Innovative Modulation Strategies for Enhancing Optical Data Throughput

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Abstract - *High-capacity optical communication systems are being developed to meet the increasing demand for seamless and high-speed data transmission. Advanced modulation techniques, such as Quadrature Amplitude Modulation (QAM), Orthogonal Frequency Division Multiplexing (OFDM), Frequency Shift Keying (FSK), Phase Shift Keying (PSK), and MIMO, are being explored to unlock higher data rates and greater bandwidth utilization. These techniques leverage the inherent capabilities of light to carry data, pushing the boundaries of what is achievable in the realm of optical communication. Optical communication systems have emerged as a cornerstone technology in meeting the escalating data rate demands of the modern digital age. With advancements like wavelength division multiplexing (WDM), optical systems can achieve multi-terabit-per-second data rates, making them pivotal in global communication networks. As 5G networks roll out and 6G promises are on the horizon, optical communication systems will play an indispensable role in backhaul and fronthaul connections, supporting low latency and high data rates needed for the next generation of wireless communications.*

Key Words: High-Capacity Communications, Energy-Efficient Optical Fiber, Signal Processing Innovations.

1.INTRODUCTION

In the rapidly evolving landscape of high-capacity optical communication systems, the quest for increased data rates has become paramount. As the demand for seamless and high-speed data transmission continues to surge, researchers and engineers are delving into innovative approaches to enhance the efficiency and performance of optical communication systems. Advanced modulation techniques have emerged as a pivotal area of exploration, offering the promise of unlocking higher data rates and greater bandwidth utilization. These techniques leverage the inherent capabilities of light to carry data, pushing the boundaries of what is achievable in the realm of optical communication. In this context, this exploration delves into the fascinating realm of advanced modulation techniques, shedding light on their significance, applications, and the transformative potential they hold for the future of high-capacity optical communication systems.

2. LITERATURE REVIEW

Related Work Mats Skold et al (2010) in his article, investigate the techniques for the highly precise characterization of optical data by utilising optical sampling principles, which are based on a four-wave mixture in a highly nonlinear fiber. This method provides exceptional sensitivity and sub-ps time resolution, which facilitates statistical analysis and eliminates impulse response artifacts. The all-optical approach to characterization of optical waveforms is shown to be a highly practical and compelling method for capturing the details of a diverse range of data categories. Furthermore, it is theoretically capable of scaling to exceedingly high transmission rates.[4]

Jianjun Yu et al (2010) analyse and summaries a variety of high-capacity transmission systems that operate at 100G per channel and are enabled by advanced technologies, such as hybrid EDFA/Raman amplification, digital coherent detection technologies, new low-loss and large effective area fiber, and multilevel modulation formats. He show that novel synthesis methods can be employed to generate high-speed QPSK, 8PSK, 8QAM, and 16QAM using only binary electrical drive signals in commercially available optical modulators. Furthermore, he illustrate that digital coherent detection can be employed to identify each of these modulation formats. In addition, he present most recent research findings on orthogonal DWDM transmission technologies, which enable 400 Gb/s and 1 Tb/s per channel.[5]

Eugen Lach et al (2011) investigates the technological alternatives for modulation formats that are appropriate for serial optical transmission at rates of 100 Gb/s and higher. In the initial section, an overview of the diverse modulation formats for 100 Gbit/s is presented. Included in this category are classical binary electronic time division multiplexed 100 Gbit/s NRZ systems, which operate at the maximum speed, as well as mature product solutions from system vendors that operate at lesser symbol rates. In the receiver, these solutions employ coherent technologies, digital signal processing, polarization division multiplexing, and quaternary phase shift keying. The second section is dedicated to the next generation of transmission systems, which are capable of transmitting data at channel bitrates exceeding 100 Gbit/s, including 400 Gbit/s and up to 1 Tbit/s or higher. These systems may utilise higher constellation M-QAM modulation of a single carrier or multiple electrical subcarriers and optical super channels, which also comprise a single WDM channel. The paper provides a performance comparison for 100 Gbit/s and higher bitrates in both sections, as well as the major characteristics of the modulation formats. It also determines the appropriate application areas of transport technologies for future networks.[6]

Amr M. Ragheb et al (2012) present an overview of the most promising NG-PON modulations and DSP technologies. This encompasses multilayer-based OFDM systems, as well as modulation and optical OFDM methods such as QPSK, MQAM, and MSK. He examine the diverse facets of these technologies, emphasizing the most significant contributions they have made and the obstacles they encounter in the development of next-generation access networks that are both cost-effective and perform exceptionally well.[7]

Deva K Borah et al (2012), concludes with hybrid optical wireless/radio-frequency (OW/RF) systems, which improve the overall reliability of the system by utilizing a supplementary RF link. The emphasis is on the methods of collaboration between the reliable RF subsystem and the broadband OW system.[8]

3. METHODOLOGY

3.1 Introduction

Nonlinearity induced impairments such as FWM and XPM in a traditional optical communication link may be compensated for by either allowing the residual local dispersion of the fibre to persist or by appropriately increasing the channel spacing.

