OSTİM TECHNICAL UNIVERSITY

INSTITUTE OF SCIENCE

ELECTRICAL ELECTRONICS ENGINEERING DEPARTMENT

ELECTRICAL ELECTRONICS ENGINEERING

MASTER'S PROGRAMME

Project 2 – Polarization-Mode Dispersion (PMD) and System Penalty

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ABSTRACT

One of the most significant factors limiting performance in high-speed fibre optic communication systems is Polarisation Mode Dispersion (PMD). PMD arises due to random birefringence along the fibre and causes two orthogonal polarisation modes to propagate at different speeds. This leads to optical pulse broadening and degradation in system performance.

The aim of this study is to model and analyse the effect of Polarisation Mode Dispersion (PMD) on optical pulse propagation. Within the scope of the project, Differential Group Delay (DGD), polarisation-dependent pulse broadening, and system penalty were quantitatively investigated for various fibre parameters.

As a method, the formulation $\Delta\tau_{DGD} = D_{PMD}$ x sqrt{L} has been used to calculate the DGD $\Delta\tau_{DGD}$ as a function of the PMD coefficient D_{PMD} and fibre length (L). PMD-induced pulse broadening and its effect on the system were analysed using MATLAB simulations. The system penalty was estimated as the square of the ratio of DGD $((\Delta\tau_{DGD} / T_b)^2)$ to the bit period (T_b).

The findings confirmed that PMD-induced pulse broadening and DGD increase proportionally with the square root of the fibre length (sqrt{L}). Furthermore, it was observed that the system penalty increases quadratically with this delay ratio. In worst-case scenarios (for example D_{PMD}= 0.2ps/ sqrt{km} and L=200 km), the DGD was calculated to be of the order of = ~2.83ps

In conclusion, this study has demonstrated through simulations that PMD reduces eye opening and increases bit error probability, particularly in high-speed (e.g., 10 Gb/s) systems. These findings emphasise the importance of PMD mitigation strategies in modern optical networks.

1.0 OBJECTİVE

Model and analyse the impact of Polarization-Mode Dispersion (PMD) on optical pulse propagation. Quantify the differential group delay (DGD), pulse broadening, and system penalty using MATLAB simulations.

2.0 STEP-BY-STEP TASKS

1. **Compute DGD:** Use $\Delta\tau_{DGD} = D_{PMD}\sqrt{L}$ for all given values.
2. **Simulate PMD Broadening:** Apply time delay and superposition of polarization modes.
3. **Plot Results:** For each D_{PMD} and L, plot input/output pulses.
4. **Penalty Calculation:** Compute normalized penalty $(\Delta\tau/T_b)^2$ and discuss implications.
5. **Analysis:** Discuss the dependence of PMD penalty on L and D_{PMD}.
6. **Mitigation Discussion:** Briefly explain fiber design or compensation techniques that reduce PMD.

2.1 DGD CALCULATION

Formula: $\Delta\tau_{DGD} = D_{PMD}\sqrt{L}$

D_{PMD} coefficient: 0.05, 0.1, 0.2 ps/(nm.km)

L (km): 50, 100, 200

- Calculation outcomes given as;

Scenerio1:

For D_{PMD}= 0.05 and L=50 km, Δ τ_{DGD} = 0.05 x sqrt{50} = 0.354 ps)

For D_{PMD}= 0.05 and L=100 km, Δ τ_{DGD} = 0.05x sqrt{100} = 0.500 ps)

For D_{PMD}= 0.05 and L=200 km, Δ τ_{DGD} = 0.05 x sqrt{200} = 0.707 ps)

Scenario 2:

For D_{PMD}= 0.1 and L=50km, Δ τ_{DGD} = 0.1 x sqrt{200} = 0.707 ps)

For D_{PMD}= 0.1 and L=100 km, Δ τ_{DGD} = 0.1 x sqrt{200} = 1.00 ps)

For D_{PMD}= 0.1 and L=200 km, Δ τ_{DGD} = 0.1 x sqrt{200} = 1.414 ps)

Scenerio3:

For D_{PMD}= 0.2 and L=50km, Δ τ_{DGD} = 0.2 x sqrt{200} = 1.414 ps)

For D_{PMD}= 0.2 and L=100 km, Δ τ_{DGD} = 0.2 x sqrt{200} = 2.00 ps)

For D_{PMD}= 0.2 and L=200 km, Δ τ_{DGD} = 0.2 x sqrt{200} = 2.828 ps)

2.2 PENALTY RATIO CALCULATION

The second step of the project is to calculate the ‘cost’ or ‘penalty’ to the system of the DGD values we just calculated.

This penalty represents the risk of bits mixing with each other due to the expansion of the stroke and how much the ‘eye opening’ closes.

Formula: $\text{Penalty} \propto \left(\frac{\Delta\tau_{DGD}}{T_b}\right)^2$

Δ τ_{DGD}: Calculated at section 2.1

T_b= 100 (Bit period, unit is ps)

- Calculation outcomes given as;

Scenerio1:

- For D_{PMD}= 0.05 and L=50 km, Δ τ_{DGD} = 0.354 ps

  Penalty Ratio = $(0.354/100)^2$ = 0.0000125

- For D_{PMD}= 0.05 and L=100 km, Δ τ_{DGD} = 0.500 ps

  Penalty Ratio = $(0.500/100)^2$ = 0.0000250

- For D_{PMD}= 0.05 and L=200 km, Δ τ_{DGD} = 0.707 ps

  Penalty Ratio = $(0.707/100)^2$ = 0.0000500

Scenerio 2:

- For D_{PMD}= 0.1 and L=50km, Δ τ_{DGD} = 0.707 ps)

  Penalty Ratio = $(0.707/100)^2$ = 0.0000500

- For D_{PMD}= 0.1 and L=100 km, Δ τ_{DGD} = 1.00 ps)

  Penalty Ratio = $(1.0/100)^2$ = 0.0001000

- For D_{PMD}= 0.1 and L=200 km, $\Delta \tau_{DGD}$ = 1.414 ps)

  Penalty Ratio = $(1.414/100)^2$ = 0.0002000

Scenerio3:

- For D_{PMD}= 0.2 and L=50km, $\Delta \tau_{DGD}$ = 1.414 ps)

  Penalty Ratio = $(1.414/100)^2$ = 0.0002000

- For D_{PMD}= 0.2 and L=100 km, $\Delta \tau_{DGD}$ = 2.00 ps)

  Penalty Ratio = $(2.0/100)^2$ = 0.0004000

- For D_{PMD}= 0.2 and L=200 km, $\Delta \tau_{DGD}$ = 2.828 ps)

  Penalty Ratio = $(2.828/100)^2$ = 0.0008000

TABLE 2.2.1 – Result Table Of $\Delta \tau_{DGD}$ Values and Penalty Ratio Calculation

DPMD (ps/sqrt(km))	L (km)	DGD (ps)	Penalty Ratio (10G)
0.05	50	0.354	0.000013
0.05	100	0.500	0.000025
0.05	200	0.707	0.000050
0.10	50	0.707	0.000050
0.10	100	1.000	0.000100
0.10	200	1.414	0.000200
0.20	50	1.414	0.000200
0.20	100	2.000	0.000400
0.20	200	2.828	0.000800

2.3 MATLAB Simulation Application

MATLAB Simulation and Graph Creation

In this step, we will see in MATLAB how the theoretical 'DGD' (delay) values calculated in Step 1 physically broaden the 'input pulse'.

