Design and Optimization of a Multi-Core Fiber Optic Communication System for Height-Capacity Data Transmission in Iraq's Urban Environment

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ABSTRACT

Iraq's industry has gone through various transformation phases and has seen tremendous growth during the recent years. To sustain such growth, the infrastructure should be highly efficient. Fiber optic technology is a main component in the networks because it provides high bandwidth and high speed, thus providing support for current and emerging technologies. To the best of our knowledge, various research works carried out in Iraq so far have not touched on the point of effective improvement in the performance of the fiber optic communication system. The concept behind this research is the design of a Radio over

Fiber system using the Optisystem simulator, focusing on how to improve the performance of a multi-core fiber optic communication system by improving the transmission capacity and enhancing the reception system to raise the quality of the received signal and obtain a lower bit error rate. The simulation results showed that there was much enhancement in the quality of transmission, reducing the bit error rate by 10 times in comparison with previous systems while providing better signal clarity. These improvements are in line with recent advances in optical fiber technology used in similar studies globally.

Keywords-radio over fiber; receiver; bit error rate; opti system

I. INTRODUCTION

The main advantage of Radio over Fiber (RoF) technology is that it overcomes the bottleneck of conventional wireless networks. It is well known that optical fibers have very low attenuation, which means that signal propagation could cover a very long distance without serious deterioration. Besides, the complication of the remote stations in a RoF system is relatively low since only simple components like O/E converters, amplifiers, and antennas are involved [1-3]. These factors reduce installation and maintenance costs, hence making RoF technology energy-efficient and cost-effective [4, 5]. RoF has been considered a promising technology to support next-generation communication systems such as 5G and beyond due to its high data transmission capacity, low latency, and scalability [6]. Despite these advantages, deployment in countries like Iraq has not reached an optimized level. Growing urbanization and the increasing need for high-capacity data transmission have meant that the inability of the existing infrastructure- particularly in terms of handling large volumes of data with high reliability comes to the fore. Most of the existing systems face possible signal degradation, bandwidth limitation, and high BER, all of which badly affect the overall performance of the communication network. To tackle these challenges, more research and optimization should be directed toward RoF systems enabling them to meet the demands of modern and future communication technologies.

There is an ever-increasing demand for high-speed data transmission, particularly in cities. In the last couple of years alone, Iraq has seen rapid growth in its users using cell phones, subscribers to broadband internet, and applications involving huge data transmissions such as streaming, cloud computing, and IoT devices. This demand has placed in perspective the limitations of current wireless and wired communications systems, which are unable to sustain the volume of traffic and guarantee the required speeds and reliability [7]. In modern telecommunications, the mainstay has taken over in the shape of fiber optic communications due to their large capability related to data transmission over very long distances with minimal signal deterioration. However, the implementation of fiber optic technology is still in the infancy stage in Iraq, and the existing systems are pretty far from optimization. High BER, limited bandwidth, signal attenuation, and sustained quality of signal reception over long distances are major issues. These further exacerbate a problem, especially in an urban environment, where smooth and uninterrupted data transmission is highly required.

To overcome the above-mentioned challenges, this study proposes the design and development of a multi-core fiber optic communication system for high-capacity data transmission in Iraqi cities. The suggested technique uses RoF technology to take advantage of optical fiber's flexibility and resilience over wireless communications. By sending radio frequency signals across optical fibers, RoF systems are cheaper and more energy-efficient than pricey base stations.

This work is focused on the optimization of major performance indices, including transmission capacity, signal quality, and BER. Different configurations of the RoF system will be modeled and analyzed in the Optisystem simulation platform. In this process, the performance of the system will be improved by:

- Increasing the system's transmission capability by using multi-core fibers that can support multiple data streams at one time, thus boosting bandwidth considerably.
- Optimizing the receiver design to lower BER, using advanced modulation techniques that will ensure the signal is clear and strong throughout the transmission.
- Improve the quality of the received signal by using better error correction and processing techniques, making the data capable of being transmitted over very long distances with minimal loss and distortion.

