

Significant Concepts in Optical Fibre Communication Systems: An Overview

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Abstract- Due to their ability to transmit gigabits of data per second across short or long distances, optical fibres have emerged as the primary medium for terrestrial communication. Optical fibre communication uses lightguides for transmission based on thin and flexible fibres made of glass or plastic. An optical fibre functions as a waveguide, either directly or through complete internal reflection at the fibre boundaries, to direct the propagation of optical waves for communication. Optical fibre communication technology exhibits technological superiority considering the fact that no current flows in it. Therefore, this study presents a concise review of the important technological concepts in optical fibre communication systems. It also pinpoints the capability of Artificial Intelligence (AI) techniques to solve the technical problems associated with optical fibre data transmission in communication technology.

Index Terms- Communication; Engineering; Optical fibre; Telecommunication; Transmission

I. INTRODUCTION

The use of small strands of glass or plastic, known as optical fibre, to conduct information as light pulses is referred to as optical fibre communication. The technologies involved in optical fibre communication are long-distance transmission of information with a high-speed communication system. It also involves a low signal loss and resistance to electromagnetic

interference. The current global socioeconomic technology strongly relies on the use of internet technology for the survival of human beings [1]. Many scientific and technologically based efforts have been sustained to improve access to internet services, especially through the utilization of optical fibre communication systems [2,3]. The technology of optical fibre communication transmits information from one point to another using light to transport the data involved through electromagnetic waves [4]. The impact of optical fibre communication on the communication industry is highly versatile from both economic and technological perspectives [5,6]. The use of optical fibre communication starts with the generation of an optical signal and sending it through the fibre while monitoring its strength and clarity during its conversion into an electric signal [7]. Hundreds or a few of the optical fibre cables can be used in optical fibre communication, depending on the communication requirements and the structure of an optical fibre system is shown in Figure 1. However, immediately after the strength protection member of the cable is the coating, followed by the cladding layer of glass that encircles the glass fibre core. The buffer tube layer protects the cladding, while the jacket layer shields the individual strands. For high-performance and long-distance data networking, fibre optics is used.

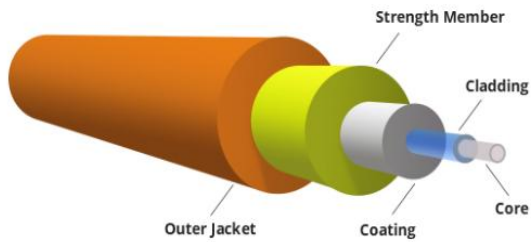


Figure 1: Optical fibre cable structure

Fibre protection guards against environmental harm, bending losses, and breakage. The longevity is intended to last 20 to 30 years in extreme circumstances, and performance is reduced when signals are affected by attenuation and dispersion. In order to choose the appropriate cable for applications, it is imperative to comprehend this layered design. As a result, an optical fibre is composed of three fundamental components that share a central line. Figure 1 illustrates the core, cladding, and exterior coating. Depending on the required gearbox range, glass or plastic is typically used to make the core cylindrical dielectric. The fibre's light-transmitting section is called the core. With a lower refractive index, the cladding is often composed of the same material as the core. since of this index variance, light travels down the fibre and does not escape through the sidewalls since 100% internal reflection occurs at the index boundary along the fibre's length. One of the primary purposes of the cladding is to preserve the fibre core and give it mechanical strength while minimising light loss from the core to the surrounding medium. Light only travels via the core; hence, cladding does not take part in light wave transmission. To minimise the signal losses brought on by scattering, the core and cladding mix is crucial [8]. Consequently, this study presents a review of the important and core aspects of optical fibre communication technology.

