The obtained results are consistent with expectations. Under weak turbulence conditions, even for lower values of the Rician K-factor ($K=6$), high-quality images can be achieved. Under moderate turbulence, the MSE increases on average by 31%, while under strong turbulence the increase reaches up to 80%.

If PSNR is analyzed, its values under weak, moderate, and strong turbulence for $K=6$ are 37.79, 36.73, and 35.57, respectively, while for $K=10$ the corresponding values are 40.08, 38.91, and 37.39. Before transmission through the channel, the PSNR value was 46.01. These results are also consistent with expectations. Under weak turbulence conditions, even for lower values of $K=6$, the image quality is good. When the PSNR exceeds 40 dB, the image is of excellent quality. In the specific case of $K=10$ under weak turbulence, the image quality is excellent. Under moderate turbulence, PSNR decreases by 3.5%, and under strong turbulence by 6.5%. With this level of degradation, images for $K=10$ can still be considered of good quality.

MSE and PSNR provide quantitative measures of the accuracy of the obtained information, allowing the assessment of differences in quality between transmitted and received data. The combination of these metrics contributes to the reliability and detail of the results, offering a comprehensive insight into system performance. In the analysis of the transmitted image, the embedding coefficient of the digital watermark was set to $K_u=5$; this level is relatively low and does not significantly affect additional image quality degradation. However, if the coefficient were higher, it can be expected that the error level would also increase, potentially causing error transfer from the watermark to the image after extraction. Therefore, K_u must be carefully selected to ensure that, with adequate visibility of the watermark before extraction, high-quality information transmission is maintained.

4. Conclusion

From the analysis of the transmitted images, it can be concluded that as the Rician K-factor increases, the quality of the transmitted images improves. As the turbulence intensity increases, the image quality decreases, making the quality of images questionable for lower K-factor values. Analysis of the images indicates that transmitted images can be considered of satisfactory quality only for $K \geq 10$. According to the results, to achieve high-quality images regardless of turbulence strength, $K \geq 20$ is required.

From the perspective of FSO systems, increasing the K-factor can be achieved by enlarging the receiver or transmitter aperture, increasing the transmitted power, and expanding the bandwidth. Additionally, one of the effective solutions is the implementation of adaptive optics to improve the performance of FSO systems under the influence of atmospheric turbulence. Future research plans include the application of adaptive optics in FSO system implementation, aiming to enhance the quality of transmitted information.

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