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Performance Evaluation of 2R BMOR & CMOR Cascade in Hybrid FSO-Fiber System

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Abstract

This paper evaluates the performance of 2R- Burst Mode Optical Regenerators (BMOR) and 2R-Continuous Mode Optical Regenerators (CMOR) cascades in a hybrid Free-Space Optical (FSO)-fiber system. The bit-error-rate (BER) degradation over various transmission distances and under varying turbulence conditions for different normalized transmit power levels is analysed. The finding helps in identifying optimal regeneration strategies for hybrid FSO-fiber Communication systems.

1. Introduction

Free-Space Optical (FSO) communication offers high data rates but suffers from performance degradation due to atmospheric turbulence. Hybrid FSO-fiber systems address this by combining FSO's flexibility with fiber's reliability. Optical regenerators (ORs), such as Burst Mode Optical Regenerators (BMORs) and Continuous Mode Optical Regenerators (CMORs), mitigate signal degradation [1], [2], [3]. Studies show that optical limiting amplifiers in BMORs improve signal quality in high-turbulence environments [4]. This paper evaluates 2R-BMOR and CMOR cascades in hybrid FSO-fiber systems, focusing on Bit Error Rate (BER) under varying atmospheric turbulence and normalized transmit power levels.

2. Methodology

2.1 Hybrid FSO-Fiber System

In a hybrid FSO-fiber system, data transmission involves optical signals being transmitted through both free-space and fiber-optic links as shown in figure 1. The performance of these systems is highly influenced by atmospheric turbulence, which is modeled using the Rytov variance σ_R^2 . This parameter captures the fluctuations in the phase and amplitude of the signal and is given by,

$$\sigma_R^2 = 1.23 \cdot C_n^2 \cdot \frac{2\pi^{7/6}}{\lambda} \cdot L^{11/6} \quad (1)$$

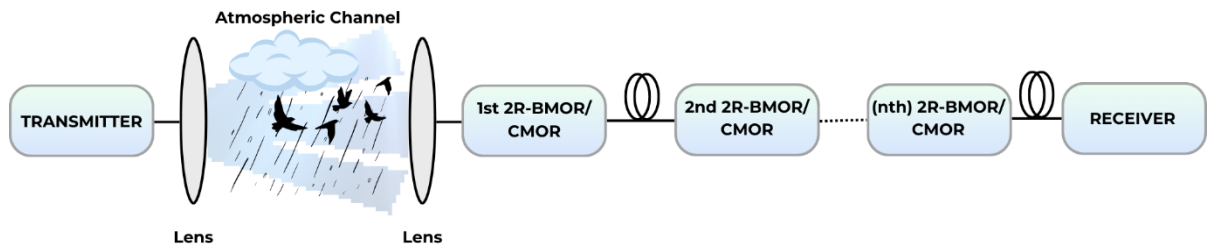


Fig. 1. Model diagram of a hybrid FSO-Fiber system

where C_n^2 is the refractive index structure parameter, λ is the wavelength, and L_{sig} is the transmission distance [5].

Fig. 1 shows the system investigation which includes a transmitter, receiver, and cascaded 2R-Optical Regenerators (ORs) that counteract signal degradation at various stages of the transmission. The communication channel between transmitter to 1st OR is FSO channel and subsequent channel sections are optical fibre consisting of optical amplifiers to boost the signal strength. Optical regenerators are employed to reshape and re-amplify (2R) the signal. A key performance metric in such systems is the bit-error-rate (BER), which can be calculated using the integral of the probability density functions (PDFs) of '1' and '0' signals. The BER is evaluated using,

$$BER = \frac{1}{2} (P_{1|0} + P_{0|1}) \quad (2)$$

To investigate the impact of atmospheric turbulence on the signal in presence of ASE noise, the PDF of the product distribution is used, where in f_X is the pdf of signal affected by ASE noise (X), f_Y is the gamma-gamma distributed pdf for atmospheric turbulence (Y). Z represents the overall transmitted signal and since $Z=XY$, f_Z is the product distribution given as [1]:

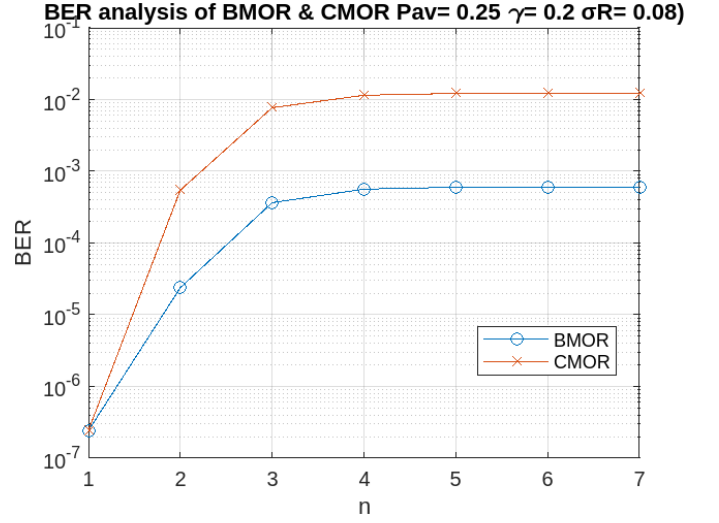
$$f_Z(z) = \int_{-\infty}^{\infty} f_X(x) f_Y\left(\frac{z}{x}\right) \frac{1}{|x|} dx \quad (3)$$