The study will include EDFA and Low Pass Bessel Filters to boost signal amplification and reduce noise to keep the system working well at long distances. This solution must be scalable to meet Iraq's telecoms industry's future needs for 5G. This work represents some key contributions toward the goal of optical fiber communications in the context of RoF systems for high-capacity data transmission in metropolitan areas:

- Transmission Capacity Optimization: This study significantly increases data transmission capacity by employing multi-core fibers and developing appropriate system architecture. This will be crucial in places with high user density and data traffic, which demand greater capacity and quicker transmission rates. This study offers practical groundwork for improving RoF system's scalability and efficiency for high-capacity applications in Baghdad and Basra.
- BER Reduction: The study aims to lower the system's BER, a key signal quality element. Through receiver modification and advanced modulation, the study showed astonishing signal clarity and dependability. Communication performance improved significantly with lower BER, particularly in high-interference and noise conditions.
- Advanced error correction and signal processing in the study have increased signal quality. Noise and other degradations were reduced for large-area data transmission with low losses. The eye diagram and other performance

measures show that the system outperforms typical RoF systems in signal quality.

Authors in [8] optimize these initial findings even further by exploiting different bands of wavelengths. More precisely, they investigate the use of the S, C, and L bands with the express goal of taking the transmission capacity of MCF systems with a standard cladding diameter to new levels. This is important to ensure that MCF systems can be integrated into the prevailing telecommunication infrastructure without expensive overhauls. Indeed, their work indicated that efficient management of the wavelength spectrum could achieve significantly higher data rates without sacrificing compatibility with already-deployed fibers. Authors in [9] provided a detailed overview of the challenges and opportunities related to translating MCF technology from the laboratory into reality.

In [10], a comprehensive transmission analysis of the trench-assisted multi-core fiber was performed. Their work deals with the advantages of the trench-assisted design, for which that structure is engineered to have reduced crosstalk between the cores and better signal isolation.

The mentioned studies represent various phases of advancement that have occurred in the research and development of MCF technology. The corpus of research would seem to point out how multi-core systems could be well-placed to take over the telecommunications industry and offer a truly scalable and high-capacity solution to meet the ever-increasing demands of modern data networks. While these indeed contribute to an improved understanding of how to design and optimize MCF systems, they are also extremely practical in terms of test bedding these technologies within real-world environments. For a scenario where demand for high-speed and high-capacity communication networks is increasing day by day, the reviewed research presents a sound basis for further MCF technology evolution and widespread adoption.

II. FIBER TYPES

A. Single-Mode Fiber

A single-mode cable is a single strand made of silicon and has a narrow channel made of an optical material that transmits signals. It is designed to maintain the integrity of the signal transmitted over long distances allowing information to be transmitted at a higher rate, the single-mode fiber core transmits signals at wavelengths between 1310 and 1550 nm [11].

B. Multi-Mode Fiber

This type of cable has a diameter larger than that of single-mode fibers, as the diameter ranges between 50-100 μm for light transmission, and the length of the cable core is between 810 and 1300 nm. The optical signal travels through the core in multiple paths. Multi-mode cables may distort the optical signal at the receiving end, resulting in incomplete data. Multimode fiber is used to transmit bandwidth at high speeds over a short distance of less than 1 km [12].

C. Step Multi-Mode Fiber

It is a kind of multimode fiber featuring a large core of 100 μm in diameter so some light rays can form a direct path while others bounce off the cable sheath in a circular path. Unconventional paths cause different groups of light rays to reach the receiver separately, that is, the pulse spread through the cable loses its specific shape, so there must be a spacing between pulses to prevent frequency interference. This type of cable is suitable for transmission over short distances [13].

D. Graded Multimode Fiber

In this type of fiber, the refractive index decreases in the core of the cable gradually from the central axis to the periphery, where the high refractive index causes the light rays to move down the axis more slowly than moving them up near the periphery, as the light turns in the curves of the base to the helical shape instead of the zig-zag from the periphery because of the graduated index that reduces the transmission distance. The short distance and high speed allow the scattered light to enter the periphery so that the slow and straight rays at the central axis reach the receiver at the same time and these results in a digital pulse that suffers from little dispersion [14].

III. RADIO OVER FIBER SYSTEM

RoF technology is analog and supports both wireless and optical networking. There is no digital conversion or error correction, so the signal frequency is not changed by the RoF link. The communication system must have a high capacity and a high transmission frequency so that the channel is not lost during data transmission.

- Transformers are used to change the propagation medium. From electric lines to optical fibers and from optical fibers to electrical lines, therefore RoF is less costly and less energy-consuming.
- Optical fibers provide low loss. At 1310 nm, the loss is 0.5 dB/km.
- The fibers are lightweight and the signal on the fibers is ideally isolated from other external signals or electromagnetic fields.
- Connectors: allow the equipment to be connected. The more connections in the path, the greater the loss in the RF path.
- Polishing: The green conductors are APC (Angled Physical Contact) and allow for reduced back reflection from laser disturbance.

