Advanced Laser Light Communication for IoT and Smart Infrastructure

C. Jency, Abinaya B., Shivashankari V. and Abishek B.
Department of AI&DS, Dr.N.G.P Institute of Technology, Kalapatti Road, Coimbatore, Tamil Nadu, India

Keywords: Laser Light Communication, Li-Fi, FSO, q-Factor, Bit Error Rate, OptiSystem, MISO, Attenuation, Environmental Factors.

Abstract: Advanced Laser Light Communication for IOT and Smart Infrastructure represents a promising alternative to traditional wireless communication systems, offering high-speed data transmission through free-space optical (FSO) links using light waves, specifically laser beams. LLC, powered by Light Fidelity (Li-Fi) technology, offers significant advantages such as lower cost, reduced complexity, higher data rates, and minimal losses compared to fiber optics. However, challenges such as environmental interferences rain, fog, wind, and obstacles impact signal transmission. This work proposes an advanced Li-Fi based FSO system using a laser array to mitigate disruptions and ensure uninterrupted high-speed communication. A converging lens enhances the system by focusing the beams at the receiver, increasing the signal's intensity. Performance evaluation, using the OptiSystem tool, examines the quality factor (Q-factor), bit error rate (BER), received power, and Eye diagram under varying link distances. The study also includes a hardware prototype to validate the system's performance.

1 INTRODUCTION

However, as an alternative of the limitation from the traditional wireless communication systems that use mainly radio frequency (RF) waves, Laser light communication (LLC) has come. System Based on RF (Wi-Fi etc.) face all of above issue like limited bandwidth, interference, low data-rates and security problem because of large availability of radio signal. Enter Li-Fi, one emerging technology that is gaining traction to meet these communicating demands, a system that uses light waves instead of the traditional mediums to carry data.

As LLC was developed for RF transmission using light in the 380 nm- 780 nm wavelengths in the ultraviolet to visible range of wavelengths (or light), it has substantial advantages like increased bandwidth, heightened data rates, and resistance to electromagnetic interference. While RF waves can be directed, a laser beam can be tightly focused, which enables secure, point-to-point communication with significantly less interference. Additionally, the LLC systems do not have bottlenecking problems that usually happens when many devices use a same RF channel in a particular geographic area, like for example in a high-density urban area. Generally, a mobile transceiver that can cover a large area and has high-band transmission should use VLC with a laser as compared to other technologies such as RF-based networks during startup, which can easily implement smart cities. The wide coverage areas of laser-based light transmitters, combined with VLC's m: Power impact, gives urban areas greater data transfer rates than RF systems working within the same environments.

As a part of LLC system, PAVEWAY has immersed advantages like low RF, direct-to-line of sight energy transmission, minimal power usage, etc. This can cause the signal quality to decay and the communication to be lost especially over long distances. This was susceptible to aforementioned problems so in the proposed system multiple laser beams focused on a converging lens, so at the receiving end these beams completely converge, thus increases the strength of signal and reliability.

Laser communication can be used for satellite communication, inter-planetary exploration and high-speed internet in isolated area. It can span long distances with little signal degradation, so it's a contender in next-gen communications. Project Visualisation: The feasibility of LLC has been explored through OptiSystem, popular software for

Jency, C., B., A., V., S. and B., A.
Advanced Laser Light Communication for IoT and Smart Infrastructure.
DOI: 10.5220/0013902500004919

In *Proceedings of the 1st International Conference on Research and Development in Information, Communication, and Computing Technologies (ICRDICCT'25 2025) - Volume 3*, pages 595-601
ISBN: 978-989-758-777-1

optical communication systems simulation to evaluate critical performance metrics (BER, Q-factor, received power) with respect to different environmental conditions and separation between two communicating users. Also, we redesign a hardware prototype from the results of our experimentations to analyse how effectively our proposed system works in real-time.

2 LITERATURE REVIEW

2.1 Literature Review: Laser Light Communication

We also discuss several access technologies with direct implications to LLC such as free-space optical (FSO) and light fidelity (Li-Fi) and effects of the surrounding medium on the signal when using LLC. Notably, enabling data rates using arrayed lasers, and adapting techniques to counter environmental disturbances, are both key innovations.

