

Impact of differential group delay and environmental factors on signal quality in multimode fiber using NRZ and QAM modulation

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ABSTRACT

This study investigates the effects of polarization mode dispersion (PMD) on high-speed multimode fiber (MMF) optical communication systems, focusing on how differential group delay (DGD) and environmental conditions such as temperature and humidity influence signal quality. The research was conducted in Abuja, Nigeria, using two modulation formats—non-return-to-zero (NRZ) and quadrature amplitude modulation (QAM). Experimental measurements were carried out over fiber lengths ranging from 1 km to 38 km, and data rates from 15 Gbps to 240 Gbps. Key performance metrics such as bit error rate (BER), jitter, and signal-to-noise ratio (SNR) were analyzed in relation to DGD under varying environmental conditions. Results showed that DGD increased from 0.136 ps to 2.78 ps for NRZ and from 0.058 ps to 2.24 ps for QAM across the tested fiber lengths. Corresponding BER values for NRZ ranged from 1.18×10^{-7} to 1.35×10^{-7} , while QAM showed slightly better performance with BER values between 1.18×10^{-7} and 1.29×10^{-7} . Jitter rose from 4.26 ps to 31.20 ps in NRZ and from 4 ps to 33.54 ps in QAM. SNR values declined as DGD increased, with NRZ dropping from 34.59 dB to 54.56 dB and QAM from 34.83 dB to 52.90 dB. Environmental factors also played a role; temperature increases from 28.34°C to 29.90°C and humidity from 53.1% to 59.5% led to significant increases in DGD. The findings confirm that PMD, though less dominant in MMF than modal dispersion, still significantly affects signal quality in long-distance and high-speed MMF systems. QAM demonstrated greater resilience to PMD compared to NRZ. This study highlights the need for effective dispersion management and modulation format optimization in designing robust optical networks for environmentally dynamic regions like Abuja.

ARTICLE INFO

Article history:

Received Jul 12, 2025

Revised Sep 14, 2025

Accepted Sep 15, 2025

Keywords:

Differential Group Delay
Multi-Mode Fiber
Non-Return-To-Zero
Polarization
Quadrature Amplitude

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1. INTRODUCTION

For years telecommunication companies had been given a free ride as they grew from 90 Mbps to 270 Mbps, to 435 Mbps, and to 2.5 Gbps. An issue that started to appear in 10 Gbps systems poses a serious risk of disruption in 40 Gbps networking [1]. The networking killer known as Polarization Mode Dispersion (PMD) was introduced to the fiber optics industry for the first time [1]. Due to the asymmetry of the fiber strand and PMD, several planes of light within a fiber move at marginally different speeds, making reliable high-speed data transmission impossible. The problem was discovered in the early 1990s and could destroy the integrity of a network [2, 3].

The PMD caused by the asymmetry of the fiber optic strand is simply the result of the fiber core being slightly oval or out-of-round. This can be due to mechanical stress, or environmental stressors on the deployed fiber or inherent asymmetry in the fiber from the manufacturing process [4, 5]. PMD in optical channels has been a critical factor limiting high speed data transmission over long distance in optical networks. It is a source of intersymbol interference (ISI) and its impact increases with the transmission data rate [6]. With the increasing demand for high-speed data transmission, optical fiber networks have become the backbone of modern communication systems [7, 8].

In regions like Abuja, Nigeria, where there is rapid urbanization and infrastructure development, the need for reliable and efficient optical communication systems has escalated. Among the various types of optical fibers, multi-mode optical fibers (MMFs) are often used for short- to medium-range transmission links due to their cost-effectiveness and ability to support high data rates through multiple light propagation paths, or modes [9, 10]. In contrast to their single-mode predecessors, multi-mode optical fibers are not the best option for high speed optical communications [11, 12].

However, multi-mode fibers face significant challenges that impact their performance, the most prominent of which is modal dispersion [13]. This occurs because light travels through different spatial modes at different speeds, causing the light pulse to spread over time. As a result, pulse broadening occurs, which can lead to inter-symbol interference (ISI) and a degradation in signal integrity, especially as data rates increase [9, 14]. Unlike single-mode fibers (SMF), which are primarily affected by polarization mode dispersion (PMD), MMFs are more susceptible to modal dispersion due to the presence of multiple modes within the fiber core [15].

In addition to modal dispersion, PMD can also manifest in MMF systems under certain conditions. While PMD is traditionally a concern in single-mode fibers, it can occur in MMF systems, especially when the fiber experiences residual birefringence caused by mechanical stress, temperature fluctuations, or manufacturing imperfections. This PMD-induced distortion becomes more noticeable at high data rates and over longer fiber distances [4, 16].

To evaluate PMD-related effects on signal integrity, this study employs two digital modulation formats: Non-Return-to-Zero (NRZ) and Quadrature Amplitude Modulation (QAM). NRZ is a simple and widely used binary modulation scheme where logical '1' and '0' are represented by two distinct voltage levels without a return to a baseline between bits [17]. It is generally more tolerant of amplitude distortion but less resistant to timing jitter.

In contrast, QAM is a more advanced multi-level modulation format that encodes data using both amplitude and phase variations. This makes QAM capable of transmitting higher data rates within the same bandwidth but also more sensitive to signal impairments such as noise, phase distortion, and PMD [18]. PMD may be more pronounced in QAM systems because even small polarization-induced delays can shift the constellation points, leading to symbol misinterpretation [12]. The dense and closely spaced constellation in QAM requires precise phase and amplitude alignment; hence, any differential delay between polarization modes can distort the signal's phase reference, degrading decoding accuracy more significantly than in NRZ [12, 19].

As urban areas like Abuja expand and demand for high-bandwidth services grows, it is crucial to understand the impact of modal dispersion and PMD on the performance of MMF systems. This study explores the characterization of PMD in multi-mode fibers, focusing on how Differential Group Delay (DGD) evolves with fiber length, temperature, and humidity under real-world conditions in Abuja. By examining the performance of NRZ and QAM modulation formats, the research aims to provide insights into how these impairments affect signal quality and to propose strategies for mitigating their impact on high-speed communication networks.

2. MATERIALS

The materials used for the characterization and analysis of the impact of polarization mode dispersion on high-speed optical fibers: effects of differential group delay and environmental factors includes: Optical Fiber (Multi-mode), Polarization Controller, PMD Emulator, Bit Error Rate Tester (BERT), Temperature and humidity sensors and Optical Power Meter.

3. METHOD

The research was conducted using two modulation formats: Non-Return-to-Zero (NRZ) and Quadrature Amplitude Modulation (QAM). These formats were chosen to investigate and compare their sensitivity to Differential Group Delay (DGD) and environmental variations in high-speed optical fiber systems. All measurements and performance evaluations, including BER, jitter, and SNR, were conducted separately under both modulation schemes to enable comparative analysis.

The study employed real-time experimental testing using the time-domain and frequency-domain method to characterize and analyze Differential Group Delay (DGD) in high-speed optical fibers. The time-domain technique enabled the direct measurement of DGD by observing pulse broadening, jitter, and timing distortions over varying fiber lengths and environmental conditions. The research focuses only on standard multi-mode optical fibers, which are susceptible to Polarization Mode Dispersion (PMD) due to their support of large number of propagation modes. Fiber lengths varied from 1 km to over 40 km. Data rates ranged from 15 Gbps to 240 Gbps, and testing was conducted at central wavelengths of 1350 nm and 1450 nm. The experimental setup allowed for the measurement of DGD, jitter, Bit Error Rate (BER), and Signal-to-Noise Ratio (SNR), under varying environmental conditions, including temperature and humidity.

