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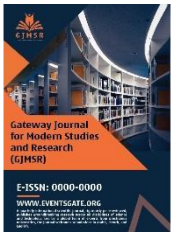

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Performance Evaluation of an IoT-Based Smart Transportation System Using Optical Fiber Communication

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Abstract: Smart transport systems have been adopting several IoT devices to collect and transmit traffic data, including vehicle counts, traffic density, and road conditions, and to monitor traffic. Nevertheless, the reliability of data transmission is a serious problem, and it becomes especially important to minimize signal degradation and reduce bit errors when transmitting data over long distances. Therefore, it is vital to examine the performance of an IoT-based intelligent transport system connected via fiber optics to ensure successful implementation. To do so, a mathematical modeling technique was applied to simulate the behavior of a fiber-optic link. Specifically, this study proposes developing a numerical simulation model to assess the performance of the intelligent transport system under varying distances and data transfer rates. Fiber lengths ranging from 10 to 80 kilometers and data transfer rates from 1 to 10 Gbps were considered. Performance criteria, such as received optical power, quality factor, bit error rate, pulse amplitude, and signal quality, were analyzed.

Keywords: Internet of Things, Intelligent Transportation, Fiber Optic Connectivity, Bit Error Rate, Quality Factor, Numerical Simulation.

Introduction

In recent years, there has been considerable progress in intelligent transportation systems, owing to the increased deployment of communication technologies, information technology, sensors, surveillance systems, and IoT-based technologies for traffic management and improved transportation efficiency. The concept of intelligent transportation centers on collecting sensor data, analyzing it, and sharing the results to improve traffic flow, reduce congestion, enhance safety, and enable real-time decision-making. IoT-based technologies have become increasingly critical in this context because they enable a wide range of connectivity options for sensors that can monitor vehicle traffic, traffic density, road conditions, and other environmental data relevant to the transport system. Recent research suggests that intelligent transportation systems enhance traffic flow and safety and reduce journey time and fuel consumption. At the same time, the increasing reliance on IoT infrastructure is necessary to realize these benefits. (Oladimeji et al.) Al., 2023; Mahmood et. Al., 2024; Mahmood, 2025)

The amount of data from Internet of Things devices in traffic systems is getting bigger. So we need ways to send this data that're fast, reliable, and stable. Things like monitoring, signal management, and accident detection need to be connected at all times with minimal delays or errors. This means the way we send the data is just as important as how good the sensors are. If the data does not come through properly, if there are many errors, or if the signal is weak, it can cause problems, and the system will not work well. Internet of Things applications still face many problems with scalability, reliability, and consistent connectivity across diverse scenarios. Internet of Things applications, such as traffic systems, need reliable communication channels to work properly. (Choudhary & Jain, 2024)

Although wireless technology is widely deployed in IoT, using these networks in an ITS system may encounter barriers, especially with numerous nodes or in situations requiring long-distance, high-rate data transfer. These main barriers include interference, changes in signal quality, network congestion, and sometimes unreliability. Hence, there has been a need to find better, more reliable forms of communication, especially those that require reliability and fast responses.

Given the above scenario, the use of optical fibers as a communication medium will be one of the best ways to enhance the performance of IoT-based intelligent transportation systems. Optical fibers offer high capacity, minimal signal loss, and the ability to carry signals over long distances. The other benefit is that they are immune to electromagnetic interference, unlike the traditional methods. The optical fiber is therefore recommended in cases where a larger capacity is required, long-distance communication, or when electromagnetic interference should be prevented. Other sources specializing in optical communications indicate that minimal signal attenuation and a stable light source are key factors in the efficiency of optical communication. (ITU, 2009)

In this respect, the use of IoT with fiber connectivity could provide a suitable connectivity infrastructure for intelligent transport systems, particularly in situations where high-speed, constant transmission of traffic information is required. Nevertheless, the effectiveness of such a combination cannot be assumed without conducting performance measurements of critical parameters, including received optical power, quality factor, and bit error rate, as well as the effects of fiber length and data transfer rate on signal quality.