2.3.1. What is the Logic of the Simulation?

The project document explains how it wants us to model this event in the 'MATLAB Implementation Guide'

1. Perfect Input Pulse: First, we will create a perfect Gaussian pulse with a width of $T_o = 20$ ps

   The formula is: $E_o(t) = e^{-(t/T0)\,\hat{}2}$

2. Split: Due to PMD, we imagine that this pulse splits into two polarisation components in the fibre: 'fast' (E_{fast}) and 'slow' (E_{slow}).

3. Delay: A time difference equal to the Δ τ_{DGD} calculated in upper sections will occur between these two components.

4. Recombination: At the end of the fibre, the two delayed components superimpose.

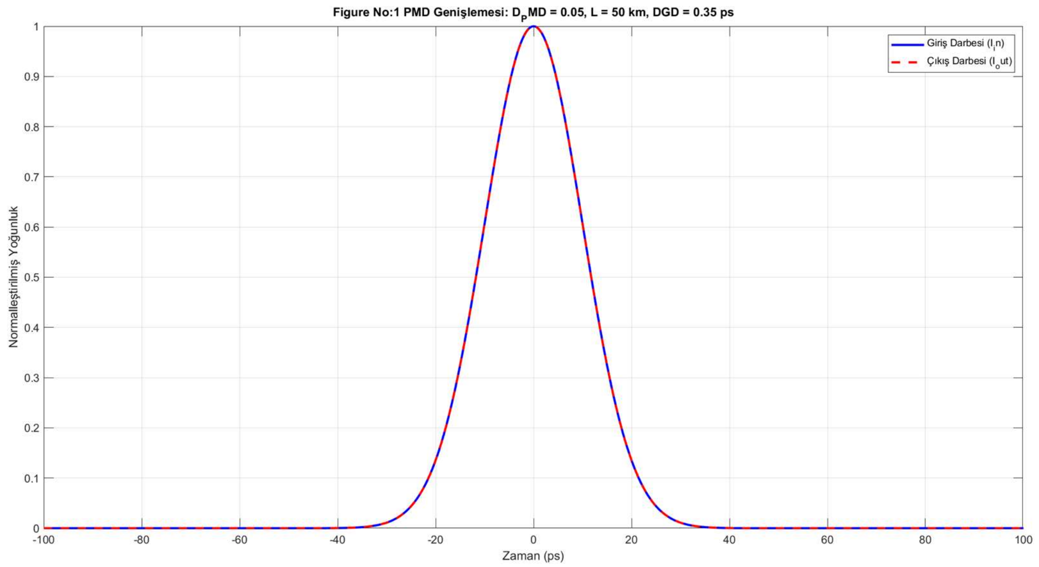
The total output intensity (what we observe) is the average of their energies.

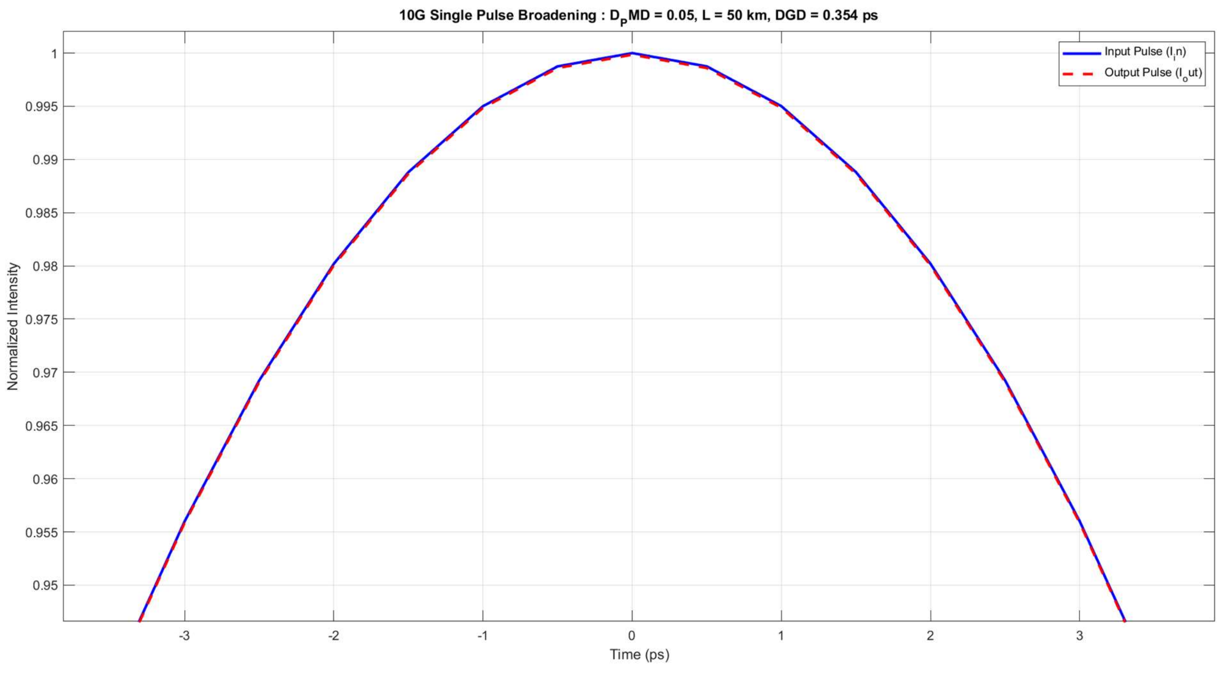
The Formula: $I_{out} = (|E_{fast}|^{\hat{}2} + |\, E_{slow}|^{\hat{}2})/2$