4. RESULTS

4.1. Polarization Mode Dispersion's Impact on Signal Metrics on Differential Group Delay for Multi-Mode NRZ Modulation Format

Figure 1 (a) The plot shows that DGD increases with fiber length, starting at 0.136 ps (1 km) and reaching 0.349 ps (14 km). This confirms that PMD, though typically more dominant in single-mode fibers, becomes more evident in MMFs over longer distances. In MMFs, this can be attributed to slight imperfections and non-uniformities in the core that introduce random birefringence, especially at splices or bends. Figure 1 (b) At extended fiber lengths (29.72 km to 38.12 km), DGD values increase significantly from 1.05 ps to 2.12 ps. This indicates that even in multimode fibers, PMD can accumulate to levels that can affect system performance, particularly at higher data rates. This also suggests that longer MMF installations in metropolitan environments like Abuja must consider PMD in link budgeting and dispersion compensation strategies.

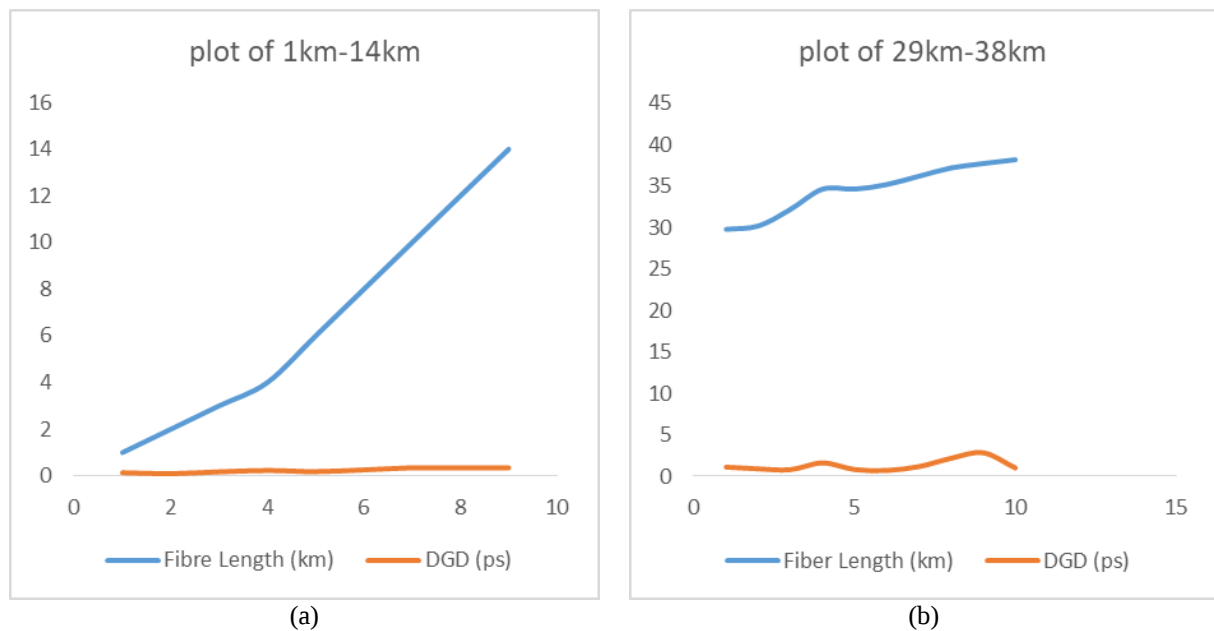


Figure 1. Plot of DGD (ps) vs fiber length (km): (a) 1 – 14 km and (b) 29 – 38 km.

In Figure 2 (a) Bit Error Rate (BER) shows a rising trend with increasing DGD. As DGD increases from 0.76 ps to 1.56 ps, BER degrades from 1.18×10^{-7} to 1.35×10^{-7} . This is due to pulse

broadening and time misalignment caused by DGD, leading to increased inter-symbol interference (ISI), especially under NRZ which lacks intrinsic error correction. Figure 2 (b) shows that even though BER values stay within the range of 1.18×10^{-7} to 1.25×10^{-7} , the variation reflects the compensating influence of SNR and error correction algorithms. However, under real-world conditions with temperature and humidity fluctuations, this margin can close quickly, causing noticeable data degradation in practical deployments.

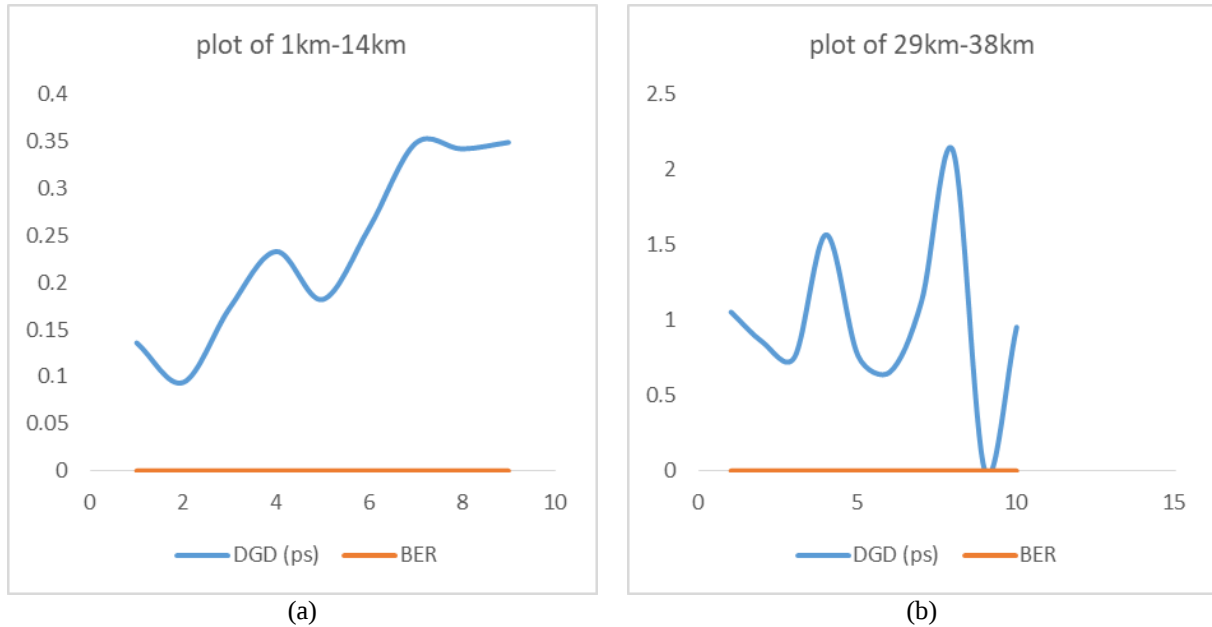


Figure 2. Plot of DGD (ps) vs BER: (a) 1 – 14 km and (b) 29 – 38 km.

Figure 3 (a) shows that Jitter increases with DGD. For instance, 4.26 ps jitter at 0.136 ps DGD grows to 23.5 ps at 0.349 ps DGD, highlighting increased timing uncertainty due to PMD. Figure 3 (b) also shows that in longer fibers, jitter continues to rise with DGD. From 25.54 ps at 0.654 ps DGD, it climbs to 31.20 ps at 2.12 ps DGD, indicating timing variations worsen with differential delay in MMF.

