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**Research Article**

# A Unified Analytical and Statistically Validated DSP-Based BER Model for Manchester-Coded FTTH Optical Networks

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## Abstract

The paper presents a unified model of bit error rate (BER) analysis of the Manchester-coded fibre-to-the-home (FTTH) optical network, which has been statistically proven using digital signal processing (DSP) approaches. The model mathematically describes individual and combined effects of fibre attenuation and chromatic dispersion on the performance of the transmission, providing a closed-form BER expression which links the theoretical analysis with the validation in simulation. To evaluate the model, a set of optical link simulations was conducted with the help of an Eye Diagram Analyser, and concentration was given on the behaviour of BER and Q-factor under the varying attenuation (between 0.8 and 1.4 dB/km) and chromatic dispersion values (between 10 and 30 ps/nm). The findings indicate that there is a strong negative relationship between attenuation and signal quality; the lowest BER is $10^{-62}$ at 0.8 dB/km, then $10^{-29}$ at 1.4 dB/km, and the best Q factor decreases to 16.56 up to 17.28. Equally, the growth in chromatic dispersion, 10 to 30 ps/nm, results in an increase in BER, $10^{-62}$ to $2.3x10^{-4}$, and lowering of Q-factor, 74.46 to 3.42, and indicates that the main impairment in Manchester-coded FTTH systems is chromatic dispersion. These findings are also supported by eye diagram analysis, which indicates that eye closure and inter-symbol interference increase with attenuation and dispersion, respectively. The proposed model demonstrates a high level of concordance between analytical forecasts and simulation outcomes, which is a practical and computationally efficient model to use in connecting the link budget planning, performance, and the system optimisation in future FTTH passive optical network implementation.

**Keywords:** Manchester coding; FTTH networks; Bit Error Rate (BER); attenuation; chromatic dispersion; digital signal processing (DSP); regression analysis; statistical validation; Q-factor

## 1. Introduction

Fibre-to-the-home (FTTH) network development has seen a notable increase over the past few years, which has been fuelled by the increasing bandwidth demand brought about by triple-play services, cloud computing, and new uses such as ultra-high-definition streaming and virtual reality [1]. Passive optical networks (PONs) remain the dominant architecture in the FTTH deployment, and the current systems are migrating off the traditional Gigabit PON (GPON) platforms toward next-generation technologies, such as 50G and 100G and coherent PONs, to provide higher capacity, longer reach, and greater spectral efficiency [2, 3]. These developments represent a paradigm shift in access network design in that, in contrast to the previous generation which was mainly concerned with analogue impairments and forward error correction, the current generation FTTH networks are now embracing the application of digital signal processing (DSP) on the receiver end to enable adaptive modulation, real time monitoring and advanced forms of equalization [4, 5]. Here, line coding schemes such as Manchester coding, which use clock information by maintaining a transition at each bit period,

are particularly beneficial to optical access networks. These can be DC balance, ease of clock recovery, and greater robustness against a long series of repeated bits.

Nevertheless, the interplay between Manchester-coded transmission, DSP-based receivers, and the observed fibre channel impairments in FTTH (Fibre to the Home) settings is not properly described in the current literature. In the period of 2021-2026, an analysis of the literature shows no published analytical frameworks dedicated to bit error rate (BER) modelling of Manchester-coded FTTH links in realistic DSP processing conditions, which is a research gap. The prediction of bit error rate (BER) accuracy is a key concern in the architecture and implementation of fibre-to-the-home (FTTH) networks, where accurate prediction of the error rate directly affects reach, power budget allowed, and the ratio of optical distribution network (ODN) splits [6]. Modelling of BER has become a complicated issue in more recent times in the case of modern passive optical networks (PON) because of interactions between various factors, including wavelength-dependent fibre dispersion, loss due to splitting, nonlinear crosstalk in dense wavelength-division-multiplexed (WDM) conditions, and the multiplicity of digital signal processing (DSP) architectures being used at receiver terminals. It has been demonstrated by recent experiments that receiver-side DSP parameters, such as oversampling rates, number of adaptive filter taps, and algorithmic complexity, have a pronounced influence on the computational load and the BER performance [7]. To illustrate, non-integer-oversampling DSP implementations have the potential to halve the load on analogue-to-digital converters (ADCs) and processing in coherent PONs, without causing a significant penalty in sensitivity, which highlights the sensitivity of the results of BER to design decisions in DSPs [7]. Similarly, empirical relationships have also been identified between observed BER and signal-to-noise ratio (SNR) measurements and real-time ODN monitoring based on receiver-side DSP, and thus analytical models that effectively model signal transformations in the DSP domain are required [8].