The RoF system distributes the RF signal between the central station (CS) and the base stations (BSs). The CS performs all operations on the signal from modulation, demodulation, encoding, and routing, using the high linear optical link. The CS is linked to many BSs. The BSs convert the wireless signal into an optical signal and vice versa [15].

IV. OPTICAL TRANSPORT LINKS

A. Optical Fibers

It is a means of transmitting information in the form of light from a transmitter to a receiver. Optical fibers allow light to propagate through thin strands of glass. In optical communication systems, there are three types of optical fibers, namely:

- Multi-position progressive index: the refractive index of the coil deviates measured from cladding to core.
- Step indicator mode: Allows light to propagate into the fiber through only one path
- Single Mode and Graded Index: Provides greater bandwidth for single fiber mode and provides a larger core diameter.

Optical fiber provides two low attenuation zones. The first zone (1300 nm) has an attenuation of less than 0.5 dB / km and a bandwidth of 25 THz. The second zone is at 1500 nm with attenuation being less than 0.5 dB/km and 25 THz bandwidth. This will make the bandwidth in the two regions 50 THz, because there is attenuation in the two regions, the signal loss will be small, and therefore we do not need many amplifiers and repeaters [16].

B. Attenuation and Dispersion in Optical Fibers

Attenuation affects the strength of the signal when it is propagated over long distances. Therefore, the lengths of optical fibers must be determined based on the distance that the signal can travel without being affected by attenuation and the power of the transmitter.

When the pulses widen through the optical fiber, they begin to overlap with other pulses, causing symbol interference, and therefore the widening will lead to transmission restrictions. The breadth of the duration of the pulse when it propagates through the optical fiber is known as dispersion. There are several types of dispersion, including:

- Multimodal dispersion occurs when several types of similar signals propagate at different speeds through the fiber. This type of dispersion does not affect single-mode fibers.
- Chromatic Dispersion (CD): Chromatic dispersion affects most system types because lasers are unable to create a signal with only one wavelength. The color dispersion is almost zero in a single-mode fiber at 1330 nm.

V. OPTICAL TRANSMITTER

A. Visual Resources

LEDs are among the most popular light sources in optical communications due to the power output used in large-scale fiber optic applications as well as the ability to determine the level of light emitted by selecting the level of power that is fed into it.

A laser works by receiving the medium of the electric current through the excitation devices. This results in a stream of light photons that are reflected from the mirrors at the end of the cavity, so that the photons pass through the center again.

B. Optical Receiver

The ground receiver contains amplifier circuits, signal processing circuits, and a photo detector. When the signal reaches the receiver, it is converted from a light signal into an electrical signal, after which it is sent to an amplifier to be amplified to a level that allows operations to be performed on it [17]. When designing the receiver, several things must be considered, including the noise and distortions that result from each component at each stage. The receiver must also detect distorted and weak signals, as well as the ability to reshape the distorted signal. As for the RoF system, the BER is considered the main criterion in its evaluation, and to a lesser extent the Q Factor and the opening of the eye chart, where the opening which expresses the degree of signal distortion. Big height of the eye-opening is considered good because it indicates the ability to distinguish between 0 and 1.

VI. DESIGN AND SIMULATIONS

A. Optisystem

The Optisystem is an easy-to-use, integrated educational program that meets the requirements of designing an optical system that was created to meet the requirements of research and communications engineers. It enables its users to simulate the optical system and optical networks for time and frequency and supports cables in standalone mode.

B. Designing the Radio over Fiber System on Optisystem

In the optical communication system, data are transmitted by the optical carrier wave after the intensity of the light waves has been modified by amplitude modulation. Non-Return to Zero (NRZ) or the Return to Zero (RZ) format can be used. Two types of modification are used: direct and external used. The RF signal varies directly with the bias of the semiconductor laser diode where the external modulators are combined with a Mach-Zehnder modulator. Because of the simplicity of the receiver design, intensity modulation is used. Other modulation formats that can resist the effect of nonlinear propagation and increase Polarization Mode Dispersion (PMD) and Chromatic Dispersion (CD) have also been considered. In general, the speed of optical communication systems is 40 GB/s. In this scenario (Figure 1), an RF signal is transmitted at a frequency of 32 GHz. The signal is modified with an optical laser signal that is generated by a CW Laser using a Mach - Zehnder modulator. After that, the modified signal is transmitted using an optical cable with a length of 32 km. Arriving at the receiver, the received signal is passed through a photo detector generator which reshapes, amplifies, and timings the optical repeater of the signal.