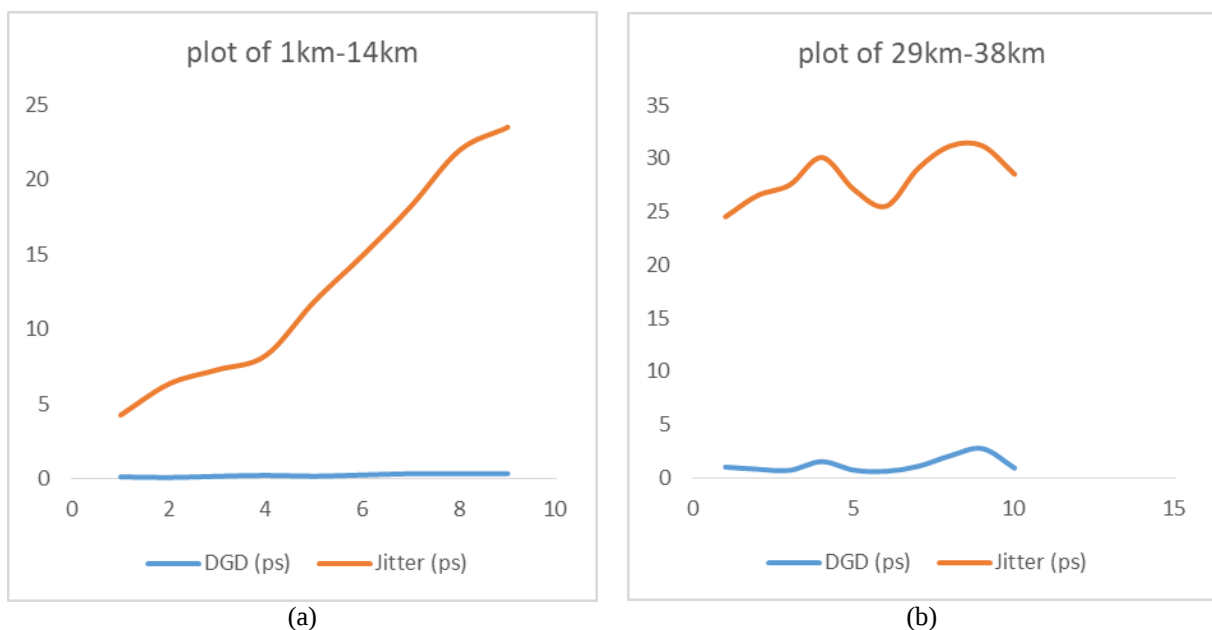


Figure 3. Plot of DGD (ps) vs signal jitters (ps): (a) 1 – 14 km and (b) 29 – 38 km.

Figure 4 (a) shows that SNR declines with increasing DGD. Initially, its 34.59 dB at 0.136 ps, dropping to 33.95 dB at 0.349 ps, showing that PMD-induced dispersion reduces signal clarity. While in Figure 4 (b) SNR varies from 59.76 dB at 1.12 ps DGD to 54.56 dB at 2.12 ps, confirming that even in MMF systems, DGD deteriorates signal quality and noise tolerance.

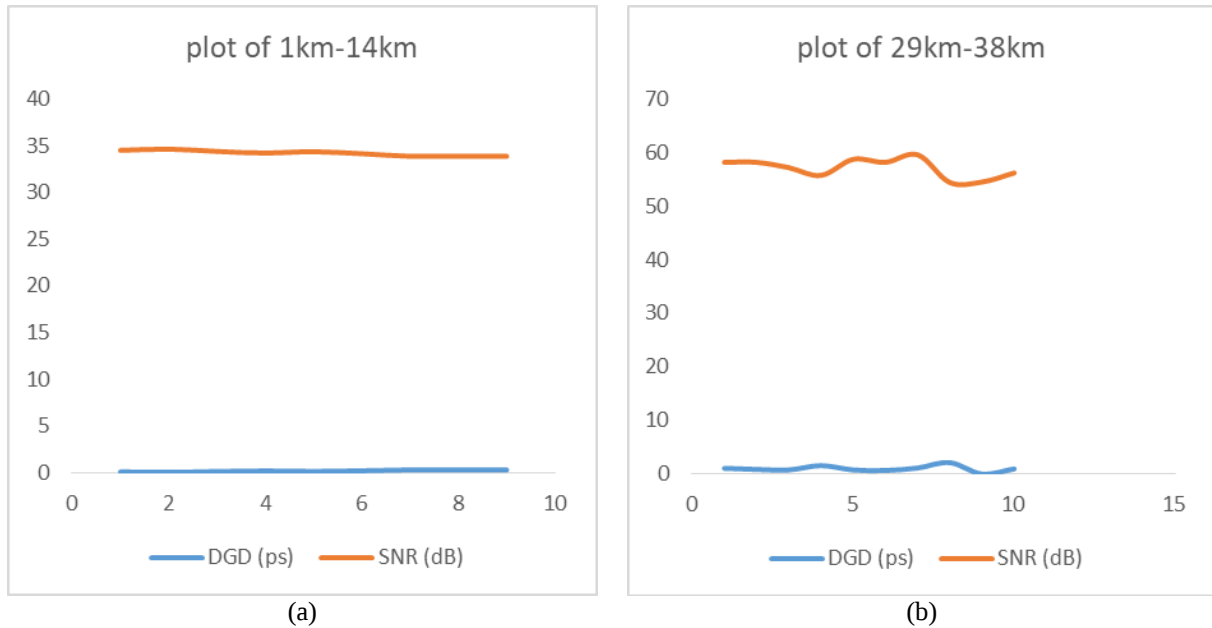


Figure 4. Plot of SNR (dB) vs DGD (ps): (a) 1 – 14 km and (b) 29 – 38 km.

Figure 5 (a) shows that as temperature increases from 28.34°C to 29.89°C, DGD rises from 0.765 ps to 1.567 ps. Thermal expansion likely modifies fiber birefringence, contributing to higher delay. Figure 5 (b) also shows that DGD also rises with humidity. From 0.75 ps at 54.9% humidity to 2.12 ps at 56.8%, this suggests that moisture alters fiber geometry or coating, affecting modal propagation and PMD.

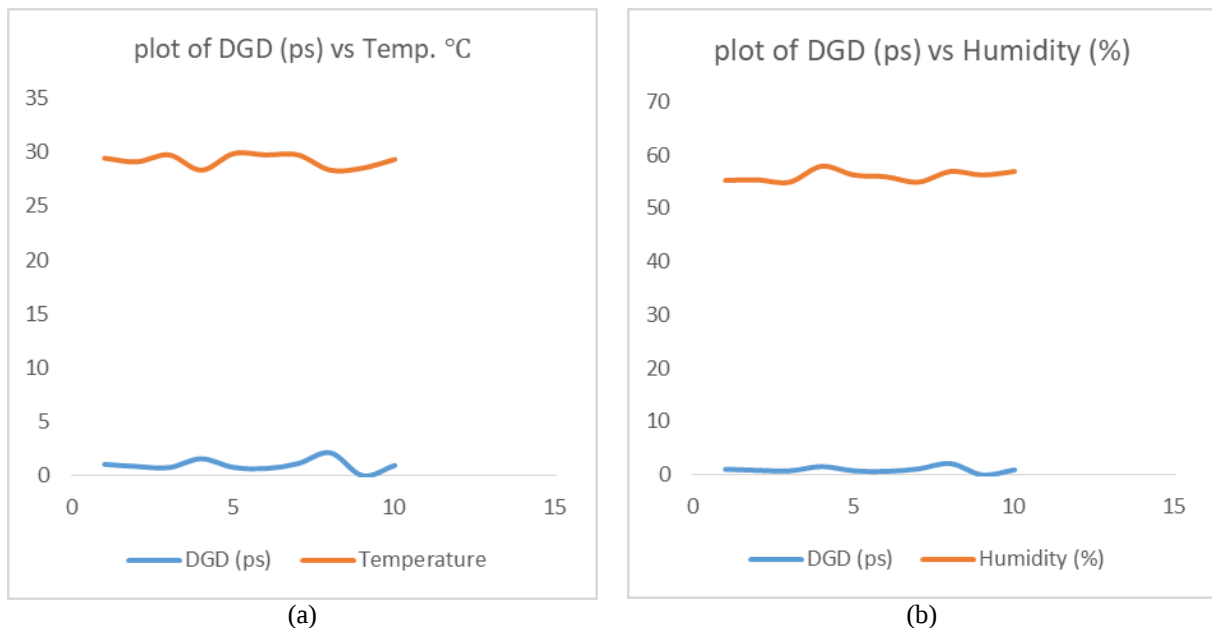


Figure 5. Plot of DGD vs: (a) temperature and (b) humidity.

