Performance Evaluation of Optical Links: With and Without Forward Error Correcting Codes

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Abstract. Optical links play a crucial role in modern communication systems, enabling high-speed data transmission over long distances with minimal loss and interference. As the demand for faster and more reliable networks continues to grow, evaluating the performance of optical links becomes paramount. There are several approaches to developing performance prediction strategies for optical links, including analytical models, numerical simulations, and experimental measurements. Analytical models are based on mathematical equations and can provide quick and accurate predictions of the link performance for simple systems. Numerical simulations use computer software to solve complex equations and simulate the link performance for more realistic systems. The prominent strategies include: link budget analysis; chromatic dispersion compensation; nonlinear impairment mitigation; error correcting codes. This work mainly focusses on analyzing the performance of optical link with various prediction strategies (hard decision-FEC, soft decision-FEC and probabilistic shaping)) using forward error correcting codes (FEC). The symbol error rate, bit error rate and achievable information rates have been analyzed for aforementioned strategies with and without FEC.

Keywords: Achievable information rate · Hard decision-FEC · Soft decision-FEC · Symbol error rate · Bit error rate · Optical links

1 Introduction

Performance prediction recipes for optical links are essential for designing and optimizing high-speed optical communication systems. These recipes are based on mathematical models that consider various factors such as fiber attenuation, dispersion, and nonlinearities, as well as the characteristics of the optical components such as lasers, detectors, and amplifiers. The goal is to predict the performance of the optical link in terms of key parameters such as bit error rate (BER), receiver sensitivity, and transmission distance, given the system specifications and operating conditions. There are several approaches to developing performance prediction recipes for optical links, including analytical models, numerical simulations, and experimental measurements. Analytical models are based on mathematical equations and can provide quick and accurate predictions of the link performance for simple systems. Numerical simulations use computer software to solve

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complex equations and simulate the link performance for more realistic systems. Experimental measurements involve actual measurements of the link performance using test equipment and can provide validation of the analytical or numerical models [1].

Some common techniques used in performance prediction recipes for optical links include: link budget analysis (this involves calculating the total losses and gains of the optical link, including fiber attenuation, connector losses, and component losses, and comparing the total received power to the minimum power required for the receiver to detect the signal); chromatic dispersion compensation (this involves using dispersion compensating fibers or dispersion compensation modules to compensate for the chromatic dispersion of the optical signal and improve the link performance); nonlinear impairment mitigation (This involves using techniques such as optical signal processing, modulation formats, or digital signal processing to mitigate the effects of nonlinear impairments such as self-phase modulation and four-wave mixing); error correction coding (This involves using forward error correction (FEC) or other error correction codes to reduce the BER of the optical link and improve the link performance). Link budget analysis is a fundamental technique used in performance prediction recipes for optical links. It involves calculating the total losses and gains of the optical link and comparing the total received power to the minimum power required for the receiver to detect the signal. Chromatic dispersion is a phenomenon that can limit the performance of optical links by causing pulse broadening and distortion. Chromatic dispersion compensation is a technique used in performance prediction recipes for optical links to mitigate the effects of chromatic dispersion and improve link performance [2, 3].

The dispersion compensation technique reduces the pulse broadening and distortion caused by chromatic dispersion, allowing for longer transmission distances and higher data rates. The amount of chromatic dispersion compensation required depends on the characteristics of the optical link, including the transmission distance, the wavelength, and the bit rate. The optimal amount of dispersion compensation can be determined by simulating the link performance using numerical simulations or by testing the link using experimental measurements. In summary, chromatic dispersion compensation is a critical technique used in performance prediction recipes for optical links to mitigate the effects of chromatic dispersion and improve the link performance. The use of dispersion compensating fibers or dispersion compensation modules can significantly improve the transmission distance and bit rate of the link, making it an essential tool for high-speed optical communication systems [4].

