Comparative Analyses of Dense Wavelength Division Multiplexing and Coarse Wavelength Division Multiplexing in Long-Haul Optical Data Transmission

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ABSTRACT

Although optical fiber communication is best known for transmitting information at a high rate, there is a growing demand to push the data rate even higher. To increase the overall data rate without increasing the number of fibers, Wavelength Division Multiplexing (WDM) is used. The two types of WDM technologies mainly used to transmit information at a very fast and high speed are Dense Wavelength Division Multiplexing (DWDM) and Coarse Wavelength Division Multiplexing (CWDM). In this research, we simulated both DWDM and CWDM systems with a payload of 10 Gb/s over 2, 4, 10, and 16 channels at distances of 5 km, 20 km, 50 km, and 100 km. Further on, a practical implementation of DWDM and CWDM systems with a payload of 10 Gb/s over 2, 4, 10, and 16 channels at distances of 1 km, 2 km, 3 km, 4 km, and 5 km was conducted. Both DWDM and CWDM systems were compared using the quality factor (QF), eye-opening factor (EOF), optical signal-to-noise ratio (OSNR), and received optical power (ROP). Both simulation results and practical results revealed that CWDM had a relatively better performance than DWDM. The results also showed that the quality and integrity of the signal decreased with increasing distances and increasing number of channels.

Keywords: Wavelength division multiplexing, Optical signal-to-noise ratio, Eye-opening factor, Channel spacing, Quality factor

1.0. INTRODUCTION

The transmission of information from the source to the destination is done by using various media like coaxial, twisted pair radio waves, and optical fiber (Andrew W. Clegg, 2012, Isaac A. Aboagye et al., 2023, Isaac A. Aboagye et al., 2017). In modern communication, optical fiber cables are used to transmit large amounts of data. Optical fibers have enormous information-carrying capacity and low attenuation. In optical fiber communications, WDM is a technology that multiplexes several optical carrier signals onto a single optical fiber by using different wavelengths (Damla, O. et al. 2015, Ali, M. H., Abass, A. K., & Al-Hussein, S. A., 2019, Dwivedi, S. et al., 2015). Most WDM systems operate on standard single-mode fiber (SSMF) optical cable. Certain forms of WDM can also be used in multi-mode fiber (MMF) cables (Kaur, G., & Sharda, A. K., 2008). Two types of WDM technologies that are primarily used are DWDM and CWDM. The spacing between individual signals and wavelengths used for transmitting through a common fiber channel serves as the way to differentiate between DWDM and CWDM. A typical DWDM system allows 40 channels at a channel spacing of 0.8 nm (100 GHz). The small channel spacing allows the system to transmit a significant amount of information simultaneously. CWDM, contrary to DWDM, multiplexes optical signals within the entire frequency band ranging between 1271 nm to 1610 nm (Mahmud S. M. N., & Talukder, A. A., 2009). A typical CWDM system allows 18 channels at a channel spacing of 20 nm (2500 GHz). Due to its large channel spacing, CWDM sends and receives less information as compared to DWDM. CWDM is perfect for the gradual upgrade and expansion of existing systems since it is cost-effective (Saha, A., & Manna, N., 2011). Many research papers have been published which is aimed at increasing bandwidth using different technologies. In doing this, some take into consideration the network architecture, channel spacing, and the best multiplexing techniques to use.

Robinson et al. (Robinson, S., Jasmine, S., & Pavithra, R. 2015) proposed a "Hybrid WDM (DWDM and CWDM) Free Space Optical Communication System". They investigated the effect of free space atmospheric attenuation on the performance of free space optical (FSO) communication systems. This hybrid system incorporated four CWDM and eight DWDM input signals. The transmitted hybrid WDM-FSO signal after the multiplexer had a corresponding signal power of about 15 dBm for DWDM channels and 5 dBm for CWDM channels. This variation in received power was due to the losses in the components that were employed in the link and linewidth of the proposed system. However, the proposed hybrid WDM-FSO system could support an achievable distance of up to 0.64 km when the atmospheric attenuation was increased. Mohsen et al. (Mohsen, D. E., Hammadi, A M., & Alaskary, A. J. 2021) researched a "Design and Implementation of 1.28 Tbps DWDM based RoF system with External Modulation and Dispersion Compensation Fiber". They designed and implemented a 1.28 Tbps DWDM-based Radio over Fiber (RoF) system with external modulation and DCF. Channels 1, 4, 8, 12, 16, 20, 24, 28, and 32 were selected as samples for the investigation. The proposed system was based on the utilization of 32 channels by 40 Gbps and could achieve a bit rate of 1.28 Tbps. The investigation for the system performance considered different distances of 60, 120, and 180 km. Despite this method showing higher reliability and adaptability, it had higher insertion loss and fiber dispersion effect.

