JOURNAL OF MECHANICS OF CONTINUA AND MATHEMATICAL SCIENCES
www.journalimcms.org

ISSN (Online) : 2454 -7190 Vol.-19, No.-6, June (2024) pp 80-98 ISSN (Print) 0973-8975

IMPLEMENTATION OF AN EFFECTIVE FSO WDM SYSTEM UNDER DIFFERENT ATMOSPHERIC CONDITIONS WITH DIFFERENT CODING SCHEMES

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https://doi.org/10.26782/jmcms.2024.06.00007

(Received: March 23, 2024; Revised: May 25, 2024; Accepted: June 06, 2024)

Abstract

In different atmospheric conditions, Free Space Optical (FSO) transmission is vital because it sends data via light beams through the atmosphere. This technique transmits data quickly and efficiently with low signal attenuation in clear weather. This makes it ideal for short- to medium-range communication, especially in urban areas where cables or radio frequency spectrum are impractical. However, fog, rain, and snow can absorb or disperse the light signal, reducing transmission range and reliability for FSO. This research creates an effective FSO system that supports many channels and transmission distances. The suggested system will be tested in four weather conditions (light air, light rain, medium rain, and heavy rain) with attenuation values of 0.47, 1.988, 5.844, and 9.29 dB/km. Optisystem program version 21 designs and evaluates system performance based on QF, BER, and other criteria. In this research, multiple modulation formats are evaluated for best performance. QF exhibited a reversal relationship with distance, while BER showed a direct one. The suggested system can transmit for 25 km, 12 km, 10 km, and less than 6 km in light air, light rain, medium rain, and severe rain. This research also examines system performance under NRZ and RZ modulation formats. NRZ modulation is better for light air and clear weather transmission than RZ modulation *since it requires less equipment and is easier to install. Since NRZ modulation requires no clock recovery overhead, bandwidth efficiency is usually higher. In light rain, RZ modulation minimizes optical fiber dispersion, extending transmission distances and improving signal quality. NRZ excels within 10 kilometers. NRZ works for 6 km and 4 km in medium and severe rain, although RZ's dispersion tolerance and synchronization make it better for longer transmission distances. For short distances, NRZ is suitable, but for longer distances, RZ is more resilient due to its better dispersion management and signal transmission.*

Keywords: FSO, NRZ, Optisystem, RZ, Radio Frequency, WDM.

I. Introduction

In the middle of the 20th century, it is possible that the first ideas about the transmission of information via the use of modulated light were first conceived. These first ideas were centered on the concept of free space optics, sometimes known as FSO. An investigation was conducted by researchers [XVII, XI] to evaluate the feasibility of optical communication as an alternative to traditional wired networks. Beginning in the 1970s and continuing into the 1980s, the first experimental FSO systems were first developed. In the beginning, the major purpose of the research was to ascertain whether or not it was feasible to transfer data into free space by making use of modulated laser beams. [II] The findings of these investigations provided a foundation for later developments in the field of study. There were significant advancements in optical technology throughout the 1990s, including advances in laser diodes, detectors, and optical components. These advancements were made possible by the decade. This progression took place throughout the previous ten years. The introduction of these advances paved the path for the creation of FSO systems that are more trustworthy and applicable to common situations. From the latter half of the 1990s to the beginning of the 2000s, the FSO technology transitioned from the experimental stage to the commercialization stage [XXIV, XXV]. This event occurred throughout the period. A great number of companies began creating communication solutions that were based on FSO to give an alternative to traditional wired networks. Applications such as last-mile connectivity were the inspiration for the development of these technologies [I].

It became clear that there were difficulties associated with the conditions of the environment, the stability of the signal, and the accuracy of the alignment when FSO systems were employed in actual scenarios. Adaptive modulation techniques, error correction mechanisms, and atmospheric compensation methods were developed as a result of ongoing research and technological advancements that were targeted at addressing these difficulties [III]. FSO research is still being conducted by researchers to improve its resilience to a variety of environmental situations, expand its range, and improve its performance. Integration with other wireless technologies, advancements in quantum communication, and the exploration of fresh applications in the creation of communication networks are some of the potential future applications for FSO. In addition, the development of innovative strategies that are used to lessen the effect of these extreme weather conditions [IV, V, XX, XIX, XXI].

As a result, this paper designs a WDM FSO system with 16 channels to effectively work under different rainy conditions with different falling levels ranging from light to heavy falling. Also, different coding techniques would be included for achieving optimal performance and evaluating the proposed system

II. Methodologies

This section will mention the most important techniques and concepts related to the presented paper.

