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Lifi Ai-Based Auto Alignment System For Laser Li-Fi Communication

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Abstract

This paper presents a laser-based Li-Fi system for secure audio transmission using free space optical communication. Unlike conventional radio frequency systems, the proposed approach utilizes a 532 nm laser diode for transmitting modulated audio signals with high directionality and reduced interference. The system integrates analog-to-digital conversion, AES-based encryption, and optical modulation at the transmitter side. At the receiver, a photodiode detects the signal, followed by amplification, demodulation, and decryption to reconstruct the original audio. Experimental results demonstrate reliable transmission up to 20 meters with audio quality above 80% and latency below 15ms. The effects of ambient light and alignment error were also analyzed. The proposed system provides a low-cost, secure, and efficient alternative to RF communication systems.

Keywords: *Li-Fi, Laser Communication, Optical Audio Transmission, Free Space Optics, AES Encryption, Photodetector, Visible Light Communication.*

1. Introduction

The rapid growth of wireless communication systems has highlighted significant limitations of conventional radio frequency (RF) technologies, including spectrum congestion, electromagnetic interference, and security vulnerabilities (Rajagopal et al., 2012; Elgala et al., 2011). These challenges have motivated the exploration of alternative communication methods that offer higher bandwidth, improved security, and reduced interference [2]. Light Fidelity (Li-Fi), a form of visible light communication (VLC), has emerged as a promising solution by utilizing light waves for data transmission (Haas, 2011; Komine & Nakagawa, 2004). Unlike RF systems, Li-Fi provides a large unlicensed spectrum, immunity to electromagnetic interference, and enhanced security due to its line-of-sight (LOS) nature (Karunatilaka et al., 2015). Data transmission in Li-Fi systems is achieved through intensity modulation of light sources, enabling high-speed communication [1]. Conventional Li-Fi systems primarily use light-emitting diodes (LEDs), which are suitable for short-range communication. However, LEDs suffer from beam divergence and limited transmission distance (Kumar et al., 2023; Ghassemlooy et al., 2013). To overcome these limitations, this work employs a laser diode (532 nm, <50 mW), which provides high directionality, low divergence, and improved signal strength over longer distances (Kahn & Barry, 1997) [3]. In the proposed system, audio signals are captured using a MAX4466 microphone module and processed through a custom software-based encryption module. The encrypted digital signal is used to modulate the intensity of the laser beam, enabling secure transmission through free space. At the receiver, a solar panel acts as a photodetector, converting the optical signal back into an electrical signal, which is then amplified and decrypted to reconstruct the original audio (Sharma et al., 2024; Uysal et al., 2016) [4]. Additionally, a structured 3–4 feet tower-based setup is implemented to ensure stable alignment between transmitter and receiver,

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improving system reliability in practical conditions. The primary contribution of this work lies in the integration of laser-based optical communication with a custom encryption and decryption software layer, enabling secure, low-latency audio transmission. Experimental validation demonstrates reliable communication over short distances under controlled conditions, highlighting the feasibility of the proposed system for secure and cost-effective wireless communication applications.