The objectives of this project are to design and implement a system that will utilize both CWDM and DWDM in long-haul optical data transmission, evaluate the performance of the two systems, and determine the best system for long-haul optical data transmission (Dhadhal, D., Thummar, R., & Vivekanand, V., 2021, Dikoliya, M. V., & Sharma, P., 2021, Kim, H. D., & Kim I., et al., 2017). This research paper has been divided into five major sections. Section 1.0 provides a background introduction to the concept of fiber transmission, Wavelength Division Multiplexing (DWDM and CWDM), and related works. It touches on the relevance of this research, the problem statement, and the objectives that have to be met to solve the problem. It also provides information on reviewed research papers as well as a deep study based on the proposed infrastructures and their advantages. Section 2.0 focuses on the design process for the development of the WDM systems. It explores the physical and software design of both DWDM and CWDM systems in detail. It also outlines the design requirements and specifications for the design of both DWDM and CWDM systems. Section 3.0 spells out the implementation of the system and the results obtained from testing the system. It evaluates the comparative analysis of the two WDM systems. Section 4.0 concludes the research and outlines the accomplishments of the research. It highlights the results achieved and provides recommendations as to how the research can be further enhanced.

2.0 SYSTEM DESIGN AND METHODOLOGY

Two different systems were designed for the CWDM and DWDM respectively. The system was first simulated using the OptiSystem v7 and it was then implemented. Different wavelengths were allocated to each channel. A channel spacing of 0.8 nm and 20 nm were used in DWDM and CWDM respectively. The system comprises various elements which include light sources, multiplexers and demultiplexers, modulators, and optical amplifiers. The number of channels used for both simulation and actual implementation are 2, 4, 10, and 16 with a data rate of 10 Gbps for each channel. Distances of 5 km, 20 km, 50 km, and 100 km were used for the simulation while distances of 1 km, 2 km, 3 km, 4 km, and 5 km were used for the actual implementation of the work. A standard single-mode fiber was used. Figures 1 and 2 below show an architectural diagram of a DWDM and CWDM system in both simulation and actual implementation. It is made up of three main sections; transmitter, transmission medium (optical fiber), and receiver. The multiplexes the data streams to be transmitted simultaneously over a single-mode fiber. At the receiving end, the data streams are separated using