The performance of the Internet of Things-based Intelligent Transport System with fiber connections should be tested to demonstrate how transmission distance and data transmission rate affect connection performance. Although optical fibers have many benefits compared with other media, increasing transmission distance and data transmission rate can negatively affect transmission due to signal distortion and increased bit error rate; therefore, there should be a systematic analysis of performance indicators to determine their value. Hence, this research will assess the performance of an intelligent IoT-based fiber-optic transmission system. (Mahmood, 2024)

Related Studies

The current literature has also considered smart transportation systems an essential element of smart cities, owing to their use of communication technology, sensors, data analysis, and vehicle-infrastructure integration to make traffic management more efficient, safe, and sustainable. (Elassy et al., 2024) have highlighted that smart transportation systems encompass various applications, such as composite networks, smart traffic signals, traffic forecasting, and connectivity applications that enhance the performance of smart sustainable cities and Transportation Management. The concept is built on the idea that the effectiveness of intelligent transportation systems depends not only on data gathering but also on a communication framework that facilitates reliable, fast data analysis.

Likewise, Zeng et al. (2024) found that IoT plays a crucial role in building smart cities by enabling devices and sensors to capture, generate, process, and transmit information for various applications, such as transportation. In their systematic review, the authors identified IoT applications for smart cities in transportation, disaster management, security and privacy, and new applications. They explained the communication technologies and protocols used to transmit sensor data. It is further justified by the significance of researching suitable communication technology for IoT-based smart transport systems, especially where traffic data is continuous and highly reliable.

The author Avcı (Avcı et al., 2024) further discussed the technological aspects of the intelligent transportation system, including its architecture, applications, communication technologies, and emerging trends. According to this discussion, the Internet of Things enables connectivity among physical objects through sensors, actuators, and devices that capture and transmit data over a network. This observation will help establish that the proposed research topic has a basis, as the suggested intelligent transportation system uses IoT technology to collect data.

From the perspective of communication infrastructure, ITU sources highlight the importance of fiber optics in modern telecommunication systems for its ability to transmit information efficiently over long distances and its low attenuation compared with other communication media. The ITU Guide on Fibers, Cables and Optical Systems states that the properties of fiber optics make it possible to use in telecommunications where high-capacity, stable signal transmission is required (International Telecommunication Union, 2009). Therefore, fiber-optic technology is appropriate for ITSs when rapid, stable information transfer between IoT nodes is required.

In evaluating the performance of optical communication technology, many researchers have used parameters such as the Q-factor, bit error rate, received power, and the effect of distance on the signal. According to Burdah et al. (2019), Q-factor and BER analyses are key parameters for assessing the performance of optical communication technology, whether implemented over single-mode fiber or in free-space optical communication.

Recent research on optical communication technologies has further revealed that the BER and Q-Factor are common indicators for measuring the quality of signal transmission and for assessing the influence of physical parameters such as attenuation, noise, dispersion, and distance on the system's efficiency. In this regard, Meneżla et al. (2025) note that reducing errors in fiber-optic systems is a serious problem that can be addressed by assessing system quality using BER criteria. Indeed, it reflects the modern methodology of the research in question.

From the above, it is evident that previous literature reviews have examined the role of IoT in smart transportation. Also, some studies have addressed the attributes of optical fiber and the performance parameters of optical communication systems. The integration of a smart transportation system using IoT, with performance analysis across different transmission distances and data rates, has not been addressed clearly through quantitative analysis. Therefore, the current literature review aims at evaluating the performance of the developed IoT-based smart transportation system using indicators such as the quality coefficient, bit error rate, and pulse amplitude.

Methodology

The proposed research involves developing an IoT-enabled Intelligent Transport System model, in which fiber-optic communication is an essential component for transmitting data among different parts of the system. This study seeks to develop an intelligent transport system model in which data collected by IoT sensors and devices placed on roads, in cars, and at traffic facilities can be transmitted via a fiber-optic channel to the receiving end or the processor node for assessing transmission capabilities and efficiency.

The system's architecture is based on four primary modules: the data-collection module, the transmission module, the fiber-optic connection, and the receiving and analysis module. In the data collection module, IoT data refers to traffic data and can be collected by speed detectors, traffic density detectors, cameras, vehicle trackers, and road condition monitors. The data is translated into a digital chain of data for communication.