A- Wavelength Division Multiplexing (WDM)

a method that enables several signals to be sent over a single optical fiber at the same time via a single optical fiber. In optical communication systems, this technique is now being used. To split the available optical bandwidth into a large number of channels, each of which runs at a different wavelength, is the basic notion that underpins wavelength division multiplexing (WDM) [VI]. Because of this, it is possible to transmit data streams simultaneously, which eventually leads to a significant increase in the capacity of the infrastructure that is comprised of optical fiber [VII, X]. Optical communication systems with enormous capacities, Metropolitan Area Networks (MANs), and long-distance telephony are all common applications of WDM, which is a method. WDM is shown in Figure 1.

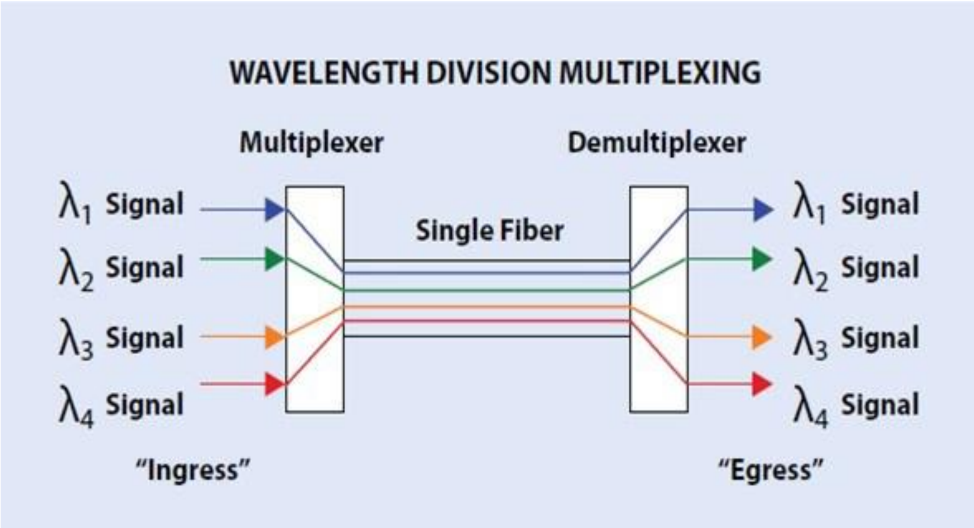

Fig. 1. : WDM concept [X].

B- Rain weather conditions

The meteorological conditions in the atmosphere have the potential to have a considerable impact on FSO transmission, which in turn may affect the signal's reliability and quality. Clear air is the first requirement that has to be taken into consideration. This means that the FSO communication can attain its highest level of performance under conditions when there is minimal air interference and clear weather. The combination of low humidity and a small number of air particles results in reduced signal attenuation, which in turn enables higher data rates and longer communication distances [IX, XXXIX, XVI].

On the other hand, the rain itself is the second meteorological condition that should be taken into consideration. The presence of droplets in the atmosphere might cause the optical signals to scatter and be absorbed, which would result in a reduction in the power of the signal. The influence of rain on FSO transmission is amplified when it occurs at higher frequencies and across larger distances. There is a possibility that heavy precipitation might result in a short disruption of the signal or a decrease in the performance of the connection [XIII, XVIII].

C- Proposed system design

The Optisystem software will be used to carry out the installation of the FSO WFM system, which will consist of sixteen channels and the following activities will be carried out:
The first step is to use the CW laser tool to create the optical signal source, which will then be followed by the formation of the optical arm of the MZM modulator. The channel spacing was set to be equal to 200 GHz, which is equivalent to 0.2 THz, and the specified wavelength range was between (170 and 193 THz).

The second step involves the generation of binary data at a data rate of 2.5 gigabits per second (Gbps) for each of the 16 channels in the system. Following this, the binary data is converted into the needed modulation format, which may be either Non-Return to Zero (NRZ) or Return to Zero (RZ), to create the electrical arm of the MZM modulator. In the third step, the MZM modulator is used to combine the signal from the optical source with the signal from the electrical source, and afterward, the optical signal is output from each channel of the 16 WDM system. The fourth step is the last stage, which involves connecting each output connection from the MZM to a 16x1 Mux device. This allows all of these channels to be sent over a single FSO link. These tables, Table 1 and Table 2, respectively, include a listing of the characteristics that have been specified for the parameters in this section as well as the Mux device. Figure 2 illustrates that the most recent version of the Optisystem software, version 21, has the option to merge the four tools mentioned above into a single block that is referred to as the WDM transmitter. This is something that should be taken into consideration. Implementation of the Optisystem simulation software may be simplified by using this approach, which can be utilized to lessen the complexity of the implementation process.