II. BASIC CONFIGURATION IN OPTICAL FIBRE COMMUNICATION

The use of optical fibre in telecommunication has numerous technologies associated with it. Optical fibre communication technology is based on the high speed required for modern communication, compared to the traditional copper wires used in

communication. On the other hand, optical fibres employ lasers to send data as light pulses, which move at the speed of light and are roughly 100 times quicker than conventional electrical signals. Figure 2 shows the basic optical communication structure for the application of optical fibre in telecommunication. In modern communication, optical fibres are impervious to radio frequency interference and electromagnetic interference, thereby making the system immune to interference from external signals. There are a few easy steps that make up the optical communication process, which are:

- A terminal, such as a computer, sends an electrical signal.
- An electrical-to-optical converter transforms an optical signal into a communication signal.
- The signal travels down the optical fibre, propagates, and is then transformed back into an electrical signal at the receiving terminal by the communication system of the optical-to-electrical (O/E) converter.

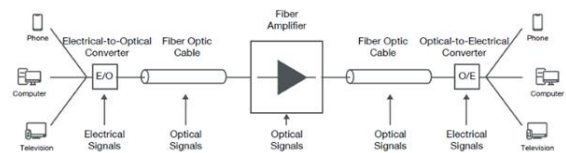


Figure 2: Basic configuration of an optical fibre communications system

III. OPTICAL FIBRE CABLES

Based on the number of light paths (modes), optical fibres are divided into two primary types: Multimode Fibre (MMF), which has a larger core for multiple light paths and short distances, and Single-Mode Fibre (SMF), which has a small core for a single light path and long distances as shown in Figure 3. However, the concept of optical fibres can also be further divided by their refractive index profile, as shown in Figure 4. A single-mode fibre is a single path that permits only one light beam to pass through it; however, because of its extremely thin core, light travels in it with virtually no refraction angles, meaning the distance the light travels in it is the same length as the actual fibre and arrives quicker than in multi-mode fibres and with less dispersion delay. Contrarily, the Multi-mode fibres have a comparatively larger light signal loss than single-

mode cabling, but their manufacturing costs are more affordable. Given all of these considerations, multi-mode fibre optic cables are typically chosen for data transfer in "Local Area Networks" where there are numerous connections, the distance is low, and end-user handling is taken into consideration.

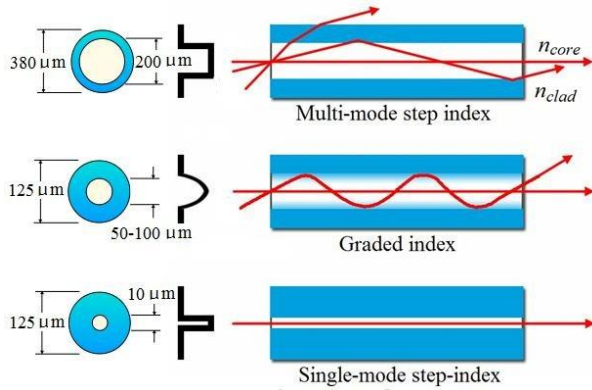


Figure 3: Different optical fibre cables based on different modes [9]

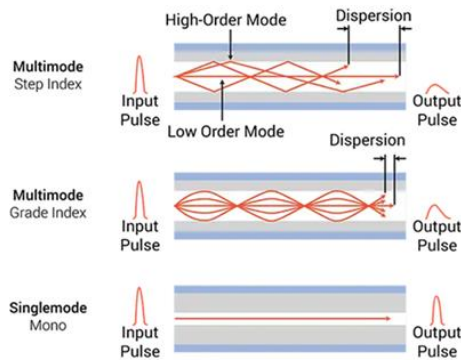


Figure 4: Optical fibre cable based on signal index types [9]