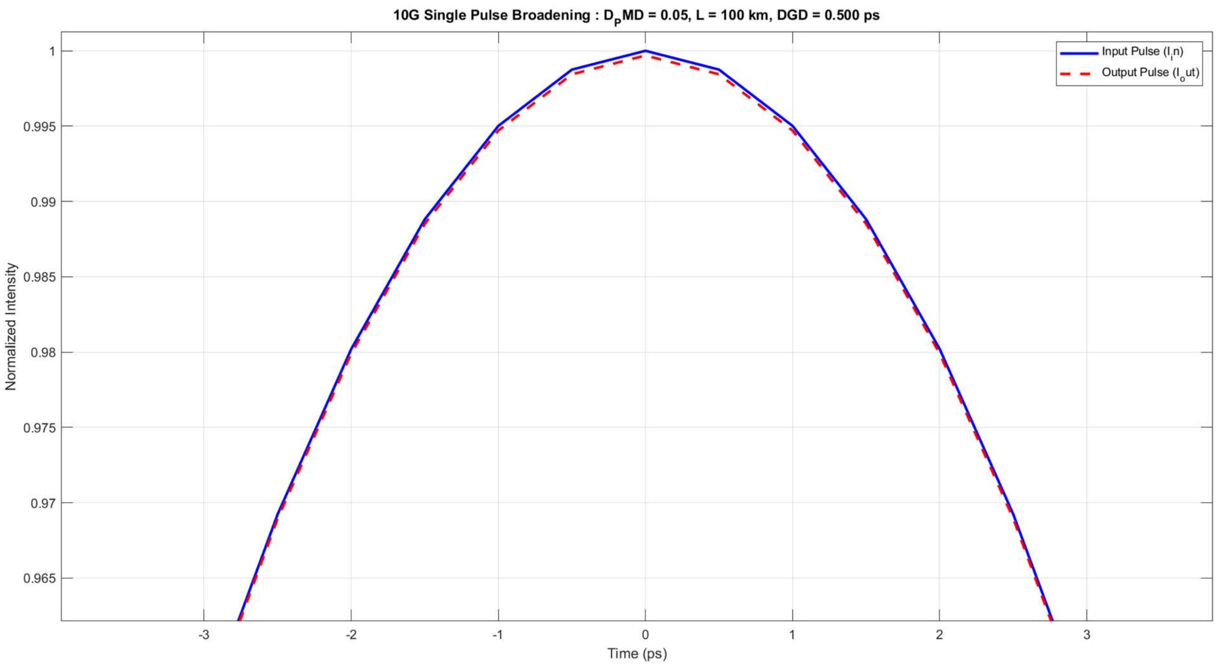
The best modelling approach is to distribute the ATDGD delay equally between these two components:

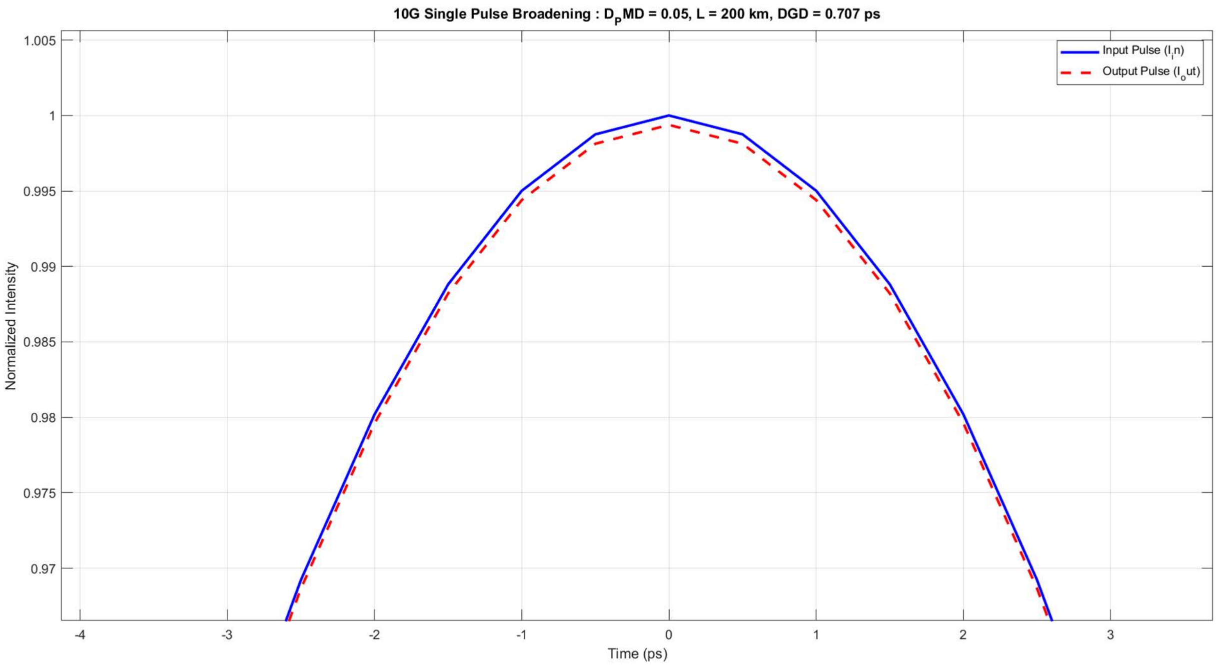
- **E_{fast}** shifts forward by Δ τ_{DGD} /2 on the time axis (arrives early).
- **E_{slow}** shifts backward by Δ τ_{DGD} /2 on the time axis (arrives late).

