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Mitigating atmospheric turbulence in FSO communications using Reed-Solomon coding: A performance analysis

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Abstract

Free-space optical (FSO) communication offers a high-bandwidth solution for modern networks, yet its reliability is critically undermined by atmospheric turbulence. This work thoroughly examines Reed-Solomon (RS) coding as an essential mitigation strategy. We evaluate the performance of the industry-standard RS(255, 223) code under moderate Gamma-Gamma turbulence. Through detailed simulations, we first quantify the coding gain, showing that the RS code breaks through the uncoded system error floor and provides a gain of over 3 dB at a bit error rate (BER) of 10^{-3}. Secondly, we isolate the performance penalty imposed by turbulence, which amounts to approximately 2.5 dB compared to a clear-sky channel. Finally, we investigate the critical impact of link distance by simulating the system over 300 m, 1000 m, and 2000 m. This reveals a significant performance penalty for longer links due to the cumulative effect of turbulence. This study definitively establishes that forward error correction (FEC) is a crucial element for dependable free-space optics (FSO), while also quantifying the practical performance constraints imposed by turbulence and distance.

1. Introduction

The constant need for higher data rates in modern telecommunications has driven extensive research into new and complementary technologies beyond traditional radio frequency (RF) systems [1]. Free-space optical (FSO) communication is becoming increasingly popular because it offers high bandwidth, requires no license to use the spectrum, is highly secure, and can be set up quickly [2, 3]. Because FSO systems modulate a laser beam to send data through the atmosphere, they are ideal for inter-building links, satellite communications, and “last-mile” connectivity [4, 5].

The primary barrier to the widespread adoption of FSO is its susceptibility to meteorological conditions. The refractive index of air varies unpredictably due to atmospheric turbulence caused by fluctuations in temperature and pressure. Scintillation, or fading, refers to the rapid variations in the received signal intensity resulting from fluctuations that distort the optical wavefront [6, 7]. Significant signal power degradation due to fading may result in numerous bit mistakes and potential link breakdown [8, 9].

To address this inherent constraint, several mitigating approaches have been suggested, including adaptive optics and diversity systems [10]. Among the most effective and practical solutions is the implementation of forward error correction (FEC) codes [11–13]. FEC codes improve link reliability by incorporating structural redundancy into the transmitted data, enabling the receiver to identify and correct errors without requiring retransmission [14].

Reed-Solomon (RS) codes, a category of non-binary cyclic block codes, are especially advantageous for fading channels such as FSO communication [15]. Unlike simple codes that correct individual bit errors, RS codes operate on symbols (groups of bits) and are exceptionally powerful at correcting burst errors (long sequences of consecutive bit errors), which are characteristic of signal fades caused by turbulence.

This paper aims to quantify the performance enhancement provided by the industry-standard RS code, RS(255, 223), in an FSO system operating under moderate

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atmospheric turbulence. We employ the widely accepted Gamma-Gamma distribution to model channel fading and use extensive Monte Carlo simulations to derive the bit error rate (BER) performance curve.

2. System and channel model

The end-to-end communication system simulated in this work comprises a transmitter, an atmospheric channel, and a receiver (Fig. 1).

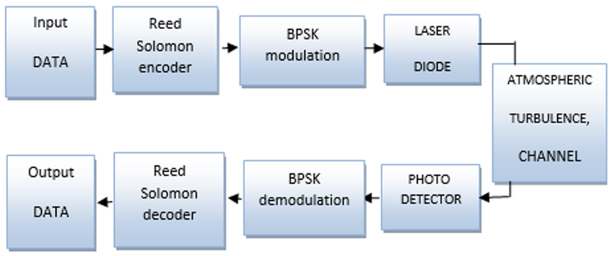

Fig. 1. Block diagram of the coded RS-FSO [14].

2.1. *FSO system with RS coding*

The transmitter generates a stream of random binary data. Initially, this data is encoded using the RS(255, 223) encoder. This specific code operates over the Galois field GF(2^8) and has five bits per symbol. A code word of $n = 255$ symbols (2040 bits) is created by encoding a block of $k = 223$ data symbols (1784 bits) and adding $(n - k) = 32$ redundant parity symbols. Up to $t = (n - k)/2 = 16$ incorrect symbols can be fixed within a single code word by this potent code [16]. A simple binary phase-shift keying (BPSK) is then used to modulate the encoded bits, mapping bits 0 and 1 to signal levels −1 and +1, respectively.