Table 1: Properties of the Tx part

Parameter	Value	Unit
Number of output ports	16	-
Frequency	190	THz
Frequency spacing	200	GHz
Power	10	dBm
Extinction ratio	30	dB
Linewidth	10	MHz
Initial phase	0	deg
Bit rate	2.5	GBits/s
Modulation type	NRZ-RZ	-

Table 2: Mux properties on the Tx side

Parameter	Value	Unit
Number of input ports	16	-
Bandwidth	10	GHz
Insertion loss	0	dB
Depth	100	dB
Filter type	Bessel	-
Filter order	2	-

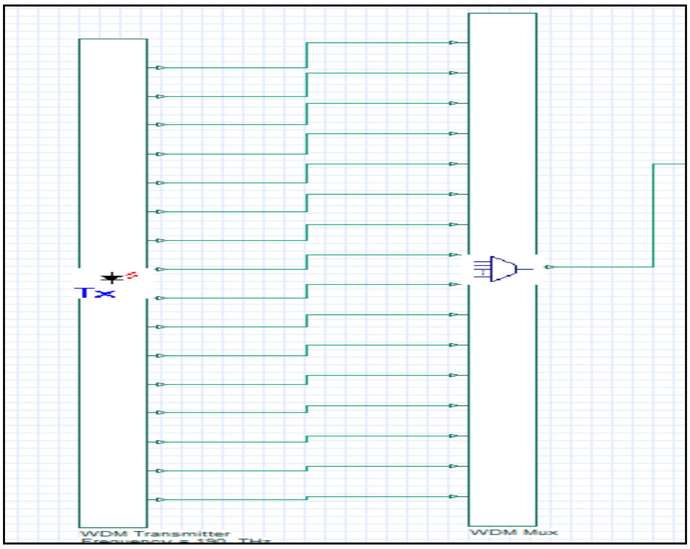

Fig.2. The Tx part of the proposed system.

As can be seen in Figure 3, the medium part constitutes the second component of the system that has been suggested. This component involves the use of an optical amplifier and the FSO channel model.
When it comes to the amplifier, the execution of the system involves the use of two amplifiers simultaneously, both before and after the transmission of the laser signal via a variety of weather conditions. On the other hand, the FSO model is a representation of the various atmospheric circumstances that will be used to test the system that has been developed. These conditions include a range of transmission lengths that includes between 2 and 25 kilometers, as well as the utilization of various attenuation values to simulate various weather situations. One may see the influence of attenuation by referring to Table 3, which illustrates the various situations encountered.
Through the process of amplifying the optical signal, FSO networks can communicate across longer distances without the need for additional optical components or signal regeneration locations when they do so. In particular, this is of the utmost importance for FSO lines that are required to traverse challenging weather conditions or tremendous geographical distances.

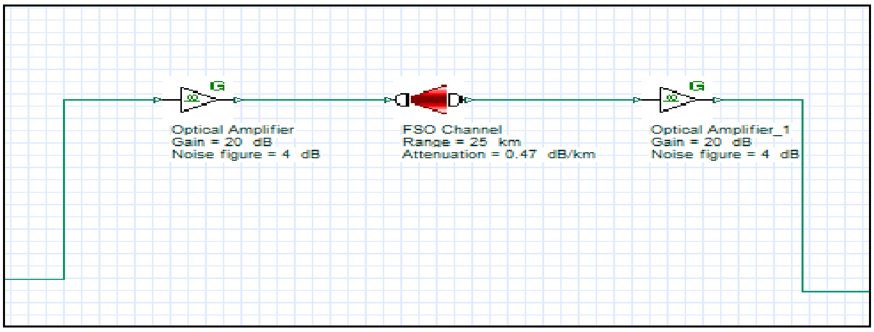

Fig.3. The medium part.

Table 3: Transmission part properties

Parameter	Value	Unit
Range	Up to 25	km
Attenuation	varied	dB/km
Geometrical loss	1	-
Transmitter aperture diameter	5	cm
Receiver aperture diameter	20	cm
Beam divergence	2	mrad
Transmitter loss	0	dB
Receiver loss	0	dB
Additional losses	0	dB
Propagation delay	0	ps/km
Operation mode	Gain Control	-
Gain	20	dB

Finally, for the Rx part, it starts with a 1x16 Demux device, the data that is being transferred from the FSO media may be separated using a single connection. This allows the WDM system to operate each of its 16 channels more efficiently. Figure 4 demonstrates the Rx part of the proposed system. Take note that the bandwidth that is set for the Mux and demux, together with the wavelength that is given for each channel, should be the same, with the same ranges and values applicable to both. Implementing the function of turning the optical signal back into an electrical signal by using the PD with type PIN. In cases when accurate detection of low light levels is needed, the usage of PIN PDs is preferred over other types of PDs. This is because PIN PDs often have less inherent noise than APDs, which makes them more sensitive. In contrast, APD has a greater gain and may be more sensitive in some circumstances, such as when the signal is weak. Following the transformation of the optical signal into an electrical one, it is necessary to use a filtering device that is of the Bessel filter type to mold the signal that has been received. Because it provides a maximum flat group delay, this filter is crucial because it guarantees that all wavelength channels have the least degree of time delay distortion that is conceivable. Since this eliminates Inter-Symbol interference (ISI) and maintains the integrity of the signals that are conveyed in WDM systems, it is of utmost significance in high-speed communication systems, where precise timing is of the utmost importance. A list of the characteristics of the Rx component may be seen in Table 4. Making use of the 3R generating tools that are included in the Optisystem software to give a system connection that is both feasible and less expensive. Lastly, see the parameters that will be utilized for the assessment of the proposed system by making use of the BER analyzer tool.