2.4.1 Simulation Results

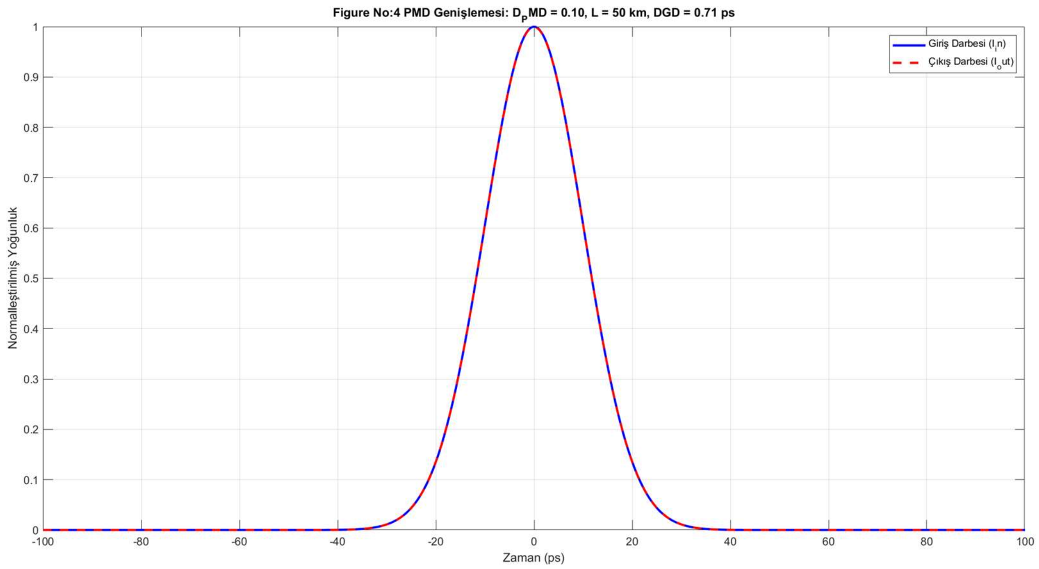


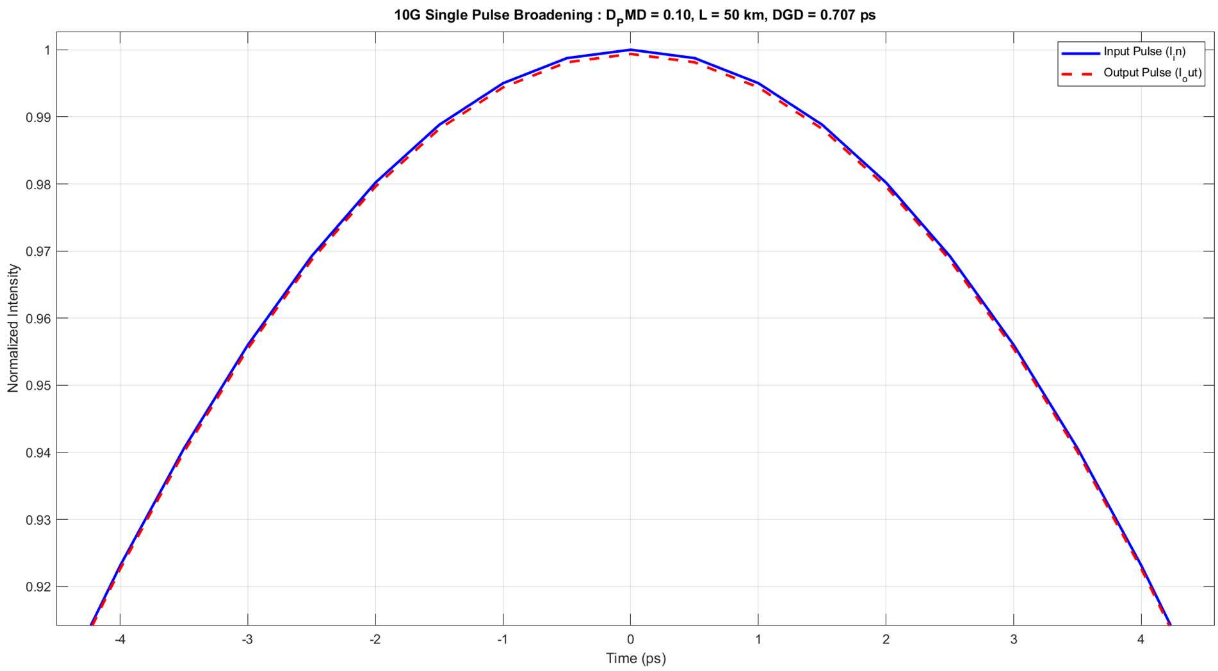


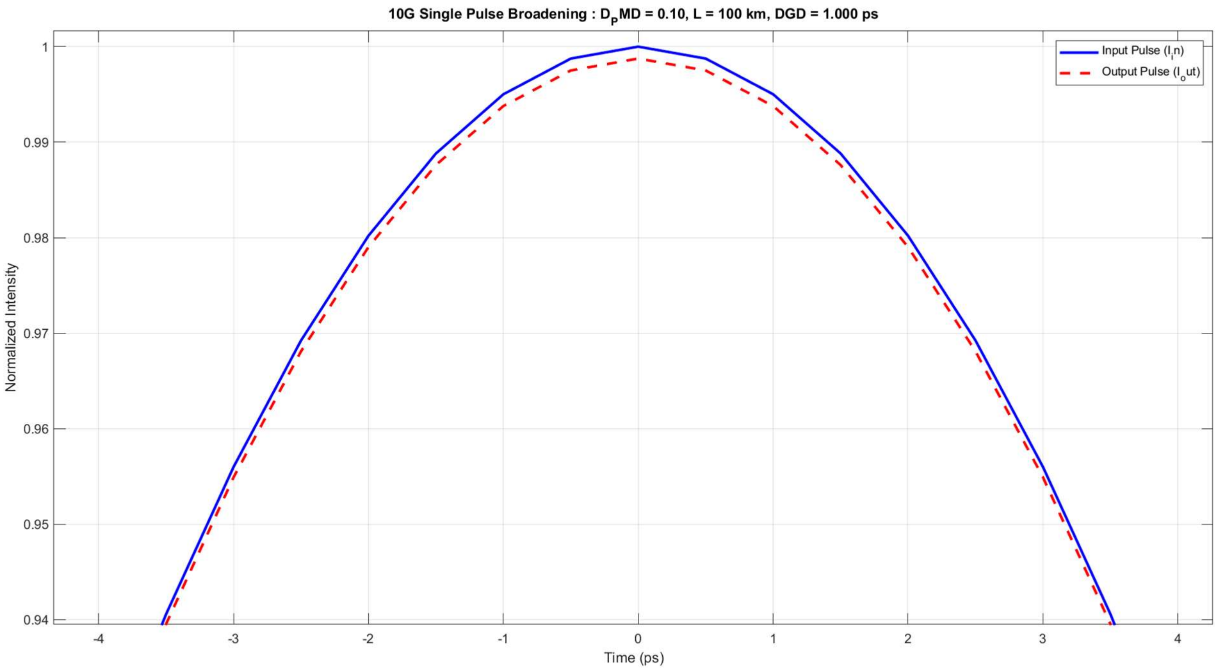

10G Single Pulse Broadening : D_PMD = 0.05, L = 100 km, DGD = 0.500 ps
Input Pulse (I_in)
Output Pulse (I_out)
Normalized Intensity
Time (ps)

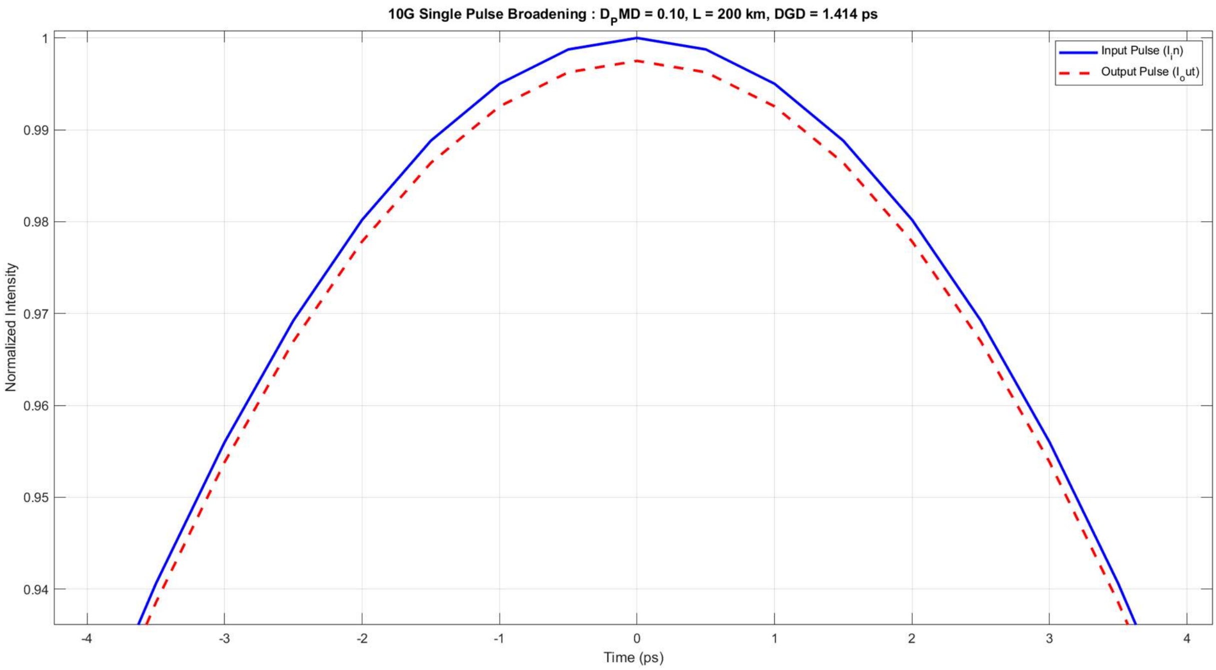

10G Single Pulse Broadening : D_PMD = 0.05, L = 200 km, DGD = 0.707 ps
Input Pulse (I_in)
Output Pulse (I_out)
Normalized Intensity
Time (ps)