Since dispersion is a linear process, dispersion correction may be applied at the receiver end or sporadically across the connection to balance the buildup of dispersion along the transmission fiber.

However, this makes the system more difficult than those that use optical fibres with lower dispersion values to avoid the need for dispersion control.

3.1.1 Mach–Zehnder Modulators

The concept of interference drives Mach-Zehnder modulators, as opposed to electro-absorption modulators.
There is an input coupler separating the two incoming light beams.
A phase modulator is used on one route to accomplish the regulation of the phase difference between the two optical beams by the applied voltages V1, 2.
Depending on the phase difference that is produced, this applied electrical voltage may produce either constructive or destructive interference, a phenomenon called as intensity modulation.

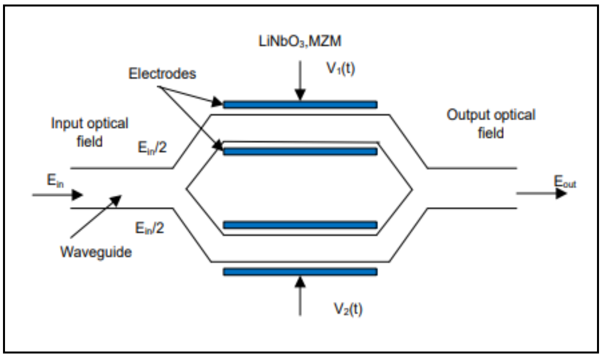

Fig.1: Optical intensity modulator based on Mach-Zehnder interferometric structure

3.1.2 Modulation Formats under investigation

To choose the best modulation format, a number of factors need to be taken into account, such as power margin, tolerance against GVD, SPM, XPM, FWM, and SRS, as well as spectrum efficiency and tolerance against fibre nonlinear effects. Because the NRZ format is so simple to create, detect, and analyze, it is the most basic format that has been widely utilized in IMDD systems to date. In light of the fact that optical systems are integrating DWDM and optical amplifiers to accommodate larger data rates, the NRZ modulation format may not be the best option for big capacity optical systems in the recent past [25,26]. However, because of its historical domination, wide field deployment, and simplicity, NRZ would be a useful benchmark.

3.1.3 Non Return to Zero (NRZ) Format

The NRZ format is now the most extensively utilised in commercial goods due to its simplicity. Compared to phase shift keying, it is less vulnerable to laser phase noise, has a smaller electrical bandwidth for transmitters and receivers, and has the simplest transmitter and receiver setup. Fig. 3.2 displays the NRZ coding format.

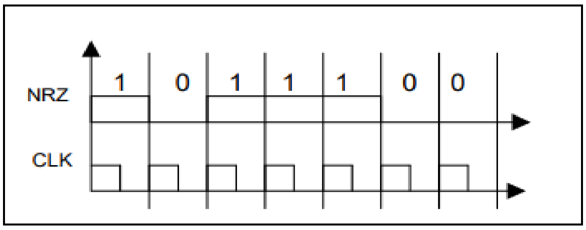

Fig.2: Representation of the NRZ code.

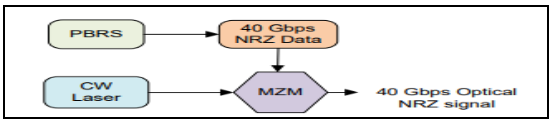

Fig.3: Block diagram of NRZ transmitter

Fig. 3.3 shows the schematic block design for the 40 Gbps NRZ transmitter. A 40 GHz NRZ data stream powers the MZM by ON/OFF keying an optical signal produced by the continuous-wave (CW) laser source. The applied electric field, whose voltage varies according to a preset function, modulates the intensity of the carrier light wave. An electrical NRZ signal is used to drive the MZM at the quadrature point of the modulator power transfer function. NRZ optical transmissions are detected by a simple photodiode at the receiver, which transforms the optical power of the signal into an electrical current. The term "direct detection" describes this. In this thesis, other modulation kinds are also detected using the same direct detection approach, as long as they are not indicated explicitly.