Nonlinear impairment mitigation is critical for performance prediction recipes for optical links because it can significantly improve the link performance and increase the maximum achievable bit rate. The optimal nonlinear impairment mitigation technique depends on the specific characteristics of the optical link, including the transmission distance, the bit rate, and the modulation format. In summary, nonlinear impairment mitigation is a crucial technique used in performance prediction recipes for optical links to mitigate the effects of nonlinearities and improve link performance. This technique can be accomplished by using modulation formats that are resistant to nonlinearities or by using digital signal processing techniques to estimate and compensate for the nonlinear distortion. Error correction coding is a technique used in performance prediction recipes for optical links to improve the reliability of data transmission and reduce the error rate. Error correction coding involves adding redundant information to the data before transmission, which can be used to detect and correct errors at the receiver. There are two types of error correction coding: block codes and convolutional codes. Block codes divide the data into fixed-length blocks and add redundant information to each block, while convolutional codes add redundant information to each data bit based on a sliding window of previous bits. One commonly used error correction code for optical communication is the Reed-Solomon code, which is a block code that adds redundant symbols to the data. The Reed-Solomon code can detect and correct errors in the received data, making it particularly useful in optical links where errors can occur due to noise or other impairments. Another commonly used error correction code for optical communication is the forward error correction (FEC) code, which is a type of convolutional code that adds redundant bits to the data [5–7].

The FEC code can detect and correct errors in the received data, and it can be designed to provide varying levels of error correction based on the specific requirements of the optical link. The use of error correction coding is critical in performance prediction recipes for optical links because it can significantly improve the reliability of data transmission and reduce the error rate. The optimal error correction coding technique depends on the specific requirements of the optical link, including the transmission distance, the bit rate, and the desired level of error correction. In summary, error correction coding is an essential technique used in performance prediction recipes for optical links to improve the reliability of data transmission and reduce the error rate. The use of block codes or convolutional codes, such as the Reed-Solomon code or the FEC code, can provide varying levels of error correction based on the specific requirements of the optical link [8, 9].

Performance prediction recipes for optical links are important for designing and optimizing high-speed optical communication systems and can help ensure reliable and efficient communication. These recipes are constantly evolving as new technologies and techniques are developed, and future research will continue to refine and improve these recipes. Therefore, in this work the performance prediction recipes for improvising the optical link performance in terms of BER have been estimated by employing FEC. The BER for various prediction strategies have been compared with and without employing FEC.

2 Literature Review

The basis for merging probabilistic shaping (PS) and forward error correction (FEC) is provided by [10]. Probabilistic amplitude shaping is a real-world application of the layered PS-FEC architecture, which consists of a PS encoder and an FEC encoder. Information-theoretic concepts are used to obtain attainable PS encoding rates and achievable FEC decoding rates. Based on data from optical transmission trials, the created tools are used to build and evaluate the performance of optical transponders. To assess post-FEC BER for systems with SD-FEC and PS, GMI is not applicable. Asymmetric information (ASI), normalized GMI (NGMI), and a feasible FEC rate have been suggested in [11] as alternatives for such cases.

The authors of [12] analysed the characteristics and coherence features of inter channel nonlinear interference (NLI) after evaluating models and mitigation methods. Based on the findings of this investigation, we developed an NLI mitigation technique that takes use of the synergistic interaction between subcarrier multiplexing with symbol rate optimization and correction for phase and polarization noise (PPN). The synergistic impact of symbol-rate optimization and phase-noise correction is examined in [13] following a discussion of models and mitigation techniques for inter channel nonlinearity. Practical applications of this phenomenon include the determination of capacity lower limits and nonlinearity mitigation. In [14], the authors have created new 4-PAM with any labelling closed-form BER expressions.

The spectral efficiency (SE) of fiber-optic systems may be easily changed via probabilistic amplitude shaping (PAS). By identifying the prerequisites for choosing the PC component codes, the authors of [15] has shown PAS may be used to bit-wise hard decision decoding (HDD) of product codes (PCs). In [16], the authors use probabilistic amplitude shaping (PAS) to make fiber-optic communication systems more spectrally efficient. They have considered probabilistic shaping using hard decision decoding (HDD), in contrast to earlier research in the literature. A proposed [17] multinary-signaling-based coded-modulation (CM) system outperforms traditional CM schemes in terms of both spectrum and energy efficiency, making it appropriate for a variety of applications ranging from multi-Tb/s to multi-Pb/s data rates. A design algorithm for the related multinary signal constellation is also put forward.