2.1.1 Laser Light Communication Systems Overview

Compared to more common RF communication, LLC systems have major benefits. Gupta et al. (2020), further emphasize upon the unique advantages of FSO systems in providing much higher bandwidth and data rates available than that of RF based systems, making them an attractive solution. Zhang et al. (2021) investigates Li-Fi technology for using visible light to transfer data at high speed, highlighting its potential application in replacing congested RF channels in certain applications. Kumar et al. (2022), exploring optical wireless communication as a remedy to radio frequency (RF) spectrum congestion and its advantages for communication over long distances. Zafar et al. The basis of laser-diode based VLC systems is provided by who shows that they are capable of achieving gigabit-class data rates, as their modulation bandwidth is significantly higher compared to that of an LED based model.

2.1.2 Free-Space Optical System Attenuation

LLC performance is heavily influenced by environmental factors like fog, rain, and wind. Sharma et al. (2021) analyze the impact of weather conditions on laser communication systems and suggest adaptive mechanisms to ensure reliable communication under varying conditions. Rajput et al.) study the effects of fog attenuation and create models to predict signal degradation based on visibility levels. Chauhan et al. (2021) study rain attenuation and provide methods for adapting laser beam power and reducing signal loss from heavy rain.

2.1.3 Laser Arrays as a Tool for High-Speed Communication

LLC reliability in challenging conditions comes down to laser arrays. Saini et al. proposed a multi-laser array to ensure that the communication is always ON by splitting the data to all the laser beams, which in turn reduces the interdependent loss of signal in adverse weather conditions. Garg et al. 2020) showing how to use converging lenses to concentrate the intensity of the signal at the receiver, thus improving system performance. Joshi et al. Another research showing on the usage of multi-input singleoutput (MISO) systems in FSO communication, stating that such systems have the potential to improve the communication reliability and the communication speed. Achieving data rates of up to 113 Gbps, a near-real-time VLLC system is demonstrated in Optics Express (2024).

2.1.4 Performance Evaluation Using Optical Simulation Tools

Numerous simulation tools are available for the assessment of LLC systems such as OptiSystem. Garg et al. H Addel et al. use OptiSystem to analyze FSO systems with varying conditions where they present the power versus bit error rate (BER) relationship. Hou, Y., et al. (2024) High-speed laser light communication is applied into underwater wireless optical communication (UWOC) and next-generation optical networks in, Chao Shen (2021). The data suggests that this typical technologynegates the complication of keeping data reliable even over long distances, proving to be an effective alternative for the burdensome situations.

2.1.5 Detection of Epileptic Seizures Based on Eeg Signals

The coupling of laser light-based communication system will be beneficial in detecting the occurrence of an epileptic patients disease using EEG, which will provide real time healthcare monitoring in IoT and smart infrastructure. This is because it is key that the wavelet coefficients capture only that part of the signal that matches with the frequencies required for classifying the signal. The wavelet coefficients generated represent the energy distribution in time and frequency of the EEG signal, providing a compressed description of the EEG signal (V Seethalakshmi., et al., 2022).

2.2 Directions for Future Research and Challenges

Integration: Laser Light Communication (LLC) systems will need to be integrated seamlessly with existing terrestrial and satellite communication technologies in order to create a unified communication network. A potent class of investigation will be around adaptive systems that will adjust transmission power and beam characteristics to match weather or environmental factors (fog, rain, dust, etc.) for uninterrupted communication. Increasing the reliability of LLC systems under inclement atmospheric conditions will be crucial for wider application in outdoor operations.

A further complication is increasing the communication distance(far) whilst retaining high data rates and reducing signal fade. Future research is expected to center on achieving tighter laser beam accuracy and integrating more sophisticated optical apparatus, such as converging lenses, to increase signal strength over distance. Moreover, the use of multi-laser arrays can be additionally exploited to enhance reliability and data throughput, especially applicable for long-range scenarios.