IV. NETWORK CONFIGURATION AND CONCEPTUAL PERFORMANCE PARAMETERS

Topologies and the application of technologies such as Wavelength Division Multiplexing (WDM), which sends numerous light signals over a single fibre, define the configurations of optical fibre communication networks. Fibre-to-the-Home (FTTH), Fibre-to-the-Premises (FTTP) and the fibre-to-the-room FTTR are important configurations for optical fibre communication, creating a backbone network. They are responsible for connecting various areas with metro networks. While optical amplifiers

enhance communications over long distances, WDM uses multiplexers (MUX) and demultiplexers (DEMUX) to combine and separate wavelengths. To organise, create, and maintain these intricate physical infrastructures, network management tools are also essential. Figure 5 shows the different kinds of network configuration by using dense wavelength division multiplexing (DWDM), coarse wavelength division multiplexing (CWDM) and digital subscriber line (xDSL). In consequence, due to effective network configuration, optical fibre communication has the following advantages:

- Higher bandwidth than copper cable.
- Strong security with a high difficulty to tap the connection.
- Absence of cross-talk.
- Greater flexibility with faster speed for longer transmission distances.
- Improved latency and light weight.
- Limited loss of power in transmission for longer distances.
- Resistance to electromagnetic interference.

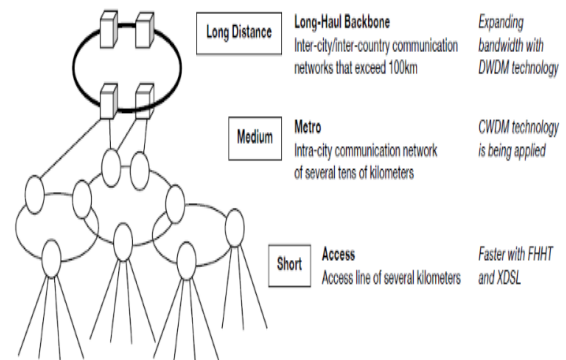


Figure 5: network configuration based on the level of communication distance in optical fibre

4.1 Optical Fibre Transmission Bandwidth

The number of signals that can be transferred in a second is the measure of optical fibre communication speed. The amount of information that can be transferred increases with transmission speed. A wide transmission bandwidth in data communication refers to a high communication speed. Because signal attenuation rises with coaxial cables, there is a practical limit to how quickly communication speed can be increased. Large volumes of data may be transmitted using optical fibre since there is no

attenuation, even as the transmission speed rises. Many applications today demand a lot of bandwidth. Because optical cables are lightweight and have a relatively small diameter, they are straightforward to install and save conduit space in these types of settings [10]. As a result, many end users have space limits, which should be taken into account.

4.2 Long Distance Signal Transmission

Compared to metallic-based systems, optical systems provide significantly longer intervals of signal transmission due to their low attenuation and improved signal integrity. It is fairly uncommon for optical systems to extend beyond 100 kilometres (km) without a repeater station, but single-line, voice-grade copper systems longer than a few kilometres need an in-line signal for adequate performance [11].

4.3 Signal Security

An optical signal offers a high level of data security since it is well contained within the waveguide. Additionally, in applications where information security is crucial, this makes fibre appealing. The dielectric structure of optical fibre precludes remote detection of the signal being conveyed within the cable, in contrast to metallic-based systems [12]. Getting to the optical fibre is the only method to accomplish this. Security surveillance can simply identify the intervention needed to access the fibre. Because of these factors, fibre is very appealing to banks, government agencies, computer networks, and military activities. The expense of deployment is the only drawback of optical fibre technology.

4.4 Non-conductivity

Additionally, because optical fibre is dielectric, it can be put in locations where radio frequency interference (RFI) and other forms of electromagnetic interference (EMI) are present. Railroad tracks, power-carrying lines and utility wires are among the locations with considerable electromagnetic interference. Additionally, locations with a high frequency of lightning strikes are best suited for all-dielectric cables [13]. Consequently, unlike copper-based wiring, optical fibre does not corrode.

4.5 Improved latency

Many of the latency problems users encounter with cable internet are resolved by fibre optic networks, especially when downloading or uploading videos or watching HD material. VoIP users benefit from lower latency since it allows them to download and upload large files without interruption, transfer more programs to the cloud, and collaborate with other users more effectively.