The literature available for performance prediction strategies of optical links based on error detecting codes and modulation schemes employing various strategies like; SD, HD, and probabilistic shaping. Here, in this work the performance of these strategies has been analyzed by incorporating FEC codes. The BER for aforementioned strategies has been evaluated and compared with and without FEC.

3 Methodology

The appropriate performance statistic for the system under consideration relies on the receiver's decoding method (SD, HD, bit-wise, symbol-wise, etc.). The decoding technique in an ideal receiver should take into consideration the precise nonlinear and bursty input-output relationship of the channel [18]. Since the precise relationship is typically unclear, a mismatched receiver built using a streamlined (auxiliary) 15 channel model is typically used. Usually, when designing a receiver, it is assumed that the output samples are simply distorted by an AWGN with a variance per dimension of (1).

$$\sigma^2 = \frac{1}{DN} \sum_{n=1}^{N} \|y_n - s(i_n)\|^2 \tag{1}$$

3.1 Strategies with HD-FEC

For each received vector y_n, the receiver makes an educated guess (i_{n1}) about the sent data in (i_n). The HD FEC decoder then receives this data for potential error correction.

Using (2), the most prevalent HD rule (minimal Euclidean distance) has been represented [19].

$$i_{n1} = \underset{j \in \{1, 2, 3..M\}}{argmin} \|y_n - s(i_n)\|^2 \tag{2}$$

The symbol error rate (SER) and bit error rate for HD-FEC can be represented using (3) and (4) respectively, where the δ function is 1 if the decision is true, otherwise it is zero.

$$SER^{HD} = \frac{1}{N}\sum_{n=1}^{N} \delta\left(i_n \neq \tilde{\text{i}}_n\right) \tag{3}$$

$$BER^{HD} = \frac{1}{mN}\sum_{n=1}^{N}\sum_{k=1}^{m} \delta\left(b_k(i_n) \neq b_k\left(\tilde{\text{i}}_n\right)\right) \tag{4}$$

The achievable information rate for HD-FEC is represented using (5) with binary entropy function (H_2) with various code rates R_c.

$$\mathrm{AIR_b^{HD}} = \mathrm{m(1 - H_2(BER^{HD})) \geq mR_c} \tag{5}$$

3.2 Strategies with SD-FEC

In these strategies, the decision has been taken on output sequence y_n based on the soft information available. The achievable information rates for these strategies have been estimated through symbol wise and bit wise and are represented using (6) and (7) respectively [15].

$$AIR_s^{SD} = m - \frac{1}{N}\sum_{n=1}^{N}\left\{\log_2 \sum_{j=1}^{M} q(y_n, s(j)) - \log_2 q(y_n, s(i_n))\right\} \tag{6}$$

$$AIR_b^{SD} = m - \frac{1}{N}\sum_{n=1}^{N}\sum_{k=1}^{m}\left\{\log_2 \sum_{j=1}^{M} q(y_n, s(j)) - \log_2 \sum_{j=1}^{M} \delta(b_k(j))\right\} \tag{7}$$

3.3 Strategies with Probabilistic Shaping

Probabilistic shaping [19], whose shaping operation is frequently realized via distribution matching (DM), has emerged as the most well-liked PS approach in recent years. The symbol entropy ($\mathrm{H_s}$) which is represented using (8). These strategies use bit wise FEC codes for decoding whose values are represented using (9).

$$H_s = -\sum_{j=1}^{M} p_l log_2 p_j \tag{8}$$

$$L_{n,k} = \ln \frac{\sum_{j=1}^{M} \delta\left(b_k(j) = 0) p_j(y_n, s(j))\right)}{\sum_{j=1}^{M} \delta\left(b_k(j) = 1) p_j(y_n, s(j))\right)} \quad (9)$$