Table 1. PMD induced degradation of signal metrics in multi-mode fibre using NRZ Modulation.

Fibre length (km)	Modulation	DGD (ps)	PSP (deg)	Jitter (ps)	Output optical power (dBm)	BER	SNR (dB)	OSNR (dB)
1	NRZ	0.136	126	4.26	-2.3	1.3×10^{-9}	34.59	39.59
2	NRZ	0.094	162.2	6.35	-0.28	1.0×10^{-9}	34.72	39.72
3	NRZ	0.173	152.3	7.29	-0.7	1.7×10^{-9}	34.48	39.48
4	NRZ	0.233	23.5	8.25	-1.93	2.5×10^{-9}	34.3	39.3
6	NRZ	0.182	172.5	11.85	-0.12	1.8×10^{-9}	34.45	39.45
8	NRZ	0.258	114	14.93	-2.24	3.0×10^{-9}	34.23	39.23
10	NRZ	0.348	14.8	18.22	-2.33	5.5×10^{-9}	33.96	38.96
12	NRZ	0.342	24.5	21.95	-1.04	5.3×10^{-9}	33.97	38.97
14	NRZ	0.349	93.1	23.5	-1.34	5.6×10^{-9}	33.95	38.95

Table 2. PMD induced degradation of signal metrics in multi-mode fibre using NRZ modulation format.

Fiber length (km)	Data rate (Gbps)	Modulation format	Wavelength (nm)	DGD (ps)	Jitter (ps)	SNR (dB)	BER	Temperature (°C)	Humidity (%)
29.72	28	NRZ	1350	1.054	24.54	58.35	1.2×10^{-7}	29.46	55.21
30.12	15	NRZ	1350	0.854	26.54	58.35	1.2×10^{-7}	29.12	55.32
32.12	15	NRZ	1350	0.754	27.54	57.35	1.2×10^{-7}	29.77	54.9
34.57	70	NRZ	1450	1.568	30.12	55.89	1.4×10^{-7}	28.35	57.89
34.57	15	NRZ	1350	0.765	27.11	58.9	1.2×10^{-7}	29.89	56.23
35.12	15	NRZ	1350	0.654	25.54	58.35	1.2×10^{-7}	29.77	55.9
36.12	70	NRZ	1350	1.123	29.1	59.77	1.2×10^{-7}	29.77	54.9
37.12	130	NRZ	1450	2.123	31.2	54.57	1.2×10^{-7}	28.35	56.89
37.65	130	NRZ	1450	2.789	31.2	54.65	1.2×10^{-7}	28.54	56.23
38.12	240	NRZ	1350	0.954	28.54	56.35	1.2×10^{-7}	29.35	56.9

4.2. Polarization Mode Dispersion's Impact on Signal Metrics for Differential Group Delay for Multi-Mode Fiber using Quadrature Amplitude Modulation

Figure 6 (a) shows that DGD grows slowly from 0.058 ps at 1 km to 0.364 ps at 12 km, showing PMD accumulation is less severe in MMF-QAM due to phase compensation. Figure 6 (b) indicates that for longer fibers (e.g., 30.2 to 38.5 km), DGD increases from 0.95 ps to 2.24 ps, affirming that distance and MMF non-uniformities induce PMD even with complex QAM encoding.

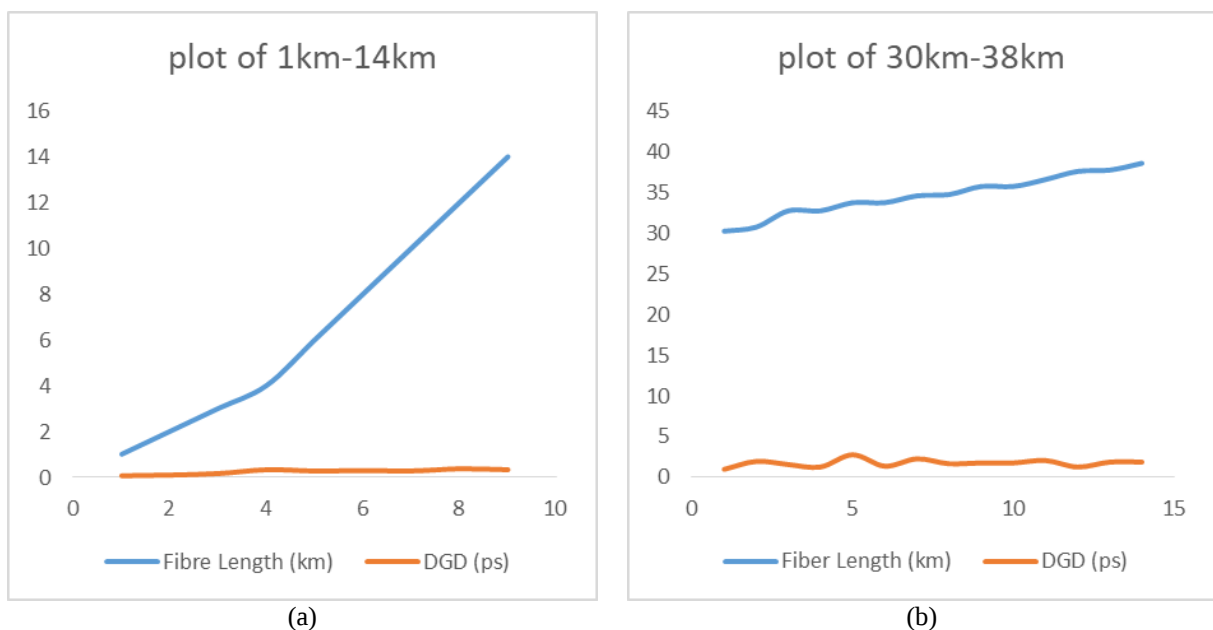


Figure 6. Plot of DGD (ps) vs fiber length (km): (a) 1 – 14 km and (b) 30 – 38 km.

Figure 7 (a) shows that BER increases with DGD: from 1.22×10^{-7} at 0.95 ps to 1.27×10^{-7} at 2.74 ps, suggesting constellation misinterpretation in QAM becomes more likely as DGD increases. While Figure 7 (b) shows that BER remains relatively stable between 1.18×10^{-7} and 1.29×10^{-7} across DGD values of 0.95 ps to 2.24 ps, indicating FEC may compensate for moderate DGD-induced errors.