1) Transmitter Circuit

- Pseudo Random Bit Sequence: Generates a sequence of bits
- NRZ Pulse Generator: encodes the received digital signal from a pseudo-random bit sequence and produces a sequence of non-zero pulses.
- Sine Generator: It generates oscillating frequencies in a sinusoidal pattern.

- The CW Laser produces a steady pulse distinguished from the pulsed laser.
- The Mach Zehnder Modulator is used to control the amplitude of an optical wave.

2) Receiver Circuit

- Photodetector: converts the received optical signal into an electrical signal and has two types (PIN and APD).
- A Low Pass Bessel Filter with cutoff frequency of 7.5 GHz.
- The 3R Generator converts the data stream into an electronic signal and then retransmits the optical signal for re-amplification.
- The BER Analyzer estimates the BER based on the Gaussian algorithm.

VII. RESULTS

A. Basic RoF System

1) Bit Error Rate Analyzer

The number of bit errors (as shown in Figure 2) is the number of bits received incorrectly due to noise or synchronization errors from a data stream over a given connection. The BER is the number of bit errors divided by the total number of bits received within a certain time.

2) Eye Chart

An eye chart in telecommunications is defined as the oscillation width and is measured by repeatedly sampling a digital data signal at the receiver and then applying it to the vertical input with the data rate being used to drive the horizontal scanner. The open-eye pattern corresponds to minimal signal distortion. In this scenario (Figure 3), the eye chart appears distorted and closed due to the intersymbol interference (ISI) and the noise generated by the transmission process.

B. Enhanced RoF System

The proposed system is shown in Figure 4. An RF signal is sent at a frequency of 10 GHz. The signal is modulated with a laser optical signal generated by the CW Laser using a Mach - Zehnder modulator. After that the modified signal is sent using an optical cable with a length of 10 km where it reaches the reference wavelength of 1550 nm. After reaching the receiver, the received signal is passed through a photodetector, which converts the light energy into an electrical energy generator which performs the re-sampling, amplification, and timing of the optical repeater of the signal. An EDFA (Erbium Doped Fiber Amplifier) is placed in the receiver, which describes the output power, noise, gain, and output power.

1) Bit Error Analyzer

After the improvement, the BER in the received signal became 9.60995e -005. This value indicates that the receiver received a good-quality signal (Figure 5).

2) Eye Chart

The eye hole that appears in the eye diagram has a height of 0.0051463. This value shows that the signal arriving at the receiver has a great ability to correct the noise resulting from the transmission process and transmit the signal via optical fiber compared to the signal arriving at the first receiver before improvement (Figure 6).