At the receiver, the incoming optical signal is converted into an electrical signal, which is subsequently demodulated. A hard-decision detector uses a zero threshold to identify received bits. Lastly, the received code word is processed by the RS decoder to correct any errors the channel may have introduced.

2.2. *Atmospheric turbulence channel*

The atmospheric channel is the most critical component of the model. The effect of turbulence-induced scintillation is modelled using the Gamma-Gamma probability distribution, which is well-validated for a wide range of turbulence conditions, from weak to strong [17]. The probability density function of the signal irradiance h is given by [18]:

$$f(I) = \frac{2(\alpha\beta)^{\left(\frac{\alpha+\beta}{2}\right)} I^{\left(\frac{\alpha+\beta}{2}\right)-1}}{\Gamma(\alpha)\Gamma(\beta)} K_{\alpha-\beta}(2\sqrt{\alpha\beta I}), \qquad I > 0, \quad (1)$$

where $\Gamma(\cdot)$ is the Gamma function, $K_{\alpha-\beta}(\cdot)$ is the modified Bessel function of the second kind [19], and α and β are the parameters representing the large-scale and small-scale atmospheric eddies, respectively [20]. These parameters can be directly related to atmospheric conditions according to

$$\alpha = \left[\exp\left(\frac{0.49\sigma_R^2}{\left(1 + 0.69\sigma_R^{\frac{12}{5}}\right)^{\frac{5}{6}}} \right) - 1 \right]^{-1} \quad (2)$$

$$\beta = \left[\exp\left(\frac{0.51\sigma_R^2}{\left(1 + 0.69\sigma_R^{\frac{12}{5}}\right)^{\frac{5}{6}}} \right) - 1 \right]^{-1} . \quad (3)$$

These parameters are directly related to the Rytov variance σ_R^2, which quantifies the strength of the turbulence [14]:

$$\sigma_R^2 = 1.23 C_n^2 k^{\frac{7}{6}} L^{\frac{11}{6}} . \quad (4)$$

C_n^2 denotes the refractive index structural parameter, $k = 2\pi/\lambda$ is the wave number for a wavelength λ, and L is the link distance [21]. Additive white Gaussian noise (AWGN) also messes up the received signal to simulate thermal noise at the receiver.

3. Simulation setup

The performance of the FSO system was evaluated using Monte Carlo simulations focusing on the widely used RS(255, 223) code, which offers a high code rate (≈ 87.5%) and is a standard in many communication systems. The key simulation parameters are outlined in Table 1.

Table 1
Simulation parameters.

Parameter	Value	Description
FEC code	RS(255, 223)	RS over GF(2^8)
Modulation	BPSK	Binary phase-shift keying
Wavelength (λ)	1550 nm	Standard for FSO communications
Turbulence strength (C_n^2)	2×10^{-15} m$^{-2/3}$	Moderate turbulence conditions
Channel model	Gamma-Gamma	Accurate turbulence model
Simulation stop criteria	300 errors	To ensure statistical significance
Link distances (L)	300 m, 1000 m, 2000 m	Practical link ranges

In the design of FSO systems, several modulation schemes are commonly considered. On-off keying (OOK) is often favoured for its simplicity but requires a complex adaptive threshold [22]. Pulse position modulation (PPM) offers excellent power efficiency at the expense of poor bandwidth efficiency [23]. For this study, a BPSK was selected. Its antipodal signal constellation provides maximum robustness and its optimal fixed detection threshold at zero allows unambiguous evaluation of channel code performance without confounding variables. Our analysis is divided into three key comparisons:

1) *Coded vs. uncoded system:* to demonstrate the fundamental benefit of FEC.
2) *Turbulent vs. clear-sky channel:* to quantify the penalty imposed by turbulence.
3) *Impact of link distance:* to evaluate system performance over practical operating distances of 300 m, 1000 m, and 2000 m, while keeping the turbulence strength parameter C_n^2 constant.