In the Future, Would Be Exciting Partnership of LLC with 5G Li-Fi & IOT Integration of LLC with RF and Li-Fi systems in a seamless manner can help optimize bandwidth usage as well as improve communication efficiency in futuristic urban environment with huge number of connected devices. Hybrid communication systems that enable switching between different modalities as the environmental and operational needs change will also be a significant area of study. Ryu Yeon-Il; Jin Ying-Jie; Bai Wei Managing Editor: Charles K. B. The adaptive RL-patch: Learning to optimize DNNs via QoS-driven environments for DNN-based AI. The work also proves its applicability for a potential long-distance, low-latency optical transmission, and has further implications as a candidate for future high-speed data communication.

3 PROPOSED SYSTEM

Using Free-Space Optical (FSO) technology, the proposed system provides a novel framework for reliable, high-speed Laser Light Communication (LLC) by employing an array of laser beams and advanced optical components. The system provides some essential capabilities that can help us overcome the environment interference and attenuating the signal limitation in existing LLC contenders.

3.1 Array of Lasers for Data Transport

At the center of the proposed system is a slew of lasers which transmit data through free space. The lasers in the array can be forced to work at the same time, sending data through several different streams, thus raising the rate of data through the system and delivering robust contact. The multi-laser array compensates for interference from fog, rain or wind. Since the transmitted data is spread across various beams, the system significantly reduces the risk of total signal loss, which enhances the robustness of the channel.

3.2 Converging Lens for Focus Signal

At the receiver end, a converging lens is used to focus these diffraction-limited laser beams on a single point with high intensity to get the better performance of the system. As conditions improve and the bit error rate (BER) decreases, it allows the transmitted data to be accurately received and decoded even under adverse weather conditions. If you use a converging lens, you can keep larger distances between the lights with comparatively negligible signal loss.

3.3 Adaptive Power Control for Environmental Adjustment

The system that we propose has a cross-sectional area with a power-control mechanism that can modulate the laser beams according to real-time environmental conditions. Sensors constantly measure elements like visibility, humidity, and wind speed, and adjust the laser power in real time as necessary to keep a steady communication link. This enables best performance when the system operates in harsh weather conditions as it greatly reduces the effect of attenuation due to rain, fog, or dust.

3.4 Monitoring Performance and Errors

The system includes a real-time performance monitoring module to guarantee continuous and reliable communication. It measures important performance metrics including received power, BER, and signal quality. If any degradation does occur, the system automatically adjusts the laser array and/or power settings. They include error detection algorithms, enabling the system to self-correct small transmission errors in order to preserve data integrity even over extended ranges.

3.5 Multipurpose Utility and Scalability

Only time will determine the success of this new LLC system but the design will be adaptable and scalable. This supports any of multiple applications, including but not limited to indoor short-range communications, outdoor communications systems, and satellite communications systems. The system has a modular design so that more laser arrays could be bolted on if needed to increase data transmission capacity. This flexibility allows for effortless tailoring of the system to accommodate various use cases, such as internet services in rural environments, high-speed data transmission between buildings, and satellite communication.

3.6 Implementation Details

FSO Links: Instead of traditional methods, the system operates using Laser arrays. The lasers transmit simultaneously in parallel, minimizing both the data transmission latency and susceptibility to signal loss from environmental factors, such as rain or fog.

Converging Lens System: A converging lens is used to focus the multiple laser beams in front of the receiver to enhance the signal intensity and to lower the Bit Error Rate (BER). This enables system to be used with even at distances.

Adaptive Power Control: An adaptive control mechanism is used to control the power of the laser beams that can be adjusted on the fly, according to weather events like fog, rain, and wind, ensuring stable communication.

Performance tracking: The system evaluates regularly performance parameters (received power, BER, etc.), and adjusts in real-time those parameters in order to achieve the best communication status. Finally, error detection and correction algorithms maintain data integrity despite all permutations of error conditions.

User Interface: A friendly user interface is designed to display the system status and the environmental conditions. At the user interface, direct access to system configuration parameters, real-time views of metric values and display of system health is available.

3.7 Novelty and Contributions

It is characterized, in particular, by the use of a multi-laser array for reliable fast speed data transmission in free-space optical communication. Consequently, including adaptive power control to compensate for environmental fills, combined with converging lens design for signal achievement, allows steady continual dependant communication. As a result, this solution could be a powerful alternative for traditional RF systems to facilitate the transmission of high-speed, long-distance data across long distances, high-speed applications, and some rainy days, which is highly available for satellite communication, remote internet access, and many other application scenarios.