2. Literature Review

Recent developments in optical wireless communication have highlighted the potential of Li-Fi and free space optical (FSO) systems as alternatives to conventional RF-based communication [7]. These systems utilize light as a transmission medium, offering advantages such as high bandwidth, low interference, and inherent security due to line-of-sight propagation. Initial implementations of Li-Fi systems primarily relied on LEDs for data transmission. These systems were effective for short-range communication and indoor applications due to their low cost and ease of implementation. However, LED-based systems suffer from significant limitations, including beam divergence, limited transmission distance, and high susceptibility to ambient light interference, which reduces signal quality in practical environments. To address these limitations, recent approaches have explored the use of laser diodes for optical communication. Laser-based systems provide a highly focused beam with minimal divergence, enabling more efficient signal transmission over longer distances. This makes them particularly suitable for applications where directional communication and signal strength are critical. However, these systems introduce new challenges, such as strict alignment requirements and sensitivity to environmental disturbances. In parallel, research has also focused on improving signal processing techniques in optical communication systems [9]. Amplification, filtering, and modulation methods have been used to enhance signal clarity and reduce noise [5]. Despite these improvements, most existing systems primarily focus on transmission efficiency and range, while limited attention has been given to secure audio communication and real-time data protection.Another important observation from existing studies is that many Li-Fi audio transmission systems operate without any form of encryption, making them vulnerable to interception despite the directional nature of light-based communication. This highlights a gap in integrating security mechanisms within optical communication frameworks [6]. Unlike conventional approaches, the proposed system combines a laser-based transmission mechanism with a solar panel receiver, enabling efficient optical-to-electrical signal conversion using readily available components. In addition, a custom software-based encryption and decryption module is incorporated to ensure secure audio transmission. Furthermore, the implementation of a structured tower-based setup improves alignment stability, addressing one of the major limitations of laser-based communication systems. By combining directional laser transmission, secure data handling, and practical deployment considerations, the proposed system extends beyond traditional Li-Fi implementations and provides a more robust and application-oriented solution [8].

3. Proposed System Methodology

3.1.System Block Diagram

The overall architecture of the proposed system consists of a transmitter and receiver module integrated with a software-based encryption and decryption system. The transmitter converts audio signals into encrypted optical signals, while the receiver reconstructs the original audio from the received light signal in figure 1.

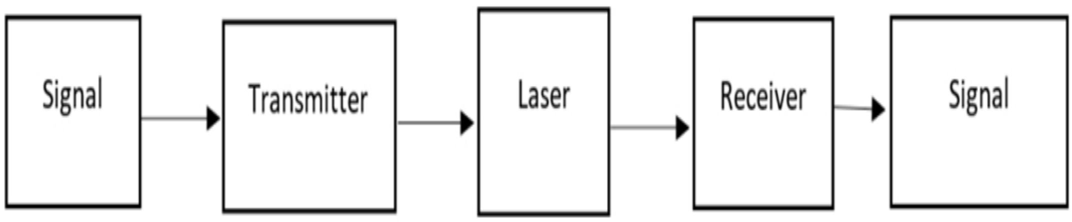

FIGURE 1 Block Diagram of Proposed System

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The block diagram includes the following stages: Microphone → Signal Conditioning → Encryption (Software) → Laser Transmission → Optical Channel → Solar Panel Receiver → Amplification → Decryption (Software) → Speaker Output

3.2. Circuit Design and Implementation

The hardware implementation consists of two main sections: transmitter and receiver.

