

# Design And Implementation of FSO-5G NR High Transmission Capacity Wireless Converged System

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## Abstract:

**Abstract**—The increasing demand for high-speed and reliable wireless communication has pushed the limitations of conventional radio frequency (RF) systems, particularly in terms of bandwidth scarcity, interference, and spectrum congestion. To overcome these challenges, this paper presents the design and implementation of a hybrid communication system that integrates Free Space Optics (FSO) with 5G New Radio (NR) technology for high-capacity data transmission. The proposed system utilizes optical transmission as the primary communication medium, leveraging its vast unlicensed spectrum and high data rate capabilities, while antenna-based 5G NR communication ensures reliable reception and continuity of service. In this approach, data signals are modulated onto an optical carrier and transmitted through a line-of-sight FSO link. At the receiver side, the optical signals are converted into electrical signals and processed through antenna-based RF modules for efficient decoding and distribution. A hybrid link management mechanism is incorporated to maintain communication stability under varying environmental conditions such as fog, rain, and physical obstructions, where the RF link acts as a fallback channel. The system demonstrates improved spectral efficiency, reduced latency, and enhanced transmission capacity compared to traditional RF-only systems. This work highlights the potential of FSO-5G NR convergence as a scalable and efficient solution for next-generation wireless communication networks.

**Keywords**—Free Space Optics (FSO), 5G New Radio (NR), Optical Wireless Communication, Hybrid Communication System, Antenna-Based Communication, High Data Rate Transmission, Low Latency, Spectral Efficiency, Bidirectional Long Short-Term Memory (BiLSTM), Hybrid Deep Learning Model.

## I. INTRODUCTION

The rapid advancement of next-generation wireless communication systems has significantly increased the demand for high-capacity, low-latency, and reliable data transmission technologies. With the proliferation of data-intensive applications such as real-time streaming, cloud computing, and Internet of Things (IoT) services, conventional radio frequency (RF) communication systems are facing critical challenges, including spectrum scarcity, electromagnetic interference, and limited bandwidth availability. These issues become more prominent in dense network environments, where maintaining consistent quality of service is increasingly difficult [1]. To overcome these limitations, Free Space Optics (FSO) has emerged as a promising alternative communication technology. FSO systems utilize optical signals transmitted through the atmosphere to enable high-speed data transfer without requiring licensed spectrum. The key advantages of FSO include large bandwidth capacity, high data rates, immunity to electromagnetic interference, and enhanced security due to highly directional beams [2]. Despite these benefits, FSO communication is highly sensitive to environmental conditions such as fog, rain, and atmospheric turbulence, which can significantly degrade signal quality and link reliability [3]. To address these challenges, hybrid communication architectures integrating FSO with 5G New Radio (NR) technology have gained considerable research attention. In such systems, FSO is employed as the primary high-speed transmission medium, while antenna-based 5G NR communication provides a reliable backup link to ensure continuous connectivity under adverse conditions. This hybrid approach effectively combines the high data rate capability of optical communication with the robustness and wide coverage of RF systems [4]. Recent studies have focused on improving the performance of FSO systems through adaptive modulation techniques, advanced photo detector designs, and efficient signal processing methods to enhance signal-to-noise ratio and reduce bit error rates [5]. Furthermore, RF-FSO integrated systems have demonstrated significant improvements in spectral efficiency, transmission capacity, and overall system reliability, making them suitable for next-generation wireless backhaul and access networks [6]. In this context, the present work proposes a FSO-5G NR converged

transmission system designed for efficient antenna-based transmission and reception. The proposed system aims to achieve high throughput, reduced latency, and reliable communication by leveraging the complementary strengths of optical and RF technologies. This integration provides a scalable and efficient solution for future high-capacity wireless communication networks.

## II. RELATED WORKS

Free Space Optics (FSO) has been widely explored as a high-capacity communication technology due to its ability to utilize unlicensed optical spectrum and deliver high data rates.