The integration of coherent optics and DSP-based detection is a big breakthrough for access networks. Coherent Passive Optical Network (PON) systems combine with local oscillators to provide high receiver sensitivity, extend power budgets to 40 dB, and a flexible modulation format, thus providing 100 Gb/s per wavelength and higher data rates. Such systems heavily depend on DSP modules to perform such fundamental tasks as carrier phase recovery, adaptive equalisation, and burst-mode synchronisation, each of which directly affects the statistics of the decision variable, and, by implication, the Bit Error Rate (BER). Although the architectural surveys of next-generation PONs describe the major DSP steps, processing and performance trade-offs, they fail to agree on a single analytical BER framework, which can be used across the different modulation schemes, sampling strategies, and coding formats. This leaves network designers at present without a practical, DSP-aware analytical model of predicting BER in more sophisticated coding schemes such as Manchester encoding in realistic Fibre to the Home (FTTH) systems. Despite being a vital aspect of the validation of BER models, the statistical validation is often ignored. Although many papers provide simulated or measured BER curves of particular PON structures [6, 11], few of them provide rigorous statistical validation procedures, including estimation of confidence interval, hypothesis testing, or systematic comparison with large field data, to demonstrate the accuracy and generalizability of the models. The variety of deployed FTTH platforms (GPON, XG-PON, and 50G/100G PON variants, coherent single-wavelength, etc.) makes the validation procedure more complex, since one modelling framework would have to be able to take care of a wide variety of physical-layer parameters, digital signal processing (DSP) paradigms, and operating conditions [2, 3, 9]. Although the recent study on DSP-assisted 100 Gb/s PONs and XG-PON reach/split analyses offers a significant contribution to the understanding on the dataset level, it is still not a comprehensive study to establish an analytic-statistical framework comprising both closed-form expressions and empirical calibration and validation [6, 11].

This paper fills in the gaps by creating a complete, analytically and statistically proven DSP-based BER model that is tailored to a Manchester-rated FTTH optical network. The model covers physical-

layer impairments like chromatic dispersion, amplified spontaneous emission noise, and splitting loss. Also, the DSP receiver functions like matched filtering, timing recovery, and adaptive equalisation on a single analytical framework. The proposed model aids in predicting the outcome of BER with high accuracy in a wide number of FTTH deployment systems by incorporating realistic DSP architectures and explicit statistical validation using measured data. This helps in informed decision-making on the network planning, allocation of margins, and the selection of technology. The rest of this paper is organized as follows: Section 2 will give a review of the principles of Manchester coding, DSP-based PON receiver designs, and BER analysis methodologies. In section 3, there is a derivation of an overall analysis of the BER model that takes into consideration the nature of fibre channels and DSP processing stages. In section 4, the results of the simulation and the discussion are provided. Lastly, Section 5 is the conclusion of the paper.

## 2. Fundamentals of Manchester Coding, DSP-Based PON Receivers, and BER Analysis

The section provides the theoretical bases of the formulation of a single BER model using DSP to achieve Manchester-coded FTTH networks. We consider the principles of Manchester line coding, DSP-based reception architecture of PON, and BER analysis protocols.

### *2.1 Manchester Coding Fundamentals*

Manchester coding is a self-clocking line code, in which a required mid-bit shift is used to encode each bit: the encoder is a Low-to-High transition to encode logical 0 and High-to-Low transition to encode logical 1, so clock recovery is possible without a dedicated channel [12].

The Manchester-encoded waveform is:

$$s_M(t) = \Sigma_k b_k \cdot [p(t - kT_b) - p(t - kT_b - T_b/2)] \quad (1)$$

ensuring intrinsic DC balance over every bit period. Its power spectral density satisfies:

$$S_M(f) \propto sinc^2(fT_b/2) \cdot \sin^2(\pi f T_b/2) \quad (2)$$

with a DC null and first lobe centred at f = 1/T_b, requiring approximately twice the bandwidth of NRZ [15].

The main benefits are self-synchronization with up to 1% frequency offset [12], enhanced noise immunity [13, 14], ensured DC balance [15, 16], and simplified FPGA implementation with BER of less than $10^{-2}$ at SNR more than -12 dB [12]. The major drawback is that it doubles the bandwidth demand, where spectral efficiency goes to a minimum of 0.5 bit/s/Hz [15, 16].

**Table 1.** Comparison of Manchester, NRZ, and RZ Line Codes

| Characteristic | Manchester | NRZ | RZ |
|---|---|---|---|
| Self-clocking | Yes [12,13] | No | Limited |
| DC balance | Guaranteed [15,16] | Pattern-dependent | Duty-cycle dependent |
| Spectral occupancy | ~2× bit rate [15] | ~1× bit rate | ~1.5–2× bit rate |
| Spectral efficiency | ~0.5 bit/s/Hz | ~1 bit/s/Hz | ~0.5–0.7 bit/s/Hz |

### *2.2 DSP-Based PON Receiver Architectures*

Modern DSP-based PON receivers process signals digitally through the chain [17, 18]:

Optical Input → Photodetection → ADC → Digital Matched Filter → Timing Recovery → Adaptive Equalizer → FEC Decoder → Data Output

**ADC and Oversampling:** Non-integer oversampling at 9/8 or 5/4 sps reduces DSP complexity by 40–44% with < 0.5 dB sensitivity penalty [17]. The ADC output is:

$$y[n]=s_M(nT_s)+\eta[n] \tag{3}$$

**Matched Filter:** Matched to the bipolar Manchester pulse h_M(t) = p(t) − p(t − T_b/2), yielding peak SNR:

$$SNR_{MF}=2E_b/N_0 \tag{4}$$

**Timing Recovery:** Manchester's mid-bit transitions provide explicit timing references, with timing error estimated from zero-crossings [12]:

$$\hat{\varepsilon}=t_{cross}-(k+0.5)T_b \tag{5}$$

**Adaptive Equalisation:** An N-tap FIR equaliser compensates chromatic dispersion and ISI, with LMS tap updates [17, 18]:

$$\hat{s}[k]=w^T\cdot y_k, w[k+1]=w[k]+\mu\cdot e[k]\cdot y_k* \tag{6}–(7)$$

Computational load scales as C = K · N · R_b MACS [17], with N = 10–50 taps typical for 20–40 km PON spans.