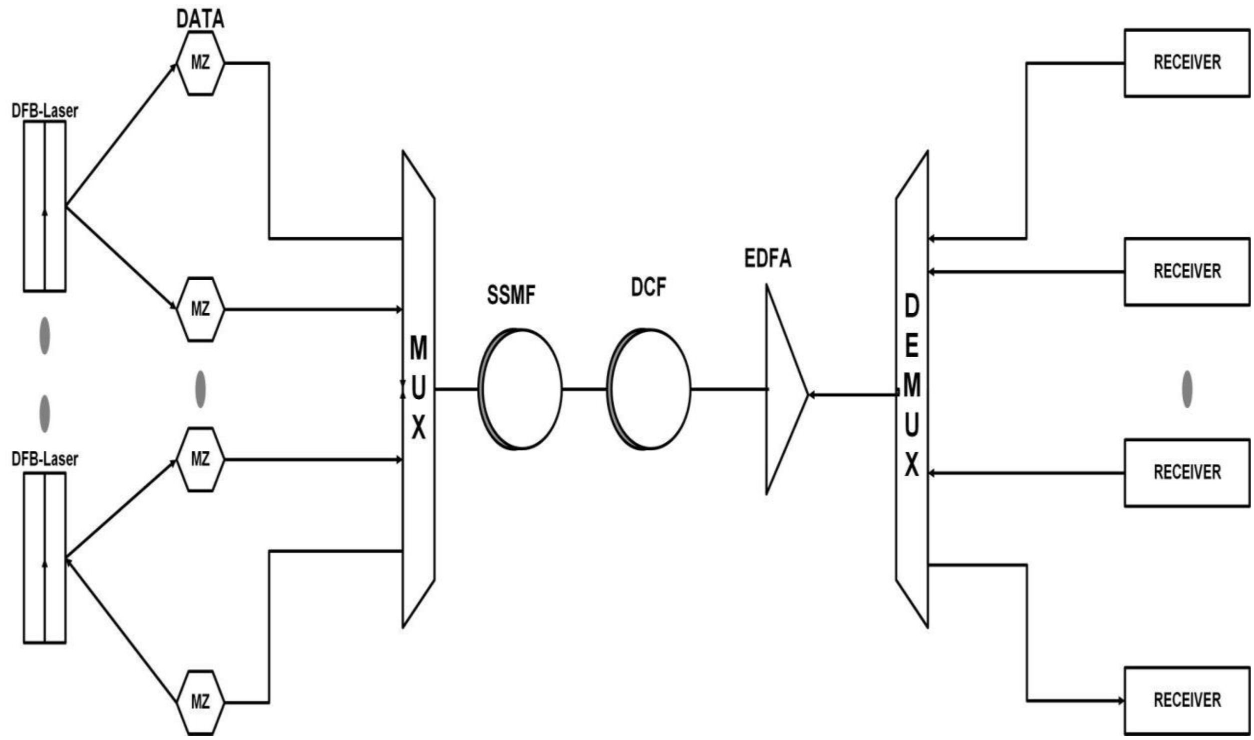

Figure 1: Architecture Diagram of DWDM and CWDM system

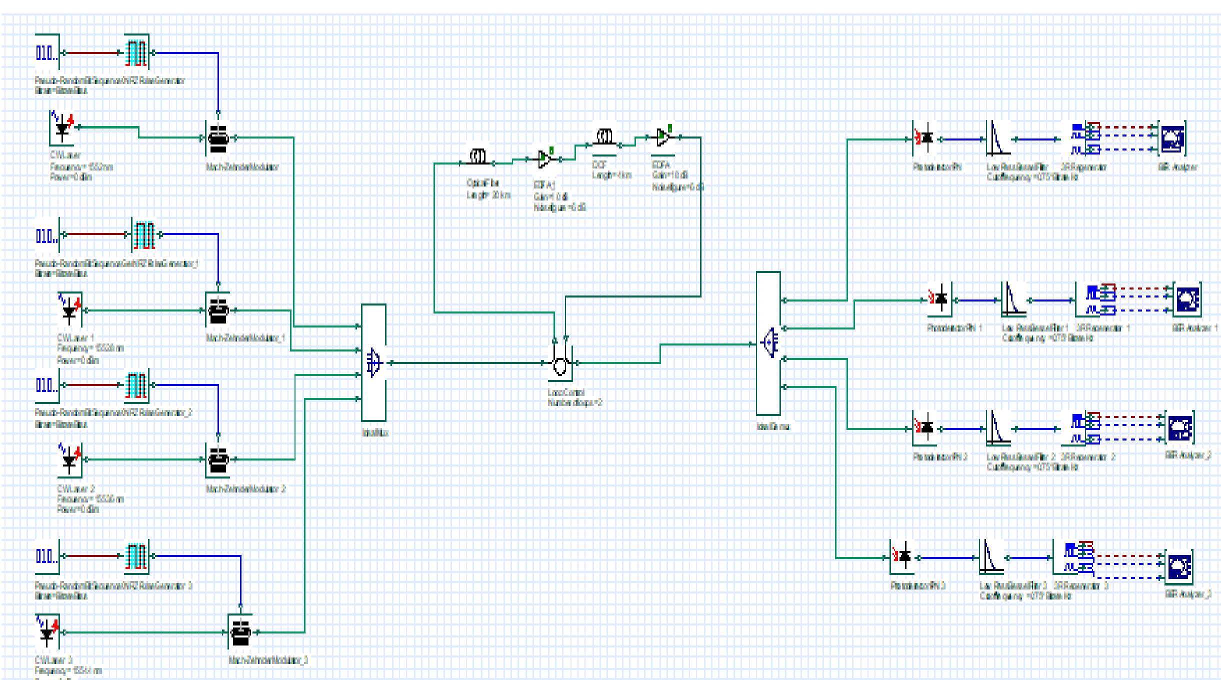

Figure 2: Simulation diagram of DWDM and CWDM system

using the demultiplexer, and individual signals will be received and analyzed. Parameters like quality factor, eye height, received optical power, and optical signal-to-noise ratio were assessed.

3.0. SYSTEM IMPLEMENTATION AND TESTING

This section presents various steps that were followed in the implementation of the two systems (CWDM and DWDM). The single-mode fiber cables were measured and spliced to determine the desired lengths using an arc fusion splicing machine. For each of the distances, simulated results were obtained for 2, 4, 10, and 16 channels respectively. A bit rate of 10 Gb/s was used throughout the simulation and distances of 5, 20, 50, and 100 km were used. Values were obtained for the quality factor, eye height, received optical power, and optical signal-to-noise ratio. For the practical implementation, results were obtained for 2, 4, 10, and 16 channels respectively. A bit rate of 10 Gb/s was used throughout the implementation and distances of 1, 2, 3, 4, and 5km were used. Values were obtained for the received optical power and the optical signal-to-noise ratio. To transmit multiple signals over the common fiber cable, a wavelength-specific transceiver was directly plugged into a network switch. The CWDM wavelength-specific transceiver ranges from wavelengths of 1270 nm to 1610 nm with a channel spacing of 20 nm in accordance with the CWDM Wavelength ITU channels guide for CWDM. The DWDM wavelength-specific transceiver, on the other hand, ranges from wavelengths of 1548.1 nm to 1577.03 nm with a channel spacing of 0.8 nm in accordance with the DWDM Wavelength international telecommunication union (ITU) channels guide. The wavelength-specific transceiver modules were connected to a Mux/Demux module using patch cables for multiplexing to occur. The signal was transmitted across the length of the fiber cable to another Mux/Demux module at the receiver side which separated the signals into discrete wavelengths.