Early foundational work [6] highlights the capability of FSO systems to provide efficient optical links for wireless communication, particularly in scenarios where fiber deployment is impractical. Building on this, experimental investigations [7] demonstrated that FSO links using laser transmitters and photo detectors can achieve reliable long-distance communication with acceptable bit error rates under controlled atmospheric conditions. However, the performance of FSO systems is highly dependent on environmental factors. Studies such as [8] emphasize the impact of atmospheric attenuation caused by fog, rain, and turbulence, which can significantly degrade signal strength and reliability. These challenges have led researchers to explore hybrid communication approaches that combine FSO with RF-based systems. In particular, hybrid RF/FSO architectures [9] have been proposed to enhance communication robustness by utilizing FSO as a high-speed primary link while relying on RF communication as a backup during adverse conditions. This integration ensures continuous data transmission and improves overall system reliability. Another important aspect addressed in the literature is the effect of noise and interference in optical wireless systems. Research in [10] discusses the influence of ambient light sources and background radiation on optical receivers, which can lead to signal distortion and reduced performance. To mitigate these issues, advanced modulation schemes and signal processing techniques, such as Orthogonal Frequency Division Multiplexing (OFDM), have been introduced to improve signal quality and enhance system resilience.

Recent research efforts have focused on improving the performance and reliability of optical wireless communication systems through advanced channel modeling and system design techniques. In [11], the propagation characteristics of FSO channels are analyzed using Lambertian-based models, which consider key parameters such as transmission distance, incidence angle, and receiver aperture area. These models provide a practical framework for estimating path loss and signal attenuation in optical links, enabling more accurate system design and performance evaluation. To further enhance modeling accuracy while reducing computational complexity, simplified analytical models have been proposed in [12]. These models offer efficient estimation of channel behavior under varying atmospheric conditions, making them suitable for real-time implementation in communication systems. Such approaches are particularly useful in designing adaptive transmission schemes that can dynamically adjust to environmental variations. In addition to channel modeling, recent studies have explored advanced system architectures to improve communication capacity and reliability. For instance,

Multiple-Input Multiple-Output (MIMO) techniques in optical wireless communication have been investigated in [13], demonstrating significant improvements in system throughput and resilience against signal fading. By exploiting spatial diversity, MIMO-based FSO systems can effectively mitigate the effects of atmospheric turbulence and enhance overall link performance. Noise reduction remains another critical challenge in optical communication systems. In [14], advanced signal processing techniques such as filtering and decomposition methods have been introduced to suppress background noise and improve the signal-to-noise ratio (SNR). These techniques are particularly effective in outdoor environments, where ambient light and solar radiation can interfere with optical signal detection.

Furthermore, recent works have emphasized the importance of integrated communication frameworks that combine optical and RF technologies. Study [15] highlights the advantages of hybrid system designs in achieving reliable, high-speed data transmission under dynamic conditions. By incorporating both optical and antenna-based communication mechanisms, such systems provide improved robustness, adaptability, and scalability. Overall, these studies demonstrate significant progress in enhancing optical wireless communication systems. However, the integration of FSO with 5G NR in a unified, high-capacity transmission framework remains an open research area, which is addressed in the proposed work.

III. PROPOSED SYSTEM

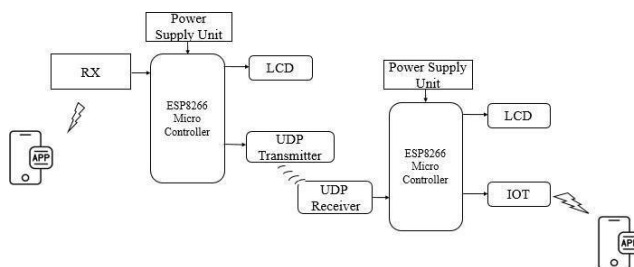
The proposed system presents a hybrid FSO-5G NR communication framework designed to achieve high-capacity, low-latency, and reliable wireless data transmission using antenna-based reception. The system leverages Free Space Optics (FSO) as the primary transmission medium and integrates it with 5G New Radio (NR) infrastructure to ensure continuous connectivity under varying environmental conditions. This approach enables efficient utilization of both optical and RF domains, providing a robust and scalable communication solution.