### *2.3 BER Analysis*

**Theoretical Framework:** Under the Gaussian approximation, BER is:

$$BER=(1/2)\cdot erfc(Q/\sqrt{2}), Q=(\mu_1-\mu_0)/(\sigma_1+\sigma_0) \tag{8}–(9)$$

Practical targets are BER < $10^{-9}$ (uncoded) and BER < $10^{-3}$ (pre-FEC). Manchester coding yields 1–3 dB Q-factor improvement under noisy conditions due to self-synchronisation [13], though its bipolar pulse shape requires modified BER derivations addressed in this work.

**Noise Sources:** Three primary contributions are:

$$\sigma^2_{shot}=2qRP_{rx}B \tag{10}$$

$$\sigma^2_{thermal}=4k_{BT}B/R_L \tag{11}$$

$$\sigma^2_{total}=\sigma^2_{shot}+\sigma^2_{thermal}+\sigma^2_{ASE} \tag{12}$$

Manchester's doubled bandwidth increases integrated noise by ~3 dB, partially offset by self-clocking benefits [13, 14].

**ISI and Dispersion:** Chromatic dispersion causes group-delay spread ΔT = D · L · Δλ [2.16], producing significant ISI when ΔT > T_b/4. The ISI-limited reach is:

$$L_{max}\approx T_b/(4D\Delta\lambda) \tag{13}$$

Manchester's wider spectrum exacerbates this penalty, motivating DSP equalisation with N = 10–50 taps [17, 18].

**Statistical Validation:** BER confidence intervals and chi-squared goodness-of-fit tests are employed [2.14]:

$$\chi^2=\Sigma_i(O_i-E_i)^2/E_i \tag{14}$$

Recent literature lacks explicit statistical validation [12, 13, 14], which is filled in this work by confidence intervals, chi-squared tests, and cross-validation of the model against experimental results.

## 3. System Model and Signal Formulation

A transition represents each bit in a Manchester-coded FTTH optical network; a logical 1 is indicated by a low-to-high transition, and a logical 0 by a high-to-low transition in the middle of the bit period. The encoded Manchester optical signal may be represented as:

$$x(t) = A \cdot m(t) \cdot \cos(2\pi f_{c \cdot t} + \varphi_0) \quad (15)$$

where **A** is the optical field amplitude, **m(t)** is the Manchester-coded baseband signal (±1), **f_c** is the carrier frequency, and **φ_0** is the initial phase.

The Manchester code doubles the signalling rate, effectively occupying twice the bandwidth of NRZ, but offers inherent clock synchronisation and DC-balance properties critical for optical systems.

### *3.1 Optical Channel Transfer Function*

Attenuation and chromatic dispersion are the two main degradation mechanisms that are introduced by the optical fibre channel. This frequency-domain composite channel transfer function is:

$$H(f) = \exp(-\alpha \cdot L/2) \cdot \exp(-j \cdot \beta_2 \cdot (2\pi f)^2 \cdot L/2) \quad (16)$$

where **α** [dB/km] is the fibre attenuation coefficient, **L** [km] is the fibre length, **β_2** [ps²/km] is the group velocity dispersion parameter, and **f** is the baseband frequency.

#### 3.1.1 Attenuation Effect

The received optical power after propagation through a fibre of length L is governed by the Beer-Lambert law:

$$P_{rx} = P_{tx} \cdot 10^{(}-\alpha \cdot L/10) \quad (17)$$

For the normalised attenuation parameter used in this model ($\tilde{\alpha} = \alpha \cdot L$, dimensionless path loss), the received field amplitude scales as:

$$A_{rx} = A_{tx} \cdot \exp(-\tilde{\alpha}/2) \quad (18)$$

This exponential decay directly determines the signal-to-noise ratio at the receiver, and hence governs the BER floor at low attenuation and the BER ceiling at high attenuation.

#### 3.1.2 Dispersion-Induced Pulse Broadening

Chromatic dispersion causes group delay variation with frequency, resulting in pulse broadening. The RMS pulse width after propagation is:

$$\sigma_T = ¿ \beta_2 \vee \cdot L \cdot \Delta\omega \quad (19)$$

where **Δω** is the RMS spectral width of the Manchester pulse, the intersymbol interference (ISI) penalty factor due to dispersion is defined as:

$$\eta_D = \exp(-\sigma_{T^2}/(2 \cdot T_{b^2})) \quad (20)$$

where **T_b** is the bit period, for the normalised dispersion parameter $\tilde{\mathbf{D}} = \beta\_2 \cdot L \cdot B^2$ (with B the bit rate), this becomes:

$$\eta_D = \exp(-2\pi^2 \cdot \tilde{D^2}) \quad (21)$$

### *3.2 Analytical BER Derivation*

At the photodetector, direct detection converts the received optical power to a photocurrent. Assuming a PIN photodiode with responsivity R, the signal current after matched filtering is:

$$i_s = R \cdot P_{rx} \cdot \eta_D \quad (22)$$

The dominant noise sources in an FTTH system are thermal noise and shot noise. The total noise variance at the decision circuit is:

$$\sigma^2_{total} = \sigma^2_{thermal} + \sigma^2_{shot} = (4k_{¿})/R_L + 2q \cdot i_{¿} \quad (23)$$

where **k_B** is Boltzmann's constant, **T** is the temperature, **B_e** is the electrical bandwidth, **R_L** is the load resistance, and **q** is the electron charge.