3.1 Testing and Results

By comparing the simulated results of both DWDM and CWDM to the practical results of both DWDM and CWDM, a trend was noticed as the distance increased. This affected other parameters that were being measured.

A. Comparative Analysis of Simulated Results

3.1.1 Comparison of CWDM and DWDM Based on Average Quality Factor

The average quality factor obtained for both CWDM and DWDM at distances of 2, 4, 10, and 16 km in simulation is shown in Table 1. Figure 3 shows a graph of the simulation results for both CWDM and DWDM obtained from the average quality factor based on our simulated setup. It can be seen from both graphs that as the distance increases, the average quality factor decreases. Moreover, as the number of channels increased, the average quality factor also decreased. This signifies that as the number of channels and distances increases, the quality of the signal deteriorates. The CWDM system in this case has better signal quality compared to that of the DWDM system.

Table 1: Distance (km) against average quality factor at different channels

TECHNOLOGY	DISTANCES (km)	CHANNELS			
		2	4	10	16
DWDM	5	23.3276	22.0584	21.1368	20.2116
	20	17.9604	15.8145	14.0212	11.9261
	50	7.0429	6.1277	4.8148	4.6409
	100	3.5516	3.3766	2.9378	2.6332
CWDM	5	23.4794	22.1026	21.3837	20.6695
	20	18.3578	16.3984	14.3212	12.0723
	50	7.2542	6.3887	5.1519	4.9212
	100	3.9117	3.5706	3.1263	2.8665

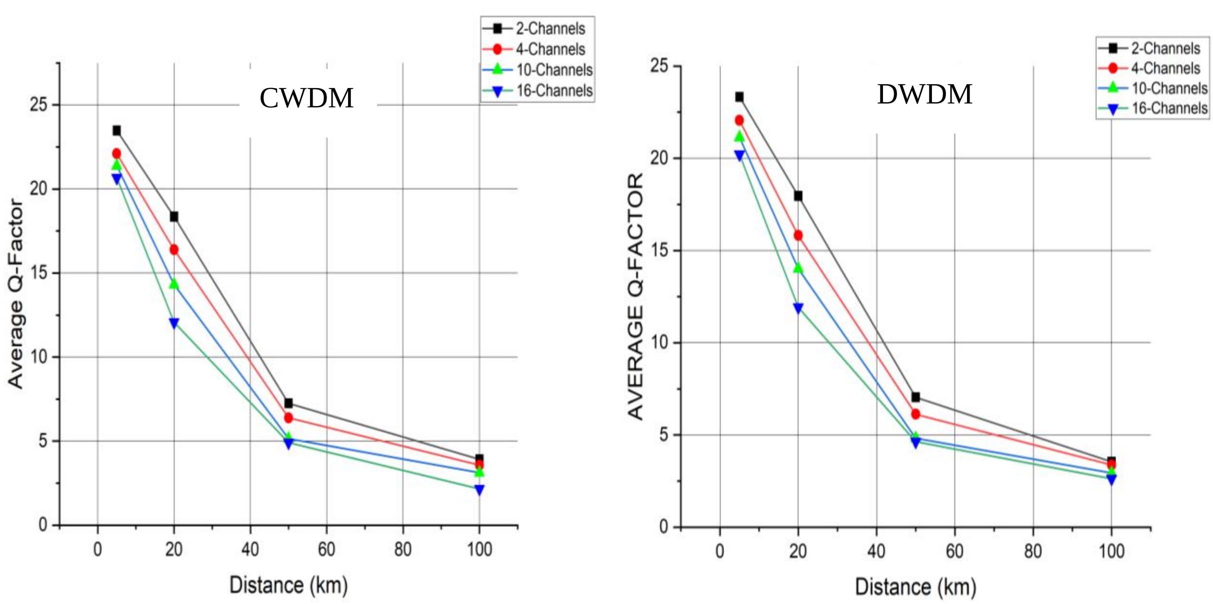

Figure 3: Distance (km) against average quality factor at different channels for CWDM and DWDM

3.1.2 Comparison of CWDM and DWDM Based on Average Eye Height

The average eye height obtained for both CWDM and DWDM at distances of 2, 4, 10, and 16 km in simulation is shown in Table 2. Figure 4 shows a graph of the simulation results for both CWDM and DWDM obtained from the average eye height based on our simulated setup. It can be seen from both graphs that as the distance increases, the average eye height decreases. Moreover, as the number of channels increases, the average eye height also decreases. This signifies that as the number of channels and distances increases, the eye height closes. The CWDM system in this case has better signal strength compared to that of the DWDM system.