The transmission of digital data occurs within the transmission layer, where digital data is converted into electrical signals that, through a virtual optical transmitter, are converted into light signals. Transmission in the model uses a simple technique known as On-Off Keying (OOK), where a value of 1 indicates the presence of light signals, whereas a value of 0 indicates their absence or reduction. This type of transmission model works perfectly in prototypes as it facilitates the examination of the impact of distance and noise on signal quality.

The optical signal is then sent through a single-mode optical fiber link. The optical fiber was used owing to its ability to transmit data over longer distances and at higher rates with minimal attenuation. Performance evaluation of the system in this case has been conducted at link lengths of 10, 20, 40, 60, and 80 kilometers to assess how these lengths affect the received optical power, quality factor, and bit error rate. The system's performance has also been assessed at data rates of 1, 2.5, 5, and 10 Gbps.

The received signal is converted into an electrical form by a virtual photoreceiver on the receiver side. Then the received signal is compared to the original signal to measure the KPIs. These KPIs include received optical power, Q-factor (quality factor), BER (bit error rate), and pulse amplitude affected by scattering. All these KPIs help determine the performance of the proposed scheme for transmitting IoT data in the intelligent transport environment.

The proposed model provides a way to analyze connectivity performance by quantifying correlations among transmission distances, throughputs, and signal quality. Such a model will help identify situations that require fiber-optic connectivity for IoT-based intelligent transport systems, given the continuous need to transmit real-time traffic data.

The study employed a simulation-based approach to evaluate the performance of an IoT-enabled, fiber-optic-based intelligent transport system. The simulation method involved designing a model to capture the scenario in which data is sent via the Internet of Things over fiber-optic cables. The analysis examined the effects of fiber-optic length and data transfer rate on system performance. The simulation method enables understanding of the system's performance without actually building it.

During the initial stage, a random binary data string in the form of IoT data extracted from the smart transport system, like data related to traffic, vehicular movement, density of traffic, and surveillance data, was created. It was used to represent the data to be communicated through the optical communication link. The binary data were converted into an OOK/NRZ signaling pattern, where 1 denotes the presence of a light signal, and 0 denotes its absence.

Once the transmitted signal was generated, it was fed into a single-mode fiber-optic channel model. Attenuation due to fiber length was accounted for. Thus, an attenuation coefficient of 0.2 dB/km, commonly used in the modeling of single-mode optical fibers, was also included in the model. Losses due to conductors and link losses were considered to make the model more realistic. The amount of optical power received at the output end of the fiber-optic link, based on the total loss from both attenuation and link loss, was computed.

The other factor considered during the simulation was the influence of chromatic scattering on the light beam signal; the pulse amplitude resulting from this phenomenon was calculated using a scattering coefficient of 16.75 ps/nm/km. The spectral width of the laser beam source was taken to be 0.1 nm. The use of this effect helped estimate signal degradation as the fiber optic cable length and data transfer speed increased.

In the received process, random noise was superimposed on the received signal to simulate the influence of noise on the photoreceiver. Subsequently, a comparison of the original and received signals was performed using a numeric decision threshold to determine whether the received signal corresponded to 0 or 1. Through a comparison of received bits against the original bits, the BER (bit error rate) was calculated by the Monte-Carlo approach. The Q-factor was also estimated as the indicator of a clear distinction between the 0 and 1 levels.

The simulation was carried out at transmission distances of 10, 20, 40, 60, and 80 kilometers, as well as at data transfer speeds of 1, 2.5, 5, and 10 Gbps. For each parameter, the received light power, pulse amplitude, dispersion ratio, quality factor, and bit error rate were determined. The results obtained during the simulation were used to create tables and graphs. Table 1 shows the Parameters and the Values for the proposed system.

Table 1: The Parameters and the Values for the proposed system.