2.4.2 Simulation Results

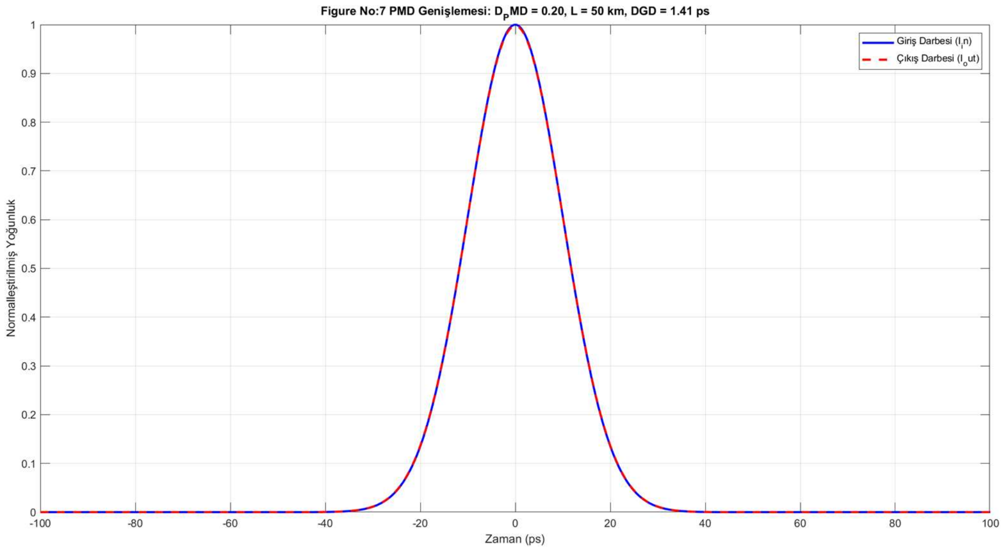


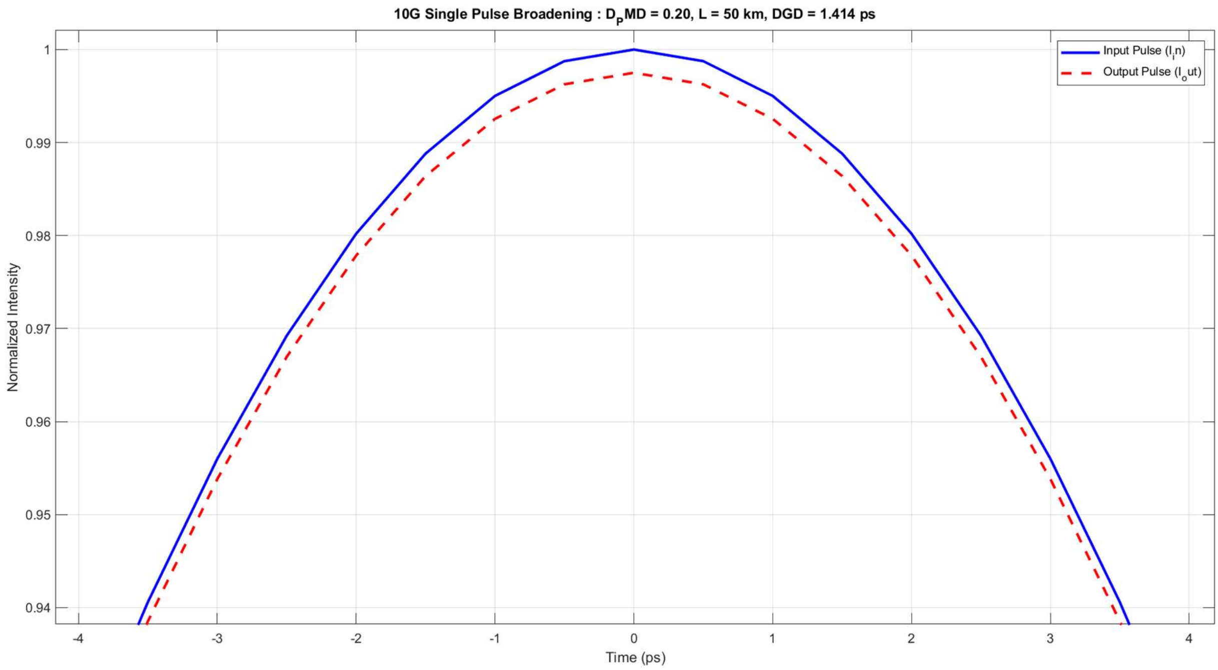


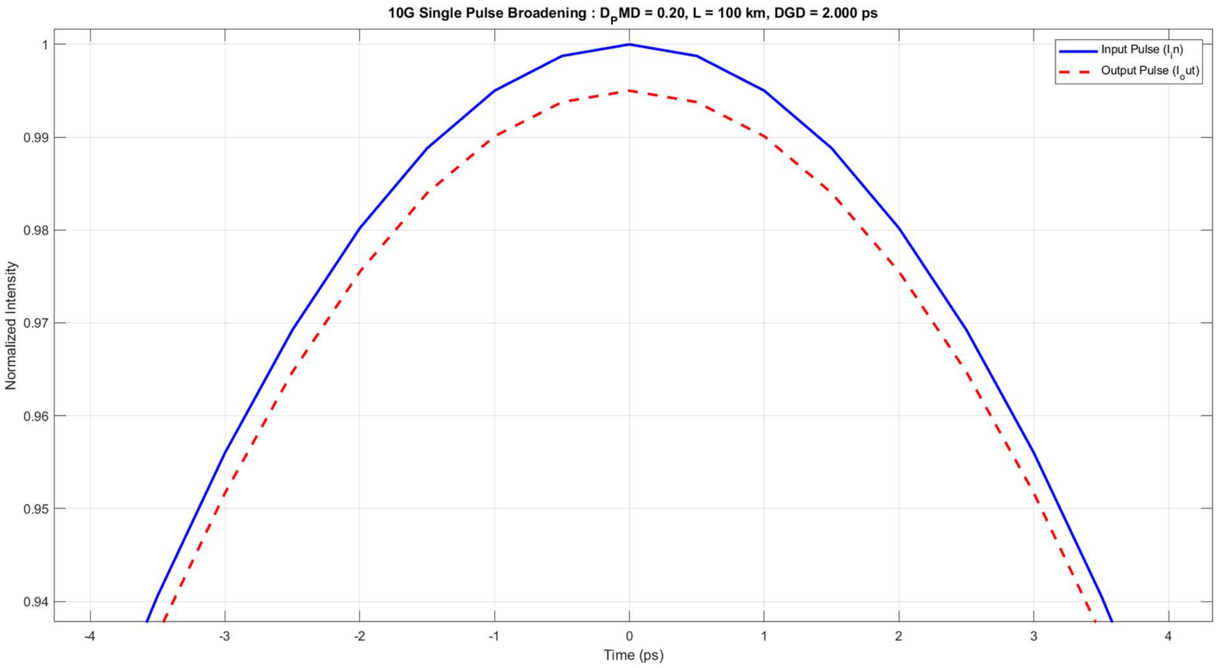

10G Single Pulse Broadening : D_PMD = 0.10, L = 100 km, DGD = 1.000 ps
Input Pulse (I_in)
Output Pulse (I_out)
Normalized Intensity
Time (ps)