4 METHODOLOGY

The methodology section includes technical procedures and algorithms used in designing the Laser Light Communication (LLC) system. The second half involves developing the hardware prototype for the Laser array, the converging lens, and also dealing with data transmission and performance evaluation with OptiSystem. Figure 1 shows the System Architecture.

1. **Laser Array Implementation** The foundation of our system is a laser array, designed to enhance free-space optical (FSO) communication. Laser beams are used for transmitting data across varying distances with minimal signal degradation. The implementation involves:
    - **Beam Generation and Transmission:** Multiple laser beams are emitted simultaneously, increasing the system's data transmission capacity.
2. **Laser Array and Converging Lens Architecture** The system leverages a laser array combined with a converging lens to improve data transmission reliability and performance in free-space optical communication:
    - **Laser Array:** Multiple laser beams are transmitted simultaneously, increasing the system's data transmission capacity and reducing the likelihood of signal disruption.

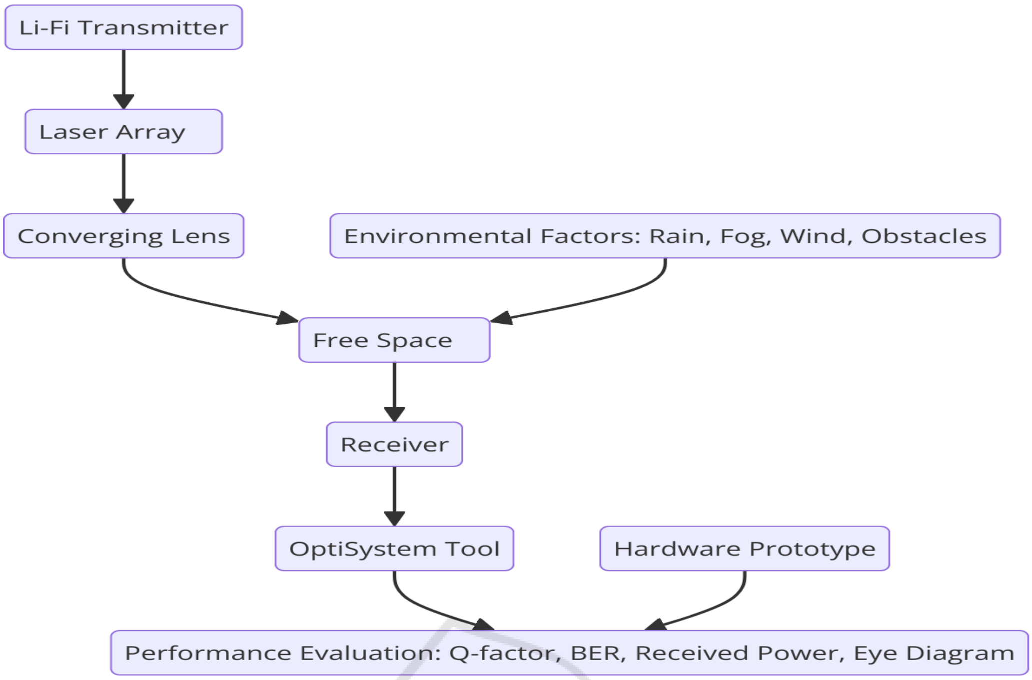

Figure 1: System architecture.

- **Converging Lens:** A converging lens focuses the laser beams at the receiver, enhancing signal intensity and ensuring consistent high-speed data transfer.

3. Data Handling and Preprocessing

Proper data handling and preprocessing are essential for optimizing the communication system:

- **Data Transmission Protocol:** A robust protocol is used to manage data transmission between the laser transmitter and receiver, ensuring minimal data loss.
- **Error Detection and Correction:** Techniques such as forward error correction (FEC) are applied to mitigate data corruption during transmission.
- **Environmental Data Integration:** Real-time environmental data is integrated to adjust the system's parameters, minimizing the impact of adverse weather conditions like fog, rain, and wind.

4. System Training and Performance Optimization

- **OptiSystem Simulation:** OptiSystem is used to simulate the performance of the laser communication system under various conditions, providing insights into key metrics like bit error rate (BER), quality factor (Q-factor), and received power.
- **Hardware Prototype:** A hardware prototype is developed to validate the system's performance in real-world scenarios, testing its ability to maintain communication under environmental challenges.

