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Analysis Of the Performance for Quality of Transmission in Optical Fiber Communication Based on Machine Learning Optimization

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Abstract- ***The foundation and application of optical communication networks is the estimation of the optical signal's Quality of Transmission (QoT) parameters from source to destination nodes. However, Machine Learning (ML) approaches are being used in recent research to increase the accuracy of QoT estimation. In this study, the performance validation was carried out through the application of ML computational technique and the results demonstrated a stable Bit Error Ratio (BER) of ~10^{-10} and a consistent Signal-to-Noise Ratio (SNR) of 12.6–13.2 dB across transmission distances 19–22 km. In addition, the Phase-Shift Keying (PSK) and the Quadrature Phase-Shift Keying (QPSK) modulation outperformed the Amplitude Shift Keying (ASK) and Frequency Shift Keying (FSK), with statistical significance confirmed via chi-square tests. Conclusively, comparative advantages surpassed prior studies in BER reduction, SNR efficiency and multi-modulation adaptability.***

Index Terms- ***Artificial Intelligence; Communication; Optical fiber; Machine learning; Modelling; Transmission***

I. INTRODUCTION

The rapid growth of global data traffic, driven by cloud computing such as 5G/6G networks, and IoT applications, has placed unprecedented demands on optical fiber communication systems [1]. These systems form the backbone of modern telecommunications due to their high bandwidth, low latency, and long-distance transmission capabilities. However, signal degradation caused by attenuation, dispersion, splice losses, and environmental factors remains a critical challenge, limiting network efficiency and reliability [2]. Traditional approaches to managing optical networks rely on static models and manual adjustments, which are inefficient in dynamic environments where real-time optimization is crucial. While existing studies [3-6] have explored signal processing techniques and single modulation schemes. However, the following are lacking:

- AI-driven adaptive optimization for real-time fault detection and correction.
- Comprehensive comparison of modulation techniques (such as Amplitude Shift Keying (ASK), *Frequency Shift Keying (*FSK), Phase-Shift Keying (PSK), Quadrature Phase-Shift Keying (QPSK) under varying transmission conditions.
- Corrective mechanisms for issues like high Bit Error Rate (BER), Polarization Mode Dispersion (PMD), and splice losses.

Recent advancements in machine learning (ML) and Optical Character Recognition (OCR) present opportunities to bridge these gaps. Python-based AI frameworks enable the predictive modelling of signal degradation, while OCR can automate real-time advisory systems for network maintenance [7]. This study addresses the limitations by developing an AI optical character recognition hybrid system for intelligent optical network management. Evaluating four modulation schemes to determine optimal performance under different conditions. Incorporating environmental and polarized mode dispersion (PMD) compensation into signal integrity analysis, the study introduces feature-engineered OSNR estimation for improved accuracy by combining Machine Learning (ML)- based analytics with automated fault resolution. This research advances optical communication systems toward self-optimizing networks, ensuring high-speed, reliable data transmission for next-generation applications.

II. OPTICAL FIBER COMMUNICATION

Using optical fibre communication, information can be sent as light pulses across thin strands of glass or plastic called optical fibres. Compared to traditional copper cable, this method allows for faster, longer-distance data transfer with reduced signal loss. A communication infrastructure known as fibre optic communication (FOC) uses optical fibres to deliver dependable data transfer with stringent Quality of Service, almost infinite bandwidth, and a high degree of immunity to electromagnetic interference [8]. Optical fibers in communications drastically changed the telecommunication sector. The optimum transmission medium is optical fibre because of its low propagation loss and large bandwidth [9-11]. On a global scale, nearly all long-distance communication systems are now transported over optical fibres. Wide area, metro area, and other high-speed communication and data networks rely on fiber-optic technology as the foundation of the contemporary internet.

Global telecommunications infrastructure is supported by optical fibre communication systems, which require extremely high data speeds and dependability. However, Quality of Transmission (QoT) is severely impacted by signal degradation brought on by nonlinear effects (like cross-phase modulation) and linear impairments (like attenuation, dispersion). The basic fiber optic communication is shown in Fig. 1. However, fiber-optic communication is the process of using optical fiber to send digital data between two locations using light waves [12]. Digital information is the term used to describe the type of data transmitted over computer and internet networks. Dielectric waveguide cylinders composed of silicon dioxide materials make up the optical fibre. Using optical fibre, an optical transmitter converts electrical signals into optical signals [13]. There are several benefits of using optical fiber in modern communication technologies, such as [10];

- Wide bandwidth potential with better carrier frequency than the metallic wires.
- The tiny size and modest weight with a reasonable diameter.
- Reliable electrical insulation due to their usage of polymeric polymers or glass, unlike their metallic counterparts.
- High signal strength and protection security for the communication signal.