4.6 Quality of Transmission (QoT) Estimation

When designing and operating impairment-aware optical networks, QoT estimation before deployment is especially important. ML techniques have enhanced decision-making, reduced nonlinearities, and enhanced QoT estimation. In the end, reduce wasteful infrastructure spending and increase network capacity. Efficient routing and spectral allocation (RSA) systems rely on precise and up-to-date QoT data, which also facilitates proactive failure management, network reconfiguration, optical line optimisation inputs, and optical network automation. When designing and operating optical networks, QoT estimation before implementation is especially important. A QoT estimator tool, the Q-Tool, was introduced by Azodolmolky et al. [14]. It uses a combination of analytical models and numerical techniques to calculate the related Q-factors of a set of lightpaths given a reference topology. Jiménez et al. [34] provide an example of a QoT estimator that may use experience to make quick and accurate judgments about whether a lightpath satisfies QoT requirements. Its foundation is case-based reasoning (CBR) [15], an artificial intelligence technique that returns the most comparable examples seen in the past and provides answers to new issues by either reusing or altering them.

4.7 Optical Amplifier

The strength of optical signals decreases with distance, usually between 60 and 80 kilometres. At this stage, the weak signals can be identified and retransmitted using a different pair of lasers, a process known as regeneration. Signal pulses are enhanced at the transmit side by an optical booster amplifier (OBA) and at the receiving end by an

optical pre-amplifier (OPA). Similarly, optical line amplifiers (OLA) are always positioned at various separations from the source to recover the signal before noise deteriorates it. Typically, optical transmissions lose strength over distances of 60 to 80 kilometres. At this point, a technique called regeneration can be used to locate the weak signals and retransmit them using a different pair of lasers [16]. An optical pre-amplifier (OPA) at the receiving end and an optical booster amplifier (OBA) at the transmitting side both improve signal pulses. Similarly, optical line amplifiers (OLA) are always placed at different distances from the source to recover the signal before it is weakened by noise.

4.8 Optical Transmitter

Light-emitting diodes (LEDs) and semiconductor lasers are the two main optical sources utilised in telecommunications. Lasers are utilised for long-distance and high data rate applications, while LEDs are utilised for short-distance and low data rate (<200 Mb/s) applications. These days, semiconductor lasers serve as high-power laser sources in a variety of devices, including CD players, printers, fax machines, and optical reading and recording devices, in addition to fibre optic communication. The majority of transmission system applications use current modulation to encode data into the laser output. However, external modulators are utilised to encrypt the data for certain high data rate applications that need long-distance transmission [17].

4.9 Optical Receiver

The signals sent over the fibre at various wavelengths must be recovered on the receiving end. since photodetectors are wideband devices by nature. Before arriving at the detector, the optical signals undergo demultiplexing [18]. There are two kinds of photodetectors that are commonly used. The Avalanche Photodiode (APD) and the Positive-Intrinsic-Negative (PIN) photodiode. The principles of PIN photodiodes are similar to those of LEDs, although they operate in reverse. In other words, photons are changed into electrons and light is absorbed rather than released. APDs work similarly to PIN photodiodes, but they use an amplification technique to provide gain. Numerous electrons are

released when a single photon strikes the apparatus [19]. While APDs offer greater receiver sensitivity and accuracy, PIN photodiodes have other benefits, including affordability and dependability. APDs cost more than PIN photodiodes, though. They are sensitive to temperature and can demand very high currents [20].

4.10 Transmission Length

The nonlinear effect and light interaction increase with the length of the fibre link. Fibre attenuation causes the optical beam's power to drop as it travels the link length [21]. The two main problems with optical transmission over long distances (often >100 km) are signal fading and attenuation. For instance, a transmission link over 100 km long on a fibre optic cable will suffer from noticeable drop-out, variable attenuation, and substantial packet loss.