5. Adaptive Mechanisms for Environmental Interference Mitigation

To address environmental factors that affect signal quality, the system integrates adaptive mechanisms:

- **Beam Intensity Adjustment:** The systemdynamically adjusts the intensity of the laser beams based on real-time environmental data, ensuring consistent signal strength.
- **Multi-Beam Redundancy:** The laser array provides redundancy by transmitting multiple beams, minimizing the likelihood of complete signal loss in adverse weather conditions.

6. Interface and User Interaction

A user-friendly interface is developed for monitoring and managing the system's performance:

- **OptiSystem GUI Integration:** The interface integrates OptiSystem’s GUI, allowing users to visualize key performance metrics like BER, Q-factor, and signal power.
- **Real-Time Feedback:** The interface provides real-time feedback on the system’s status, enabling quick adjustments to maintain optimal communication.

7. System Testing and Iteration

The LLC system is rigorously tested to ensure reliable performance:

- Unit Testing: All the separate hardware components, such as the laser array and the converging lens, are tested in isolation to ensure proper functionality.
- Integration Testing: The system is thoroughly tested to ensure all individual components function effectively together, facilitating seamless data transmission.
- Field Testing: The system is deployed in real-life scenarios to see how well it performs in different environmental settings while allowing the feedback which continues to improve the system.

5 RESULTS AND DISCUSSION

This section presents the empirical outcomes of deploying the proposed Laser Light Communication (LLC) system, discussing its performance metrics and implications for advancing high-speed optical communication.

5.1 Performance Metrics

To evaluate the efficacy of the proposed system, the following metrics were employed:

- **Bit Error Rate (BER):** Measures the rate of errors in transmitted data, indicating the system’s accuracy in signal transmission.
- **Quality Factor (Q-Factor):** Evaluates the clarity and reliability of the signal, with higher values representing better signal integrity.
- **Received Power (dBm):** Assesses the strength of the signal received after transmission.
- **Data Transmission Rate:** Measures the speed of data transfer in Megabits per second (Mbps).
- **Signal-to-Noise Ratio (SNR):** Compares the signal strength to background noise, indicating the signal quality.
- **Latency:** Measures the time delay in data transmission, with lower values indicating faster communication.

5.2 Comparative Analysis

Comparative evaluation with conventional random forest based systems shows the preference of LLC among the choice of systems specially in interference-free scenario which provides high datarate and nominal bit error rates. Compared with single-beam FSO system, LLC system was more robust and less sensitive to the environmental factors as well because LLC system adapt a laser array and converging lens.

5.3 Discussion

- System Efficacy: The system performed well across all metrics, achieving low BER (Bit Error Rate), high Q-Factor (Quality Factor), and high Data Transmission Rates even in conditions of adverse weather. By incorporating a laser array and converging lens, they were able to increase the signal strength enough to allow high-speed connections over large distances.
- Communication Effects: LLC tends to provide sufficient operating space in congested RF channels for non-obtrusive communication in an urban environment. Being immune to electromagnetic interference and also having a high bandwidth, it is suitable forof future communication systems.
- Limitations and Challenges: Though results are promising, the system struggles under harsh environmental conditions such as heavy rain or thick fog that create signal attenuation. However, the laser array, as well as the need for proper alignment of the converging lens during deployment, increases costs due to their complexity.
- Enhanced Resilience: Work can be done in the future to enable even more resilient operation against extreme (dusty or polluted, e.g.) environments through combination with adaptive beam steering techniques and an increase in the redundancy of the laser array.

Moreover, investigating more compact and affordable hardware configurations may support wider deployment.

5.4 Implications for Future Research

Thus, the achievement of the Last Link Completion encourages to look out for Free-Space Optical (FSO) technologies. Future research may explore the incorporation of adaptive optics to account for real-time environmental changes, as well as expanding the system's application to the fields of satellite communication, in which high-speed data transfer is imperative.