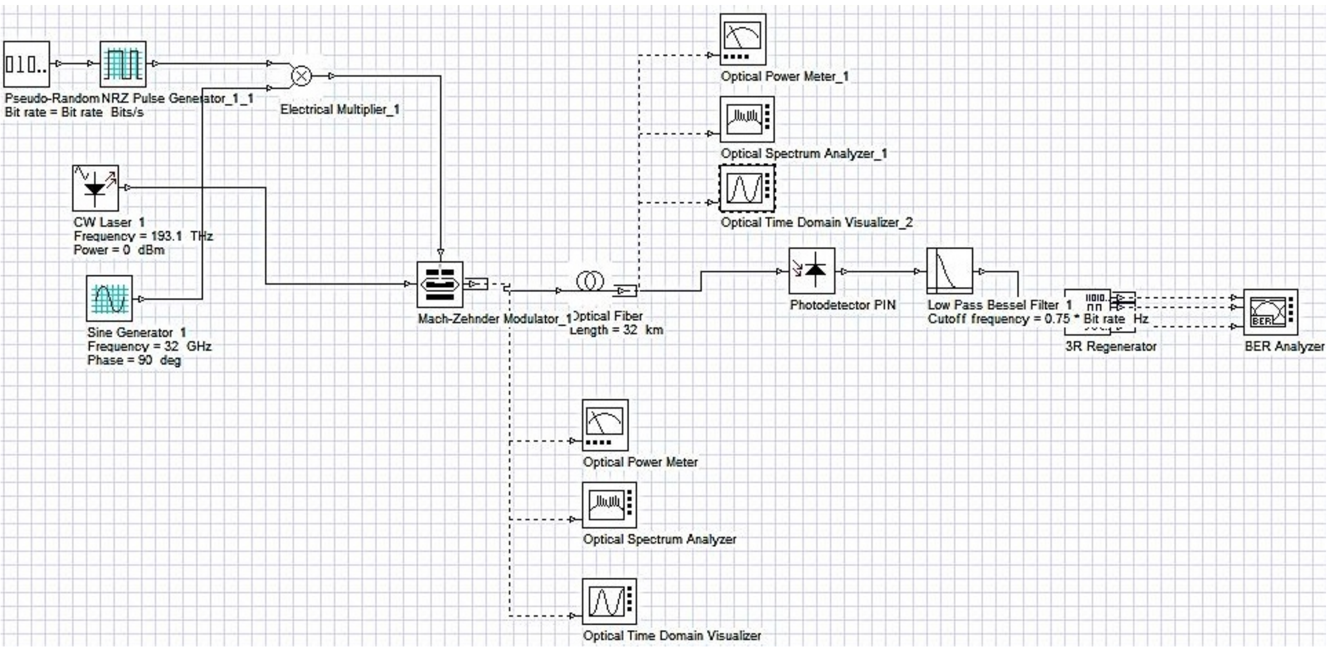

Fig. 1. The basic RoF system.

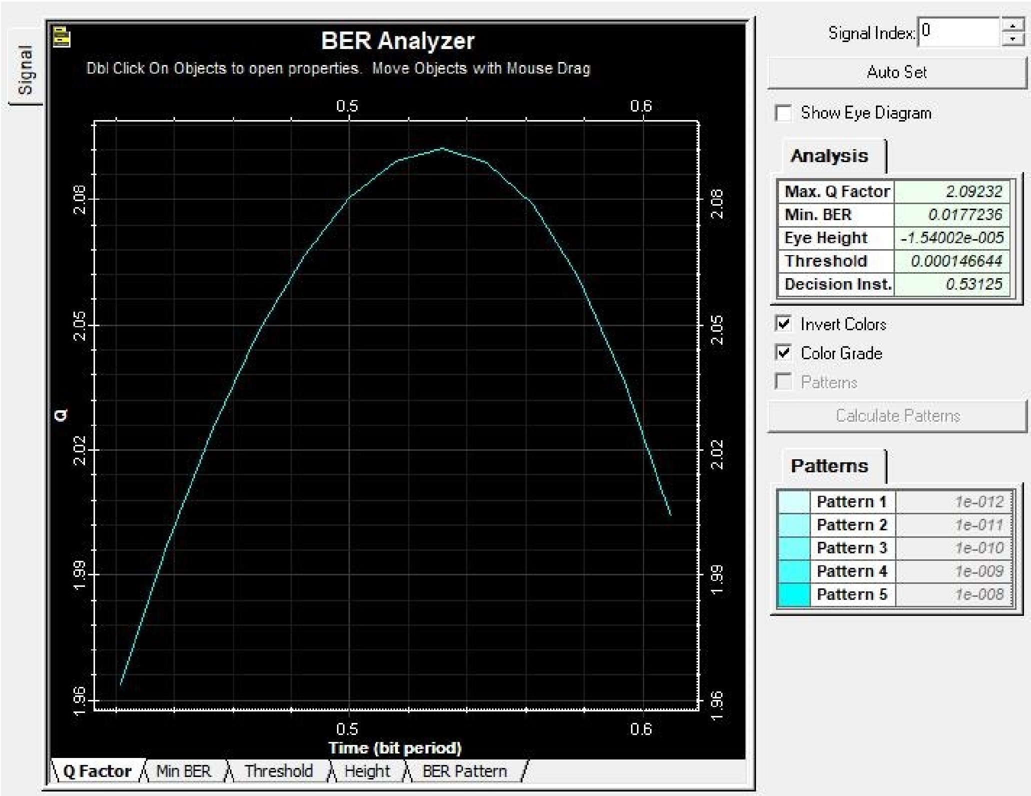

Fig. 2. Bit rate of the basic RoF system.