Parameter	Value
Modulation type	OOK/NRZ
Fiber Type	Single-mode optical fiber
Optical Power Transmitted	0 dBm
Attenuation coefficient	0.2 dB/km
Conductor losses	1.0 dB
Link losses	0.5 dB
Tested fiber lengths	km80 ،60 ،40 ،20 ،10
Data transfer rates	Gbps10 ،5 ،2.5 ،1

Dispersion coefficient	16.75 ps/nm/km
Laser Source Spectral Width	0.1 nm
Number of bits used in the simulation	200,000 bit

Results and discussion

In this section, findings from several numerical simulation studies are presented to assess the performance of an IoT-enabled smart transport system using optical fibers. Performance analysis has been carried out for transmission distances of 10km, 20km, 40km, 60km, and 80km, and data transmission speeds of 1 Gbps, 2.5 Gbps, 5 Gbps, and 10 Gbps. Some critical performance parameters that have been considered include the following:

Received Optical Power

Figure 1 displays the graph of distance and optical power obtained in the developed communication system. There is an inverse relationship between the two variables, with optical power decreasing gradually as distance from the fiber increases. For instance, the received power was -3.5 dBm at 10 km, then -5.5 dBm at 20 km, followed by -9.5 dBm and -13.5 dBm at 40 km and 60 km, respectively, and finally -17.5 dBm at 80 km. This reduction can be attributed to the cumulative effects of optical fiber attenuation and connector losses within the simulation setup. It is worth noting that the reduction in received power follows a near-linear trend with increasing distance, as expected from the physical phenomena in optical fibers that cause signal loss over distance.

This implies that as the length of the connection increases, the strength of the signal reaching the receiver decreases, thereby affecting the quality of digital signal detection, especially in systems operating at high data transfer rates. The lower the power level, the greater the likelihood of noise and signal dispersion, resulting in a low quality factor and a high bit error rate.

These results reveal that when designing an intelligent transport system for an IoT application based on optical fiber, one needs to consider the distance between the sending and receiving ends, as excessive link length may reduce data transfer reliability. Thus, to ensure efficient system operation, it is necessary to maintain the appropriate level of received power. As such, the optical input power is a critical initial metric for determining system performance, as it reflects the fiber-optic system's ability to retain signal power over various distances and sets the stage for understanding other performance measures such as Q-Factor and BER.

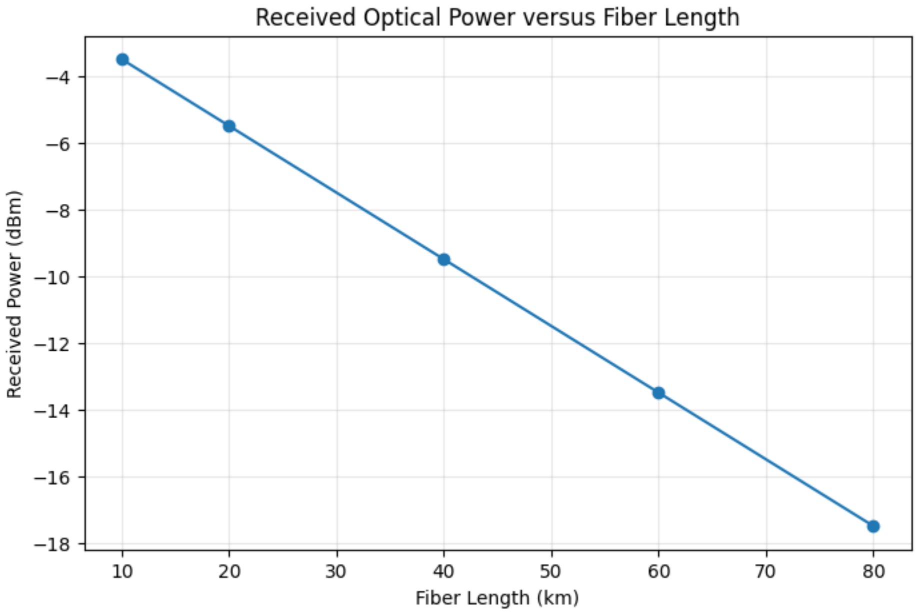

Figure 1. Received optical power as a function of fiber length in the proposed IoT-based smart transportation system.