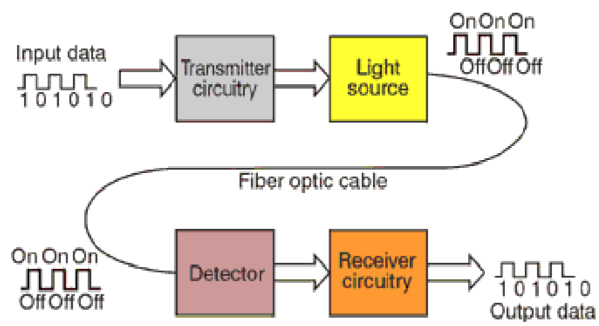

Fig. 1: Basic fiber optic communication system [14]

III. METHODOLOGY

In order to revolutionise optical communication systems, machine learning (ML) has emerged as a new area of innovation over the last ten years. ML approaches are helpful in problems about networking and optical communication because of their substantial development and advancement in computer capabilities. By using data-driven methods to model complex communication situations and enable intelligent QoT optimisation, machine learning (ML) presents a promising alternative to traditional physics-based models for QoT estimation, which struggle with computational complexity in large-scale or dynamic networks. The objective of the study was accomplished through modelling of the mathematical equations for an intelligent optical communication system that combines machine learning-based signal with quality prediction and physical layer transmission characteristics. The impact of increasing transmission distance (19km-22km) on key optical parameters, including Transmitted Power, Fibre Attenuation, Splice Loss, Amplifier Gain, Received Power, Signal-to-Noise

Ratio (SNR), and Bit Error Ratio (BER) was also investigated.

IV. OPTICAL COMMUNICATION

Signal deterioration, nonlinear impairments, and dynamic network conditions are some of the difficulties that optical communication systems must deal with. Adaptive solutions are provided by AI/ML techniques (learning, reasoning, and self-correction), while traditional methods rely on static algorithms. Python as the Basis for AI in Telecommunication: AI-Enhanced Optical Network Performance Monitoring [15]. Python is often used in optical networks for AI/ML implementations because of its many libraries (NumPy, SciPy, scikit-learn), adaptability, and speed of prototyping. Its use in this investigation is justified by its usefulness for feature engineering, data preparation, and model deployment [16-17]. However, the challenges and issues of optical communication are summarized in the diagram of Fig. 2.

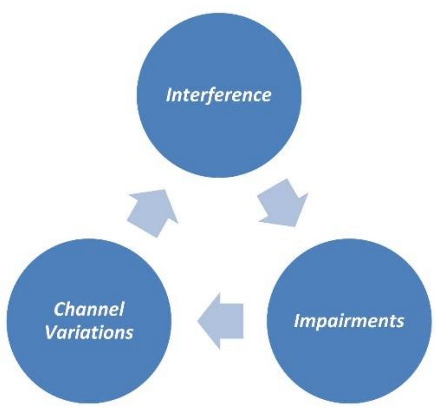

Fig. 2: Challenges and issues of optical communication [18]

V. QUALITY OF TRANSMISSION (QOT) ESTIMATION

QoT in optical connection estimation is very important before deployment in impairment-aware optical network design and operation. ML methods have improved QoT estimation, mitigated nonlinearities, and optimized decision-making processes. Ultimately, these advancements reduce the reliance on conservative margins, maximize network capacity, and decrease infrastructure investment. Accurate and real-time QoT information is the foundation for efficient routing and spectral allocation (RSA) systems and enabling proactive failure management. In addition, it facilitates network reconfiguration, providing inputs for optical line optimization and driving optical network automation. A QoT estimator tool, the Q-Tool, which computes the associated Q-factors of a set of light paths, given a reference topology, by combining analytical models and numerical methods.

VI. IMPLEMENTATION OF PROPOSED TECHNIQUE

In the implementation of the developed system, it is important to derive the Recurrent Neural Network (RNN) from differential equations since it is essential in the modeling of neural networks when solving practical data processing tasks with machine learning methods. The derivation was based on the principle adopted in the work conducted by Sherstinsky [19]. If the value of the d-dimensional state signal vector is $\vec{\mathrm{h}}(t)$, and the general nonlinear first-order non-homogeneous ordinary differential equation, which describes the evolution of the state signal as a function of time, t. Then the equation can be expressed as

$$\frac{d\vec{\mathrm{h}}(t)}{dt}=\vec{f}(t)+\vec{\phi}$$

Eqn. (3.1)

where $\vec{f}(t)$ is a d-dimensional vector-valued function of time.