3. Results

The performance of 2R-BMOR and 2R-CMOR with a non-linearity reshaping parameter, $\gamma = 0.2$ [1], [2], was evaluated under varying turbulence conditions ($\sigma_R^2 < 0.1$ is weak and $0.1 < \sigma_R^2 < 10$ is strong [5]) and varying normalised transmit power (P_{av}) levels. In fig. 2, for $P_{av} = 0.25$ (low power level), as link length increases, BER obtained at the output of 1st OR degrades as the FSO channel becomes more turbulent, σ_R^2 value increases. Clearly, OR performs well under weak turbulence ($\sigma_R^2 = 0.08$) while strong turbulence ($\sigma_R^2 = 1.1$) worsens the BER.

Fig. 3 shows the BER performance for various BMOR/CMOR in the cascade (n), for low power level, $P_{av} = 0.25$. Under weak turbulence ($\sigma_R^2 = 0.08$), BMORs consistently maintains lower BER values compared to CMORs, with BMORs saturating around 10^{-5} and outperforming CMORs. In strong turbulence ($\sigma_R^2 = 1.1$) case, BMORs exhibits gradual BER degradation, while for CMORs BER rapidly degrades after stage 4, reaching BER values near 0.18, showing BMOR's robustness under harsher conditions.

Finally, fig. 4 shows the BER performance for normalised transmit power variation ($P_{av} = 0.1$ to 0.75). Cascade of BMORs performs better at lower power levels ($P_{av} = 0.1, 0.25$), but CMOR outperforms BMOR at higher power levels, $P_{av} = 0.5$ and 0.75 , maintaining lower BER values around 10^{-5} and 10^{-7} respectively.



(a) BMOR & CMOR performance with Rytov variance (σ_R^2) = 0.08

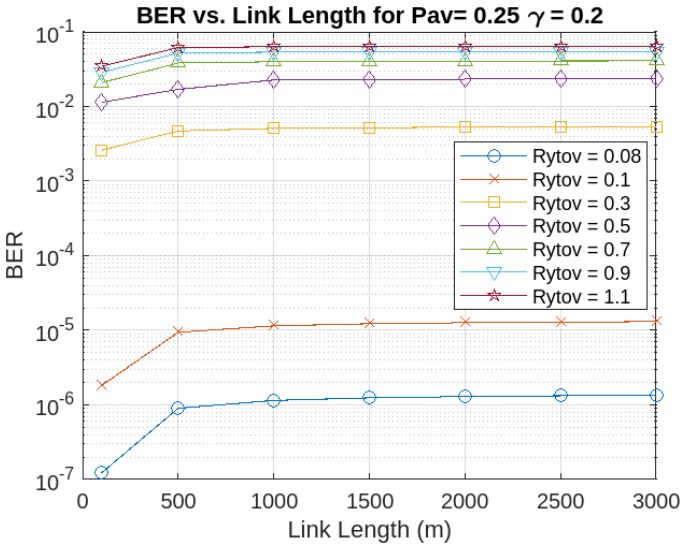
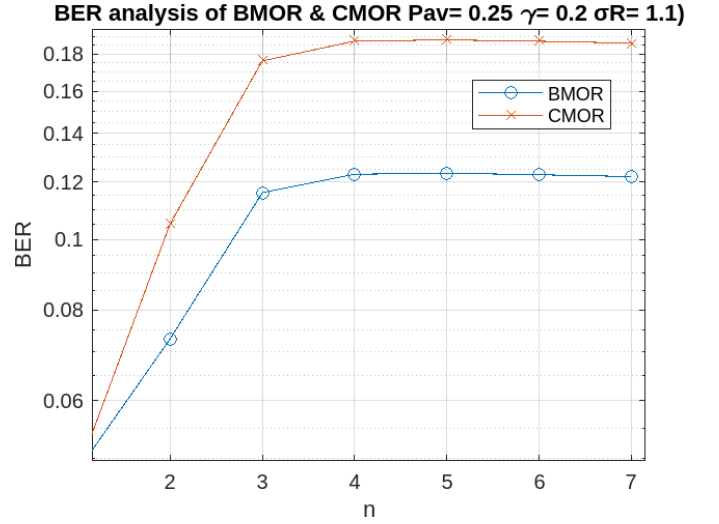
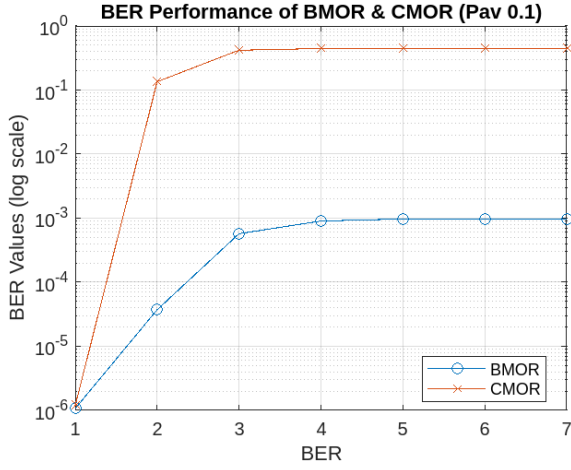