The decreased on-off transitions cause the NRZ pulses to have a limited optical spectrum. Improved dispersion tolerance and enhanced spectral efficiency are made possible by the narrower spectral width; still, ISI occurs in between the pulses. Since an NRZ modulated optical signal is less resistant to the fibre nonlinear effect than its RZ equivalent, more study is being done on the RZ format [27].

3.1.4 Return-to-Zero (RZ) Format

Higher data rates, such 40 Gbps, have a greater influence on non-linearity, and the RZ signal format performs better than the NRZ signal format. As shown in Fig. 3.4, the power level in RZ format is 0 for the 0 bit continually. After half the duration, it returns to 0 for the logical 1 bit.

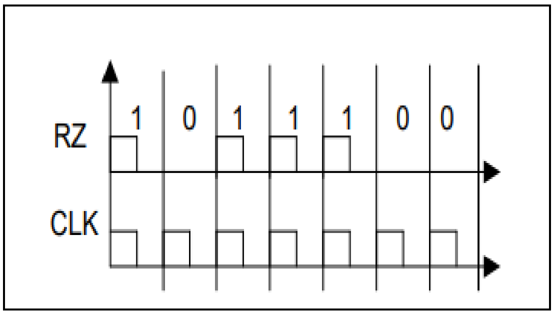

Fig.4: Representation of the RZ code.

3.2 Transmitter Design for Carrier Suppressed Return-to-Zero (CSRZ) Format

Many transmission experiments have used the CSRZ format, which is a modification of the RZ format and has a smaller pedestal shape of the optical spectrum than the original RZ format [27]. It is also very resistant to the combined effects of SPM and GVD. The π phase shift that occurs between successive data points sets the CSRZ signal apart from ordinary RZ. Unlike correlative coding schemes, like duobinary, the sign reversals happen at every bit transition and are independent of the signal's information-carrying part. When successive bit locations alternate, the fundamental frequency components are lowered to half of the data rate. For CSRZ, there is no carrier component as a consequence of this phase shift in the optical domain [28, 29].

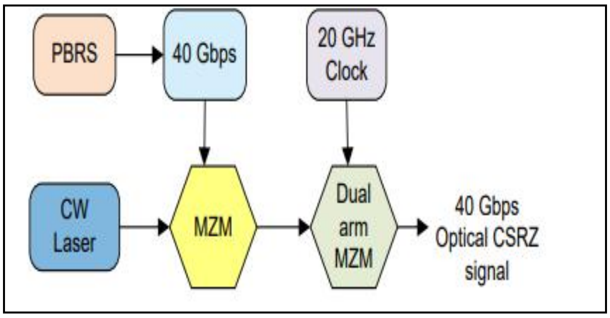

Fig.5: Block diagram of CSRZ transmitter

Due to its lower optical power needs, CSRZ can accommodate more multiplexed channels during transmission and can withstand chromatic dispersion more well. Furthermore, carrier suppression in WDM systems lowers the efficiency of FWM [29]. The CSRZ transmitter setup that is being analysed is shown in Fig. 3.5 Two MZMs may be concatenated to create a CSRZ optical signal. The first MZM uses 40 Gbps NRZ data to control light intensity coming from a CW laser source. The resulting NRZ optical signal is then modulated by the second MZ modulator, which is driven by a clock operating at half bit-rate (20 GHz in this example). An optical signal with CSRZ is produced as a consequence of this technique.

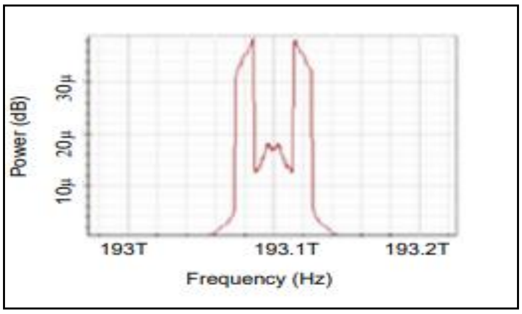

Fig.6: Spectrum of CSRZ signal

At the transmission minimum, the optical field transfer function of the MZM changes sign, resulting in phase inversions between neighbouring bits. As seen in Fig. 3.6, this causes a pi phase shift to be created between any two consecutive bits. As a result, the carrier frequency centre peak is suppressed and the spectrum is altered.

3.3 Opti System

Research and development activities make considerable use of Opti System 10.0, a powerful optical communication system design simulation tool that examines and simulates an optical link [31–33]. It has been used in the present thesis to build and simulate optical communication systems to assess their performance while taking the proper properties of system components into account. The fair modelling accuracy and ease of use of this programme make it suitable with both Windows and UNIX platforms. Each block in the picture represents a subsystem or component of the optical communication system; the system is shown as a connected collection of blocks. Similar to how actual signals are exchanged in a real-world communication system, the OptiSystem simulation transfers "signal" data between component models.