The bit error rate and the achievable information rate using these strategies are represented using (10) and (11) respectively, where ASI is the asymmetric information available at each receiving vector y_n.

$$BER_b^{PS} = \frac{1}{mN} \sum_{n=1}^{N} \sum_{k=1}^{m} \delta\left(L_{n,k} \leq 0\right) \quad (10)$$

$$AIR_b^{PS} = H_s - (1 - ASI)m \quad (11)$$

4 Simulation Parameters

To simulate the bit error rata of an optical link, several parameters need to be considered which helps in accurately predicting the optical link performance. Table 1 provides the detailed list of parameters used for simulation.

Table 1. Execution Parameters

Parameter	Description
Data samples (N)	106
Mean (μ)	0
Variance(σ^2)	0.01
Constellation Symbol Dimension (D)	2 (for QAM)
Modulation	64-QAM
Symbol entropy (H_s)	6bits/symbol
SNR	5–30 dB

5 Simulation Results

The performance prediction of an optical link has been evaluated for various strategies with the help of MATLAB simulation software. The prediction strategies such as; hard decision, soft decision and probabilistic shaping have been analyzed based on forwarding error correcting codes (FEC) and compared the performance measures with and without employing FEC codes. Figure 1, shows the symbol error rate (SER) using hard decision-FEC has been estimated and compared the performance measures with and without FEC. It is clearly depicted in Fig. 1, that the SER is low for obtained output sequence with FEC when compared to SER without FEC.

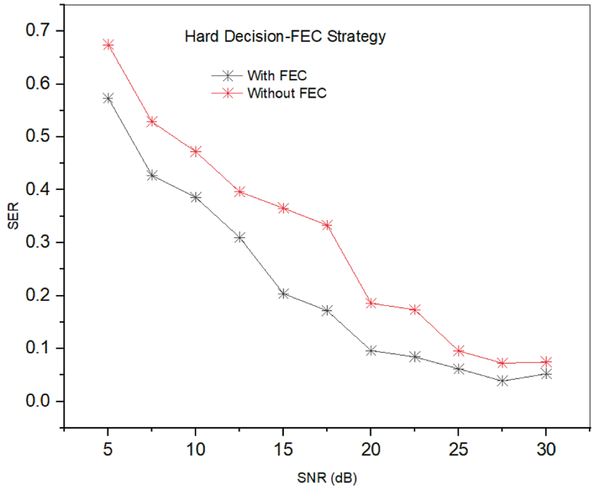

Fig. 1. SER Vs SNR for hard decision FEC strategy.

The BER for hard decision strategy has been evaluated and is depicted in Fig. 2. Similar to SER, the BER also is very low for the prediction strategy with FEC codes when compared to the strategy without FEC. It is evident from Fig. 2, 40% reduction in BER at an SNR of 5dB has been achieved for HD-FEC by employing FEC codes. Similarly, at 30dB, the BER is reduced to 50% (see the black line). The hard decision strategy with FEC achieves a BER of almost 0(zero) at an SNR of 30dB, whereas, the same strategy without FEC archives a BER of 0.4 at 30dB.

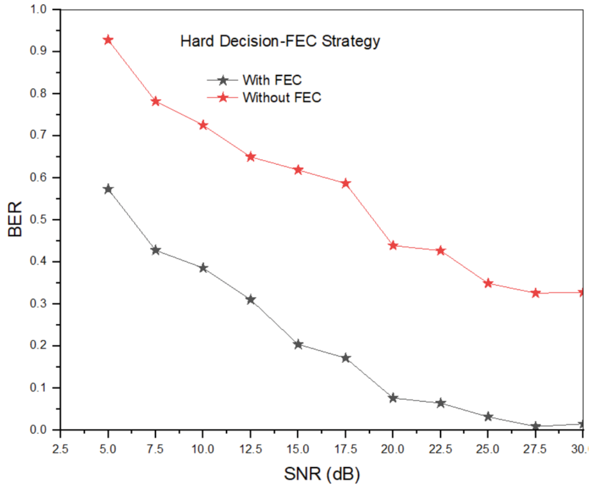

Fig. 2. BER Vs SNR for hard decision FEC strategy.