Quality Factor (Q-Factor)

Figure 2 shows that the optical power received decreases as the optical fiber length increases, from -3.5 dBm at 10 km to -17.5 dBm at 80 km. The decline in optical power results from attenuation accumulated in the optical fiber and losses caused by the connectors in the simulation model. The observation clearly indicates that the transmission medium's distance coverage significantly influences signal strength and can affect parameters such as Q-Factor and BER. It is clear from the above findings that the quality factor decreases significantly as fiber length and data transfer rate increase. The quality factor at 1 Gbps was highest at 10 km (30.163) and steadily declined to 23.889, 14.898, 9.222, and 5.668 at distances of 20, 40, 60, and 80 km, respectively.

At 2.5 Gbps, the Q factor decreased from 18.979 at 10 km to 2.736 at 80 km. This clearly shows that the performance of the communication system is satisfactory at short and medium distances but deteriorates at long distances. At 5 Gbps, the values were 13.179 for 10 km and 9.766 for 20 km, then decreased to 4.859, 2.267, and 1.048 at 40, 60, and 80 km, respectively.

At 10 Gbps, the degradation was faster, with a quality factor of 8.694 at 10 km, a decrease to 5.445 at 20 km, then to 1.861 at 40 km, 0.666 at 60 km, and 0.262 at 80 km. These results indicate that the transmission rates used over longer distances need further modification, for example, by applying dispersion compensation techniques and using amplifiers.

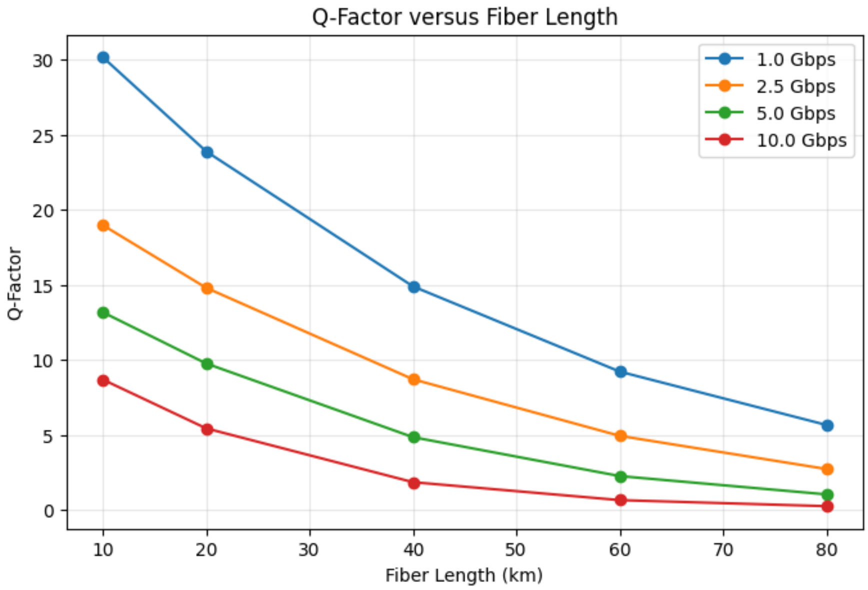

Figure 2. Q-Factor variation with fiber length at different data rates.

Bit Error Rate (BER)

Figure 3 shows that the BER value follows the same trend as the Q-factor test. At a transmission speed of 1 Gbps, the bit error rate was extremely low across all distances, with a minimum of 7.22×10^{-9} at 80 km.

At 2.5 Gbps, BER was very low at short and medium lengths but increased to 3.12×10^{-3} at 80 km, where transmission reliability begins to degrade. However, when the data rate increased to 5 Gbps, at short lengths of 10 km and 20 km, BER remained very low, although it rose to 5.00×10^{-6} at 40 km and 1.17×10^{-2} at 60 km.

At 10 Gbps, performance degradation was even more evident: BER at 20 km was 2.59 x 10^{-8}; at 40 km, it increased to 3.16 x 10^{-2}; at 60 km, it was 2.53 x 10^{-1}; and at 80 km, it was 3.98 x 10^{-1}. It seems that using 10 Gbps is only viable over short distances; otherwise, it becomes unreliable.

