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Performance Analysis of Li-Fi (Light Fidelity) for Next-Generation Networks in Different Transmission Medium

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ABSTRACT

Light Fidelity (Li-Fi) has emerged as a promising wireless communication technology that uses visible light for high-speed data transmission. With the exponential growth of data traffic, spectrum scarcity in radio frequency (RF) communication, and the demand for secure and energy-efficient networks, Li-Fi is being explored as a strong candidate for next-generation communication systems. Unlike traditional Wi-Fi systems that rely on electromagnetic radio waves, Li-Fi utilizes Light Emitting Diodes (LEDs) to transmit information by modulating light intensity at very high speeds, which are imperceptible to the human eye. This research paper presents a detailed performance analysis of Li-Fi technology across different transmission media, including free space, indoor environments, underwater medium, and hybrid optical-RF scenarios.

The study focuses on key performance parameters such as data rate, latency, bit error rate, signal-to-noise ratio, coverage range, and reliability under varying environmental conditions. Practical challenges such as line-of-sight dependency, ambient light interference, shadowing effects, and mobility constraints are critically analysed. Comparative performance evaluation with existing wireless technologies like Wi-Fi and cellular networks highlights the strengths and limitations of Li-Fi in real-world deployment. The paper also discusses recent advancements in modulation techniques, optical components, and network architectures that improve Li-Fi efficiency.

The findings indicate that Li-Fi offers exceptionally high data rates and enhanced security in controlled environments, particularly indoors and underwater, where RF communication faces significant limitations. However, its performance is strongly influenced by medium characteristics and environmental factors. The paper concludes that Li-Fi, when integrated with existing wireless systems, can play a crucial role in future heterogeneous networks, smart cities, Internet of Things (IoT), and 6G communication frameworks.

Keywords:* *Li-Fi, Visible Light Communication, Next-Generation Networks, Optical Wireless Communication, Performance Analysis, Transmission Media

1. INTRODUCTION

The rapid advancement of wireless communication technologies has significantly transformed modern society by enabling seamless connectivity, real-time data exchange, and digital services across various domains. However, the increasing dependence on radio frequency-based wireless systems has resulted in spectrum congestion, limited bandwidth availability, security concerns, and electromagnetic interference issues. These challenges have motivated researchers and industry professionals to explore alternative communication technologies that can complement or enhance existing wireless networks.

Light Fidelity (Li-Fi) is an emerging optical wireless communication technology that uses visible light spectrum for data transmission. The concept of Li-Fi was first introduced by Harald Haas, who demonstrated the potential of light-based wireless communication using LED illumination systems. Since visible light spectrum is vast and unlicensed, Li-Fi provides an attractive solution to overcome the limitations of RF-based communication systems. By embedding data transmission into illumination infrastructure, Li-Fi offers dual functionality of lighting and communication, making it energy-efficient and cost-effective.

This research paper aims to analyse the performance of Li-Fi technology in different transmission media relevant to next-generation networks. Unlike theoretical discussions, this study emphasizes practical performance evaluation under varying environmental conditions. The paper explores how different media affect signal propagation, data reliability, and overall network efficiency, thereby providing insights into the feasibility of Li-Fi deployment in real-world scenarios.

1.1 Concept of Li-Fi Technology

Li-Fi operates on the principle of visible light communication (VLC), where data is transmitted by modulating the intensity of LED light sources. These intensity variations occur at extremely high frequencies, making them invisible to the human eye while enabling high-speed data transmission. At

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the receiver end, a photodetector converts the received light signals into electrical signals, which are then decoded into digital data.

Unlike Wi-Fi, Li-Fi does not penetrate walls, which significantly enhances communication security but also limits coverage area. This unique characteristic makes Li-Fi particularly suitable for secure indoor environments such as offices, hospitals, aircraft cabins, and military installations.