The achievable information rate is proportional to SNR with hard decision strategy in both the cases such as: with and without FEC. But hard decision with FEC attained more AIR when compared to hard decision without FEC (see Fig. 3). At low SNR values (from 5 to 20 dB), the AIR in both cases is similar, but at high SNR values the achieved AIR is more in hard decision with FEC when compared to hard decision without FEC.

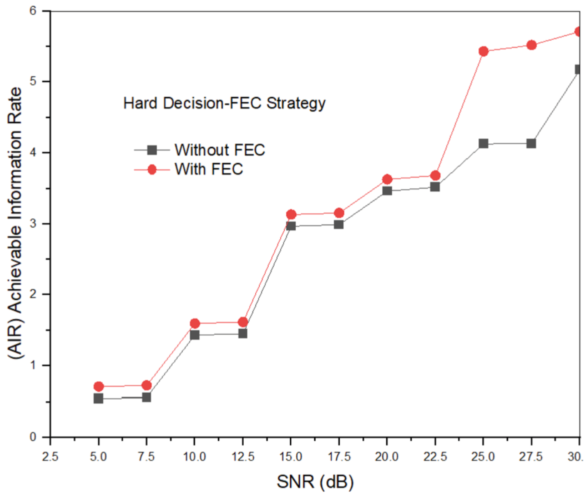

Fig. 3. AIR Vs SNR for hard decision FEC strategy.

In soft decision strategy, the AIR has been evaluated via symbol wise (see Fig. 4) and bit wise (see Fig. 5). Similar to hard decision FEC, the AIR is proportional to SNR but in soft decision FEC the maximum AIR of 7.5 has achieved. Whereas, in hard decision FEC the maximum AIR of 5.8 has achieved.

Probabilistic shaping for optical link performance prediction strategy has been widely used and most popular strategy. It is also evident from Fig. 6, the maximum BER at low SNR is 0.3 without FEC and 0.2 with FEC. It is observed from Fig. 7, the AIR with probabilistic shaping has attained maximum value when compared to hard decision and soft decision FEC.

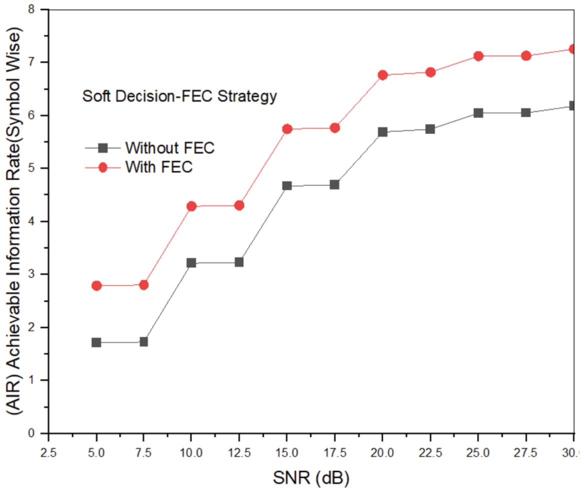

Fig. 4. AIR (symbol wise) Vs SNR for soft decision FEC strategy.

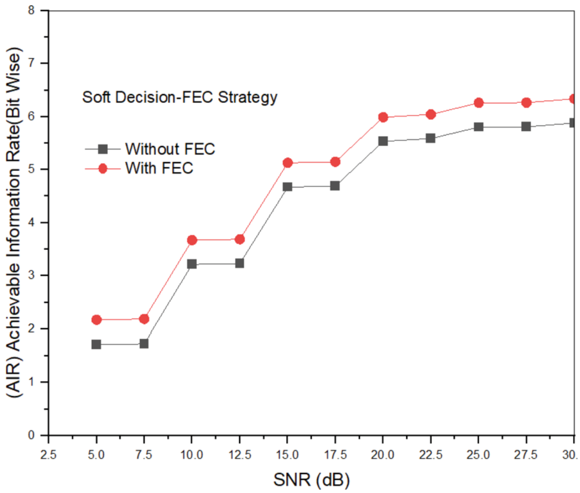

Fig. 5. AIR (bit wise) Vs SNR for soft decision FEC strategy.