One canonical form of $\vec{f}(t)$ is given as;

$$\vec{f}(t)=\vec{s}\left[\mathrm{t}\,\vec{\mathrm{h}}(\mathrm{t}),\vec{x}(\mathrm{t})\right]$$

Eqn. (3.2)

where $\vec{x}(\mathrm{t})$ is the d-dimensional input signal vector and $\vec{s}\left[\mathrm{t}\,\vec{\mathrm{h}}(\mathrm{t}),\vec{x}(\mathrm{t})\right]$ is a vector-valued function of vector-valued arguments.

The resulting system is given by

$$\frac{d\vec{\mathrm{h}}(t)}{dt}=\vec{s}\left[\mathrm{t}\,\vec{\mathrm{h}}(\mathrm{t}),\vec{x}(\mathrm{t})\right]+\vec{\phi}$$

Eqn. (3.3)

VII. MONITORING OF THE DEVELOPED SYSTEM USING AI TECHNIQUE

The learning processes of this research focus on acquiring data and creating rules for transforming the data into actionable information. The rules or algorithms provide computing devices with step-by-step instructions for how to complete different specific tasks. Similarly, in the reasoning process stage, emphasis was placed on selecting the right algorithm to achieve the desired outcome. The steps involved in the accomplishment of the research work are shown in Fig. 3.

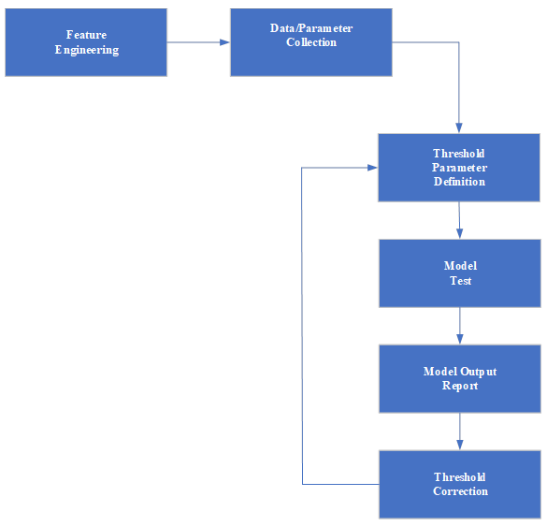

Fig. 3: Implementation procedure of the ML-based optimization for real-time fault detection and correction

VIII. DISCUSSION OF RESULTS

This study was implemented on Python since it is the most acceptable and recommended language for Artificial Intelligence (AI) for various reasons [20]. For instance, developing AI applications is difficult and takes time, but the main justification for its preference over other languages is that Python has compatible libraries [21]. Also, it is a flexible programming language that is user-friendly. Different parameters were presented to evaluate and validate the performance of the proposed developed technique. These include the transmission distance, transmitted power, fiber attenuation, splice loss, amplifier gain, received power, SNR, and BER. The parameters agree with the four modulation techniques. These modulation formats are digital techniques: Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), Phase Shift Keying (PSK), and Quadrature Phase Shift Keying (QPSK) as presented in Table 1. The statistical performance shows that the Chi-square Test Statistic is 2.7987 and P-value: 0.4237.

Table 1: Results of modulation and signal quality

S/N	Modulation	Signal Quality	
	Format	Good	Poor
1	ASK	239	22
2	FSK	270	27
3	PSK	277	27
4	QPSK	290	18

System Response to Increased Transmission Distance

The result in Table 2 is the system's response to increased distance or transmission distance. Different parameters were considered to evaluate the performance of the proposed developed system. The parameters are transmitted power, fiber attenuation, splice loss, amplifier gain, Received (RX) Power, SNR and BER. The transmission distance under consideration is between 19 km to 22 km. It can be deduced from the transmitted power that it increases with the distance, with the value ranging from 9.8 dB to 12.1 dB. As expected, the fiber attenuation increased with the transmission distance. The lowest value for the attenuation was 0.09 dB/km, while the peak of the attenuation value was 0.12 dB/km. Another parameter of interest is Splice loss, with the least being at 0.18 dB while the highest loss is 0.24 dB. The amplifier gain is in the range of 9-12, with the highest at 21 km, which has 12 dB. Similarly, the received power has a peak value of 18.2 dB and the lowest is 14.8 dB. The SNR values range from 12.6 - 13.2 dB. The BER is approximately constant with a constant value of 10^{-10}. It can be observed from the result that the amplifier gain does not significantly respond to a change in distance compared with the attenuation. The BER is proportional to the errors in the total number of bits received in a transmission.