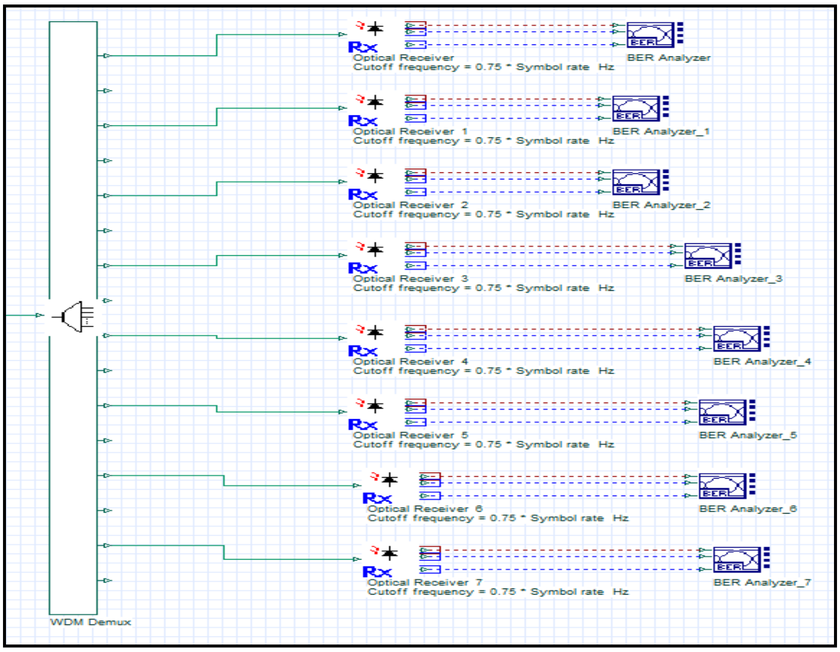

Fig. 4. Rx part of the proposed system.

Table 4: Rx part properties

Parameter	Value	Unit
Number of output ports	16	-
Bandwidth	60	GHz
Insertion loss	0	dB
Depth	100	dB
Filter type	Bessel	-
Filter order	2	-
Photodetector	PIN	-

III. Results and discussion

This section will analyze the performance of the proposed system based on the studied parameters of Quality Factor (QF) and Bit Error Rate (BER).

A- QF based results

The link between QF and distances is investigated for the instances of light air, light rain, medium rain, and heavy rain, which are listed in Table 5, Table 6, Table 7, and Table 8, respectively. The cases are light air, light rain, medium rain, and heavy rain. This relationship is shown clearly and concisely in Figure 5, which demonstrates that there is an inverse relationship between QF and distance, since the increase in distance results in a decrease in QF. The suggested system can successfully execute transmission for a distance of 25 kilometers when the air is light. However, when the rain is light, the transmission may reach a distance of 12 kilometers. When the rain is medium, the transmission range is decreased to 10 kilometers. Lastly, the system is capable of successfully transmitting information across a distance of less than six kilometers when there is severe rain.

Raindrops have the power to intercept and scatter FSO signals as they travel through the atmosphere. This is the reason why this is the case. Absorption and dispersion are the two processes that lead to attenuation, which is the reduction of the signal strength that is received by the receiver. There is a large increase in attenuation when there is an increase in rainfall.

Table 5: QF results for light air conditions.

Channel/ Distance	QF results for the case of 0.47 dBm/km Attenuation									
	2 km	4 km	6 km	8 km	10 km	12 km	15 km	17 km	20 km	25 km
Ch 1	315.64	228.37	166.47	127.04	91.04	72.64	48.14	40.77	26.83	16.35
Ch 3	287.21	211.80	157.57	117.82	90.81	69.73	51.84	36.52	28.09	15.58
Ch 5	296.95	220.30	153.92	120.39	88.02	68.75	48.72	38.87	26.91	15.46
Ch7	299.83	217.51	165.18	117.85	88.13	71.42	46.56	40.25	26.08	16.25
Ch 9	293.30	221.45	155.77	120.35	88.85	68.40	48.18	39.99	27.61	16.08

Ch 11	294.61	211.60	164.74	120.40	92.71	70.41	49.00	36.92	25.77	16.43
Ch 13	282.43	209.73	155.60	125.95	88.01	68.09	46.36	38.00	26.92	16.25
Ch 15	290.26	208.55	156.00	113.15	86.95	71.66	50.97	39.42	26.88	15.20
Average	295.03	216.16	159.41	120.37	89.31	70.14	48.72	38.84	26.89	15.95

Table 6: QF results for Light rain conditions.