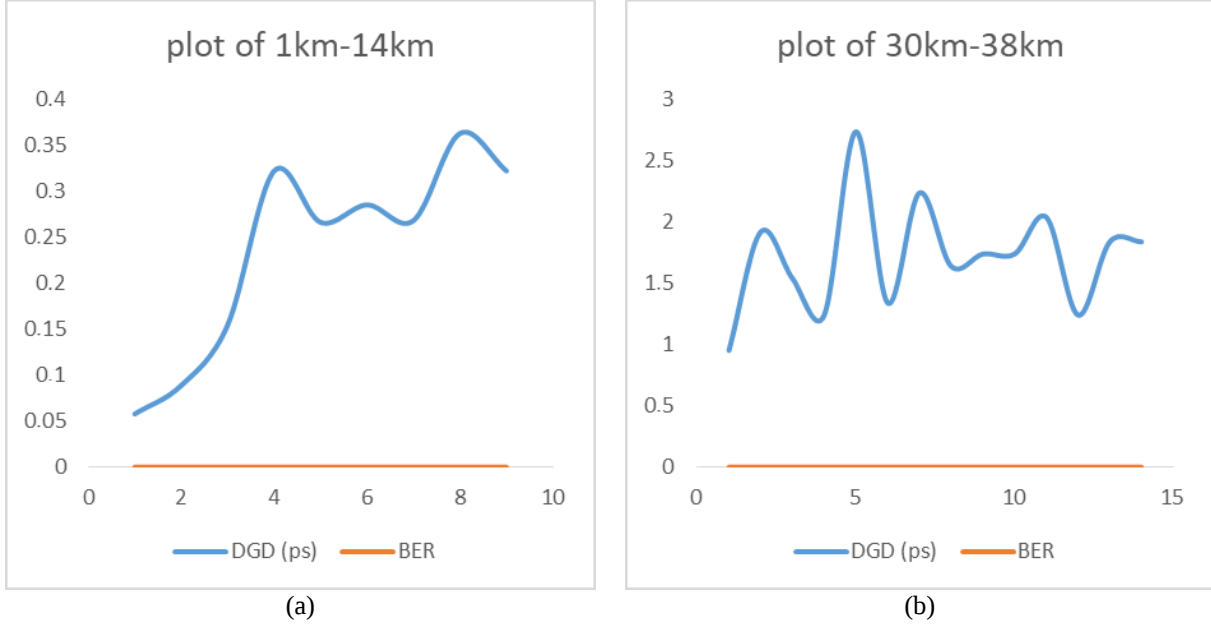


Figure 7. Plot of DGD (ps) vs BER: (a) 1 – 14 km and (b) 30 – 38 km.

In Figure 8 (a) Jitter rises from 4 ps at 0.058 ps DGD to 24.36 ps at 0.364 ps DGD, showing QAM is highly sensitive to PMD-induced timing fluctuations. While in Figure 8 (b) for longer MMF links, jitter increases from 25.54 ps at 0.95 ps DGD to 33.54 ps at 2.74 ps DGD, reinforcing the impact of DGD on temporal signal stability.

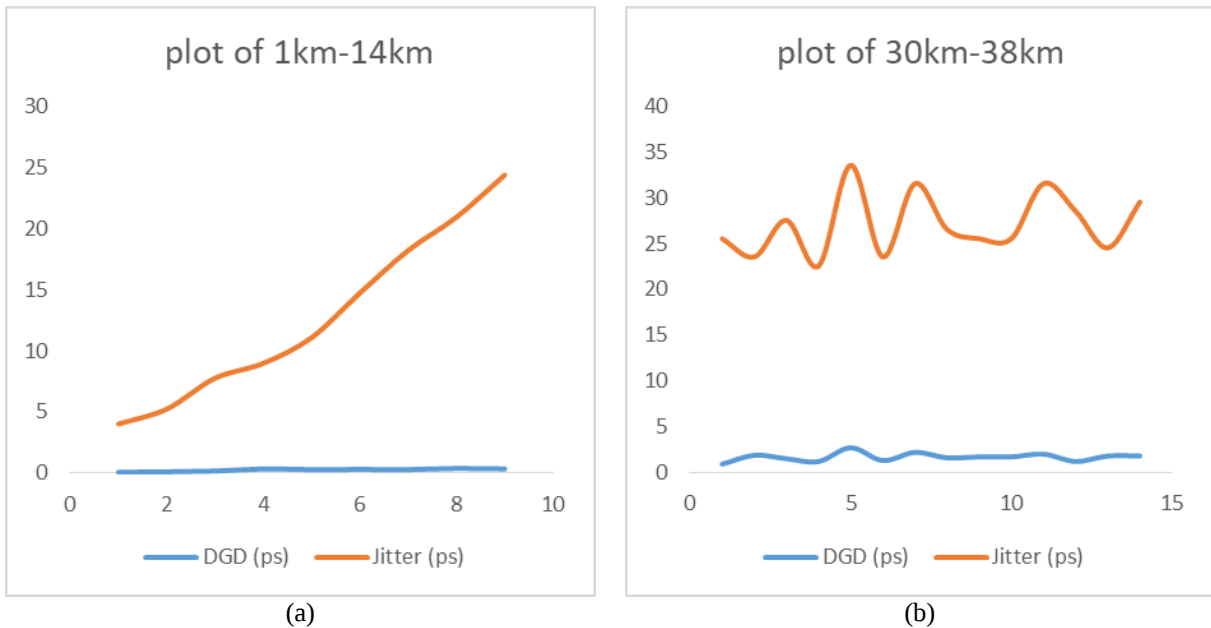


Figure 8. Plot of Signal jitters vs DGD: (a) 1 – 14 km and (b) 30 – 38 km.

Figure 9 (a) illustrates that SNR drops from 34.83 dB at 0.058 ps DGD to 33.91 dB at 0.364 ps, suggesting increasing DGD reduces the precision of QAM signal detection. Figure 9 (b) also shows that SNR varies from 59.34 dB at 1.24 ps to 52.90 dB at 2.04 ps, confirming that higher DGD lowers SNR in MMF-QAM, affecting transmission robustness.

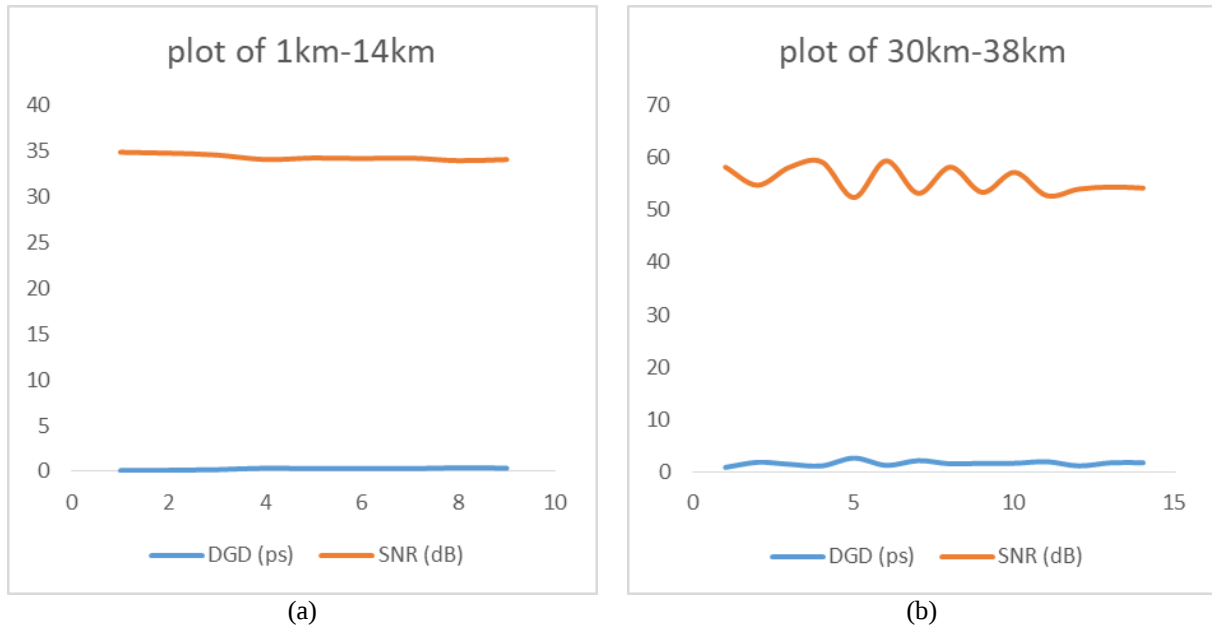


Figure 9. Plot of SNR (dB) vs DGD (ps): (a) 1 – 14 km and (b) 30 – 38 km.