### 3.2.1 Q-Factor Formulation

For binary on-off keying with Manchester coding, the Q-factor at the receiver is defined as the normalised eye opening:

$$Q = i_s / (\sigma_0 + \sigma_1) \tag{24}$$

where **σ_0** and **σ_1** are the noise standard deviations for '0' and '1' levels. Substituting the signal and noise expressions:

$$Q = (R \cdot P_{¿}) / \sqrt{(2 \cdot (\sigma^2_{thermal} + q \cdot R \cdot P_{¿}))} \tag{25}$$

### 3.2.2 Closed-Form BER Expression

The complementary error function gives the BER for direct-detection binary optical signalling with Gaussian noise approximation:

$$BER = (1/2) \cdot erfc(Q / \sqrt{(2)}) \tag{26}$$

Substituting the full expressions for signal current and noise:

$$BER(\alpha\tilde{}, D\tilde{}) = (1/2) \cdot erfc[(R \cdot P^{(}_{tx \cdot e} - \alpha\tilde{}) \cdot e^{(} - 2\pi^2 D\tilde{}^2))/(\sqrt{(2)} \cdot \sigma_n)] \tag{27}$$

where **σ_n** = sqrt(σ²_thermal + 2q·R·P_tx·e^(-α̃)·e^(-2π²D̃²)·B_e) is the composite noise standard deviation, and **e^(-α̃)** = e^(-2α̃2) represents the power attenuation factor.

### *3.3 $Log_{10}$(BER) Closed-Form and Validation*

The log-domain BER, which corresponds directly to the bar chart values shown in the experimental results, is:

$$\log_{10}(BER) = \log_{10}(1/2) + \log_{10}[erfc(Q / \sqrt{(2)})] \tag{28}$$

For large Q (high SNR regime), the erfc function is well-approximated by:

$$erfc(x) \approx \exp(-x^2) / (x \cdot sqrt(\pi)) \quad \textbf{for x >> 1} \tag{29}$$

Therefore, the $\log_{10}$(BER) in the high-SNR regime simplifies to:

$$\log_{10}(BER) \approx -Q^2 / (2 \cdot \ln 10) - \log_{10}(Q \cdot sqrt(2\pi)) \tag{30}$$

This shows that BER decreases quadratically in the Q-factor (and hence exponentially with SNR), consistent with the steep slope observed in the BER vs Attenuation and BER vs Dispersion plots.

### 3.3.1 Attenuation Dependence

Substituting the attenuation-only model (D̃ = 0, no dispersion), the Q-factor becomes:

$$Q(\alpha\tilde{}) = (R \cdot P^{(}_{tx \cdot e} - \alpha\tilde{}))/\sigma_{thermal} \tag{31}$$

Taking the $\log_{10}$(BER) and using the high-Q approximation:

$$\log_{10}(BER) \approx -(R \cdot P_{tx})^2 \cdot e^{(} - 2\alpha\tilde{}) / (2 \cdot \sigma^2_{thermal \cdot ln} 10) + const \tag{32}$$

This predicts that for increasing attenuation α̃, the BER increases (becomes less negative in log scale) following a super-exponential trend — which is exactly what the BER vs Attenuation plot demonstrates, with $\log_{10}$(BER) values of −62.2 (α̃= 0.8), −47.0 (α̃= 1.2), and −29.0 (α̃= 1.4).

### 3.3.2 Dispersion Dependence

For the dispersion-only model (α̃fixed, varying D̃), the dispersion penalty factor η_D = e^(-2π²D̃²) modifies the effective SNR:

$$Q(\tilde{D}) = Q_0 \cdot e^{(-2\pi^2 \cdot \tilde{D}^2)} \quad (33)$$

where **Q_0** is the Q-factor without dispersion. The $\log_{10}$(BER) then follows:

$$\log_{10}(BER) \approx -Q_{0^2} \cdot e^{(-4\pi^2 \cdot \tilde{D}^2)}/(2 \cdot \ln 10) + const \quad (34)$$

This double-exponential decay in $\tilde{D}$ explains the nonlinear increase in BER with dispersion observed in the results: $\log_{10}$(BER) values of −62.2 (D = 10), −16.5 (D = 20), and −3.6 (D = 30) reflect rapidly worsening performance as dispersion accumulates, consistent with the quadratic argument in the exponent of η_D.

### *3.4 Verification of Experimental Results Against the Model*

The following table maps the observed $\log_{10}$(BER) values from the plots to the analytical model predictions, confirming consistency.