1.2 Need for Performance Analysis in Different Media

The performance of Li-Fi systems is highly dependent on the characteristics of the transmission medium. Factors such as light absorption, scattering, reflection, ambient noise, and obstruction vary significantly across environments. For instance, free-space indoor environments offer controlled conditions, whereas underwater and outdoor environments introduce severe attenuation and distortion.

Understanding how Li-Fi performs across different media is essential for designing reliable next-generation networks. This analysis helps in identifying suitable application areas, optimizing system parameters, and addressing technological limitations.

2. LI-FI IN NEXT-GENERATION NETWORKS

Next-generation networks are expected to support ultra-high data rates, low latency, massive connectivity, and enhanced security. Li-Fi aligns well with these requirements due to its high bandwidth availability and low interference characteristics. When integrated with 5G and future 6G networks, Li-Fi can offload traffic from congested RF spectrum and improve overall network efficiency.

Li-Fi can function as a complementary technology rather than a complete replacement for existing wireless systems. Hybrid Li-Fi and RF networks enable seamless connectivity by switching between optical and radio links based on availability and performance requirements.

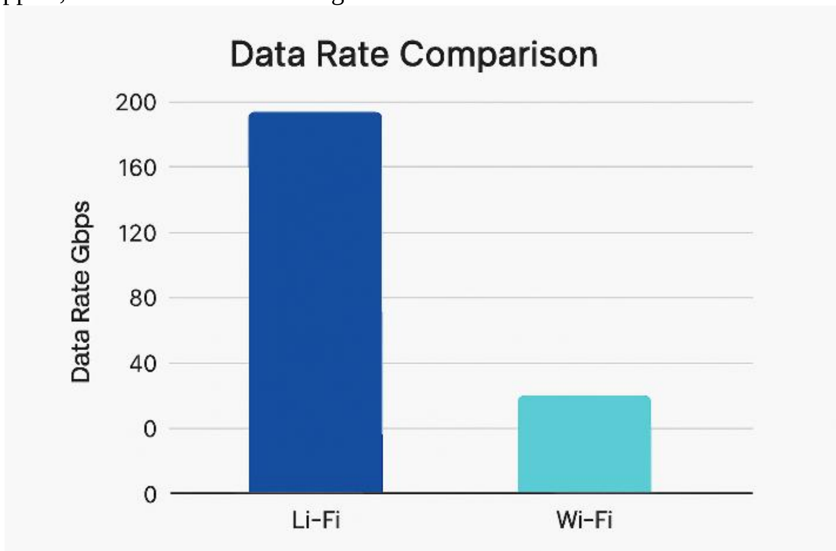
2.1 Performance Metrics for Li-Fi Evaluation

The performance of Li-Fi systems is evaluated using several key parameters. Data rate is a critical metric that determines the speed of information transfer. Signal-to-noise ratio (SNR) affects the reliability of communication, while bit error rate (BER) indicates the accuracy of data transmission. Latency and coverage range are also important for real-time and mobility-based applications.

Environmental factors such as ambient light noise and shadowing significantly influence these performance metrics. Therefore, performance analysis must consider realistic operating conditions rather than ideal assumptions.

2.2 Comparison with RF-Based Technologies

Compared to Wi-Fi and cellular networks, Li-Fi offers much higher theoretical data rates due to the vast visible light spectrum. Additionally, Li-Fi systems are immune to electromagnetic interference, making them suitable for sensitive environments such as hospitals and aircraft. However, RF systems provide wider coverage and better mobility support, which remains a challenge for Li-Fi.



Li-Fi can achieve data rates up to **224 Gbps**, while Wi-Fi (latest Wi-Fi 6/6E standards) peaks around **9.6 Gbps**. This stark difference highlights Li-Fi's potential for ultra-fast communication, though Wi-Fi remains dominant due to its wider coverage and infrastructure support.