It offers a range of simulation engines together with corresponding simulation approaches. This allows for the most flexibility in the modelling and simulation of systems, such as large metro networks with feedback loops and EDFA transients due to the addition and removal of channels, ultra-long-haul DWDM telecom systems, and short-distance data communication links. The data post-processing and display capabilities of Optisytem provide a flexible and easy-to-use graphical measurement interface that may be used as a virtual laboratory instrument set. Among the interactive and post-processing features that allow for the simulation of a project once and the subsequent analysis of the results are graph superimposition, correlation graphs, interactive cursor read-out data, peak search, eye-diagram measurements, and BER/Q evaluation. These features help to save time during the design process.

3.3.1 Simulation Set-Up for CSRZ format

This thesis has constructed three different dispersion compensation systems (pre-, post-, and symmetrical compensation) to adjust for the accumulated dispersion. In the pre-compensating situation, DCF acts as a pre-compensating factor for the accumulated dispersion of the transmission fibre. The gain G of the amplifier, which compensates for the fibre loss in the DCF, may be found after the DCF by:

where L is the DCF's length and ATC is the dispersion compensating fiber's attenuation coefficient. A similar equation applies to the gain of the amplifier that comes after the transmission fibre, where αTF is the transmission fiber's attenuation coefficient.

$$G = \alpha_{TF} L_{TF} \qquad (3.2)$$

To account for the dispersion of the transmission fibre, the following factors should be considered when choosing the linear dispersive compensation length, or LDCF:

$$L_{DCF} = \frac{L_{TF} D_{TF}}{-D_{DCF}}$$

(3.3)

where L is the transmission fiber's length, H is the transmission fiber's dispersion, and D is the DCF's dispersion. The DCF post makes up for the transmission fiber's dispersion in a post-compensating situation. In a symmetrical compensation scenario, the sequence of placement of fibres is transmission fibre, DCF, and transmission fibre [34]. The proposed 32-channel DWDM system, consisting of the transmitter section, optical receivers, and fibre, is shown in Figure 3.7. 193.1 THz is the first channel's central frequency. Table 3.1 provides specifics on the implemented simulation parameters.

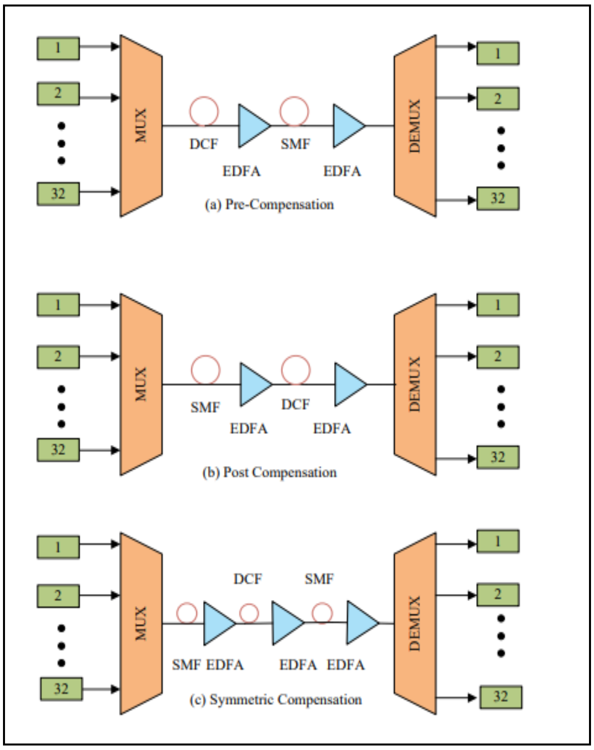

Fig. 7: Schematic of simulation setups

Pre-compensation, post-compensation, and symmetrical compensation schemes are the three types of compensation schemes. By mixing fibres with normal and anomalous GVD to create a dispersion map, the transmission link's design maintains a low average GVD while permitting a high local GVD across the link's length [35]. This technique is known as periodic dispersion management. To put it another way, the DCF and SMF parameters are selected so as to guarantee that the first-order dispersion is accurately compensated (D= 0), where D is the associated fiber's first-order dispersion parameter [ps/nm/km] and L is the total length of the SMF or DCF per span.