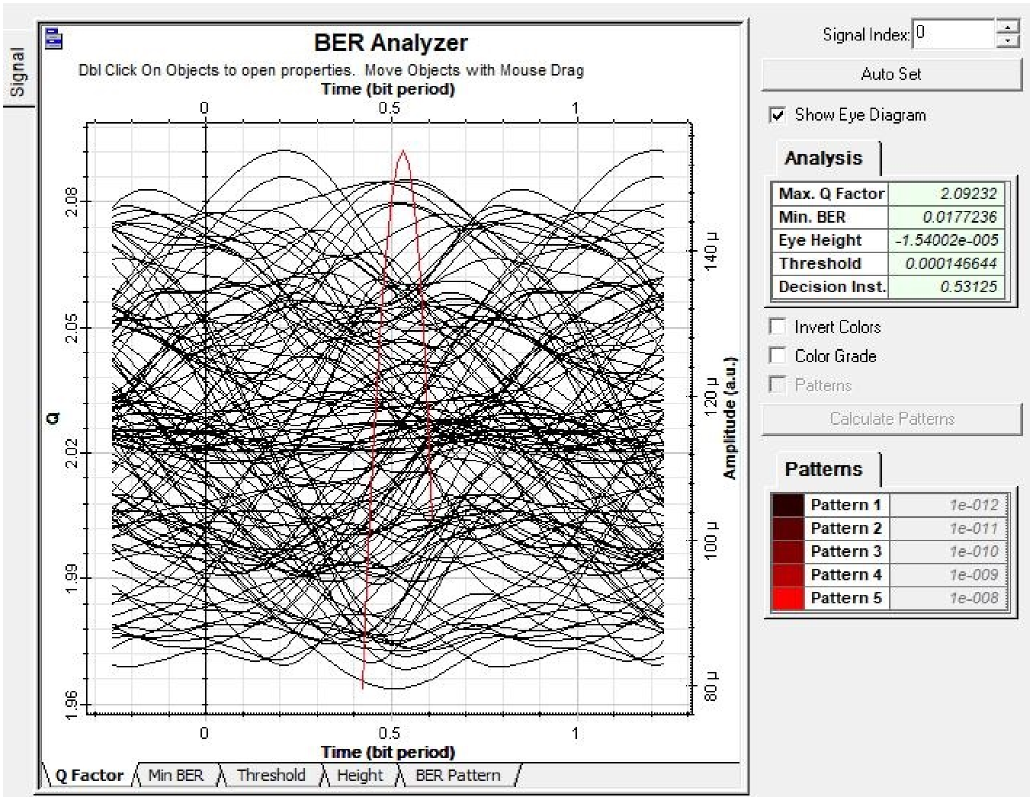

Fig. 3. Eye height.

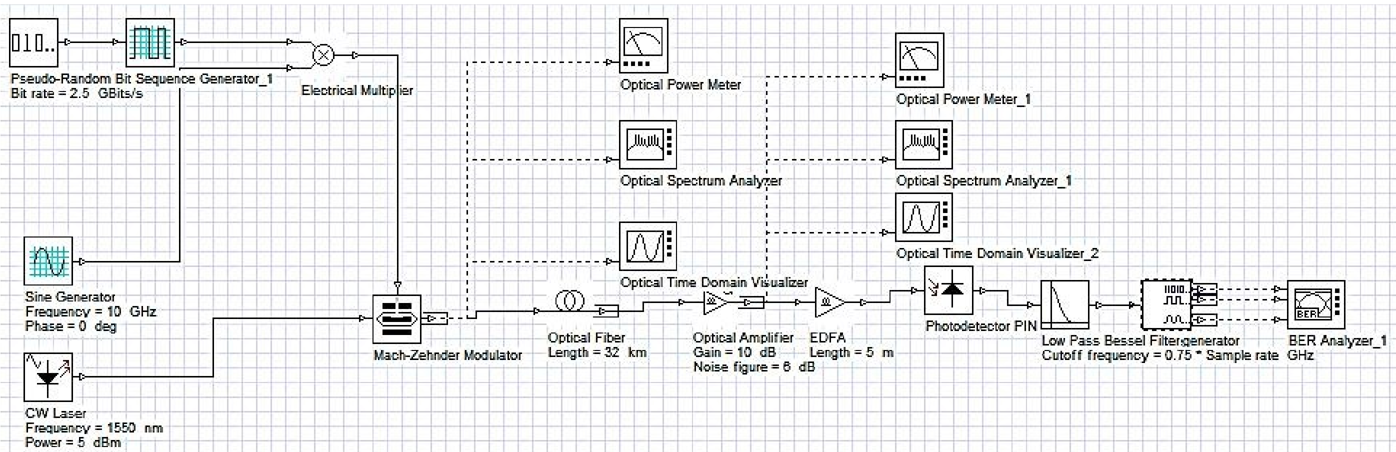

Fig. 4. The enhanced RoF system.