Channel/ Distance	**QF results for the case of 1.988 dBm/km Attenuation**									
	2 km	**4 km**	**6 km**	**8 km**	**10 km**	**12 km**	**15 km**	**17 km**	**20 km**	**25 km**
Ch 1	289.28	142.39	70.92	32.74	15.15	7.08	0	0	0	0
Ch 3	257.89	141.25	67.69	32.90	16.07	7.06	0	0	0	0
Ch 5	257.58	135.73	67.47	33.73	15.29	6.68	0	0	0	0
Ch7	264.61	141.18	67.60	31.92	15.49	7.18	0	0	0	0
Ch 9	267.20	134.21	65.93	32.03	15.77	7.29	0	0	0	0
Ch 11	267.97	142.09	68.47	31.06	15.74	6.90	0	0	0	0
Ch 13	254.64	135.90	67.78	32.03	15.53	7.36	0	0	0	0
Ch 15	258.91	135.13	65.35	32.33	15.22	7.25	0	0	0	0
Average	264.76	138.49	67.65	32.34	15.53	7.10	0	0	0	0

Table 7: QF results for medium rain conditions.

Channel/ Distance	**QF results for the case of 5.844 dBm/km Attenuation**									
	2 km	**4 km**	**6 km**	**8 km**	**10 km**	**12 km**	**15 km**	**17 km**	**20 km**	**25 km**
Ch 1	178.19	27.47	17.54	7.05	3.27	0	0	0	0	0
Ch 3	168.40	26.26	16.23	7.04	3.14	0	0	0	0	0
Ch 5	167.62	27.21	16.29	6.78	3.11	0	0	0	0	0
Ch7	167.47	27.00	17.07	6.92	3.21	0	0	0	0	0
Ch 9	162.60	26.75	15.96	6.54	3.04	0	0	0	0	0
Ch 11	166.06	26.11	16.54	7.01	0.00	0	0	0	0	0
Ch 13	166.95	27.17	17.44	7.13	3.21	0	0	0	0	0
Ch 15	160.40	28.54	17.88	7.95	0.00	0	0	0	0	0
Average	167.21	27.06	16.87	7.05	2.37	0	0	0	0	0

Table 8: QF results for heavy rain conditions.

Channel/ Distance	QF results for the case of 9.29 dBm/km Attenuation									
	2 km	4 km	6 km	8 km	10 km	12 km	15 km	17 km	20 km	25 km
Ch 1	95.53	46.54	4.11	0	0	0	0	0	0	0
Ch 3	91.53	47.32	3.92	0	0	0	0	0	0	0
Ch 5	92.27	45.81	3.92	0	0	0	0	0	0	0
Ch7	90.06	45.10	3.99	0	0	0	0	0	0	0
Ch 9	88.52	46.35	3.89	0	0	0	0	0	0	0
Ch 11	89.18	47.43	3.81	0	0	0	0	0	0	0
Ch 13	91.25	47.10	3.92	0	0	0	0	0	0	0
Ch 15	85.28	46.76	4.11	0	0	0	0	0	0	0
Average	90.45	46.55	3.96	0	0	0	0	0	0	0