Fig. 2. BER Analysis at the output of first OR with Different Link Length

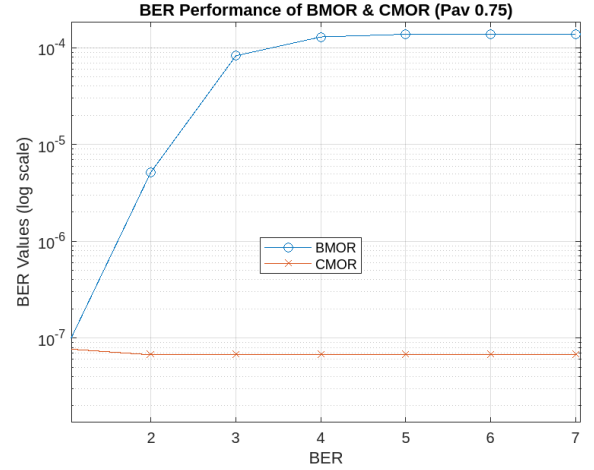


(b) BMOR & CMOR performance with Rytov variance (σ_R^2) = 1.1

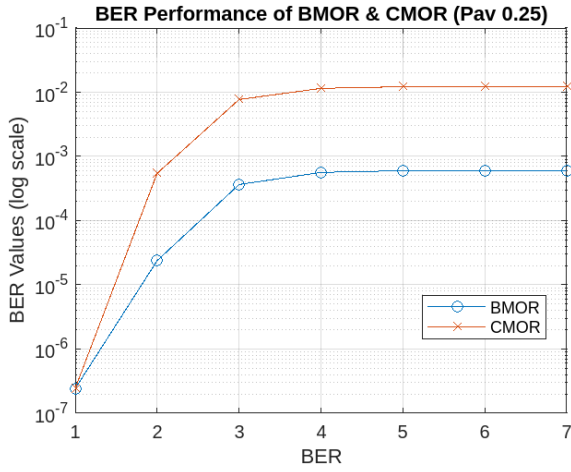
Fig. 3 BER Analysis of BMOR & CMOR with Different Rytov variance



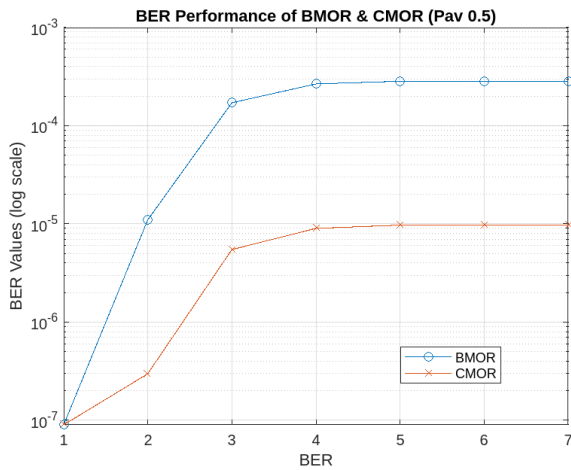
(a) BMOR & CMOR at ($P_{av} = 0.1$)



(d) BMOR & CMOR at ($P_{av} = 0.75$)



(b) BMOR & CMOR at ($P_{av} = 0.25$)



(c) BMOR & CMOR at ($P_{av} = 0.5$)

Fig. 4. BER Analysis of BMOR & CMOR $L_{sig} = 1\text{km}$, $\gamma = 0.2$, $\sigma_R^2 = 0.08$

4. Conclusion

This paper presented a performance evaluation of 2R-BMOR and CMOR cascades in hybrid FSO-fiber systems. The analysis highlighted that BMOR outperforms CMOR under weak turbulence and lower power levels, maintaining superior BER performance. However, at higher power levels, CMOR demonstrated better signal integrity. Additionally, under strong turbulence conditions, BMOR proved to be more robust, exhibiting less degradation in signal quality compared to CMOR. These findings suggest that the choice between BMOR and CMOR depends on specific system requirements, such as turbulence strength and transmit power level (normalised), to optimize signal regeneration in hybrid FSO-fiber systems.

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