Table 1: Simulation parameters

Bit rate	**40 Gbps**
Sequence length	64
Samples/bit	256
DWDM channel spacing	50 GHz
Central frequency of the 1st channel	193.1 THz
Capacity	32-channel 40-Gbps
Distance	30 Km X N Spans
Input Power	-10 dBm

3.3.2 Transmitter section

The WDM transmitter is made up of an optical multiplexer, data modulators, filters, pseudo random bit sequence (PRBS) generator, and CW lasers. The PRBS generator generates bit sequences of 27–1 bits at a 40 Gbps rate. The 193.1–194.65 THz frequency range is covered by the equally scattered frequencies emitted by the CW laser, with a 50 GHz frequency separation between neighbouring channels. MZM has an extinguishing ratio of 30 dB. Each CW laser's output port has a CSRZ transmitter linked to it, as shown in Fig. 3.7. An optical multiplexer receives optical signals from 32 of these data modulators at its 32 input terminals. To ensure linear cross-talk reduction in the frequency domain, each channel is optically filtered using a narrow transmission optical filter prior to multiplexing [28]. In this regard, consideration has been given to a 50 GHz bandwidth second-order Gaussian filter. The channel spacing and operational wavelengths comply with ITU-T regulations.

4 RESULT AND DISCUSSION

4.1 Numerical Simulation Model and System Description

Modelling the creation, propagation, and receipt of the sent signal is a part of the signal simulation process in an optical fibre transmission system. Every simulation involves a trade-off between time and accuracy. Research, development, testing, and refining of the intricate models needed to construct an optical system simulator usually take time and resources. Because the Optisystem 10.0 simulator is available in commercial optical system simulators that offer affordable prices, sophisticated simulation algorithms, and user-friendly graphical user interfaces, it was selected to assess the transmission capabilities of a wide range of phase modulation formats. With simulation modules for active and passive photonic components, several fibre types, integrated digital signal processing modules, time domain and frequency domain analysers, electrical signal sources, filters, and other relevant sub-systems, it is a widely acknowledged standard simulator. Additionally, by using other programming languages, such Matlab®, to communicate with this simulator, users may develop, construct, and integrate new modules with Optisystem.

Initially, DPSK and DQPSK formats were used to maximise performance on a 40 Gbps single-channel optical connection. The channel numbers were gradually expanded to 32 with a channel spacing of 50 GHz in order to reach an aggregate capacity of 1.28 Tb/s. For a range of fibre types, the simulation study was carried out in the C-band (1530 nm – 1565 nm) to assess the system's effectiveness for the proposed modulation settings. 193.1 THz is the centre frequency of the first channel in the 32-channel DWDM system diagram shown in Fig. 4.1. These formats have been studied in the literature with a lower transmission data rate or with fewer channels at a 50 GHz channel spacing. Both formats are examined in this study under different dispersion compensating schemes. This suggested design's non-linear mitigation performance has been examined via an analysis of pre-, post-, and symmetric compensation arrangements. To account for dispersion and non-linearities, a DCF of 10 km is used in the pre-compensation system before the 50 km-long SMF. The gain of the EDFAs used in the connection is 5 dB and 11 dB, respectively. The post-compensation technique employs a DCF of 10 km to mitigate the dispersion buildup that happens after a 50 km SMF. In the symmetrical-compensation system, a 10 km DCF is introduced between the 50 km SMF, as shown in Fig. 4.10. Three in-line EDFAs with gains of 5.5 dB, 5 dB, and 5.5 dB are used in this experiment. Consistent with the results of the literature, the post compensation approach was shown to provide the best performance for both the DPSK and DQPSK forms [38]. This tactic was therefore used in the continuing enquiry. The findings are examined in a particular instance utilising the Q value and are startling over several transmission lengths up to 1600 km.

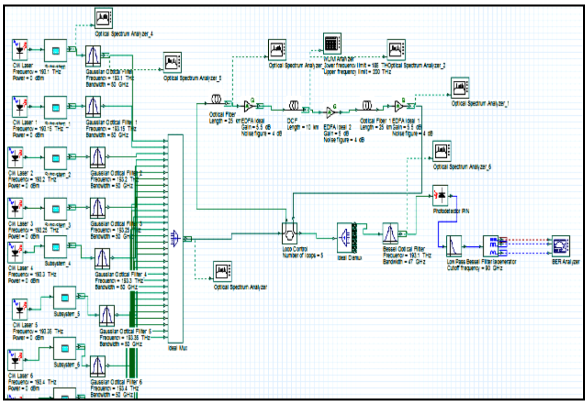

Fig. 8. Schematic of simulation setup

N spans of 60 km each are used to convey the signal once the input voltage has been adjusted. The optical multiplexer, data modulators, filters, CW lasers, and PRBS generator make up the WDM transmitter. CW lasers have uniformly spaced emission frequencies ranging from 193.1 to 194.65 THz, separated by a 50 GHz channel. It is shown that MZMs have an extinction ratio of 30 dB. A data modulator is used to drive each CW laser, as shown in Figs. 4.3 and 4.7 for DQPSK and DPSK, respectively. An optical multiplexer's 32 input terminals receive the modulated optical signal.