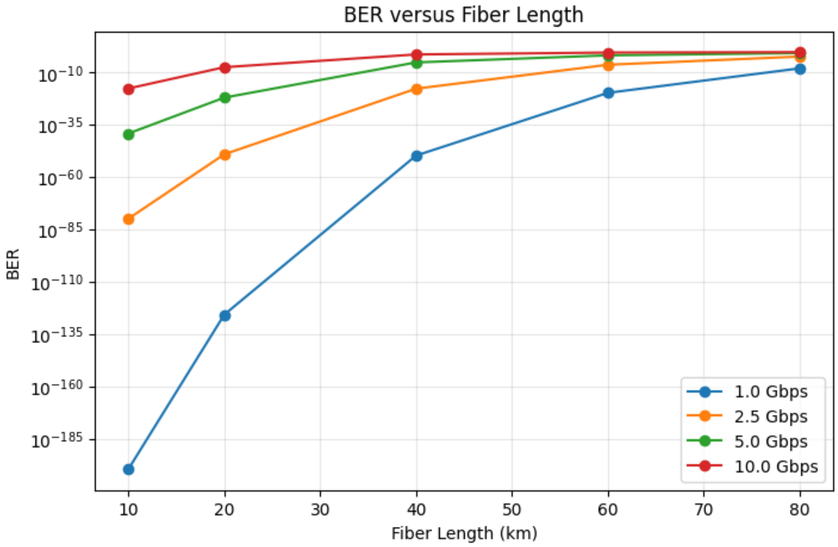

Figure 3. BER variation with fiber length at different data rates.

The effect of dispersion and pulse amplitude

From Figure 4, it can be observed that the value of the pulse amplitude is increasing gradually as the length of the optical fiber increases from 10 km to 16.75 ps, from 20 km to 33.50 ps, from 40 km to 67.00 ps, from 60 km to 100.50 ps, and at 80 km the value is 134.00 ps. This phenomenon occurs due to chromatic scattering in optical fibers, where optical signals travel at different speeds.

The dispersion ratio at varying data transfer speeds is presented in Figure 5. The findings show that the higher the data speed, the more noticeable the effect of dispersion. While dispersion was lower at 1 Gbps, at 0.134 for 80 km, the dispersion ratio became 1.34 at 10 Gbps for the same distance, which means interference may occur between adjacent bits.

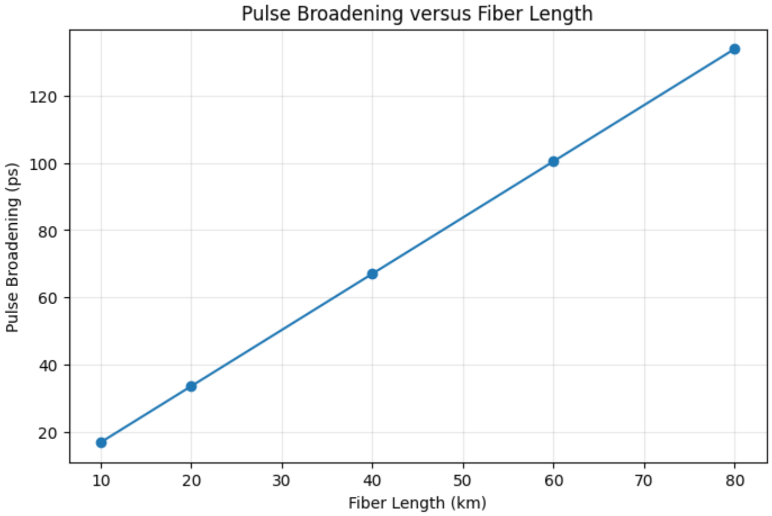

Figure 4. Pulse broadening variation with fiber length.