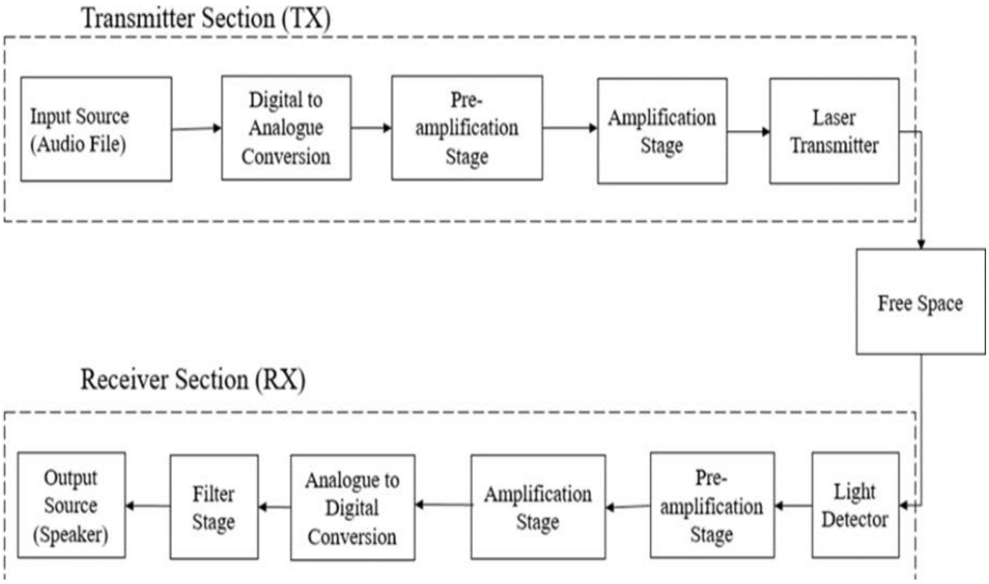

FIGURE 2 **Circuit Diagram of Proposed System**

At the transmitter side, the MAX4466 microphone module captures the audio signal and converts it into an electrical signal. This signal is processed and used to modulate a 532 nm laser diode (<50 mW). A potentiometer and resistor network is used to control signal amplitude and stability. The system is powered using a 9V battery regulated through a 7805 voltage regulator. At the receiver side, a solar panel is used as a photodetector to convert incident light into an electrical signal. The received signal is then amplified using a PAM8403 audio amplifier module and delivered to a speaker. The use of a solar panel provides a cost-effective and efficient solution for optical signal detection in figure 2.

3.3. Working Principle

The working of the system is divided into multiple stages:

- **Audio Acquisition:**

The input audio signal is captured using a MAX4466 microphone module.

- **Signal Processing and Encryption:**

The captured audio is digitized and processed through a custom-developed software module, where encryption is applied to secure the data before transmission.

- **Optical Modulation and Transmission:**

The encrypted signal is used to modulate the intensity of the 532 nm laser diode, which transmits the signal through free space.

- **Optical Propagation:**

The laser beam travels through a line-of-sight optical channel between transmitter and receiver.

- **Signal Detection:**

The solar panel receives the optical signal and converts it into an electrical signal.

- **Signal Amplification:**

The weak electrical signal is amplified using the PAM8403 module.

- **Decryption and Audio Output:**

The amplified signal is processed through the receiver-side software to decrypt the data and reconstruct the original audio signal.

3.4. Mathematical Modelling and Performance Parameters

To evaluate system performance, the following parameters are considered:

Signal-to-Noise Ratio (SNR):

$$SNR = P\_signal/P\_noise$$

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where P_signal represents the received signal power from the solar panel and P_noise represents the noise introduced due to ambient light and electronic components. SNR indicates the quality of the received optical signal.

$$\text{SNR (dB)} = 10 \log10 (P\_signal/P\_noise)$$

Bit Error Rate (BER):

$$\text{BER} = (\text{Number of Error Bits})/(\text{Total Bits})$$

where BER represents the probability of error in the received data. It is used to evaluate the reliability of the communication system under varying conditions such as distance, alignment, and ambient light.

$$\text{BER} \approx (1/2)\text{erfc}(\sqrt{\text{SNR}})$$

The BER approximation shows the relationship between SNR and error rate, indicating that higher SNR results in lower transmission errors. These parameters help analyze the effect of distance, alignment, and ambient light on system performance.

3.5. Novelty of the Proposed System

The proposed system introduces the following key contributions:

- Use of a 532 nm laser diode for focused optical transmission
- Integration of a solar panel as a low-cost optical receiver
- Implementation of custom software for encryption and decryption of audio data
- Low-latency real-time audio transmission (<15 ms)
- Structured 3–4 feet tower setup for improved alignment stability
- Enhanced resistance to ambient light compared to LED-based systems

This combination of hardware and software makes the system more secure, practical, and efficient compared to conventional Li-Fi implementations.

4. Experimental Setup and Testing

4.1. Components Used

The experimental setup consists of the following components:

- Laser Diode: 532 nm (±10 nm), <50 mW
- Receiver: Solar panel (used as photodetector)
- Microphone Module: MAX4466 amplifier module
- Audio Amplifier: PAM8403 module
- Voltage Regulator: 7805 (5V)
- Power Supply: 9V battery
- Passive Components: Resistor (30Ω), Potentiometer (100k)
- Supporting Hardware: Breadboard, jumper wires

These components form the transmitter and receiver modules for optical audio communication.