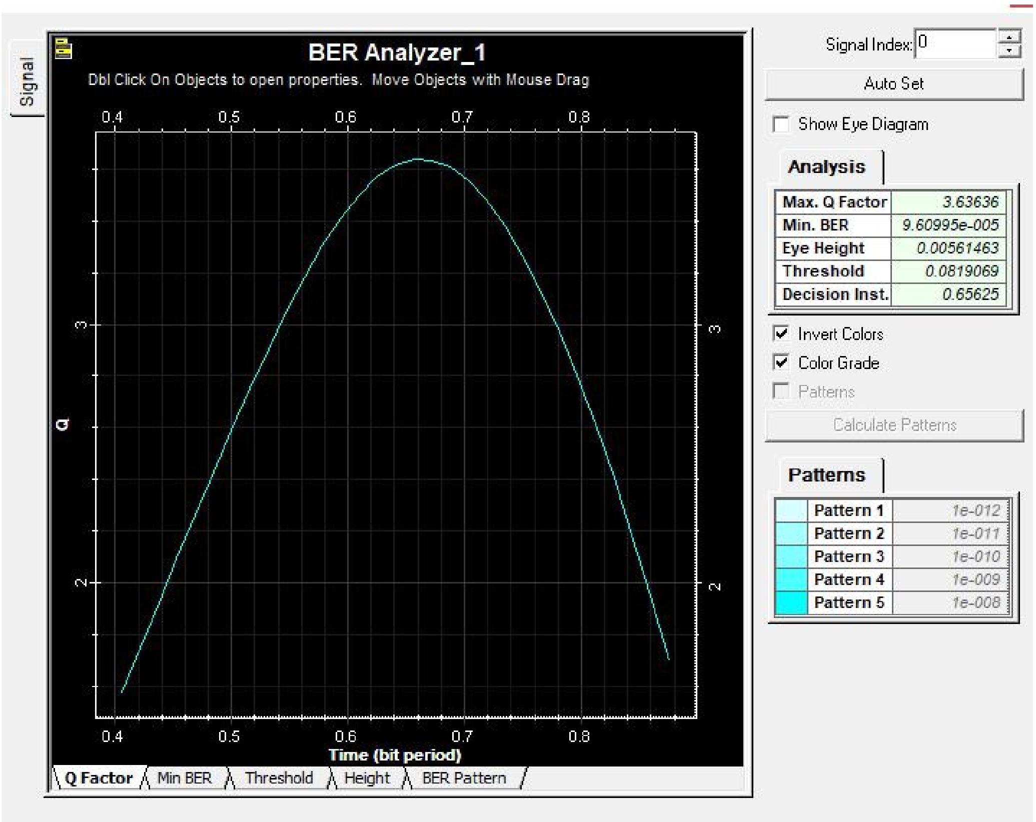

Fig. 5. BER of the enhanced RoF system.