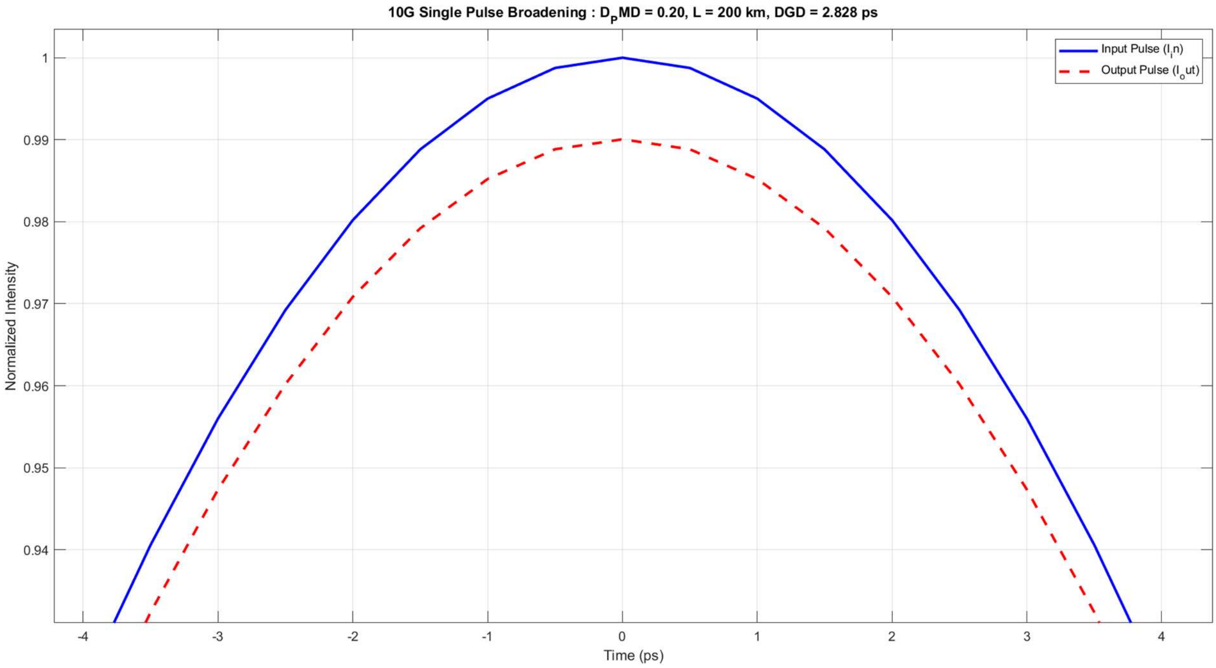

10G Single Pulse Broadening : D_PMD = 0.10, L = 200 km, DGD = 1.414 ps
Input Pulse (I_in)
Output Pulse (I_out)
Normalized Intensity
Time (ps)