Figure 10 (a) shows increasing DGD with temperature (e.g., from 0.954 ps at 28.56°C to 2.74 ps at 29.16°C), showing heat stress amplifies PMD effects. While Figure 10 (b) shows Humidity rise from 52.32% to 58.32% corresponds with DGD growth from 1.24 ps to 2.24 ps, suggesting moisture-sensitive distortion in fiber geometry or mode coupling.

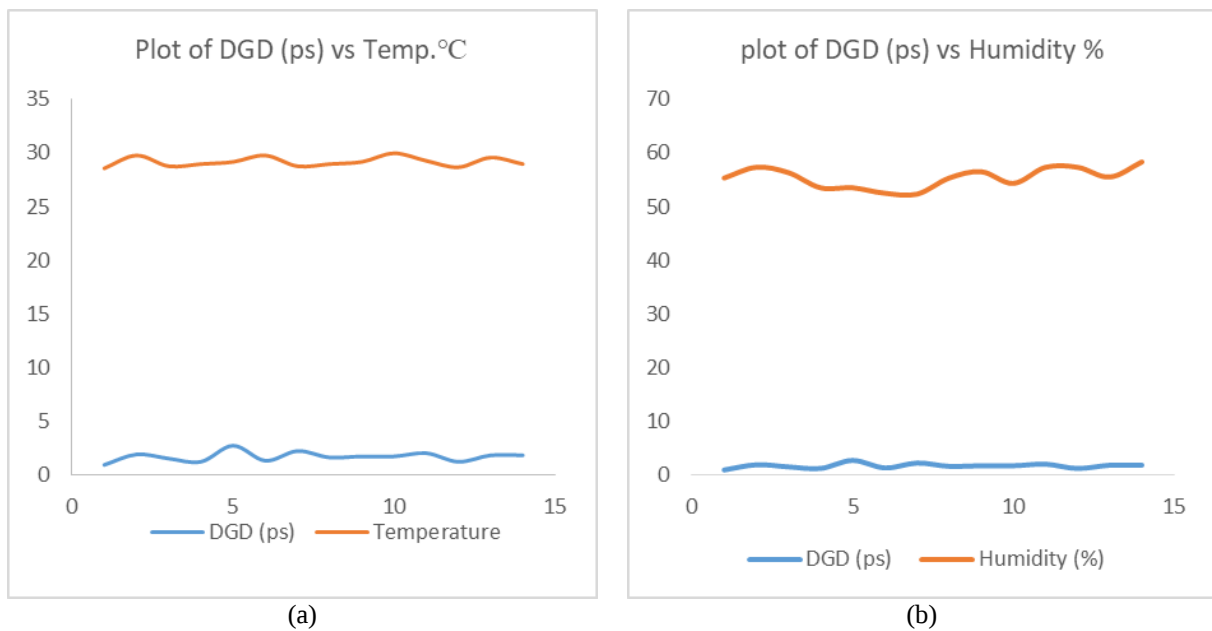


Figure 10. Plot of DGD vs: (a) temperature and (b) humidity.

Table 3. PMD induced degradation of signal metrics in multi-mode fibre using QAM modulation.

Fiber length (km)	Modulation	DGD (ps)	PSP (deg)	Jitter (ps)	Output optical power (dBm)	BER	SNR (dB)
1	QAM	0.058	62.7	4	-2	1.5×10^{-9}	34.83
2	QAM	0.089	178.8	5.22	-1.56	1.8×10^{-9}	34.73
3	QAM	0.155	135.4	7.74	-2.34	2.9×10^{-9}	34.53
4	QAM	0.323	46.8	8.96	-0.25	9.3×10^{-9}	34.03
6	QAM	0.267	84.8	11.06	-0.99	6.3×10^{-9}	34.2
8	QAM	0.286	28.9	14.71	-1.64	7.2×10^{-9}	34.14
10	QAM	0.269	15.6	18.19	-1.34	6.4×10^{-9}	34.19
12	QAM	0.364	99	20.91	-2.18	1.2×10^{-8}	33.91
14	QAM	0.323	138.7	24.36	-1.35	9.3×10^{-9}	34.03

Table 4. PMD induced degradation of signal metrics in multi-mode fibre using QAM modulation format.

Fiber length (km)	Data rate (Gbps)	Modulation format	Wavelength (nm)	DGD (ps)	Jitter (ps)	SNR (dB)	BER	Temperature (°C)	Humidity (%)
30.22	28	QAM	1350	0.954	25.54	58.35	1.2×10^{-7}	28.56	55.32
30.72	15	QAM	1350	1.923	23.54	54.9	1.3×10^{-7}	29.76	57.32
32.72	130	QAM	1350	1.543	27.54	58.35	1.2×10^{-7}	28.76	56.32
32.72	70	QAM	1350	1.243	22.54	59.35	1.3×10^{-7}	28.97	53.5
33.72	15	QAM	1350	2.743	33.54	52.55	1.2×10^{-7}	29.17	53.5
33.72	70	QAM	1350	1.343	23.54	59.55	1.3×10^{-7}	29.76	52.5
34.57	15	QAM	1350	2.243	31.54	53.35	1.3×10^{-7}	28.76	52.32
34.72	130	QAM	1350	1.643	26.54	58.35	1.2×10^{-7}	28.97	55.32
35.72	15	QAM	1350	1.743	25.54	53.55	1.3×10^{-7}	29.17	56.5
35.72	130	QAM	1350	1.743	25.54	57.35	1.2×10^{-7}	29.96	54.32

4.3. Comparison plots between NRZ and QAM Modulation formats

Both modulation formats show that DGD increases with fiber length due to the accumulation of birefringence effects along the fiber. NRZ rises from 0.136 ps at 1 km to over 2.12 ps at around 38 km, while QAM increases from 0.058 ps at 1 km to 2.24 ps over the same range. Although the early data (1 – 14 km) shows a slower DGD growth, the figure also includes extended fiber lengths up to 38 km, highlighting how DGD continues to build significantly in longer multimode fiber links. This emphasizes the importance of PMD management in long-distance deployments.