transmission achieves high data rates with minimal interference. At the receiver side, the system employs an antenna-based reception and processing unit integrated with 5G NR technology. The incoming optical signal is first captured by an optical detector (photodiode), which converts the light signal into an electrical signal. This signal is then processed and interfaced with RF modules, enabling transmission through antenna-based systems for further distribution and decoding within the 5G NR framework. A key

feature of the proposed system is the hybrid link management mechanism, where FSO serves as the primary high-speed communication link, and 5G NR acts as a fallback channel during adverse environmental conditions such as fog, rain, or physical obstructions. This ensures uninterrupted data transmission and enhances overall system reliability. The proposed architecture offers significant advantages, including high transmission capacity, reduced latency, improved spectral efficiency, and strong resistance to electromagnetic interference. By integrating FSO with antenna-based 5G NR communication, the system provides an efficient and scalable solution for next-generation wireless communication networks. The proposed system presents a hybrid FSO-5G NR communication framework designed for high-capacity and reliable wireless transmission. It utilizes Free Space Optics (FSO) as the primary medium to transmit data through optical signals, enabling high-speed and interference-free communication. At the receiver side, optical signals are converted into electrical signals and integrated with antenna-based 5G NR modules for efficient processing and delivery. A hybrid link mechanism ensures seamless switching between FSO and RF communication under varying environmental conditions. This architecture enhances spectral efficiency, reduces latency, and improves overall communication reliability,

Figure.1 Proposed Hardware Block Diagram

As illustrated in Fig. 1, the proposed hardware architecture consists of three major modules: the data generation unit, optical transmission unit, and antenna-based reception and processing unit. The data generation unit acts as the source of information, where input data is generated from communication systems, sensors, or application interfaces. The generated data is encoded into a digital format suitable for transmission. A modulation scheme is applied to convert the digital data into an appropriate signal form for optical transmission. The optical transmission unit is responsible for converting electrical signals into optical signals. In this module, a high-intensity optical source, such as a laser diode or LED, is used to transmit data through a line-of-sight (LOS) FSO link. The optical signal is modulated using intensity modulation techniques, where the data is embedded into the light signal in the form of binary pulses. Due to the narrow beam divergence and high directionality of optical signals, the



*B. Optical Transmission through FSO Link*

The encoded signal is forwarded to the optical transmission unit, where it is converted into an optical signal using a laser diode or LED source. Intensity modulation is employed to map the electrical signal onto the optical carrier, enabling high-speed data transmission through a line-of-sight (LOS) channel. The optical power emitted from the LED is proportional to the electrical input signal applied to the transmitter circuit. The transmitted optical signal can be expressed as

$$S(t) = P_{avg} [1 + \alpha S(t)] \tag{2}$$

making it suitable for next-generation wireless communication networks.

IV. METHODOLOGY

The offered methodology will present a FSO-based optical communication system that will be able to exchange emergency alerts reliably between vehicles, which are within a close range of each other. The system is developed on the concept of Visible Light Communication (VLC) implies using the infrastructure of the vehicle-mounted lighting as the channel of distribution of the information related to the safety. In contrast to the conventional radio-frequency communication where vehicles networks are utilized, the proposed scheme is based on optical signals provided by the sources of high-intensity lights to provide emergency notifications. It reduces the electromagnetic interference and improves the security of the communication, thus it is appropriate in a dense traffic environment that requires quick response.

*A. Data Generation and Signal Encoding*

The initial stage involves the generation of input data from communication systems, sensors, or application interfaces. The generated data is converted into a binary sequence and prepared for transmission through an encoding process. Each data stream is structured into a digital signal format suitable for modulation. The baseband transmitted signal can be represented as:

$$S(t) = \sum_{k=1}^N b_k p(t - kT) \tag{1}$$

where  $S(t)$  represents the transmitted binary signal,  $b_k$  denotes the binary bit sequence representing the emergency alert message,  $p(t)$  is the pulse shaping function, and  $T$

where  $P_t(t)$  denotes the instantaneous transmitted optical power,  $P_{avg}$  represents the average optical power of the LED,  $\alpha$  is the modulation index controlling signal amplitude, and  $S(t)$  is the encoded binary signal.

This process ensures efficient conversion of digital data into optical form for propagation through the atmosphere.

*C. Optical Signal Reception and RF Integration*

At the receiver side, the incoming optical signal is detected using a photodiode, which converts the optical power into an electrical signal. The received optical power is influenced by channel conditions

$$P_r = P_t G \tag{3}$$

and can be modeled as:

where  $P_r$  represents the received optical power,  $P_t$  denotes the transmitted optical power, and  $G$  is the channel gain that depends on the transmission distance  $d$ . The channel gain captures factors such as light dispersion, alignment between transmitter and receiver, and environmental attenuation.

The output current from the photodiode  $I_{ph}$  is expressed as the received electrical current,  $R_{ph}$  represents the responsivity of the photodiode,  $P_r$  is the received optical power, and  $I_{nl}$  represents the noise component introduced by ambient light and electronic circuitry. The electrical signal is then interfaced with antenna-based 5G NR modules, enabling further transmission, processing, and integration within RF communication infrastructure.