3.1.3 Comparison of CWDM and DWDM Based on Average Received Optical Power

The average received optical power obtained for both CWDM and DWDM at distances of 2, 4, 10, and 16 km in simulation is shown in Table 3. Figure 5 shows a graph of the simulation results for both CWDM and DWDM obtained from the average received optical power based on our simulated setup. It can be seen from both graphs that as the distance increases, the average received power decreases. Moreover, as the number of channels increases, the average received power also decreases. This signifies that as the number of channels and distances increases, the received optical power decreases. The CWDM system in this case has better signal strength compared to that of the DWDM system.

Table 2: Distance (km) against average eye height at different channels

TECHNOLOGY	DISTANCES (km)	CHANNELS			
		2	4	10	16
DWDM	5	8.6934	8.6034	8.5721	8.5071
	20	8.4237	8.4089	8.3859	8.3407
	50	7.1097	7.0021	6.9861	6.8932
	100	6.6729	6.5498	6.4009	6.2187
CWDM	5	8.8665	8.7823	8.7233	8.6578
	20	8.5725	8.5568	8.5209	8.4843
	50	7.3269	7.2833	7.2594	7.1943
	100	6.9012	6.8504	6.6397	6.5274

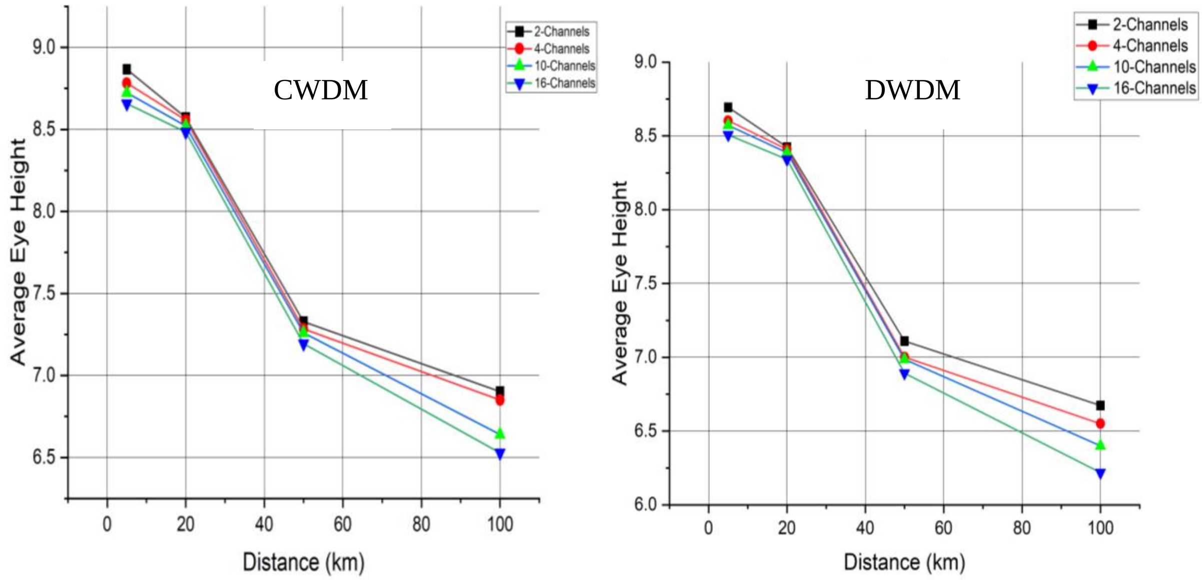

Figure 4: Distance (km) against average eye height at different channels for CWDM and DWDM

Table 3: Distance (km) against average received optical power (dBm)

TECHNOLOGY	DISTANCES (km)	CHANNELS			
		2	4	10	16
DWDM	5	-12.9637	-12.9718	-12.9973	-13.1679
	20	-13.4893	-13.7984	-13.9793	-14.0561
	50	-15.0026	-15.1780	-15.2907	-15.3450
	100	-16.9562	-16.9823	-17.1349	-17.2345
CWDM	5	-12.8822	-12.9662	-12.9507	-12.9969
	20	-13.2831	-13.3361	-13.5542	-13.6508
	50	-14.8523	-14.8737	-14.8832	-14.9219
	100	-16.5534	-16.5701	-16.6522	-16.7512