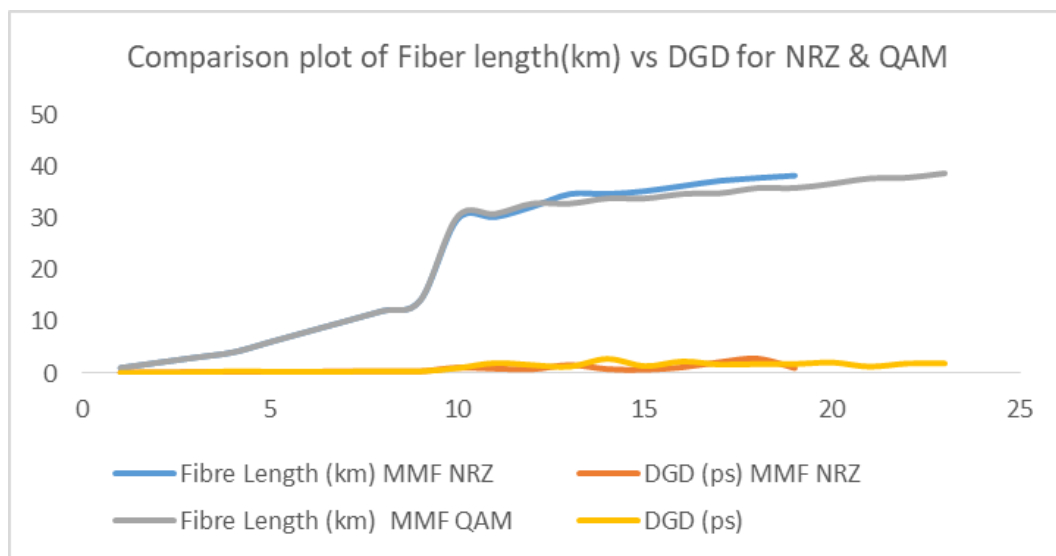


Figure 11. Plot of fiber length (km) vs DGD (ps).

Figure 12 illustrates the relationship between Differential Group Delay (DGD) and Bit Error Rate (BER) for both NRZ and QAM modulation formats in multimode fiber systems. As DGD increases, BER shows a slight upward trend in both cases, indicating that polarization-induced delay contributes to signal degradation. However, the increase in BER is more noticeable in NRZ, which rises from approximately 1.18×10^{-7} to 1.35×10^{-7} , compared to QAM, which remains relatively stable between 1.18×10^{-7} and 1.29×10^{-7} . This suggests that QAM offers slightly better resilience to PMD-induced errors, likely due to its advanced modulation and error correction capabilities.

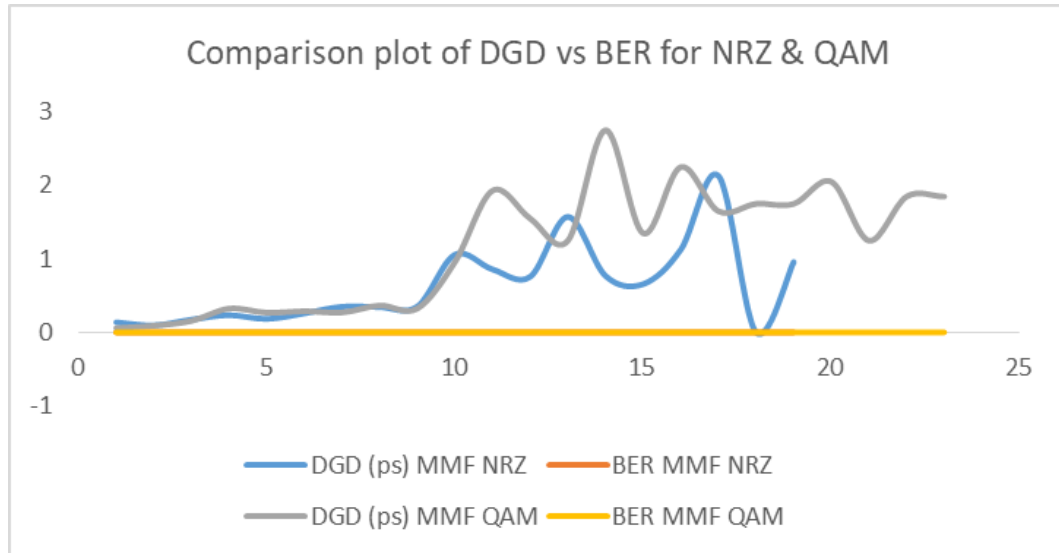


Figure 12. Plot of DGD (ps) vs BER.

Figure 13 compares the impact of temperature on DGD for both NRZ and QAM formats. In NRZ, DGD increases significantly from approximately 0.65 ps to 2.78 ps as temperature rises from 28.34°C to 29.90°C, while QAM shows a more moderate increase from 0.95 ps to 2.24 ps over the same range. This indicates that NRZ is more thermally sensitive, likely due to its simpler modulation scheme being more affected by changes in fiber birefringence. The trend confirms that temperature fluctuations in real-world environments like Abuja can significantly influence PMD performance, particularly in NRZ systems.

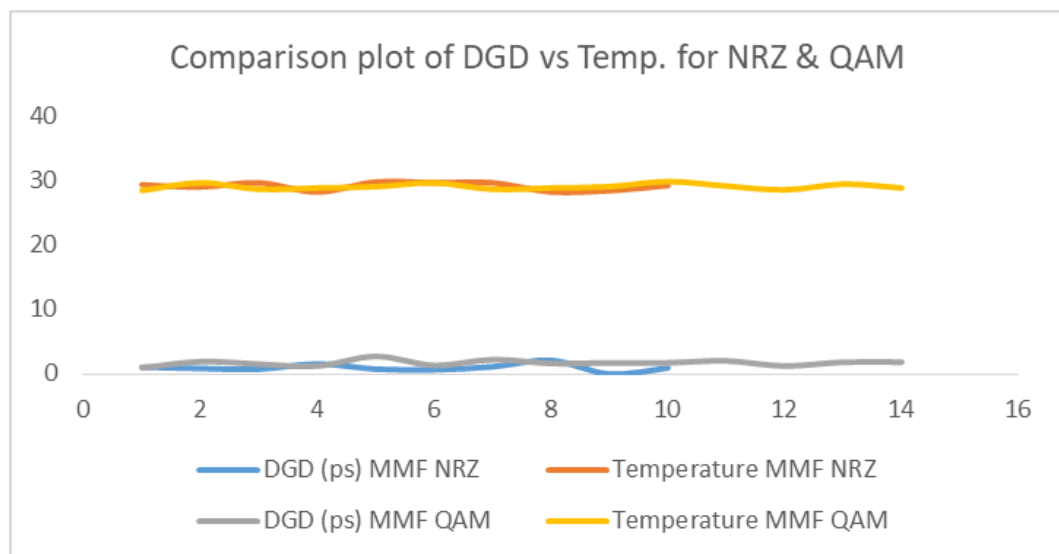


Figure 13. Plot of DGD (ps) vs Temperature (°C).

Figure 14 shows that DGD increases with rising humidity for both modulation formats. In NRZ, DGD grows from 0.75 ps to 2.94 ps as humidity rises from approximately 53.1% to 59.5%, while QAM shows a smaller increase from 1.24 ps to 2.24 ps across a similar range. This demonstrates that NRZ is more susceptible to humidity-induced birefringence, possibly due to micro-bending or moisture affecting fiber coating and structure. QAM, on the other hand, shows better stability, reinforcing its suitability for environments where humidity control is challenging.