2.4.3 Simulation Results

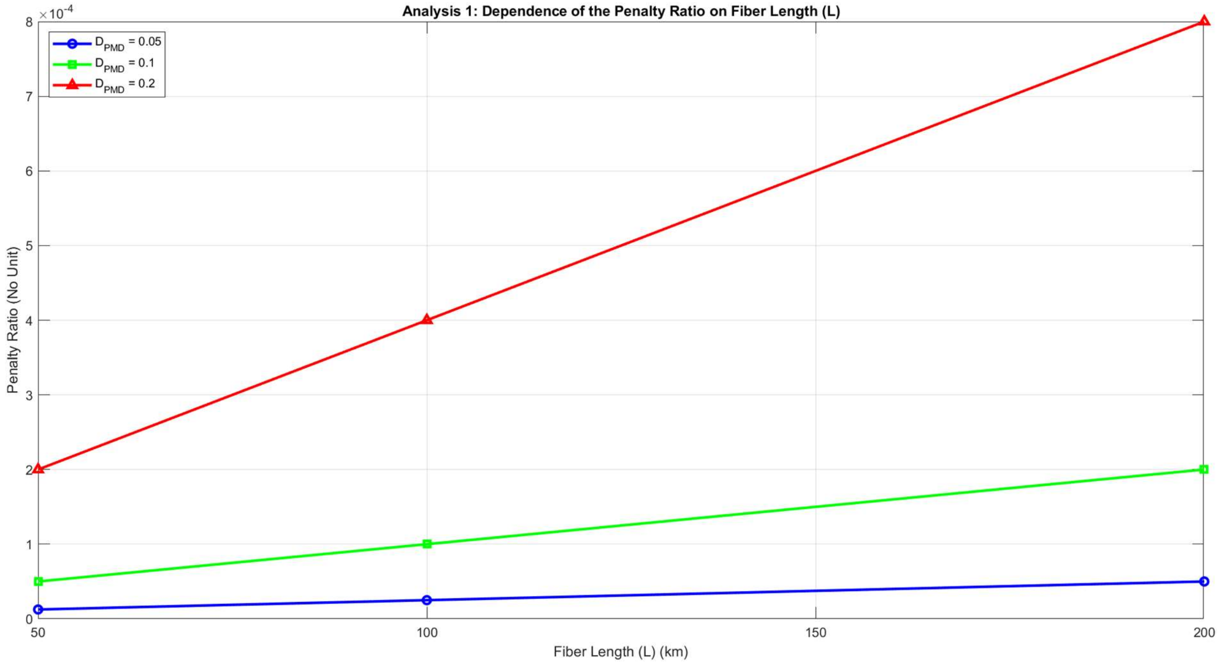


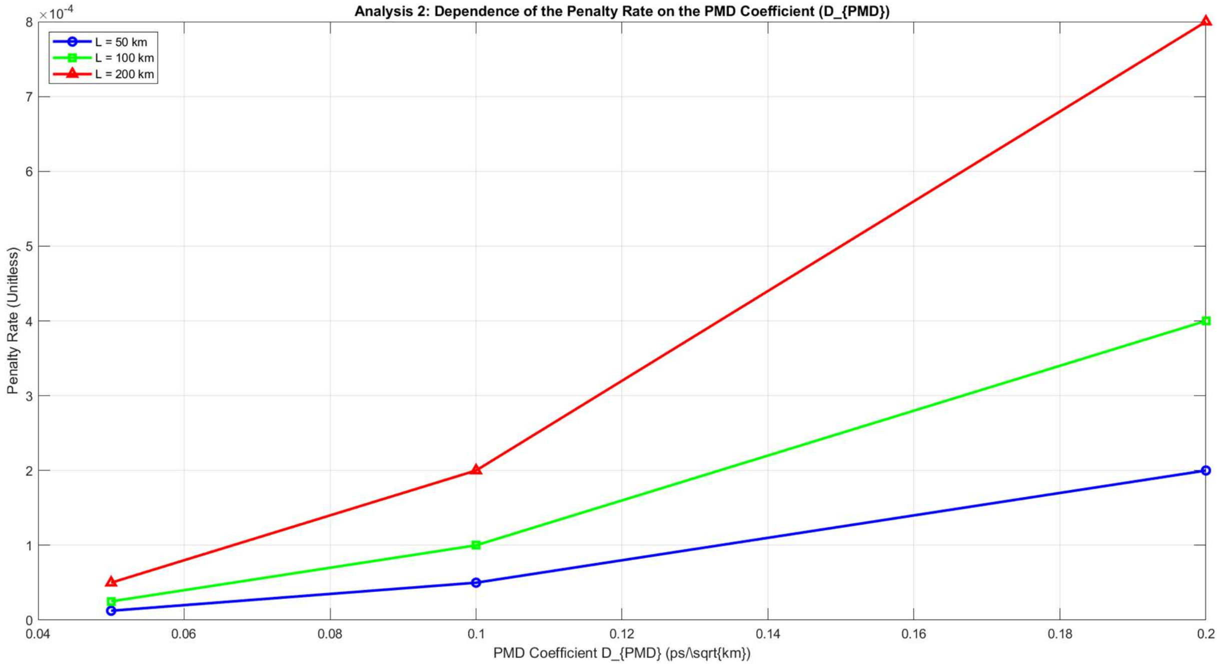



10G Single Pulse Broadening : D_PMD = 0.20, L = 100 km, DGD = 2.000 ps
Input Pulse (I_in)
Output Pulse (I_out)
Normalized Intensity
Time (ps)

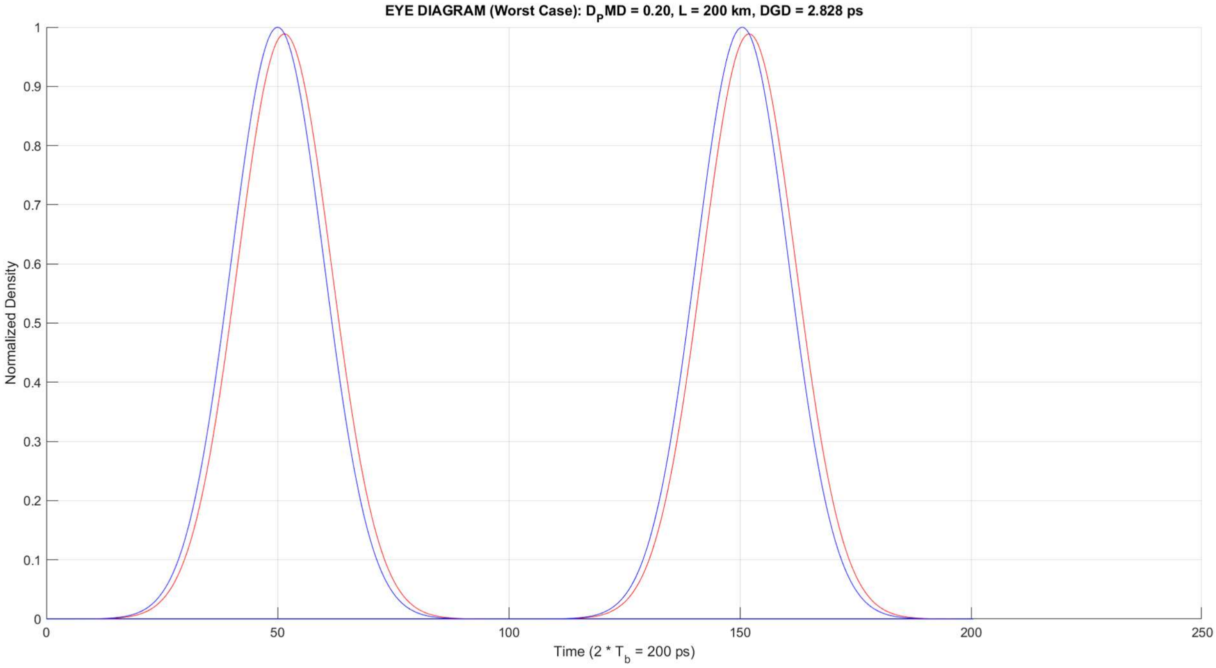

10G Single Pulse Broadening : D_PMD = 0.20, L = 200 km, DGD = 2.828 ps
Input Pulse (I_in)
Output Pulse (I_out)
Normalized Intensity
Time (ps)