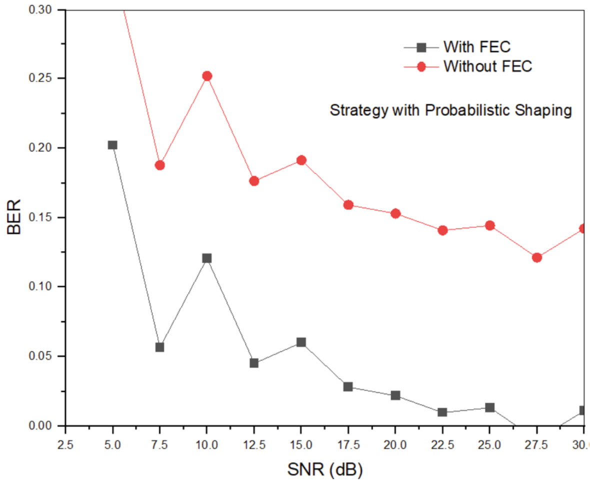

Fig. 6. BER Vs SNR for probabilistic shaping strategy.

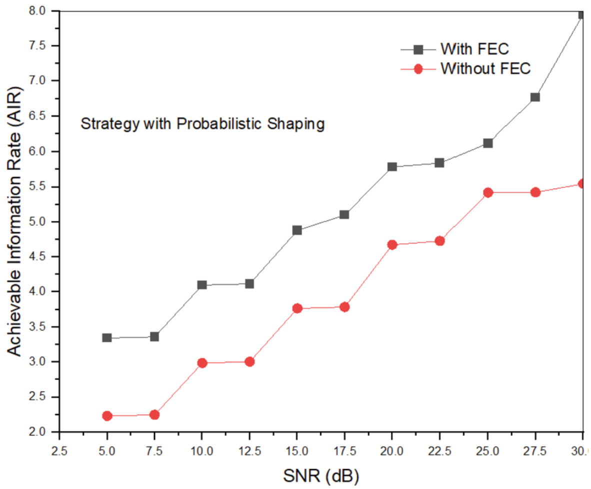

Fig. 7. AIR Vs SNR for probabilistic shaping strategy.

6 Conclusion

In this work, the performance measurements with and without the use of forwarding error correcting codes (FEC) have been compared for several prediction algorithms, including hard decision, soft decision, and probabilistic shaping. By implementing the hard decision FEC strategy, a remarkable 40% decrease in BER has been accomplished at low SNR levels. Additionally, by utilizing FEC codes, a substantial 50% reduction in BER has been achieved at higher SNR values. On the other hand, the performance of soft decision FEC has been evaluated in terms of the AIR for both symbol-wise and bit-wise approaches. The analysis reveals that the symbol-wise soft decision FEC achieves a maximum AIR of 7.5, while the bit-wise approach attains an AIR of 5.8. Comparatively, employing FEC codes with probabilistic shaping yields an even higher AIR of 8. Specifically, at low SNR values, the BER is reduced by 40% without FEC, and an impressive 80% reduction is achieved with FEC combined with probabilistic shaping. These reductions are observed when comparing the results to both the hard decision and soft decision strategies. Moreover, at high SNR levels, the BER becomes nearly negligible when FEC codes are employed. The effectiveness of FEC becomes apparent, as it ensures a highly reliable transmission with minimal errors, leading to a BER that approaches zero. Finally, the combination of FEC codes and probabilistic shaping techniques yields substantial improvements in BER performance. At low SNR values, the reductions are 40% without FEC and 80% with FEC and probabilistic shaping. Additionally, at high SNR values, the BER approaches zero when employing FEC codes, indicating a highly reliable transmission.

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