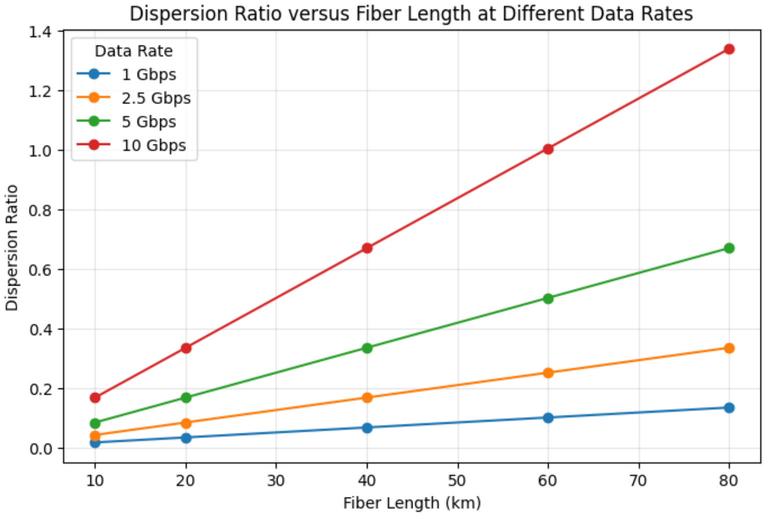

Figure 5. Dispersion ratio variation with fiber length at different data rates.

Based on the performance characteristics obtained from the received optical power, quality factor, bit error rate, and scattering ratio, the overall behavior of the system can be summarized for various data transfer rates, as shown in Table 2.

Table 2. Summary of the performance behavior of the proposed system under different data rates.

Data Rate	**Best Observed Performance**	**The beginning of the apparent deterioration**	**Performance Interpretation**
1 Gbps	Up to 80 km	No sharp deterioration has been shown	Suitable for long distances
2.5 Gbps	Up to approximately 60 km	At 80 km	Suitable for short and medium distances
5 Gbps	Up to approximately 40 km	from 60 km	Needs improvement at long distances
10 Gbps	Up to approximately 20 km	From 40 km	Suitable for short distances only in the current model

As shown in Table 1, the transmission stability at 1 Gbps was the highest across all ranges, ensuring acceptable performance up to 80 km. As for 2.5 Gbps, it was rather effective at medium distances, though the first sign of its degradation occurred already at 80 km. Finally, at 5 Gbps and 10 Gbps, a tendency toward degradation in the medium and large ranges became noticeable.

From the analysis of pulse amplitudes, one can deduce that the length of optical fibers directly amplifies the effect of scattering. The higher the length of the fiber, the higher the pulse amplitude duration, which makes it difficult for signals to be distinguished by the receiver. This effect may be less pronounced at lower data rates; however, at higher transfer rates, the pulses are more easily distorted due to their shorter duration. The reasons for this phenomenon can be seen in the significant decline in the Q-Factor, together with the increase in BER at 5 Gbps and 10 Gbps, particularly at medium-to-long distances. The reason is that at 10 Gbps, the bit period would be around 100 ps, whereas the pulse width would be around 134 ps at 80 km. Thus, the pulse width will be greater than the bit period, making them interfere.

The results indicate the possibility of using optical fibers for the transmission of data via IoT in intelligent transport systems with good effectiveness at lower and moderate speeds, although achieving higher speeds over large distances necessitates special measures to decrease the effect of dispersion. Such measures may include dispersion compensation, improved laser-source properties, a reduction in the distance between the transmitter and the receiver, or increased receiver sensitivity.

In other words, the investigation into scattering and pulse intensity reveals that the reduction in the effectiveness of the developed system results not only from a loss of optical power but also from time-related effects that influence the signal shape and digital discrimination at the receiver. Dispersion can be viewed as one of the main factors that must be taken into account while designing fiber optic networks for ITS systems relying on IoT.

Conclusion

This study aimed to evaluate the performance of an IoT-based intelligent transport system with a fiber-optic connection via a numerical simulation model in Python. The impacts of fiber optic length and data transfer rate on the received optical power, Quality factor, BER bit error rate, and pulse amplitude were analyzed. It was found that as the fiber length increases, the received optical power and quality factor decrease, and the bit error rate increases significantly, especially at high data rates. Good performance was observed up to 80 km at 1 Gbps, but a notable drop occurred at 5 and 10 Gbps due to attenuation and dispersion. From these findings, it can be concluded that a fiber-optic connection is a good choice for supporting IoT-based intelligent transport systems, especially for low and medium data transfer rates over the calculated distances. However, in cases where high data rates and long distances require transmission, additional measures should be implemented.

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