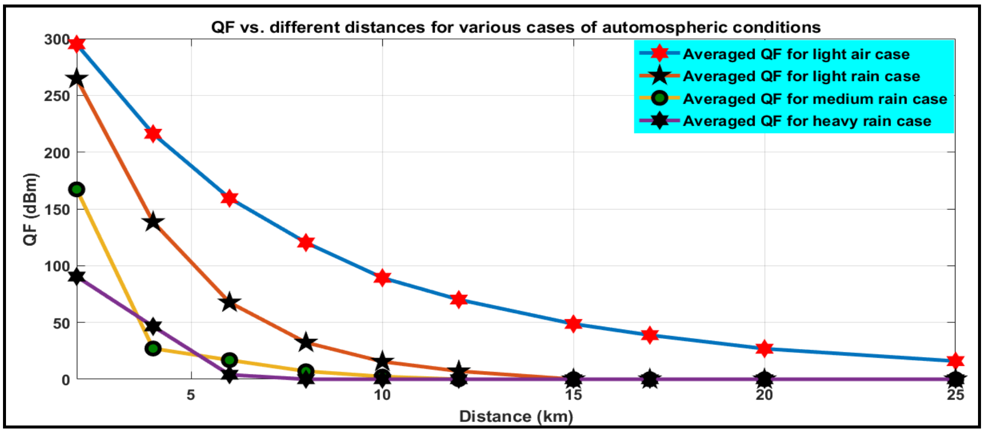

Fig. 5. QF vs. different distances for various atmospheric conditions

B- BER based results

Comparatively, the relationship between BER and distances is investigated for each of the four scenarios, which are shown in the following tables: Table 9, Table 10, Table 11, and Table 12. Because increasing the distance may dramatically increase the amount of error in the bits that are communicated, a direct relationship can be seen between the two variables. In particular, when increasing the influence of attenuation, it may lead to fluctuations in the refractive index of the atmosphere, which in turn causes scintillation manifestations. In the case of an optical signal, scintillation refers to the rapid change in both the intensity and phase of the signal, which ultimately results in a deterioration in signal quality and an increase in bit error rates. It is important to take note that the number (0) in BER indicates that the signal is very clear and does not include any errors, while the value (1) indicates that the system is unable to successfully transmit data to that extent. To determine the permissible error rates per bit sent, the BER threshold was set at 10E-6.

Table 9: BER results for light air conditions.

Channel/ Distance	BER results for the case of 0.47 dBm/km Attenuation									
	2 km	4 km	6 km	8 km	10 km	12 km	15 km	17 km	20 km	25 km
Ch 1	0	0	0	0	0	0	0	0	5.56E-159	1.65E-60
Ch 3	0	0	0	0	0	0	0	1.58E-292	4.21E-174	4.01E-55
Ch 5	0	0	0	0	0	0	0	0	6.25E-160	2.50E-54
Ch7	0	0	0	0	0	0	0	0	2.03E-150	7.91E-60
Ch 9	0	0	0	0	0	0	0	0	2.63E-168	1.40E-58
Ch 11	0	0	0	0	0	0	0	7.37E-299	6.99E-147	4.19E-61
Ch 13	0	0	0	0	0	0	0	2.34E-316	4.46E-160	9.26E-60
Ch 15	0	0	0	0	0	0	0	0	1.19E-159	1.27E-52

Table 10: BER results for Light rain conditions.

Channel/ Distance	BER results for the case of 1.988 dBm/km Attenuation									
	2 km	4 km	6 km	8 km	10 km	12 km	15 km	17 km	20 km	25 km
Ch 1	0	0	0	1.27E-235	2.96E-52	5.97E-13	1	1	1	1
Ch 3	0	0	0	7.37E-238	1.56E-58	7.16E-13	1	1	1	1
Ch 5	0	0	0	6.26E-250	3.63E-53	1.03E-11	1	1	1	1
Ch7	0	0	0	4.74E-224	1.46E-54	2.93E-13	1	1	1	1
Ch 9	0	0	0	1.44E-225	1.77E-56	1.3E-13	1	1	1	1
Ch 11	0	0	0	2.66E-212	2.9E-56	2.19E-12	1	1	1	1
Ch 13	0	0	0	1.65E-225	9.18E-55	8E-14	1	1	1	1
Ch 15	0	0	0	8.85E-230	9.88E-53	1.84E-13	1	1	1	1
Average	0	0	0	3.328E-213	5.418E-53	1.81E-12	1	1	1	1

Table 11: BER results for medium rain conditions.

Channel/ Distance	BER results for the case of 5.844 dBm/km Attenuation									
	2 km	4 km	6 km	8 km	10 km	12 km	15 km	17 km	20 km	25 km
Ch 1	0	1.46E-166	2.43E-52	4.42E-24	0.0005	1	1	1	1	1
Ch 3	0	2.31E-152	1.53E-51	4.54E-25	0.00078	1	1	1	1	1
Ch 5	0	1.78E-163	3.45E-52	6.45E-27	0.00089	1	1	1	1	1
Ch7	0	4.45E-161	7.32E-51	3.24E-25	0.00062	1	1	1	1	1
Ch 9	0	4.06E-158	4.02E-53	8.44E-24	0.00109	1	1	1	1	1
Ch 11	0	9.58E-151	3.64E-51	5.43E-23	1	1	1	1	1	1
Ch 13	0	4.95E-163	5.32E-52	5.78E-26	0.00064	1	1	1	1	1
Ch 15	0	1.46E-179	6.45E-51	8.43E-29	1	1	1	1	1	1
Average	0	1.2E-151	2.5E-51	8.5E-24	0.25057	1	1	1	1	1

Table 12: BER results for heavy rain conditions.