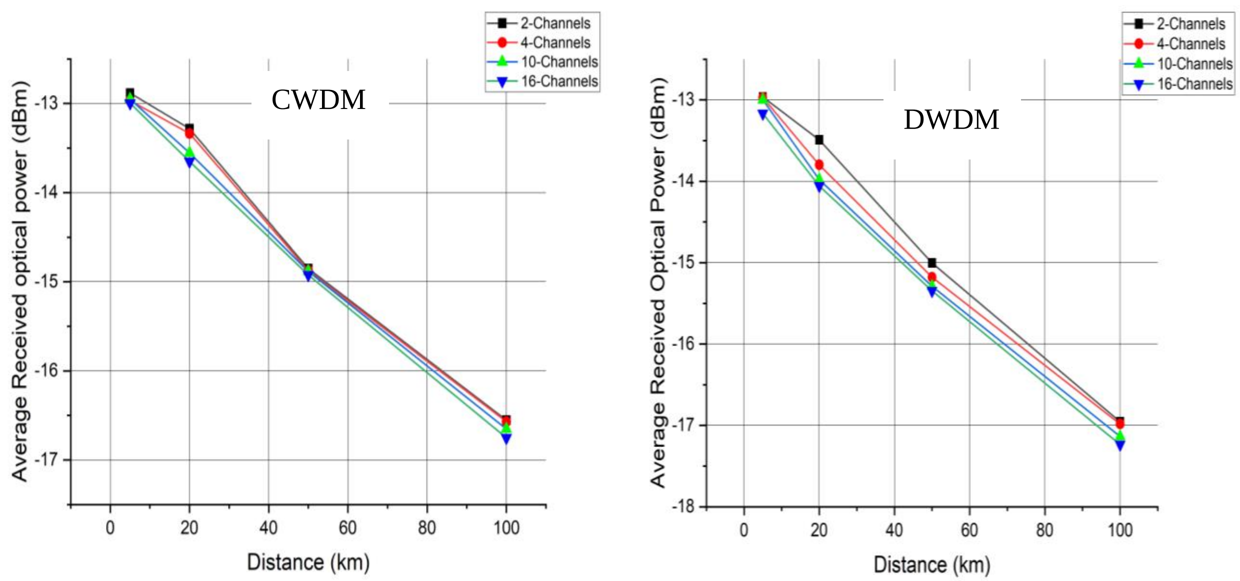

Figure 5: Distance (km) against average received optical power (dBm) for CWDM and DWDM

3.1.4 Comparison of CWDM and DWDM Based on Average Optical Signal-To-Noise Ratio

The average received optical signal-to-noise ratio obtained for both CWDM and DWDM at distances of 2, 4, 10, and 16 km in simulation is shown in Table 4. Figure 6 shows a graph of the simulation results for both CWDM and DWDM obtained from the average received optical signal-to-noise ratio based on our simulated setup. It can be seen from both graphs that as the distance increases, the average received optical signal-to-noise ratio decreases. Moreover, as the number of channels increases, the average received optical signal-to-noise ratio also decreases. This signifies that as the number of channels and distances increases, the received optical signal-to-noise ratio decreases. The CWDM system in this case has better signal strength compared to that of the DWDM system.

B. Comparative Analysis of the Practical Implementation Results

3.1.5. Comparison of CWDM and DWDM Based on Average Received Optical Power

The average received optical power obtained for both CWDM and DWDM at distances of 1, 2, 3, 4, and 5 km in the implementation is shown in Table 5. Figure 7 shows a graph of the implementation results for both CWDM and DWDM obtained from the average received optical power based on our implemented setup. It can be seen from both graphs that as the distance increases, the average received optical power decreases. Moreover, as the number of channels increases, the average received optical power also decreases. This significant that as the number of channels and distances increases, the received optical power decreases. The CWDM system in this case has better signal strength compared to that of the DWDM system.

Table 4: Distance (km) against average optical signal-to-noise ratio (dB)

TECHNOLOGY	DISTANCES (km)	CHANNELS			
		2	4	10	16
DWDM	5	17.1023	17.3457	17.4903	17.7821
	20	19.6907	19.9238	20.1257	20.3721
	50	21.9021	22.1923	22.4791	22.5659
	100	23.8178	24.0305	24.2893	24.4371
CWDM	5	16.9891	17.0892	17.2637	17.5123
	20	19.2983	19.5823	19.7123	19.9342
	50	21.5389	21.6678	21.8254	21.8591
	100	23.4341	23.7931	23.9471	24.0234