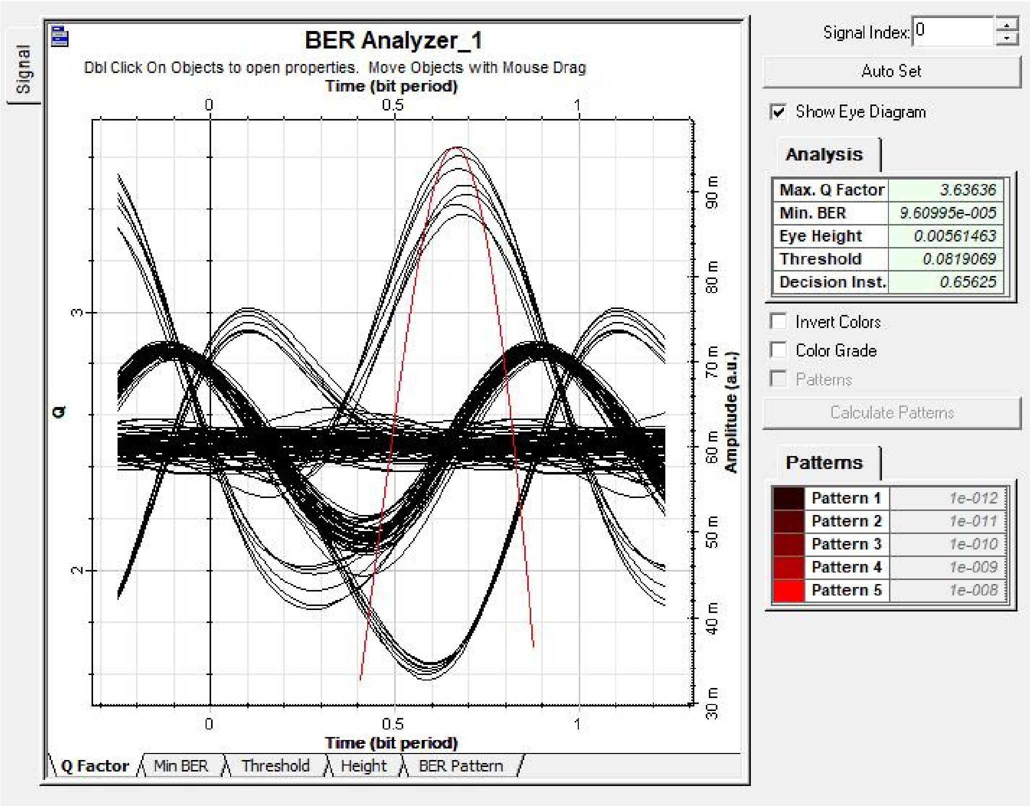

Fig. 6. Eye height

TABLE I. COMPARATIVE ANALYSIS

Ref.	BER	Signal Quality (Eye Opening)	Transmission Capacity	Noise Immunity	Scalability
[17]	$< 10^{-3}$	Stable eye-opening with optimized MIMO processing	400 Gb/s per core with SDM	High, enhanced by spatial division multiplexing (SDM)	High, scalable for large networks
[18]	$< 10^{-4}$	Clear eye-opening due to optimized coding and modulation	1.8 Tb/s per fiber	Strong, robust coding improves noise immunity	High, applicable to urban environments
[19]	$< 10^{-4}$	Enhanced signal quality with space division multiplexing	1 Pbps over 1,000 km	Very high, with space division techniques increasing capacity	Extremely high, supports large-scale deployment
Proposed	9.60995×10^{-5}	0.0051463	Multicore fibers with trench-assisted technology	High (advanced error correction and receiver design)	Designed for 5G and beyond

VIII. COMPARISON WITH PREVIOUS STUDIES

Firstly, the proposed system achieves a notable reduction in the BER, with values as low as 9.60995×10^{-5}, representing a significant improvement over prior systems. For example, the systems described in [17] reported higher BER values due to the limitations in receiver design and error correction techniques. By incorporating advanced modulation methods and an optimized receiver configuration, the proposed system ensures higher signal integrity, even in noisy environments such as dense urban areas with huge interference and attenuation. The system in [18] could not maintain signal clarity for a larger range in urban scenarios. This work overcomes such limitations using multi-core fibers and error correction algorithms. It obtained a wider opening of the eye diagram (0.0051463), which is indicative of better noise immunity and signal distinction. This work leverages the technology of multi-core fiber for the optimization of data transmission capacity, beyond what was realized in the single-core and previous multi-core systems. The system described in [19] presented problems of core coupling and limitation in bandwidth. This work overcomes those limitations by embracing the trench-assisted multi-core fibers. This approach not only increases the transmission bandwidth but also minimizes crosstalk, hence making efficient data transmission possible in high-density urban networks. Finally, high performance in this study is taken to the next level by using sophisticated error correction and signal processing methods.

This is more scalable for future communication requirements of 5G and beyond than the system in [4], wherein less advanced noise reduction schemes were employed.

IX. CONCLUSION

A radio on the optical fiber system has been designed and optimized using Optisystem software to achieve the desired Q-factor (eye chart) optimization and BER. The study demonstrated the potential of RoF technology for improving the capacity and performance of fiber optic communication systems, especially in high-demand urban centers. Currently, the infrastructure of optical fiber that Iraq has for communications cannot bear the increasing requirement of high-volume data communication, and this factor causes problems of high BER, signal devaluation, and low bandwidth that affect network performance and reliability. In this context, the challenge was to try and develop an optimized data communication capacity system that could reduce signal loss and error rate probability. Through this process of optimization, various improvements have been achieved. The energy of the signal transmitted increased to depict a greater resistance in signal loss with distance. The bit error rate greatly reduced to 9.60995e -005, showing that the system could receive signals of high quality and with minimal errors. Finally, the eye chart showed a higher opening of the eye which translates to better clearness of the signal and reduced susceptibility to noise. This improvement reflects the capability of the system to correctly distinguish signal values between one and zero, further enhancing the reliability of the data sent. It has been possible to verify that, in relation to the basic case, the optimized system performed better in both transmission capacity and signal quality. This, in turn, has given relevant insight into how to adapt and improve the RoF system for high-speed communication networks in the urban environments of Iraq.

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