V. ARTIFICIAL INTELLIGENCE IN OPTICAL COMMUNICATION SYSTEMS

Artificial intelligence (AI) systems and entities can mimic biological processes, with a focus on human cognitive processes, to carry out tasks similar to learning and decision-making. Applications of AI, such as prediction, speech recognition, and smart home appliances, are practically commonplace. Similar AI-based methods are already transforming our daily lives in ways that enhance different aspects of our lives. By automating tasks, enhancing network performance, and boosting reliability through applications including fault detection, traffic management, and signal processing, artificial intelligence (AI) improves optical communication systems. To forecast traffic, anticipate and prevent problems, and allocate resources effectively, artificial intelligence (AI) technologies, in particular, deep learning and machine learning to analyse network data. This results in decreased downtime and operational expenses. Important applications of AI include self-configuration and adaptive control of complex optical networks, improving data routing, and proactive network management. In Figure 6, the Recurrent neural networks (RNNs) are used in optical communication to process data sequentially. In recent developments, there are emerging areas of

application of AI in optical communication research and development, which include:

1. Attack and intrusion detection: The precise measurement or estimation of physical parameters forms the basis for many network control choices. We also anticipate that, in keeping with the developments discussed in Section 3, artificial intelligence will continue to be crucial in enabling cutting-edge transmission technologies such as space division multiplexing, multimode/multicore fibres, new modulation formats, and constellation shaping.
2. Automating network management tasks: The operation, administration, and maintenance of optical networks are complicated tasks due to heterogeneous (multi-technology and multi-vendor) network devices. This is because network state information, such as topology, congestion, failure discovery, etc., that is gathered from many devices has limited and varied state information, which makes data collection, processing, and decision-making extremely difficult.
3. Effective collaboration between networks and computing resources: New paradigms such as the Internet of Things [22] place strict demands on networks, including high bandwidth, availability, security, and low latency. This presents a big problem. High-speed, fault-tolerant fibre backhaul infrastructures and 5G mobile communications systems will be essential enabling technologies for these networks [22].

extracted features from the previous state as one of the current input information, and the current outputs rely on the current and previous inputs to give the neural network memory; (C) an RNN variant that can learn long-range temporal relationships among sequential data is the Long Short-Term Memory (LSTM) block diagram [22].

Furthermore, the growing bandwidth needs, network complexity, and customer expectations for quick response times have led network operators to consider integrating artificial intelligence (AI) into optical network automation in optical fibre communication. AI holds promise for increasing productivity, anticipating malfunctions and streamlining operations in optical networks. However, despite all the hype around AI, it is crucial to evaluate its practicality for real-world uses in optical communication by streamlining network lifecycle management.

CONCLUSION

In the communication industry, optical fibre holds a unique position because of its wide transmission frequency band, high anti-interference, and small signal attenuation. Optical fibre communication engineering is a type of "wired" optical communication mode that uses light waves as carriers and optical fibre as a transmission medium to transmit information from one place to another. In light of this, this paper first reviews the key network issues with optical fibre in communication technology from the perspective of communication engineering. It then briefly explains the significance of artificial intelligence (AI) in solving issues related to optical fibre communication.

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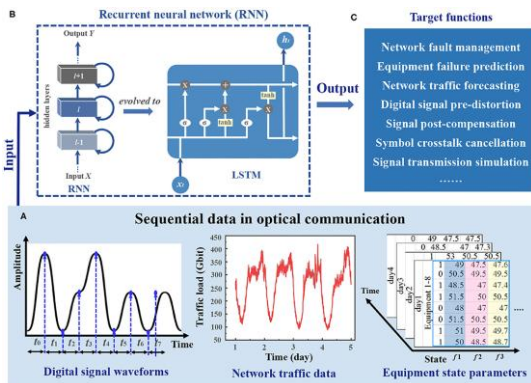


Figure 3. Application of a recurrent neural network (RNN) in optical communication for sequential data processing: (A) Sequential data in optical communication: digital signal waveforms, network traffic data, and equipment state operating parameters are summarised; (B) the RNN schematic views the

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