In DWDM systems, the reciprocal interaction of the signals and the accumulated ASE noise leads to the inevitable impairments of linear and nonlinear crosstalk. Therefore, it is essential to perform an accurate comparison between the two modulation schemes by optimising the optical and electrical filtering on both the transmitter and receiver sides [39]. Because of this, we have used receiver sensitivity to assess the filter's efficacy in terms of the received Q value. The 'elevated cosine' transfer function, whose centre is the signal carrier frequency, was used to represent the optical filters of the multiplexer and de-multiplexer.

Table 2: Multiplexer Filter optimization

Filter Order	No of loops	Q value With Bessel Filter	Q value with Gaussian Filter	Q value with Rectangular
3	1	23.56	24.29	18.85
	5	23.17	21.74	18.48
	10	21.4	19.02	17.81
	15	19.99	16.84	17.06
	20	17.71	15.41	15.66
	25	16.49	14.2	14.32
4	1	23.36	24.04	18.85
	5	22.82	21.93	18.48
	10	21.84	18.72	17.8
	15	19.61	16.95	17.06
	20	17.92	15.31	15.43

The chart clearly shows that even with the same beginning Q value as the Gaussian filter, the Bessel filter may achieve a longer transmission reach. As such, the Bessel filter has been included into our design. Because the starting Q value is too tiny for the rectangular case, the proposed connection will not be particularly stable. Furthermore, we evaluated the ideal electrical and optical filter bandwidth required for effective signal transmission. Our results suggest that shorter channel spacing requires a wider electrical bandwidth. Before multiplexing, each channel is optically filtered using a third-order Gaussian filter (bandwidth of 50 GHz for DPSK format and a fourth-order Bessel filter (bandwidth of 50 GHz for DQPSK format) to avoid crosstalk between neighbouring channels. This is taken into consideration.

When the combined optical signal is sent to the SMF, consideration is given to the dispersion, stimulated Raman scattering, unidirectional signal flow, and Kerr-nonlinearity. The usage of a scalar model for both fibre segments has served to lessen the impact of PMD. The following parameters have been considered: dispersion slope (S) of 0.08 ps/nm2/km at 1550 nm, attenuation (α) of 0.22 dB/km, D of 17 ps/km-nm, and nonlinear refractive index (n2) of 2.6×10−20 m2/W. The DCF segment used in each span at 1550 nm has the following characteristics: α = 0.5 dB/km, D = -85 ps/km-nm, S = -0.45 ps/nm2/km, n2 = 2.6× 10−20 m2/W, and Aeff = 30 μm2.

The receiver is made up of the de-multiplexer, demodulators, filters, and 3R regenerator. To evaluate required filter settings, a simulation of the 32-port demultiplexer's output has been performed. When using a third order Gaussian filter with a bandwidth of 50 GHz for DPSK, the design performs optimally; when using a second order Bessel band pass filter with a 3 dB bandwidth of 50 GHz for DQPSK, the design performs optimally. The receiver modules covered in Figs. 4.6 and 4.8 are used for DPSK and DQPSK, respectively. The 3R regenerator, which generates graphs and results including eye diagrams, BER, Q value, and eye opening, is then linked to the BER analyser.

5- CONCLUSION AND FUTURE SCOPE

In order to model, develop, and simulate the ideal circumstances for a long-haul optical communication connection in order to obtain an optimum propagation length, this thesis covers the theoretical examination and analysis of the optical channel characteristics. Using the analytical model and numerical simulation analysis of this fibre transmission channel, the designer may choose a design plan and an appropriate solution for different modulation formats within the specified operational limits. Examining the effects of linear and non-linear phase impairments that happen during pulse propagation in the fibre medium on the design of long-haul fibre optic communication systems is the main goal of the thesis. This chapter outlines possible future expansions of the intended study and summarises the results and contributions of the current work.

Enhancing the transport capacity and transmission distance of DWDM systems while lowering the cost per carried information bit has become very desirable due to the growing demand for bandwidth. It is clear that new approaches to binary data encoding over the optical carrier have been developed as a result of the constraints placed on DWDM transmission and the development of optical communication systems. This thesis focused on the difficulties these modulation methods provide throughout various stages of implementation. Generally speaking, the kind of fibre, the pace at which data is sent across the channel, and the wavelength spacing all play a role in determining which optical modulation scheme is best. Service providers may save costs by using most of the current systems with the best modulation formats and innovating their current light wave network without having to completely update.