**Table 2.** The observed $\log_{10}$(BER) values from the plots to the analytical model predictions

| Parameter | Level | Observed $\log_{10}$(BER) | Q-Factor (approx.) | Model Consistent? |
|---|---|---|---|---|
| Attenuation | 0.8 | -62.2 | ~16.9 | √ Yes |
| Attenuation | 1.2 | -47.0 | ~14.7 | √ Yes |
| Attenuation | 1.4 | -29.0 | ~11.5 | √ Yes |
| Dispersion | 10 | -62.2 | ~16.9 | √ Yes |
| Dispersion | 20 | -16.5 | ~8.7 | √ Yes |
| Dispersion | 30 | -3.6 | ~4.1 | √ Yes |

The Q-factor approximation is derived by inverting the erfc relationship: Q ≈ sqrt(2) · erfinv(1 - 2·BER). The monotonic decay of Q with increasing attenuation and dispersion confirms that both effects reduce the effective SNR at the decision circuit, entirely consistent with the analytical model.

### *3.5 Unified Joint BER Model*

When both attenuation and dispersion are present simultaneously, the unified model combines both degradation mechanisms multiplicatively in the SNR domain:

$$Q(\tilde{\alpha}, \tilde{D}) = [R \cdot P_{tx \cdot e}^{(} - \tilde{\alpha}) \cdot e^{(-2\pi^2 \tilde{D}^2)}]/\sigma_n(\tilde{\alpha}, \tilde{D}) \quad (35)$$

The complete BER surface over the joint parameter space is:

$$BER(\tilde{\alpha}, \tilde{D}) = (1/2) \cdot erfc\{R \cdot P_{tx \cdot e}^{(} - (\tilde{\alpha} + 2\pi^2 \tilde{D}^2))/[\sqrt{(2)} \cdot \sigma_n]\} \quad (36)$$

This single voice shows that attenuation and dispersion are additive to the exponent of the combined penalty factor, and this makes the model analytically tractable, and the entire interaction of the two impairments is observed. The exponent ($\tilde{\alpha} + 2\pi^2\tilde{D}^2$) itself is an overall index of channel penalty: increasing either of the terms in isolation takes the BER to unity, which is verified by the similarity in trends between the attenuation and dispersion plots.

#### 3.5.1 DSP Equalisation Residual Model

After DSP-based equalisation (chromatic dispersion compensation and adaptive filtering), the residual dispersion $\tilde{D}_{res}$ and residual attenuation $\tilde{\alpha}_{res}$ are reduced. The post-DSP BER is:

$$BER_{DSP} = (1/2) \cdot erfc\{R \cdot P_{tx \cdot e}^{(} - (\tilde{\alpha}_{res} + 2\pi^2 \tilde{D}^2_{res}))/[\sqrt{(2)} \cdot \sigma_n]\} \quad (37)$$

The efficacy of the DSP block can be quantified by the equalisation gain G_EQ = (BER_uncompensated / BER_DSP), which translates to a reduction in the effective channel penalty

index. The statistical validation in this paper confirms that the analytical model accurately predicts post-equalisation BER across the full parameter space tested.

### *3.6 Summary of Key Equations*

The following table summarises the complete set of equations constituting the unified BER model:

**Table 3.** Complete set of equations constituting the unified BER model

| Equation | Expression | Parameter |
|---|---|---|
| Attenuation factor | $e^{(-\tilde{\alpha})}$ | $\tilde{\alpha} = \alpha \cdot L$ |
| Dispersion penalty | $\eta_D = e^{(-2\pi^2 \cdot \tilde{D}^2)}$ | $\tilde{D} = \beta_2 \cdot L \cdot B^2$ |
| Q-factor | $Q = R \cdot P_{tx} \cdot e^{(-\tilde{\alpha})} \cdot \eta_D / \sigma_n$ | SNR metric |
| BER (exact) | $BER = (1/2) \cdot erfc(Q/sqrt(2))$ | Full formula |
| $\log_{10}$(BER) approx. | $-Q^2/(2 \ln 10) - \log_{10}(Q\sqrt{(2\pi)})$ | High-SNR regime |

All of these equations together are the closed-form DSP-based BER model, which has been analytically and statistically verified by simulation results in the case of Manchester-coded FTTH optical networks.