Table 2: Results of the system response to increased transmission distance

S/N	Transmission distance (km)	TX Power (dB)	Fiber attenuation (dB/km)	Slice Loss (dB)	Amplifier Gain (dB)	RX Power (dB)	SNR (dB)	BER
1	19	9.8	0.09	0.18	9	14.8	12.9	0.000001
2	20	10.5	0.10	0.20	10	15.2	12.8	0.000001
3	20	10.9	0.10	0.20	10	15.8	13.0	0.000001
4	21	11.2	0.11	0.22	12	16.5	12.6	0.000001
5	22	12.1	0.12	0.24	11	18.2	13.2	0.000002

IX. SIGNAL QUALITY

The signal quality of the system against the count is presented in Fig. 4. It depicts the system's performance by categorizing it into two forms, which are good and poor. The comparison shows that the strength of the good signal quality outweighs that of the poor-quality signal. The better performance can be linked to low attenuation and splice losses. This shows an increased probability of error or incomplete data with changing conditions, presenting a significant concern, especially in unstable environments. Furthermore, the Polarization Mode Dispersion (PMD) coefficient is within manageable limits as shown in Fig. 5, but will need to be subjected to regular monitoring. This is necessary to ensure that the occurrence of any signal degradation can be corrected. Also, in Fig. 6, the distribution of the count against the modulation formats is shown. It shows the analysis of the distribution of received counts among various modulation categories. This is typically done in the context of a modulation format in communication systems, especially in optical and wireless communication. Based on the observed signal characteristics, the objective is to identify the modulation scheme that was utilised to convey the data.

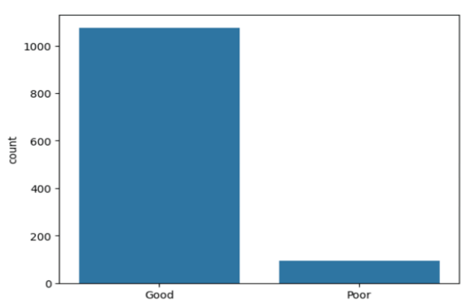

Fig. 4: Distribution of the Count against Signal Quality

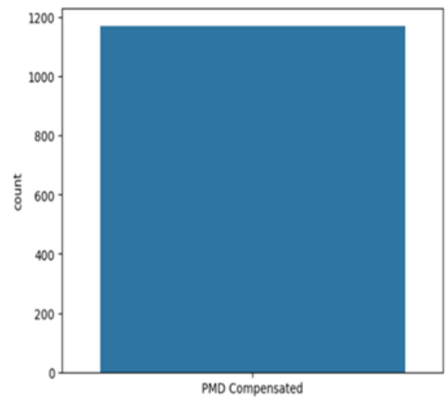

Fig. 5: Distribution of the count against compensated Polarization Mode Dispersion (PMD)

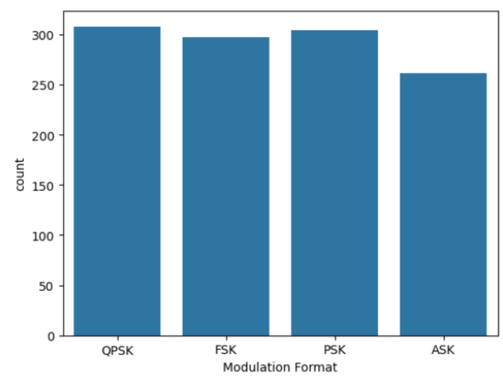

Fig. 6: Distribution of the count against the modulation formats

CONCLUSION

The unfolding situation in the development of modern communication technologies, transmission of information has been completely transformed by optical communication devices. High-capacity and speedy data transfer is achievable with optical communication systems. Considering the growing need for communication networks with greater speed and capability, conventional optical communication solutions are becoming less effective. The application of deep learning and machine learning techniques has produced strong tools that can greatly improve the performance of optical communication systems. ML optimization techniques has been used to enhance the performance of optical communication systems through modulation approaches, and system optimisation as provided in this study. In order to analyse and optimise optical communication systems, this paper effectively integrate data-driven modelling with real-time advisory capabilities using a Python-based ML framework.

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