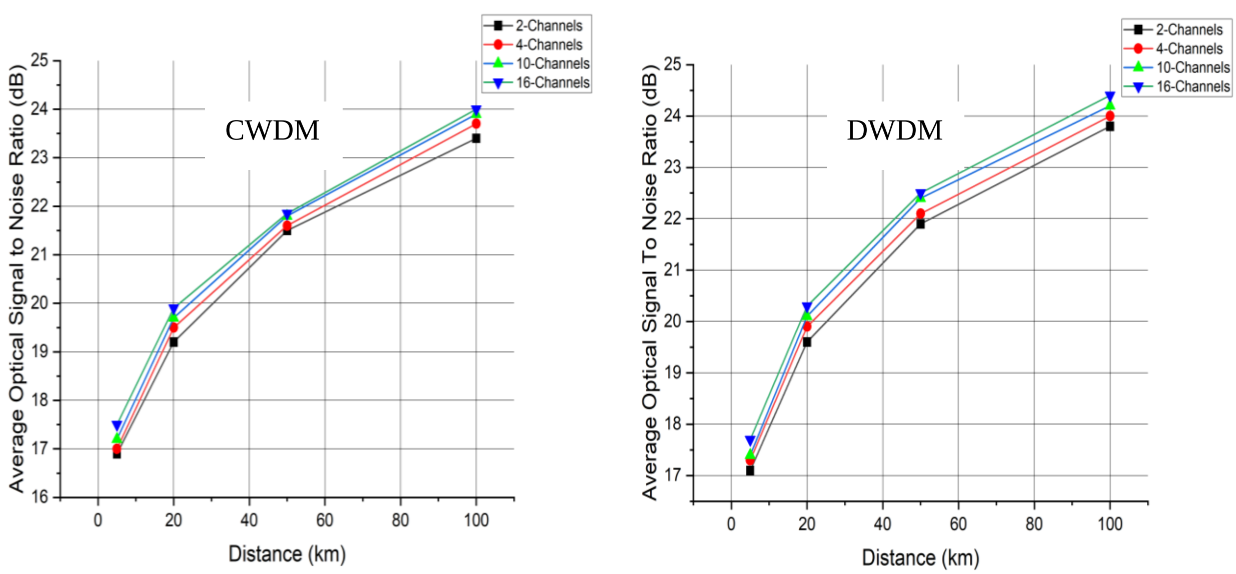

Figure 6: Distance (km) against average optical signal-to-noise ratio (dB) for CWDM and DWDM

Table 5: Distance (km) against average received optical power (dBm)

TECHNOLOGY	DISTANCES (km)	CHANNELS			
		2	4	10	16
DWDM	1	-11.0220	-11.3262	-11.9823	-12.1448
	2	-11.0664	-11.4387	-12.1486	-12.6495
	3	-11.3281	-11.6566	-12.2876	-12.7783
	4	-11.5260	-12.2124	-12.6749	-13.0325
	5	-11.6475	-12.2908	-12.8626	-13.4378
CWDM	1	-10.6446	-10.8721	-11.0954	-11.3456
	2	-10.6740	-10.9768	-11.1385	-11.4081
	3	-10.8240	-11.2381	-11.4438	-11.7241
	4	-11.0790	-11.4081	-11.8527	-12.0103
	5	-11.3723	-11.5868	-12.2090	-12.7184

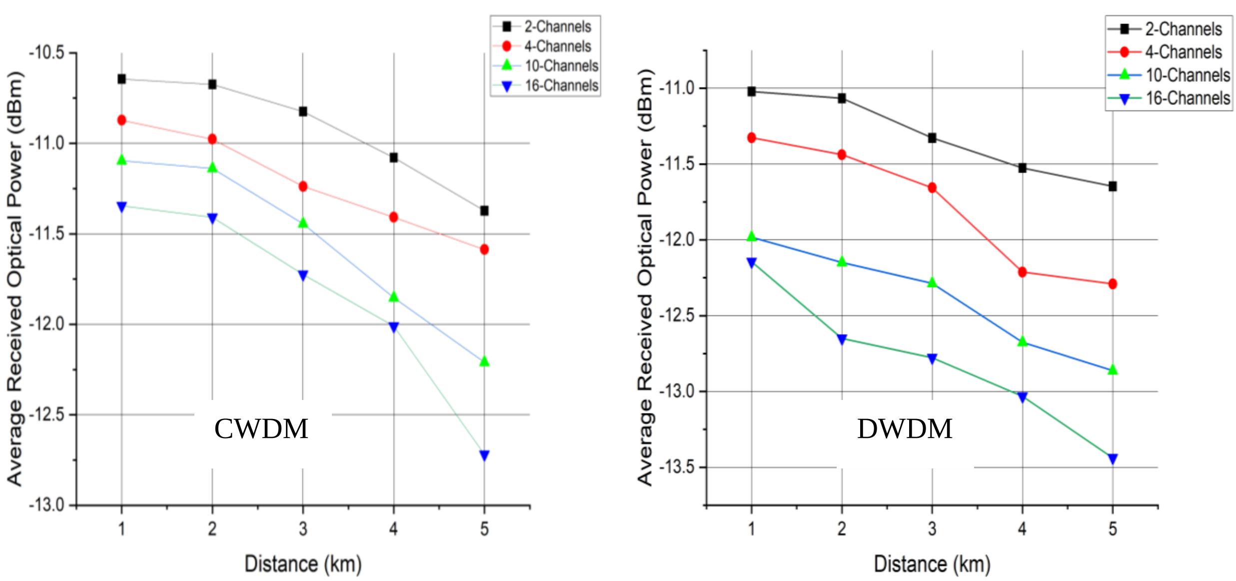

Figure 7: Distance (km) against average received optical power (dBm) for CWDM and DWDM

3.1.6 Comparison of CWDM and DWDM Based on Average Optical Signal-To-Noise Ratio

The average received optical signal-to-noise-ratio obtained for both CWDM and DWDM at distances of 1, 2, 3, 4, and 5 km in the implementation is shown in Table 6. Figure 8 shows a graph of the implementation results for both CWDM and DWDM obtained from the average received optical signal-to-noise ratio based on our implemented setup. It can be seen from both graphs that as the distance increases, the average received optical signal-to-noise ratio decreases. Moreover, as the channels increases, the average received optical signal-to-noise ratio also decreases. This signifies that as the number of channels and distances increases, the received optical signal-to-noise ratio decreases. The CWDM system in this case has better signal strength compared to that of the DWDM system.