Channel/ Distance	BER results for the case of 9.29 dBm/km Attenuation									
	2 km	4 km	6 km	8 km	10 km	12 km	15 km	17 km	20 km	25 km
Ch 1	0	2.54E-180	1.79E-05	1	1	1	1	1	1	1
Ch 3	0	5.43E-177	4.14E-05	1	1	1	1	1	1	1
Ch 5	0	4.23E-185	4.09E-05	1	1	1	1	1	1	1
Ch7	0	1.03E-181	2.98E-05	1	1	1	1	1	1	1
Ch 9	0	3.93E-186	4.53E-05	1	1	1	1	1	1	1
Ch 11	0	1.21E-188	6.27E-05	1	1	1	1	1	1	1
Ch 13	0	7.45E-182	4.13E-05	1	1	1	1	1	1	1
Ch 15	0	4.34E-184	1.82E-05	1	1	1	1	1	1	1
Average	0	6.79E-178	3.72E-05	1	1	1	1	1	1	1

C- Different Modulation format

This part will include the use of an additional modulation method of RZ for the proposed system. The purpose of this approach is to assess the performance of the system in comparison to the utilization of NRZ and to demonstrate which modulation is superior for transmission under various atmospheric circumstances. Comparative analysis of the average QF values is shown in Table 13. Additionally, the comparison between the two modulation approaches is shown in Figures 6, 7, 8, and 9 which show the four different examples respectively. As a result of the fact that NRZ modulation needs less complicated circuitry and is simpler to install in comparison to RZ modulation, it is possible to observe that the use of NRZ is superior for the transmission of information in the event of light air and clear weather. As a result of the fact that it does not need extra overhead for clock recovery, NRZ modulation often results in superior bandwidth efficiency.

In the event of light rain, utilizing NRZ is preferable for lengths less than 10 kilometers, whilst using RZ is preferable for distances more than that. This is because RZ modulation helps decrease dispersion effects in optical fibers, which enables longer transmission distances and higher signal quality. Using the NRZ is effective for transmission distances of 6 kilometers and 4 kilometers, respectively, in the event of light rain and heavy rain. This demonstrates that the RZ is superior to the NRZ in terms of its tolerance to dispersion and its ability to better synchronize transmissions over an extended distance.

Table 13: Comparison in averaged QF for NRZ and RZ modulation

Modulation	Transmission distance (km)									
	2 km	4 km	6 km	8 km	10 km	12 km	15 km	17 km	20 km	25 km
NRZ/ Light air	295.03	216.16	159.41	120.37	89.31	70.14	48.72	38.84	26.89	15.95
RZ/ Light air	265.82	200.00	148.99	115.87	86.47	69.57	48.38	37.72	27.64	16.33
NRZ/ Light rain	264.76	138.49	67.65	32.34	15.53	7.10	0	0	0	0
RZ/ Light rain	242.78	129.81	65.71	32.01	15.70	7.18	0	0	0	0
NRZ/ Medium rain	167.21	27.06	16.87	7.05	2.37	0	0	0	0	0
RZ/ Medium rain	155.55	27.38	16.98	7.13	2.38	0	0	0	0	0
NRZ/ Heavy rain	90.45	46.55	3.96	0	0	0	0	0	0	0
RZ/ Heavy rain	74.21	33.86	2.42	0	0	0	0	0	0	0

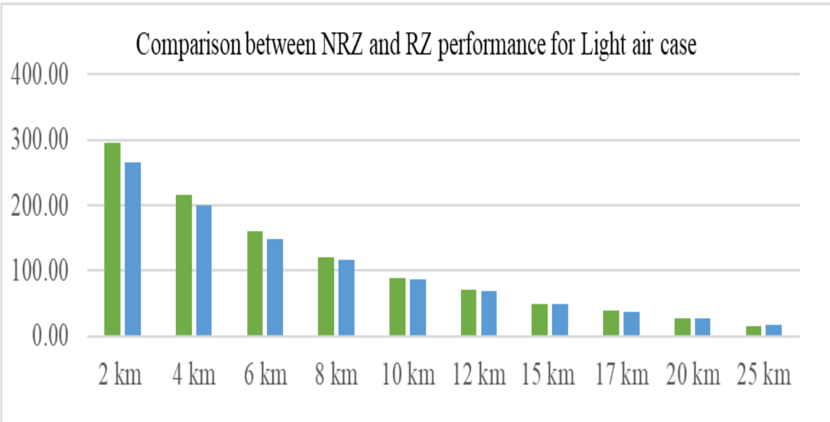

Fig. 6. Comparison between the NRZ and RZ performance for the Light air case.