4. Results and discussion

4.1. Coded vs. uncoded performance in turbulence

To vividly demonstrate the fundamental necessity of FEC for FSO communications, we present a direct comparison between the RS(255, 223) coded system and its uncoded counterpart operating under identical moderate Gamma-Gamma turbulence conditions. Figure 2 illustrates this comparison.

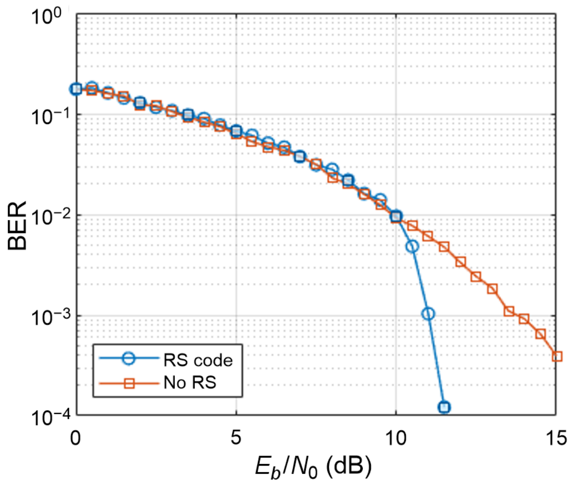

Fig. 2. BER of RS(255, 223) *vs*. uncoded in moderate Gamma-Gamma turbulence

When observing the performance of the uncoded system, a critical limitation becomes apparent: the error floor. While the BER initially improves with an increasing signal-to-noise ratio (SNR), it begins to plateau at approximately 5×10^{-3}. This flattening indicates that beyond a certain SNR threshold, the errors are no longer predominantly caused by additive noise, but by deep signal fades inherent to atmospheric turbulence. Consequently, the uncoded link demonstrates a fundamental unreliability for high-performance data transmission. Conversely, the RS(255, 223) coding system operates in a completely different manner. Initially, its performance resembles that of the uncoded system at lower SNRs; however, at about 10 dB, a distinct "waterfall" effect emerges. The RS code ability to correct burst errors caused by channel fading led to a rapid decrease in BER. The code circumvents the error floor by transforming sporadic errors into a format that can be corrected. To quantify this enhancement, we note that achieving a goal BER of 10^{-3} requires an SNR of around 13.5 dB in the uncoded system. Nonetheless, the RS-coded system achieves the same BER at a markedly lower SNR of 10.5 dB. This 3 dB difference represents a significant coding gain. Such a gain unequivocally proves that FEC is not merely an incremental improvement, but an essential enabling technology for achieving reliable FSO links in the presence of turbulent atmospheric conditions.

4.2. Fading vs. clear-sky performance

While FEC is highly effective, it is essential to understand the inherent performance penalty that turbulence still imposes on the system. Figure 3 isolates this effect by comparing the performance of the same RS(255, 223)-coded system in a turbulent channel *vs*. an ideal, clear-sky (AWGN) channel.

To precisely quantify the performance penalty imposed by atmospheric turbulence, the RS-coded system performance in a turbulent Gamma-Gamma channel was compared with that in an ideal, clear-sky (AWGN) channel. Figure 3 illustrates this comparison.

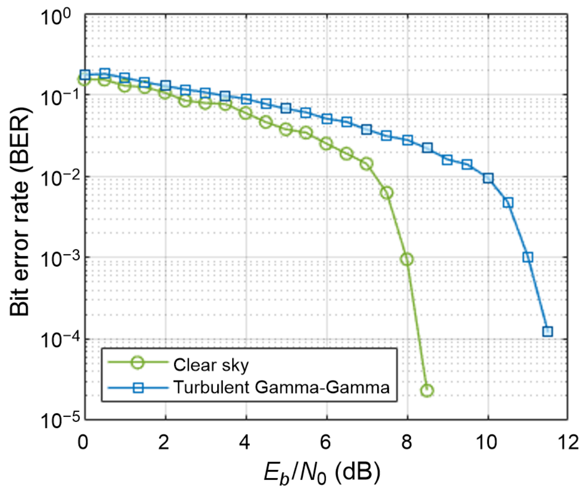

Fig. 3. BER of RS(255, 223) in Gamma-Gamma *vs*. AWGN channel.