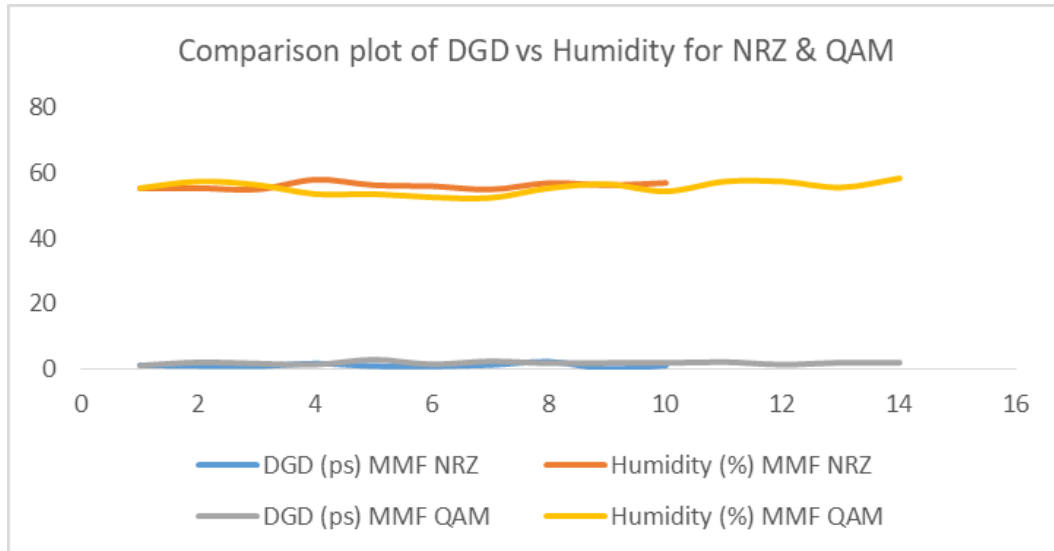


Figure 14. Plot of DGD (ps) vs Humidity (%).

5. CONCLUSION AND RECOMMENDATIONS

This study investigated the impact of Polarization Mode Dispersion (PMD) on high-speed multimode fiber (MMF) optical systems under varying environmental conditions in Abuja, Nigeria, using NRZ and QAM modulation formats. The results revealed that Differential Group Delay (DGD), a key indicator of PMD, increases with fiber length, temperature, and humidity, leading to notable degradation in signal metrics such as Bit Error Rate (BER), jitter, and Signal-to-Noise Ratio (SNR).

Comparative analysis showed that while both NRZ and QAM modulation formats are affected by PMD, NRZ consistently exhibited greater sensitivity, particularly under environmental fluctuations. QAM demonstrated better performance stability, maintaining lower BER and more consistent SNR and jitter values even at higher DGD levels. This suggests that QAM is more resilient to PMD-related impairments in MMF systems, making it a more suitable choice for high-speed and environmentally dynamic optical networks.

The findings underscore the importance of accounting for PMD in MMF deployments, especially in regions with high humidity and temperature variations. They also highlight the need for implementing dispersion mitigation strategies, such as advanced modulation formats and environmental compensation techniques, to ensure the reliability and efficiency of next-generation optical communication systems.

Recommendations:

- Deploy adaptive PMD compensation modules or dynamic polarization controllers in the optical network to automatically adjust for differential delays, particularly over long multimode fiber links where PMD effects accumulate.
- Install temperature and humidity sensors along fiber routes and integrate the data into a central network management system to monitor environmental changes and proactively address PMD-related impairments.
- Optimize fiber routing by avoiding installation near heat sources, vibration zones, or areas prone to moisture, as these environmental stressors can exacerbate PMD and degrade signal integrity.

REFERENCES

- [1] Zairmi, Y., Veriyanti, V., Candra, W., Syahputra, R. F., Soerbakti, Y., Asyana, V., Irawan, D., Hairi, H., Hussein, N. A., & Anita, S. (2020). Birefringence and polarization mode dispersion phenomena of commercial optical fiber in telecommunication networks. *Journal of Physics: Conference Series*, **1655**(1), 012160.
- [2] Du-Burck, F., Manamanni, K., Steshchenko, T., Ramdane, A. C., & Roncin, V. (2022). Effects of polarization modulation induced by electro-optic modulators in fiber-based setups. *IEEE Photonics Technology Letters*, **34**(3), 185–188.
- [3] EDFA, W. (2022). 1.1 Physical Limits and Prospects of Optical Communication Systems. *Space-Division Multiplexing in Optical Communication Systems: Extremely Advanced Optical Transmission with 3M Technologies*, **236**, 2.
- [4] Badraoui, N. (2020). Investigations on optical communication links for high data rate in 5G systems. *Budapest University of Technology and Economics*.
- [5] Eid, M. M. & Rashed, A. Z. (2021). Fixed scattering section length with variable scattering section dispersion based optical fibers for polarization mode dispersion penalties. *Indonesian Journal of Electrical Engineering and Computer Science*, **21**(3), 1540–1547.
- [6] Agalliu, R. & Lucki, M. (2018). Transmission Transparency and Potential Convergence of Optical Network Solutions at the Physical Layer for Bit Rates from 2.5 Gbps to 256 Gbps. *Advances in Electrical and Electronic Engineering*, **15**(5), 877–884.
- [7] Amiri, I. S., Rashed, A. N. Z., & Yupapin, P. (2025). High-speed transmission circuits signaling in optical communication systems. *Journal of Optical Communications*, **45**(s1), s69–s75.
- [8] Ali, F., Muhammad, F., Habib, U., Khan, Y., & Usman, M. (2021). Modeling and minimization of FWM effects in DWDM-based long-haul optical communication systems. *Photonic Network Communications*, **41**(1), 36–46.
- [9] Chen, X., Bickham, S. R., Abbott, J. S., Coleman, J. D., & Li, M. J. (2019). Multimode fibers for data centers. *Handbook of Optical Fibers*, 41–97.
- [10] Li, K., Chen, X., Mishra, S. K., Hurley, J. E., Stone, J. S., & Li, M. J. (2020). Modal delay and modal bandwidth measurements of bi-modal optical fibers through a frequency domain method. *Optical Fiber Technology*, **55**, 102145.
- [11] Dubovan, J., Litvik, J., Korček, R., Benedikovič, D., Veselovský, A., Glesk, I., Müllerová, J., & Dado, M. (2021, November). High-speed operation of fiber-optic link impaired by wind gusts. *2021 19th International Conference on Emerging eLearning Technologies and Applications (ICETA)*, 120–125.
- [12] Liang, C., Bai, Q., Yan, M., Wang, Y., Zhang, H., & Jin, B. (2021). A comprehensive study of optical frequency domain reflectometry. *IEEE Access*, **9**, 41647–41668.
- [13] Cappelletti, M., Mazur, M., Fontaine, N. K., Ryf, R., Hayashi, T., Mecozzi, A., Santagiustina, M., Galtarossa, A., Antonelli, C., & Palmieri, L. (2024). Statistical analysis of modal dispersion in field-installed coupled-core fiber link. *Journal of Lightwave Technology*, **42**(11), 4103–4109.
- [14] Chen, X., Hurley, J. E., Stone, J. S., & Li, M. J. (2023). Chromatic dispersion measurements of single-mode fibers, polarization-maintaining fibers, and few-mode fibers using a frequency domain method. *Photonics*, **10**(2), 215.
- [15] Lu, P., Lalam, N., Badar, M., Liu, B., Chorpening, B. T., Buric, M. P., & Ohodnicki, P. R. (2019). Distributed optical fiber sensing: Review and perspective. *Applied Physics Reviews*, **6**(4).
- [16] Singh, M., Sarangal, H., Singh, B., Kaur, H., & Kour, S. (2025). Qualitative analysis of PMD-induced long-haul optical fiber link. *Journal of Optical Communications*, **45**(s1), s2317–s2322.
- [17] Singh, M., Atieh, A., Aly, M. H., & El-Mottaleb, S. A. A. (2023). Performance analysis for UOWC transmission system using NRZ, AMI, and CSRZ modulation schemes. *Optical and Quantum Electronics*, **55**(14), 1259.
- [18] Xu, W. (2024). Effects of Dispersion and Phase Noise on QPSK and QAM System: Performance and Compensation Techniques. *2024 4th International Conference on Artificial Intelligence, Robotics, and Communication (ICAIRC)*, 247–252.
- [19] Paloi, F. (2023). Long-haul signal transmission using various modulator formats and frequency conversion. *University of Bedfordshire*.