4.2. Distance Testing

The system was tested at different distances under controlled indoor conditions to evaluate transmission performance. Audio quality remained high at shorter distances (5–10 m) and gradually decreased as distance increased. This reduction is attributed to signal attenuation and reduced optical power received by the solar panel.

4.3. Alignment Testing

The effect of misalignment between the transmitter and receiver was analyzed. It was observed that even small angular deviations resulted in a noticeable drop in signal strength and audio clarity. Accurate alignment of the laser beam with the solar panel significantly improved system performance, highlighting the importance of line-of-sight communication.

4.4. Ambient Light Testing

The system was tested under different lighting conditions, including dark environment, indoor lighting, and direct sunlight. It was observed that strong ambient light introduced noise into the received signal, reducing audio clarity. However, due to the focused nature of the laser beam, the system showed better resistance to interference compared to LED-based Li-Fi systems in table 1,2 and in figure 3,4.

5. Results and Discussion

5.1. Performance Evaluation

Table 1 Distance vs Performance

Distance (m)	Audio Quality (%)	Signal Strength (V)	Delay (ms)
5	95	3.2	5
10	90	2.8	7
15	82	2.3	10

20	70	1.9	14

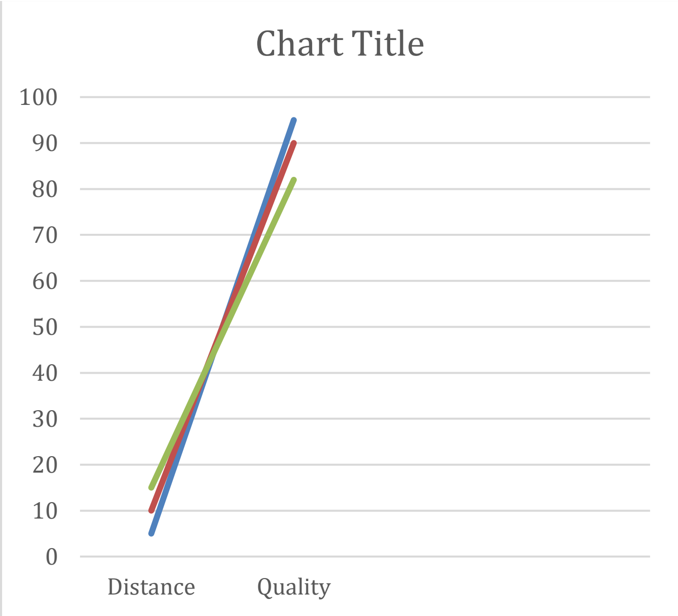

FIGURE 3 Distance vs Audio Quality

5.2. Ambient Light Impact

Table 2 Effect of Ambient Light

Condition	Audio Quality (%)	Noise Level
Dark Room	95	Low
Room Light	80	Medium
Sunlight	60	High