Performance in the clear-sky (AWGN) channel serves as an ideal benchmark. The system achieves highly efficient performance, reaching a BER of 10^{-4} at an SNR of approximately 8.2 dB. In contrast, performance over the moderate Gamma-Gamma channel is substantially degraded by turbulence-induced fading. To achieve the same target BER of 10^{-4}, a system operating in turbulence requires a significantly higher SNR of 10.7 dB.

The turbulence penalty is the horizontal distance between the two curves, which in this case is about 2.5 dB. This result shows that even with a strong FEC scheme, the physical distortion caused by atmospheric fading makes the channel much more complex and more power-hungry than a simple AWGN channel.

4.3. The impact of link distance on codes system performance

The previous sections showed that coding is important. A key question for practical use is how the system performance changes with distance. To examine this, we simulated the RS(255, 223)-coded system across link distances of 300 m, 1000 m, and 2000 m, with the findings illustrated in Fig. 4.

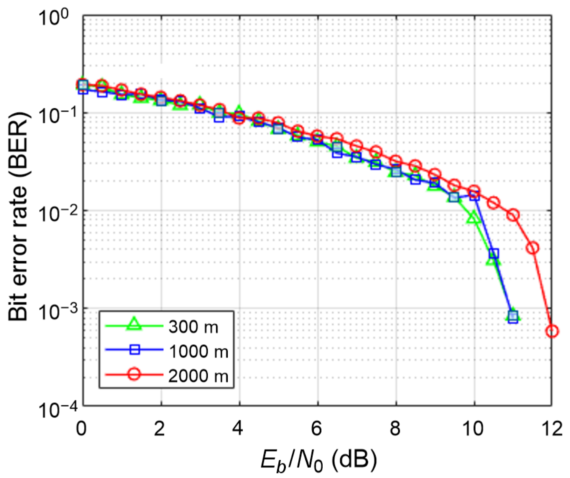

Fig. 4. BER of RS(255, 223) at different link distances in moderate turbulence.

To assess the system scalability within practical operating ranges, the influence of a link distance on the coded system performance was examined. Figure 4 shows how the performance changes for link distances of 300 m, 1000 m, and 2000 m when the same moderate turbulence parameter C_n^2 is used.

It is observed that the overall system performance degrades as the link distance increases. This degradation is attributed to the cumulative effect of turbulence, as the Rytov variance σ_R^2, which quantifies the scintillation strength, scales strongly with the link length L specifically, $\sigma_R^2 \alpha L^{11/6}$. To quantify this effect, the SNR required to achieve a target BER of 2×10^{-3} was analysed. It is shown that for the 300 m and 1000 m links, this target is reached at an SNR of approximately 10.5 dB. However, for the 2000 m link, the required SNR increases to 11.2 dB. This represents a power penalty of approximately 0.7 dB when doubling the distance from 1000 m to 2000 m.

Furthermore, the shallower slope of the 2000 m curve suggests that longer links are more susceptible to an error floor, even when coding is applied. This result demonstrates the critical need to account for link distance in the power budget design of any practical FSO system.

5. Conclusions

This paper presented a comprehensive performance evaluation of an RS-coded FSO system, yielding three principal conclusions. First, we have shown that FEC is an essential technology for FSO communications because it breaks through the error floor caused by turbulence in uncoded systems and provides a significant coding gain. Second, we have measured the inherent performance penalty due to turbulence by comparing it with an ideal clear-sky channel. This is still a problem for coded systems. Finally, our study of the effect of link distance showed that performance drops significantly as path length increases. This is because of the cumulative impact of turbulence, which makes longer links use a lot more power. This finding shows how important link distance is for the power budget and overall design of a reliable FSO network.

This work provides a clear, quantitative rationale for the use of robust channel codes in FSO systems. Additionally, it discusses the real-world constraints that atmospheric turbulence and distance of the communication link impose on them.

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