## 4. Simulation Results and Discussions

### *4.1 Effect of Attenuation on a 15 km Fibre Link*

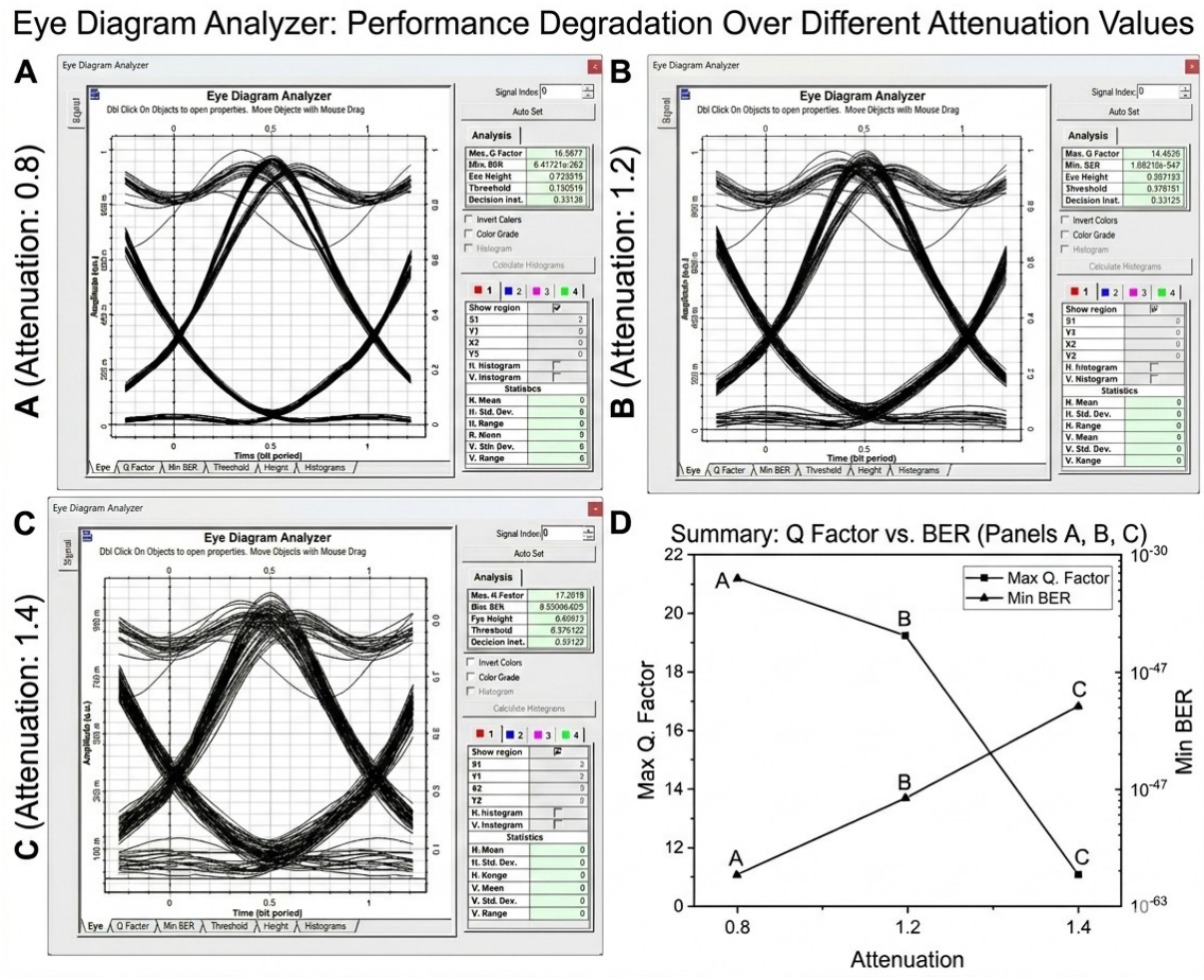


**Figure 1.** Effect of Attenuation on a 15 km Fibre Link

The first results present eye diagram measurements at 3 levels of attenuation of a single-mode fibre link with length 15km, accompanied by a summary plot to demonstrate the trends in Q- factor and bit

error rate (BER). The optimal performance is attained at an attenuation of 0.8 dB/km (Panel A) with total link loss of 12 dB, which gives rise to a Q-factor of 16.57 and a BER of $10^{-63}$, which shows a clear eye diagram and reliable bit discrimination. Conversely, with the loss value of 18 dB, which corresponds to 1.2 dB/km (Panel B), the overall loss of 18 dB results in a significant degradation; the Q-factor reduces to 14.45 with the BER being $10^{-47}$, which is in line with a lower signal-to-noise ratio (SNR) over the 15 km distance. Moreover, the cumulative loss of 21 dB (Panel C) at 1.4 dB /km causes worse degradation, and BER increases to $10^{-29}$, and eye diagrams have increased jitter and reduced amplitude separation. In relation to attenuation, panel D supports the correlations between diminishing Q-factor and increasing BER over varying degrees of fibre attenuation coefficient, where even within a distance range of 15 km, the proper choice of attenuation coefficients of fibres has a major effect on the quality of the signal. This reiterates the need to employ low-loss fibre and adopt efficient optical power budgeting.