REFERENCES

[1] Karaki, E. Pincemin, D. Grot, T. Guiliossou, Y. Jaouen, R. le Bidan and T. le Gall, "Dual- polarization multi-band OFDM versus single–carrier DP-QPSK for 100 Gbps long-haul WDM transmission over legacy infrastructure", 38th European Conference on Optical Communications (ECOC), 2012.

[2] Chen, ZY., Yan, LS., Pan, Y. et al. Use of polarization freedom beyond polarization-division multiplexing to support high-speed and spectral-efficient data transmission. Light Sci Appl **6**, e16207 (2017).

https://doi.org/10.1038/lsa.2016.207

[3] D. Wang, D. Lu, C. Lou, L. Huo and W. Yu, "Performance comparison of phase modulated formats in 160 Gb/s transmission system", IEEE Communications and Photonics Conference,

[4] Mats Skold et al (2010), All-Optical Waveform Sampling in High-Speed Optical Communication Systems Using Advanced Modulation Formats, pp. 3662-3671 (2009).

[5] Jianjun Yu (2016), recent progress on high-speed optical transmission, https://doi.org/10.1016/j.dcan.2016.03.002.

[6] Eugen Lach (2011), Modulation formats for 100G and beyond, https://doi.org/10.1016/j.yofte.2011.07.012.

[7] Ragheb and H. Fathallah (2012) "Candidate modulation schemes for next generation-passive optical networks (NG-PONs)," High Capacity Optical Networks and Emerging/Enabling Technologies, Istanbul, Turkey, 2012, pp. 226-231, doi: 10.1109/HONET.2012.6421469.

[8] Borah, D.K., Boucouvalas, A.C., Davis, C.C. (2012) A review of communication-oriented optical wireless systems. J Wireless Com Network 2012, 91 (2012). https://doi.org/10.1186/1687-1499-2012-91.

[9] L. Tao, Y. Ji, J. Liu, A. P. Tao Lau, N. Chi and C. Lu, (2013)"Advanced modulation formats for short reach optical communication systems," in IEEE Network, vol. 27, no. 6, pp. 6-13, November-December 2013, doi: 10.1109/MNET.2013.6678921.

[10] Jun He et al (2014), a survey on recent advances in optical communications, https://doi.org/10.1016/j.compeleceng.2013.11.017.

[11] X. Liu, S. Chandrasekhar and P. J. Winzer (2013) "Digital Signal Processing Techniques Enabling Multi-Tbs Superchannel Transmission: An overview of recent advances in DSP-enabled superchannels," in IEEE Signal Processing Magazine, vol. 31, no. 2, pp. 16-24, March 2014, doi: 10.1109/MSP.2013.2285934.

[12] Zhong, Kangping, (2015)"Experimental study of PAM-4, CAP-16, and DMT for 100 Gb/s short reach optical transmission systems." Optics express 23.2 (2015): 1176-1189.

[13] Jianjun Yu (2016), recent progress on high-speed optical transmission, https://doi.org/10.1016/j.dcan.2016.03.002.

[14] Jianjun Yu (2016), recent progress on high-speed optical transmission, https://doi.org/10.1016/j.dcan.2016.03.002.

[15] Alipour, A. Mir, A. Sheikhi (2016) Ultra high Alan E. Willner et al (2017), Recent advances in high-capacity free-space optical and radio-frequency communications using orbital angular momentum multiplexing, https://doi.org/10.1098/rsta.2015.0439.

[16] capacity inter-satellite optical wireless communication system using different optimized modulation formats,Optik,Volume 127, Issue 19,2016,Pages 8135-8143,ISSN 0030-4026,https://doi.org/10.1016/j.ijleo.2016.06.011.

[17] Badar, N., Jha, R.K (2017) Performance comparison of various modulation schemes over free space optical (FSO) link employing Gamma–Gamma fading model. Opt Quant Electron **49**, 192 (2017). https://doi.org/10.1007/s11082-017-1025-4

[18] Rashed, Ahmed Nabih Zaki, (2018)"Transmission performance simulation study evaluation for high speed radio over fiber communication systems." Wireless Personal Communications 103 (2018): 1765-1779.

[19] Gill, Harpreet Kaur, Gurjot Kaur Walia, and Narwant Singh Grewal (2019) "Performance analysis of mode division multiplexing IS-OWC system using Manchester, DPSK and DQPSK modulation techniques." Optik 177 (2019): 93-101.