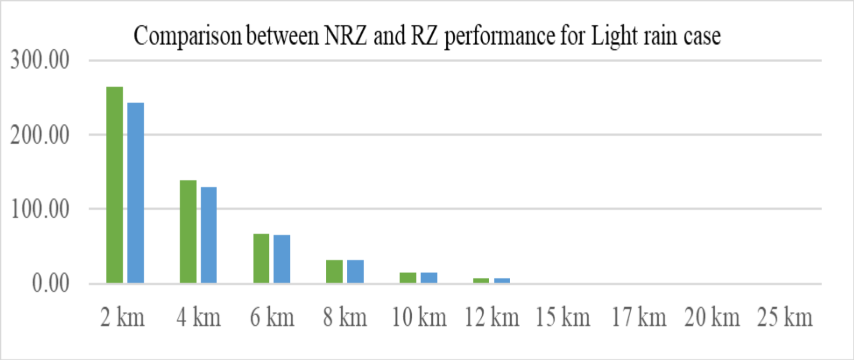

Fig. 7. Comparison between the NRZ and RZ performance for the Light rain case.

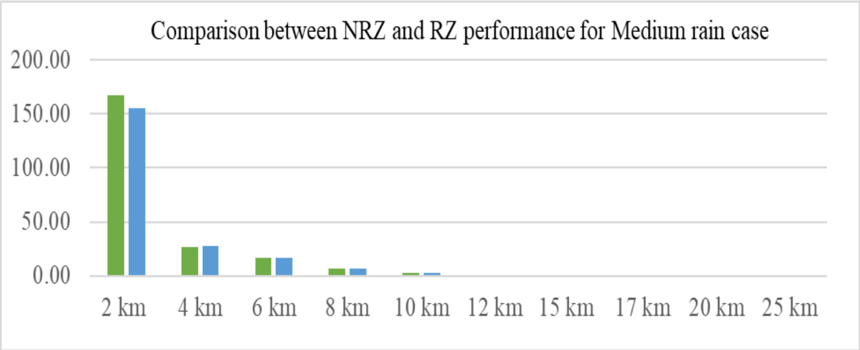

Fig. 8. Comparison between the NRZ and RZ performance for Medium rain case.

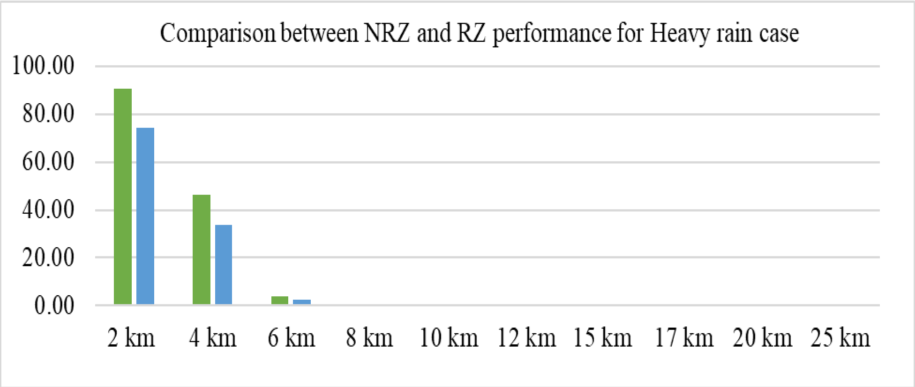

Fig. 9. Comparison between the NRZ and RZ performance for Heavy rain cases.

Future trends such as cloud computing, e-government, logical operatons, PAPR reduction techniques using TRC-SLM integration, fog computing, and efficient microstrip RF and optical devices can further improve this study [VIII, XII,XIV, XV, XXII-XXXIX].

IV. Conclusion

The Optisystem simulator is used to develop and build a 16-channel WDM FSO system with three major parts: Tx, Transmission, and Rx, to be tested up to 25 km away. The attenuation values of 0.47, 1.988, 5.844, and 9.29 dB/km indicate light air, light rain, medium rain, and heavy rain, respectively, for the proposed system assessment. Using QF and BER parameters, the chosen sample channels (1,3,5,7,9,11,13, and 15) and all tested distances per weather condition are evaluated. The QF-based conclusion shows a reverse connection between distance and QF, with greater distances mean lower QF. The research finds transmission up to 25 kilometers in light air, 12 km in light rain, 10 km in medium rain, and less than 6 km in severe rain. The receiver's signal strength is reduced by raindrops absorbing and dispersing FSO signals as they fall through the atmosphere. On the other hand, for the BER findings, increasing distance increases attenuation, which might cause ambient refractive index changes and scintillation. Scintillation leads to lower signal quality and higher bit error rates in optical signals. NRZ modulation is preferred for light air and clear weather transmission due to its simpler circuitry and easier implementation compared to RZ modulation. Since NRZ modulation does not need clock recovery overhead, it has superior bandwidth efficiency. In mild rain, NRZ is preferable for lengths less than 10 km, whereas RZ modulation mitigates optical fiber dispersion effects, enabling greater transmission range and higher signal quality. In medium and severe rain, NRZ is effective for 6 km and 4 km, respectively, demonstrating that RZ is preferable for larger transmission distances due to its improved dispersion tolerance and synchronization.

Conflict of Interest

The authors of this article declare that they have no conflict of interest to disclose.

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