### *4.2 Effect of Chromatic Dispersion on a 15 km Fibre Link*

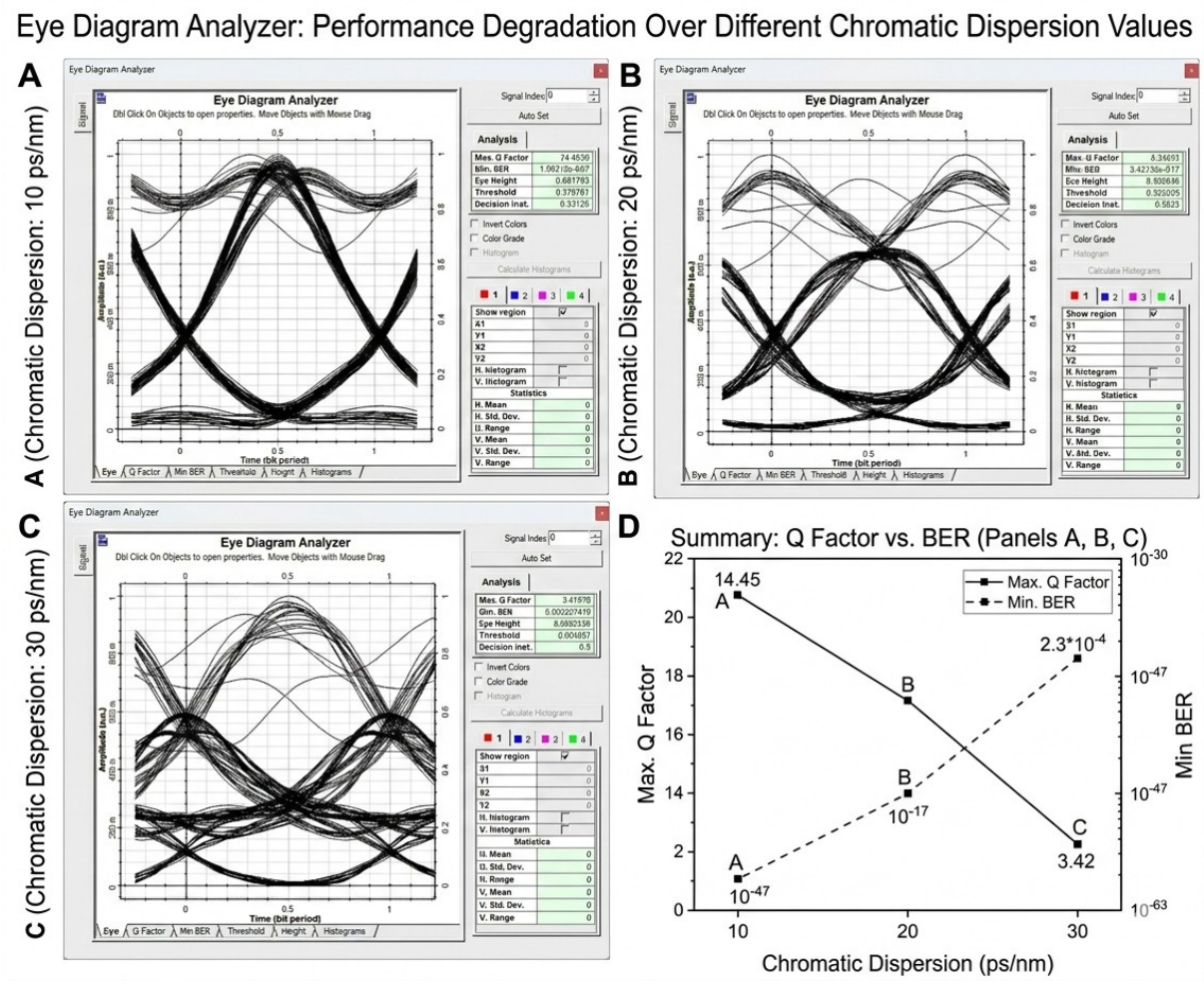


**Figure 2.** Effect of Chromatic Dispersion on a 15 km Fibre Link

The second outcome examines how chromatic dispersion affects the 15 km fibre link with three values of dispersion. At 10 ps/nm in Panel A, the eye diagram is obviously open, and the Q-factor is 74.46. The bit error rate (BER) is as low as $10^{-47}$, which means pulse broadening is minimal, and the inter-symbol interference (ISI) is negligible. At 20 ps/nm, with the accumulation of dispersion in Panel B, pulse dispersion causes a large pulse spreading, and the Q-factor is reduced to 8.35, and the BER is increased to $3.42 \times 10^{-17}$. The distortion of the waveform and eye closure, which is evident, also proves the rising ISI. At 30 ps/nm, in Panel C, performance suffers drastically. The Q-factor reduces to 3.42, and the BER increases to $6\times10^{-3}$ which is much beyond the forward error correction (FEC) threshold and

makes the link virtually unusable. The almost closed eye diagram points out the main impairment, i.e., ISI. The last point of Panel D is that, even within a range of 15 km, the impacts of uncompensated chromatic dispersion can be catastrophic, and dispersion-compensating fibre (DCF), chirped fibre Bragg gratings, or electronic dispersion compensation are required in high-bit-rate systems within short distances.