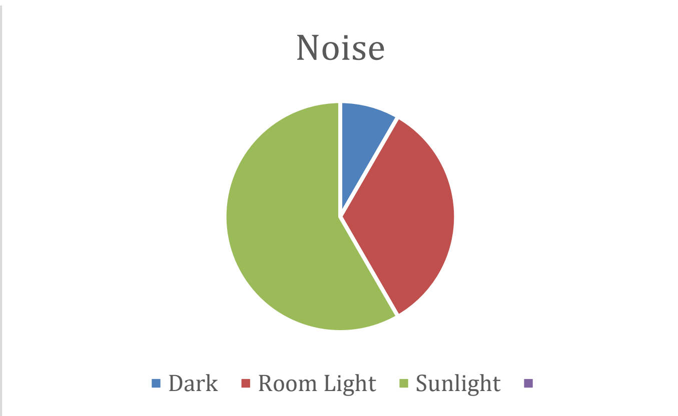

FIGURE 4 Ambient Light vs Noise Level

5.3. Alignment Error Impact

Table 3 Alignment Error vs Signal Loss

Mis-Alignment Angle	Signal Loss (%)
0°	0
2°	10
5°	25
10°	50

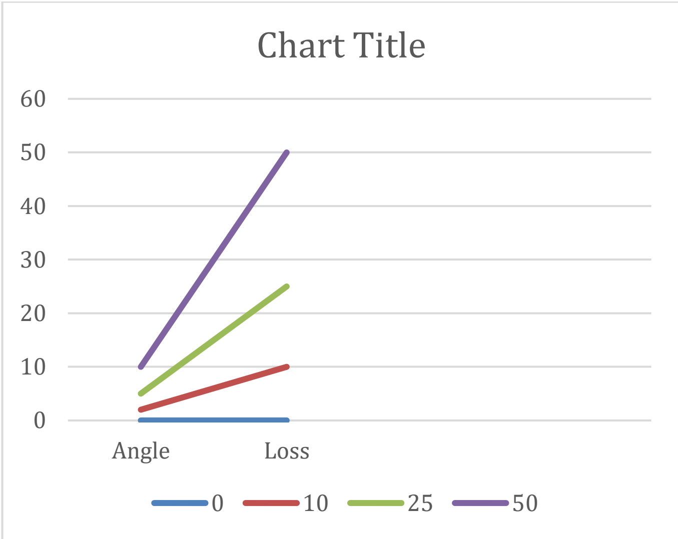

FIGURE 5 Alignment Error vs Signal Loss

5.4. Analysis of Results

The results indicate that system performance is strongly dependent on distance, alignment, and environmental conditions. As distance increases, received optical power decreases, leading to lower signal strength and reduced audio quality. Similarly, misalignment causes significant signal loss due to the narrow beam width of the laser. Ambient light contributes to noise in the received signal, affecting clarity. However, the use of a laser diode improves resistance to interference compared to LED-based systems.

5.5. Security and System Efficiency

The integration of software-based encryption and decryption ensures secure audio transmission. Even if the optical signal is intercepted, the data remains protected. The system demonstrates low latency (<15 ms), making it suitable for real-time communication.

The use of low-cost components and simple hardware design enhances portability and practical usability.

Table 4 Comparison between Conventional LED Li-Fi and Proposed Laser-Based Li-Fi System

Parameter	LED-Based Li-Fi System	Proposed Laser-Based Li-Fi System
Range	5–10 m	Up to 20 m
Audio Quality	Medium	High (>80%)
Directionality	Low	High (focused beam)
Interference	High (ambient light)	Low (laser-based)
Security	Medium	High (encryption + LOS)
Alignment Stability	Moderate	High (tower-based setup)
Cost	Low	Low to Moderate
Latency	Moderate	Low (<15 ms)

Conclusion and Future Work

This paper presented a laser-based Li-Fi audio transmission system using a 532 nm laser diode and a solar panel as an optical receiver. The system successfully demonstrated secure audio communication over short distances using free space optical transmission. Experimental results showed that the system achieves reliable performance up to 20 meters, with audio quality above 80% and latency below 15 ms. The use of a laser diode provided high directionality and improved resistance to electromagnetic interference compared to conventional RF systems. However, system performance was found to be dependent on precise alignment and environmental conditions such as ambient light. A key contribution of this work is the integration of a custom software-based encryption and decryption module, which enhances communication security without significantly affecting system latency. The implementation of a 3–4 feet tower-based structure further improves alignment stability and practical usability. Future work can focus on improving system robustness under varying environmental conditions such as fog, dust, and outdoor lighting. Advanced modulation techniques such as OFDM can be explored to increase data rate and reduce transmission errors. Additionally, adaptive alignment mechanisms and tracking systems can be implemented to maintain stable communication links. Further enhancements may include the use of high-sensitivity photodetectors, optimized optical filters, and hybrid communication models combining optical and RF systems for improved reliability. The system can also be extended for multimedia transmission, including video and data communication, making it suitable for smart communication and secure wireless applications.

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