[20] Anandkumar, D., Sangeetha, R.G (2020) "A survey on performance enhancement in free space optical communication system through channel models and modulation techniques" Opt Quant Electron 53, 5 (2021). https://doi.org/10.1007/s11082-020-02629-6.

[21] Magidi, S., Jabeena, (2021) A. Free Space Optics, Channel Models and Hybrid Modulation Schemes: A Review. Wireless Pers Commun 119, 2951–2974 (2021). https://doi.org/10.1007/s11277-021-08380-9.

[22] Abu Jahid et al (2022), A contemporary survey on free space optical communication: Potentials, technical challenges, recent advances and research direction, https://doi.org/10.1016/j.jnca.2021.103311.

[23] Garg, Deepak and Nain, Abhimanyu. "Next generation optical wireless communication: a comprehensive review" Journal of Optical Communications, vol. 44, no. s1, 2023, pp. s1535-s1550. https://doi.org/10.1515/joc-2020-0254.

[24] Jain, Vishal and Bhatia, Richa (2023) "Review on nonlinearity effect in radio over fiber system and its mitigation" Journal of Optical Communications, vol. 44, no. s1, 2023, pp. s1661-s1669. https://doi.org/10.1515/joc-2021-0044.

[25] Mahapatra and E. J. Murphy, "Electro-optic modulators," Optical Fiber Telecommunications IV,

[26] Kaminow and T. Li, Eds. New York: Academic, pp. 258–294, 2002.

[27] T. Matsuda, A. Naka and S. Saito, "Comparison between NRZ and RZ signal formats for in-line amplifier transmission in the zero-dispersion regime," IEEE Journal of Lightwave Technology, Vol. 16, pp. 340-348, 1998.

[28] Rohde, E. Gottwald, A. Teixeira, J. D. Reis, A. Shahpari, K. Pulverer and J S. Wey," Coherent Ultra Dense WDM Technology for Next Generation Optical Metro and

Access Networks", IEEE, Journal of Lightwave Technology, Vol. 32, No. 10, pp. 2041-2052, 2014.

[29] Hodzik, B. Konrad and K. Petemann," Alternative modulation formats in N X 40 Gb/s WDM standard fiber RZ-transmission systems", IEEE Journal of Lightwave Technology, Vol. 20, No

[30] Zheng, F. Lu, M. Xu, M. Zhu, Md I. Khalil, X. Bao, D. Guidotti, J. Liu, N. Zhu and Gee-Kung Chang," A dual-polarization coherent communication system with simplified optical receiver for UDWDM-PON architecture, Optics Express, Vol. 22, No. 26, pp. 31735, 2014.

[31] S. V. Kartalopoulos, "Introduction to DWDM technology: Data in a rainbow", J Wiley, 2001

[32] O.V. Shtyrina, M.P. Fedoruk and S.K. Turitsyn, "Study of new modulation data-transmission formats for dispersion-controlled high-bit-rate fibre optic communication lines", Journal of Quantum Electronics, (IOP Science), Vol.37, No. 9, pp 885 - 890, 2007.

[33] Sheetal, A. K. Sharma and R.S. Kaler, "Simulation of high capacity 40 Gb/s long haul DWDM system using different modulation formats and dispersion compensation schemes in the presence of Kerr's effect", Optik ((Elsevier), Vol.121, pp. 739-749, 2010.

[34] D. Millar, S. Makovejs, C. Behrens, S. Hellerbrand, R. Killey, P. Bayvel and S. Savory, "Mitigation of Fiber Nonlinearity Using a Digital Coherent Receiver," IEEE Journal of Selected Topics in Quantum Electronics, Vol. 16, No. 5, pp. 1217-1226, September/October 2010.

[35] C. R Silveira, D.M. Pataca, M.A. Romero and M. L Rocha, "A Cost-Benefit Analysis on Modulation Formats for 40-Gb/s Optical Communication Systems", Fiber and Integrated Optics, Vol. 30, No. 2, pp. 87-101, 2011.

[36] Rohde, E. Gottwald, A. Teixeira, J. D. Reis, A. Shahpari, K. Pulverer and J S. Wey," Coherent Ultra Dense WDM Technology for Next Generation Optical Metro and Access Networks", IEEE, Journal of Lightwave Technology, Vol. 32, No. 10, pp. 2041-2052, 2014.

[37] Hodzik, B. Konrad and K. Petemann," Alternative modulation formats in N X 40 Gb/s WDM standard fiber RZ-transmission systems", IEEE Journal of Lightwave Technology, Vol. 20, No

[38] S. K. Ibrahim, Study of Multilevel Modulation Formats for High Speed Digital Optical Communication Systems, Ph.D. thesis, University of Paderborn, Germany, 2007.