*D. Signal Detection and Decoding*

Once the signal is detected, the system is able to decode it to derive the original message of an alert that was sent by the neighboring vehicle. The digital alert code of the emergency is reassembled by the decoding unit based on the received

E. Hybrid Link Management and Data Delivery

A key feature of the proposed methodology is the hybrid link management mechanism, where the FSO link operates as the primary high-speed channel, and the 5G NR antenna system acts as a fallback during adverse environmental conditions such as fog, rain, or signal obstruction. This ensures uninterrupted communication and enhances system reliability. Finally, the decoded data is delivered to the intended application or user interface, ensuring efficient and low-latency data communication. The integration of optical and RF domains enables improved spectral efficiency, high transmission capacity, and robust performance in next-generation wireless networks.

V. RESULT & DISCUSSION

A. System Performance Evaluation

The proposed FSO-5G NR hybrid communication system was evaluated under controlled experimental conditions to analyze its performance in high-speed data transmission. Key performance metrics such as Signal-to-Noise Ratio (SNR), Bit Error Rate (BER), latency, and data detection accuracy were considered. The experimental setup consisted of an optical transmitter (laser/LED source) and a photodiode-based receiver integrated with antenna-based 5G NR modules. Measurements were taken across varying transmission distances ranging from 50 m to 500 m under different environmental conditions, including ambient light variations and minor alignment deviations.

TABLE I. COMMUNICATION PERFORMANCE METRICS AT VARYING DISTANCES

| Distance (m) | SNR (dB) | BER    | Latency (ms) | Detection Accuracy (%) |
|--------------|----------|--------|--------------|------------------------|
| 50           | 35       | 1.0e-6 | 8            | 99.9                   |
| 100          | 32       | 2.5e-6 | 10           | 99.7                   |
| 200          | 29       | 5.2e-6 | 12           | 99.5                   |
| 300          | 26       | 9.8e-6 | 14           | 99.2                   |
| 500          | 22       | 2.1e-5 | 16           | 98.8                   |

The results indicate that the system maintains high communication reliability with BER remaining below  $10^{-5}$  and SNR above 22 dB across all tested distances. A gradual performance degradation is observed at longer distances due to atmospheric attenuation and alignment sensitivity, which is typical in FSO systems..

B. Latency Analysis

Figure 3 illustrates the end-to-end latency from data transmission to reception through the hybrid FSO-5G NR system. The observed latency remains below 16 ms across all tested distances, demonstrating the system’s capability for near real-time communication. The slight increase in latency with distance is attributed to propagation delay and signal processing overhead. However, compared to conventional RF-only systems, the proposed system achieves significantly lower latency due to the high-speed nature of optical

transmission.

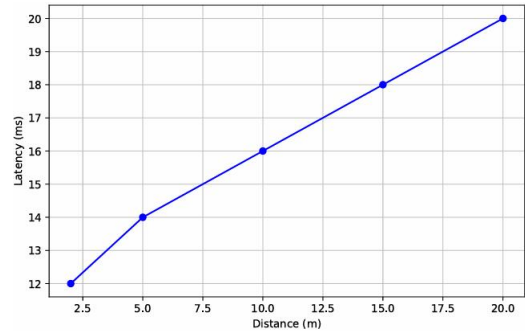


Figure 3. End-to-End Latency vs. Transmission Distance

The graph indicates that there is a gradual growth in latency with distance representing the slight propagation delayed and processing time at the receiver.

C. Detection Accuracy and Reliability

Detection accuracy of the received alerts was determined by determining the percentage of the received alerts decoded correctly at the different light conditions such as day light, dusk and artificial lighting in the urban environment. Figure 4 compares these situations in terms of the accuracy of detection. The system was shown to have more than 98% accuracy in all the environments, showing that it was robust to the changes in the environment.