Table 6: Distance (km) against average optical signal-to-noise ratio (dB)

TECHNOLOGY	DISTANCES (km)	CHANNELS			
		2	4	10	16
DWDM	1	15.4522	15.7003	15.8414	15.9536
	2	15.6418	15.8481	16.1369	16.3179
	3	15.8164	15.9365	16.4418	16.8530
	4	15.9458	16.1696	16.5183	17.0142
	5	16.2121	16.4851	17.0158	17.3302
CWDM	1	15.0478	15.2107	15.4834	15.5631
	2	15.1569	15.3079	15.5857	15.7734
	3	15.3110	15.5118	15.9329	16.3152
	4	15.4101	15.6420	16.2488	16.5095
	5	15.6511	15.8634	16.6155	16.9242

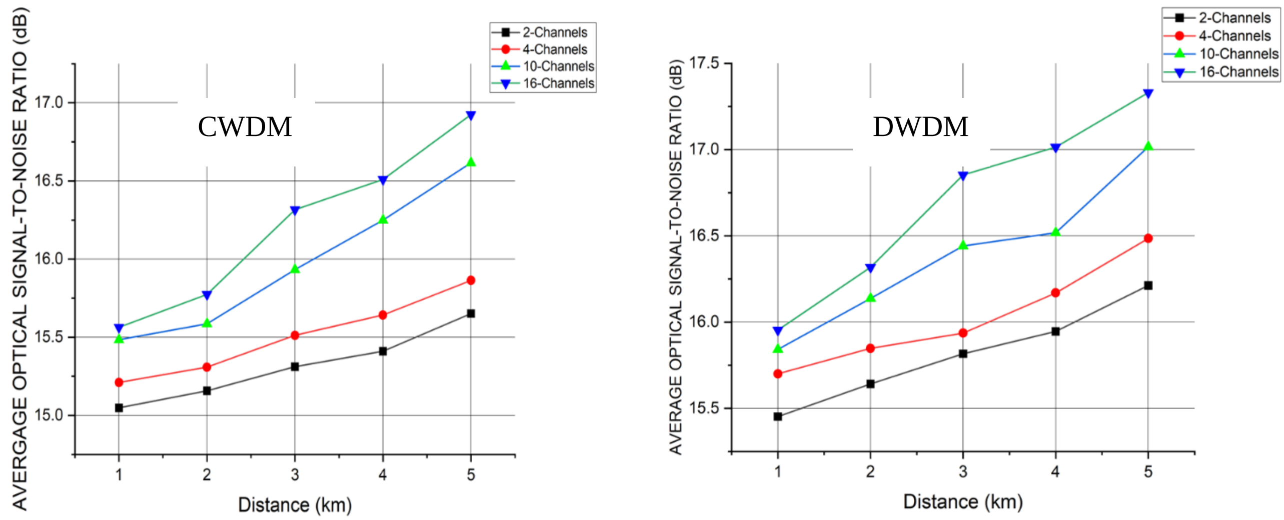

Figure 8: Distance (km) against average optical signal-to-noise ratio (dB) for CWDM and DWDM

4.0 CONCLUSION AND RECOMMENDATION

The research focused on the design and implementation of a system that utilizes CWDM and DWDM in long-haul optical data transmission to evaluate their performances. The system design was done in two phases; simulation and actual implementation. It was observed that the CWDM had higher received optical power and less interference as compared to the DWDM. This is because the channel spacings used in CWDM were higher as compared to the channel spacing used in DWDM. Also, the CWDM had a better optical signal-to-noise ratio performance than the DWDM. Both simulation results and practical results revealed that CWDM had a relatively better performance than DWDM. The results also showed that the quality and integrity of the signal decreased with increasing distances and increasing number of channels. We recommend that this study should be extended to cover unequal channel spacing. WDM systems with unequally spaced channels will serve as a buffer between CWDM and DWDM to prevent four-wave mixing (FWM) which is a dominant nonlinear effect in long-haul optical communication. A clear observation and comparison could not be made between the simulation results and the implementation results because of the different distances used.

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Abreviation Table

WDM	Wavelength Division Multiplexing
DWDM	Dense Wavelength Division Multiplexing
CWDM	Coarse Wavelength Division Multiplexing
QF	Quality Factor
EOF	Eye-Opening Factor
OSNR	Optical Signal-to-Noise Ratio
ROP	Received Optical Power
ITU	International Telecommunication Union
FWM	Four-Wave Mixing