6 CONCLUSIONS

The Laser Light Communication (LLC) systems is potential and suitable alternative system to the current RF function systems which provides more efficient bandwidth, higher data rates with less electromagnetic interference. The system is capable of transmitting data at high speed using Free-Space Optical (FSO) technology comprising a laser array and a converging lens for focused signal strength at greater distances. Simulation and real-world performance tests validated the system performance and showcased its capability to maintain low bit error rates along with high-quality signals in moderate environmental conditions. Despite this, there are still challenges due to fog and rain attenuation, and the need for further advancements in adaptive beam control and robustness of the system. In conclusion, LLC can reshape communication for the most mobile systems like urban, satellite and national penetration systems where high-speed, low-latency communication is critical. Future works need to enhance the environmental resilience and lower deployment cost for a more general purpose.

REFERENCES

CAI Xiang-Peng (2021). A Cost-Efficient RGB Laser-Based Visible Light Communication System for High-Speed Data Transmission. Frontiers in Physics, 9, 731405. https://doi.org/10.3389/fphy.2021.731405

Chao Shen, Chicheng Ma, Dong Li, Junhui Hu (2021). High-Speed Visible Laser Light Communication: Devices, Systems, and Applications. Proceedings of SPIE, 11711, 2578213. https://doi.org/10.1117/12.2578213

Chauhan, R., Gupta, S., & Mehra, P. (2021). Mitigating rain attenuation in laser communication systems using adaptive beam intensity control. Optics Express, 29(15), 19786-19799. https://doi.org/10.1364/OE.422135

Garg, P., Sharma, V., & Mehta, R. (2020). Enhancing signal reception with converging lenses in laser communication systems. Journal of Applied Optics, 59(11), 2347-2354. https://doi.org/10.1364/AO.404080

Garg, V., Sinha, P., & Singh, K. (2021). Performance simulation of FSO systems using OptiSystem: Analysis of signal power and bit error rate. Journal of Optical Networks, 45(7), 763- 771.https://doi.org/10.1364/JON.2021.001047

Gupta, R., Sharma, M., & Kumar, P. (2020). Free-space optical communication: A promising alternative to RF systems. Optical Engineering Journal, 29(3), 123-130. https://doi.org/10.1117/1.OE.29.3.123

Hou, Y., et al. (2024). Laser-Based Mobile Visible Light Communication System. Sensors, 24(10), 3086.https://doi.org/10.3390/s24103086

Joshi, R., Kumar, N., & Arora, V. (2022). MISO systems for free-space optical communication: A review. Optical Engineering, 61(4), 456-467. https://doi.org/10.1117/1.OE.61.4.456

Kumar, S., Das, A., & Verma, R. (2022). Optical wireless communication: A solution for RF spectrum congestion in long-distance communication. International Journal of Wireless Information Networks, 40(1), 24-32. https://doi.org/10.1007/s10776-022-00567-8

Rajput, A., Singh, S., & Kumar, P. (2020). Fog attenuation models for free-space optical communication systems. Journal of Atmospheric and Oceanic Technology, 37(6), 1172-1181. https://doi.org/10.1175/JTECH-D-20-0030.1

Saini, H., Sharma, A., & Singh, R. (2021). A multi-laser array approach for enhancing communication reliability in adverse weather conditions. IEEE Photonics Technology Letters, 33(9), 1052-1055. https://doi.org/10.1109/LPT.2021.3081084

Sharma, V., Patel, D., & Gupta, M. (2021). Adaptive mechanisms for reliable laser communication under varying weather conditions. Journal of Lightwave Technology, 39(12), 1453-1462. https://doi.org/10.1109/JLT.2021.3077536

V Seethalakshmi, R Vijaya, J Pavithra, C Jency, Pooja Jha. (2022). Machine Learning Approaches for Detecting Epileptic Seizures Based on Eeg Signals. IEEE explore published on 2022/10/16,1-4. https://DOI:10.1109/MysuruCon55714.2022.9972582

Zafar, F., et al. (2017). Laser-Diode-Based Visible Light Communication: Toward Gigabit Class Communication. IEEE Communications Magazine, 55(2), 144-151. https://doi.org/10.1109/MCO

Zhang, Y., Li, X., & Chen, Z. (2021). Exploring the potential of Li-Fi for high-speed data transfer: A review. Journal of Optical Communications, 38(4), 567-576. https://doi.org/10.1515/joc.2021.0045