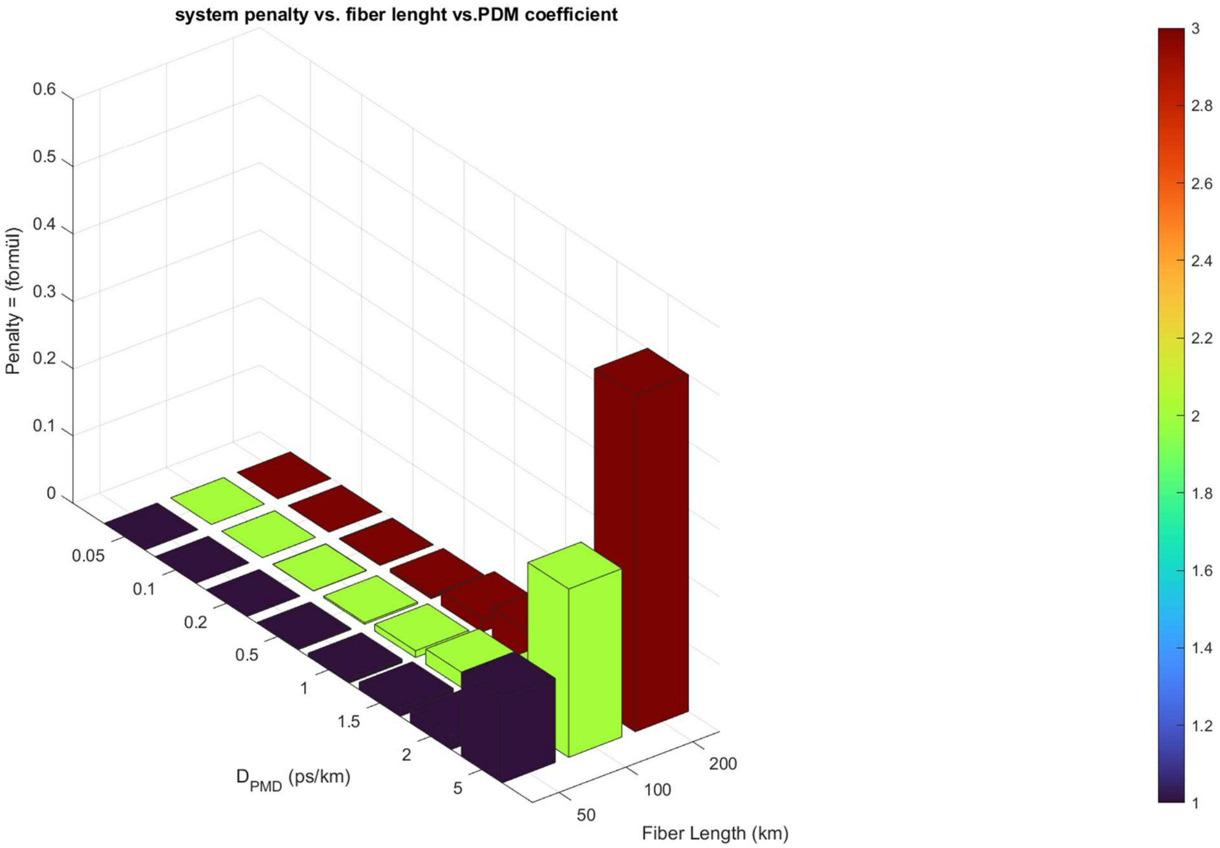
2.4.4 Simulation Results





2.4.5 Simulation Results





2.5 Analysis and Discussion

What we do until now is:

- Calculated DGD and Penalty Ratio for given initial values
- We visualised with "9" graph for how the shock expands (dispersion).

What we discuss at that part is explained below;

- How dispersion change according to Fibre Length "L".
- How the dispersion changes when we use poor quality fibres. (D_{PMD} increase)

2.5.1 Dependency 1 – Fibre Length Effect (L)

When the fixed D_{PMD} value is taken as a basis, we observe that the variable fibre cable length causes the I_{out} output pulse to expand further and the peak of the curve decrease further. The reason for that the $\Delta\ \tau_{DGD}$ formula. As the length value (L) increases, sqrt(L) also increases, which causes the DGD value to increase.

Consequently, as the fibre length increases, the DGD value increases with sqrt(L), while the system penalty value increases with 'L', they causing that the pulse signal to expands more.

2.5.2 Dependency 2 – PMD Coefficient Effect

Observations show that, when the fixed cable length used while we were using poor quality Fibre cable (D_{PMD}) red output pulse will be expand more aggressively and decrease. The reason for that DGD value increases against to D_{PMD} linear ratio basis according to formula of $\Delta\ \tau_{DGD} = D_{PMD}$ x sqrt(L)

Consequently, while the system penalty increases quadratically with D_{PMD}, D_{PMD} increases linearly. According to these findings, the D_{PMD} value has a significantly more detrimental effect on the system compared to the fibre length (L). Any slight decrease in D_{PMD} results in a quadratic increase in the system penalty.

2.6 Outcomes of Project – Pratical Explanation

An expanding pulse (the '1' bit) spills over its own time slot and "contaminates" the time slot of the next bit (which may be a '0' bit).

This is called "**Inter Symbol Interference"** (ISI). This causes the receiver to confuse whether an 'II' or an 'O' has arrived, increasing the Bit Error Probability (BEP).

The tool we use to measure this distortion is called an 'Eye Diagram,' and as PMD increases, this 'eye' closes.

2.7 Mitigation Discussion – PMD Effect Decreasing Methods

As our simulation results show, PMD is a factor that significantly limits system performance, especially at high bit rates (10 Gb/s and above). The fundamental cause of PMD is random birefringence (double refraction) occurring in the fibre. There are two main approaches in engineering to manage this effect:

2.7.1 Fibre Design (Passive Approach)

This approach aims to solve the problem before it arises, i.e. during the fibre production stage.

• **Production of Low-PMD Fibre**: The fundamental cause of PMD is the microscopic asymmetries in the geometry of the fibre core and the internal stresses on the fibre. Manufacturers strive to keep the core geometry as close to a perfect circle as possible by extremely precisely controlling the fibre drawing process. This naturally minimises the speed difference between the two polarisation modes. The scenario we simulated with DPMD 0.05 pslv/cm minimises this speed difference between the two polarisation modes. This naturally minimises the speed difference between the two polarisation modes. The scenario we simulated with a D_{PMD} of 0.05 ps/ sqrt(L) this type of modem and high-quality fibre.

• **Fibre Spinning:** During production, deliberately spinning the fibre around its own axis is a common passive mitigation technique. As the fibre is spun, the orientation of the 'fast' and 'slow' axes also continuously changes. Over a long distance, light spends an average of equal time on both axes. This 'averaging' effect significantly reduces the net DGD accumulation.

2.7.2 PMD Compensation (Active Method)

This approach aims to dynamically correct the issue after it arises (typically at the receiver end).

This is critical for upgrading older (legacy) fibre lines with high DPMD coefficients to modern high speeds.

• PMD Compensators (PMDC): These are intelligent devices placed at the end of the fibre line.

The working principle is as follows:

1. **Detection:** The device continuously monitors the incoming signal and detects the current amount of DGD and which polarisation axis is 'fast'.

2. **Compensation:** The device splits the signal into two polarisation components. It then introduces the 'fast' component, which arrives "early" from the fibre, into a variable delay line long enough to wait for the 'slow' component to arrive.

3. **Re-alignment:** When the two components are re-aligned in terms of timing, the device re-aligns them. As a result, the expanded pulse re-sharpens at the fibre output and the 'aperture' increases. The most challenging aspect of PMD is that it changes dynamically over time due to temperature variations or physical vibrations.

Therefore, PMD compensators must also be 'adaptive' and track changes within milliseconds, continuously updating their correction settings.

2.8 RESOURCES

https://www.nict.go.jp/publication/shuppan/kihou-journal/journal-vol53no2/03-05.pdf

https://www.fiberoptics4sale.com/blogs/archive-posts/95042374-polarization-mode-dispersion-pmd-tutorial

https://www.photonics.com/Articles/Polarization-Mode-Dispersion-Concepts-and/a25153

https://mail.iosrjen.org/Papers/vol2_issue7%20(part-1)/F0273240.pdf

https://www.researchgate.net/figure/Eye-opening-vs-BER-of-signal-degraded-by-statistical-samples-of-a-PMD_fig8_247777844

https://opg.optica.org/abstract.cfm?uri=ofc-2006-OFL6

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https://matlabsimulation.com/optical-fiber-simulation-in-matlab/

https://www.researchgate.net/publication/226123693_PMD_compensation_techniques

https://ei.unipaderborn.de/fileadmin/elektrotechnik/fg/ont/docs/auto/publication/PMD_in_HighBitrate_Transmission_and_Means_for_its_Mitigation_.pdf

https://www.corning.com/media/worldwide/coc/documents/Fiber/white-paper/WP5051.pdf