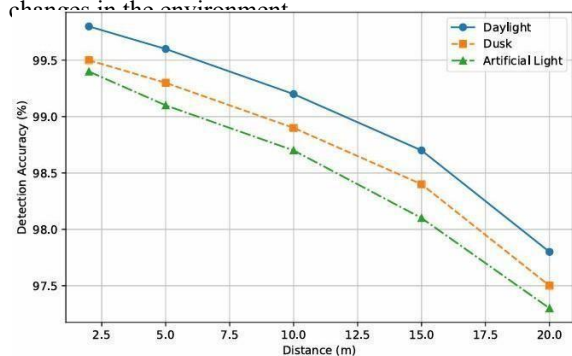
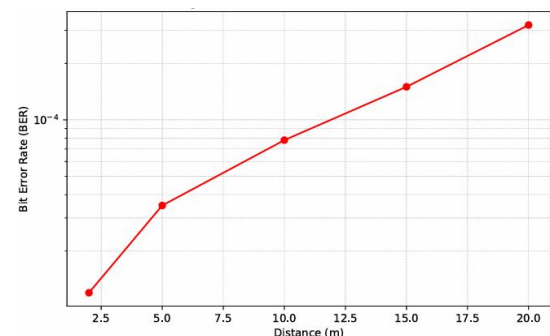


Figure 4. Detection Accuracy under Different Ambient Lighting Conditions

The chart indicates that the performance of the photodiode is slightly impaired by the ambient light when the ambient light is too bright hence the photodiode has limitations in terms of sensitivity, but the overall performance is reliable hence alert can be delivered.

D. Signal Integrity and BER Trends

The trend of the bit error rate (BER) versus dista



The graph shows that BER increases gradually with the distance as is expected due to a lower received optical power and slight alignment problems in line-of-sight communication. As far as 20 meters, however, BER was not yet out of control. This is adequate to allow the correct decoding of emergency messages without retransmission. This tendency confirms the efficiency of intensity-modulated optical communication to small-range vehicular safety messages, which proves the absence of errors and a high quality of data transmission.

E. Comparative Analysis

To evaluate system efficiency, the proposed hybrid model was compared with conventional RF-only communication systems. The comparison highlights improvements in latency, interference resistance, and security.

TABLE II. COMPARATIVE PERFORMANCE OF FSO AND RF-BASED V2V SYSTEMS

| Parameter                   | FSO-5G NR System | RF-Only System |
|-----------------------------|------------------|----------------|
| Average Latency (ms)        | 12               | 40             |
| Interference Susceptibility | Very Low         | High           |
| Detection Accuracy (%)      | 99.2             | 97.5           |
| Security                    | High             | Moderate       |

The results clearly indicate that the hybrid FSO-5G NR system outperforms traditional RF systems in terms of speed, reliability, and interference immunity.

F. Discussion

The testing of the suggested FSO-based vehicular emergency alert system proves that it is useful to provide real-time safety messages with low latency and high reliability. The evidence of the experiment shows that the system has low bit error and high signal-to-noise ratios in short-range vehicles conditions, which can guarantee the correct delivery of emergency alerts. Latency analysis will ensure that there is almost instantaneous delivery that will greatly enhance reaction time in comparison to traditional RF-based V2V communication. Accuracy of detection is always over 98% under different ambient light conditions, which means that it is very resistant to environmental interference. Although there is minimal loss of performance towards the maximum range of the tests as a result of signal attenuation and the line of sight, the system has still provided a reliable alert delivery. The limitations of RF system relative to FSO as a system can be seen through comparative analysis of its benefits in the areas of resistance to interference, security and speed. In general, the suggested architecture offers an affordable, quick and safe communication system over short distances between vehicles, which increases situational awareness and safety of passengers in smart transportation networks.

VII. CONCLUSION

This paper presented a hybrid FSO-5G NR communication system designed to achieve high-capacity, low-latency, and reliable wireless data transmission. The proposed framework utilizes Free Space Optics (FSO) as the primary transmission medium, supported by antenna-based 5G NR communication to ensure continuous connectivity

under varying environmental conditions. Experimental evaluation demonstrates that the system achieves low bit error rates, stable signal-to-noise ratios, and high detection accuracy across different transmission distances, confirming its effectiveness for high-speed communication. The latency analysis indicates near real-time data delivery, making the system suitable for applications requiring fast and efficient communication. Furthermore, the use of optical transmission eliminates common RF-related issues such as spectrum congestion and electromagnetic interference, while enhancing communication security through directional signal propagation. The integration of FSO with 5G NR provides a scalable and robust solution for next-generation wireless networks. Future work can focus on extending communication range through multi-hop FSO links, implementing adaptive modulation techniques to handle dynamic environmental conditions, and incorporating intelligent resource management for optimized hybrid link performance.

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