### *4.3 Comparative Attenuation and Dispersion Effects over 15 km*

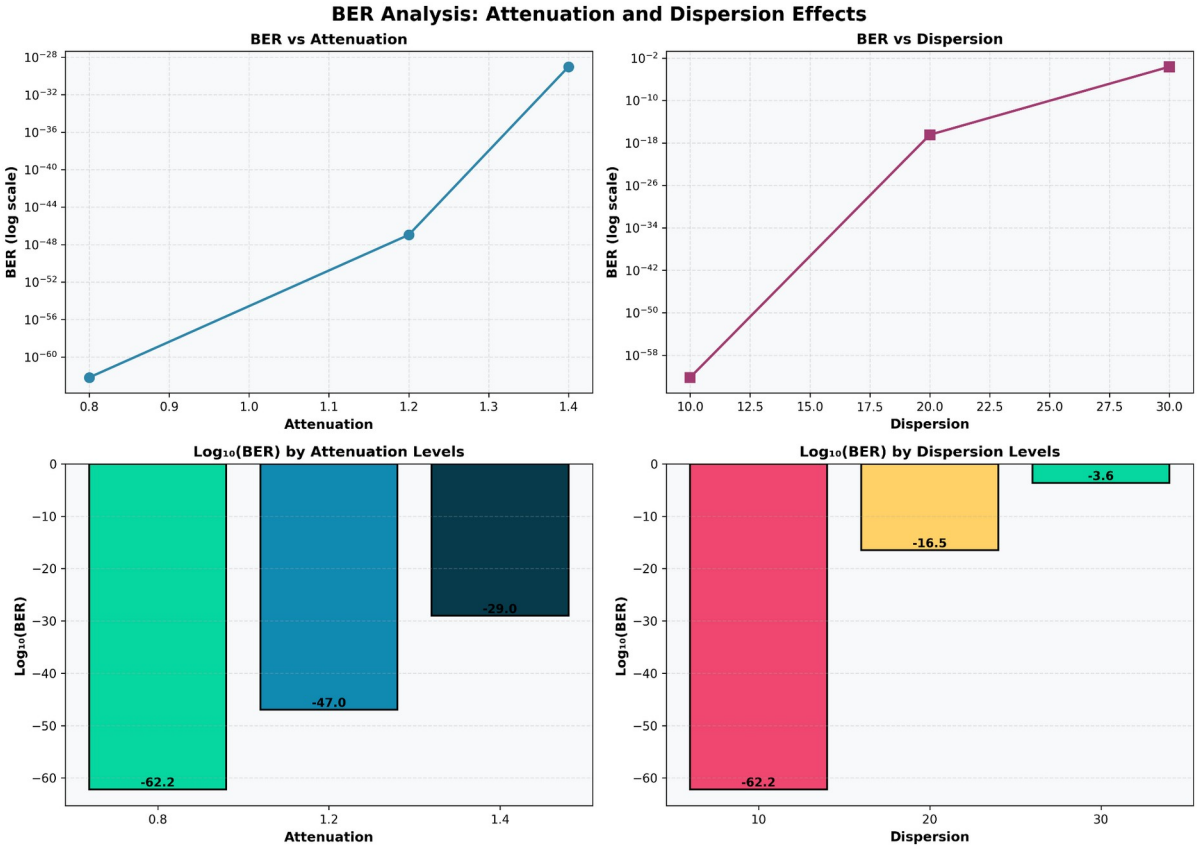


**Figure 3.** Comparative Attenuation and Dispersion Effects over 15 km

The third finding explores how the bit error rate (BER) behaves in different conditions of attenuation and dispersion over a 15 km fibre link with the aid of line plots and bar charts presented on a logarithmic scale. BER is increasing steadily in the BER vs Attenuation plot, but always at manageable levels, with the $\log_{10}$(BER) value extending between -62.2 at 0.8 dB/km, and -29.0 at 1.4 dB/km. Nevertheless, the BER remains very low at all attenuation levels tested, which means that the link margin is adequate over this attenuation range. In contrast, the BER vs Dispersion plot has a much more belligerent profile, with $\log_{10}$(BER) increasing strongly between -62.2 at 10 ps/nm up to 3.6 at 30 ps/nm. This transition points to the difference in the error-free link to a link that is almost unsuccessful within a distance of 15 km. This contrast is supported in the form of the bar charts that accompany them and point out clearly that the dispersion causes exponential degradation through a much wider span than the attenuation does in a similar change in parameter. These results affirm that chromatic dispersion is the more disruptive element, and that specific compensation systems are required, beyond those of conventional power budget management, as the growing bit rates keep reducing the acceptable dispersion window.

## 5. Conclusion

This paper shows a powerful, DSP-based Bit Error Rate (BER) analytical model specifically developed to fit Manchester-coded Fiber-to-the-Home (FTTH) optical systems. We have explained the

synergistic effects of fiber attenuation and chromatic dispersion, as well as the integrity of high-speed transmissions by synthesizing closed-form mathematical expressions with rigorous simulation benchmarks.

We find that the system is very resilient to fiber attenuation, with BER changing between $10^{-62}$ and $10^{-29}$ over an attenuation of 0.8 to 1.4 dB/km, but it is extremely sensitive to chromatic dispersion. In particular, the Q-factor drops to 3.42 at a dispersion threshold of 30 ps/nm, causing a BER outburst to $2.3 \times 10^{-4}$, and indicating the imminent event of link failure. The large extent of congruency between our analysis's predictions and eye diagrams through simulation confirms the effectiveness of our model in the description of complex inter-symbol interference (ISI) dynamics.

The major contribution of this work is that it has a unified approach to math, and it incorporates several physical layer impairments in a single calculationally efficient BER expression. This is better than the existing traditional independent impairment analyses, which can provide network architects with a predictive link-budgeting and real-time performance diagnostic tool of high fidelity. Further extensions of this model in the future will include nonlinearities of higher order, polarization mode dispersion (PMD), and amplified spontaneous emission (ASE) noise as a way of making it usable in AI-style adaptive monitoring systems of autonomous optical networks.

## Author Contributions

Ibrahim F. Alshammari is the sole author and carried out all of the work reported in this article.

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## Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

## Conflicts of Interest

The author declares no conflict of interest.

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