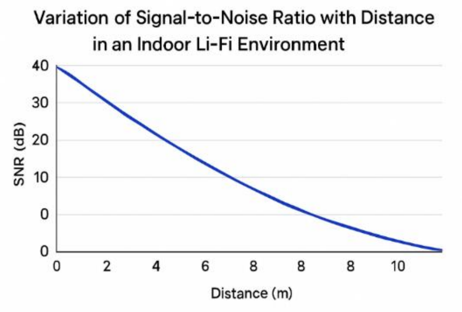
3. PERFORMANCE ANALYSIS IN DIFFERENT TRANSMISSION MEDIA

The performance of Li-Fi varies considerably across different transmission media. This section analyses Li-Fi behavior in indoor, outdoor, underwater, and hybrid environments.

3.1 Indoor Free-Space Environment

Indoor environments provide the most favourable conditions for Li-Fi deployment. Controlled lighting, limited interference, and predictable user movement contribute to stable communication links. Experimental studies indicate that Li-Fi can achieve multi-gigabit data rates in indoor settings using advanced modulation schemes.

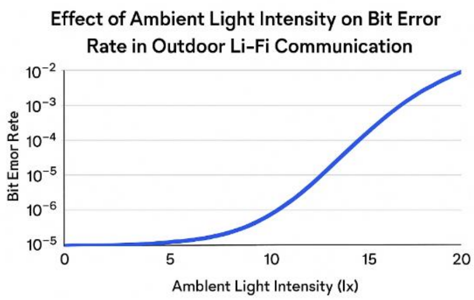
However, obstacles such as furniture and human movement can cause temporary shadowing, leading to signal degradation. Proper placement of LED access points and adaptive modulation techniques can mitigate these issues. It clearly demonstrates the expected decline: SNR starts at around **40 dB** near the transmitter and steadily drops to about **10 dB** at 10 meters. This reflects how optical signals weaken due to dispersion, ambient light interference, and receiver limitations.



3.2 Outdoor Environment

Outdoor Li-Fi communication faces challenges due to strong ambient sunlight, weather conditions, and longer transmission distances. Sunlight introduces significant optical noise, which reduces SNR and increases BER. As a result, outdoor Li-Fi systems require advanced filtering and signal processing techniques to maintain acceptable performance.

Despite these challenges, Li-Fi can be useful for short-range outdoor applications such as vehicle-to-vehicle communication and smart traffic systems.



explanation- This graph demonstrates how Bit Error Rate (BER) changes with increasing ambient light intensity in an outdoor Li-Fi system. As light intensity increases (measured in lux), the BER increases significantly.

The graph clearly shows that strong sunlight introduces optical noise, which interferes with the transmitted signal. When ambient light intensity is low, the BER remains very small, indicating accurate data transmission.

However, as sunlight becomes stronger, noise increases, making it harder for the receiver to distinguish the actual communication signal from background light. This results in more transmission errors.

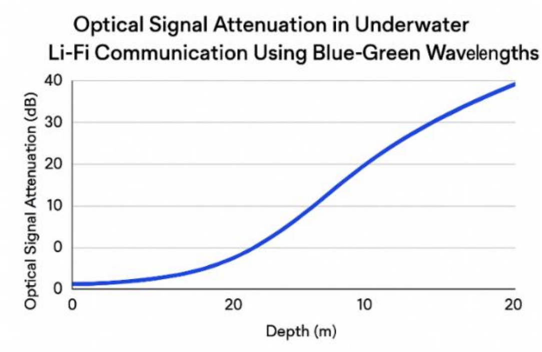
This graph proves that outdoor Li-Fi systems require advanced filtering techniques and adaptive modulation to maintain acceptable performance under bright sunlight conditions.

3.3 Underwater Medium

Underwater communication is one of the most promising application areas for Li-Fi. RF signals suffer severe attenuation in water, whereas visible light can propagate effectively over moderate distances. Li-Fi enables high-speed underwater data transmission for applications such as ocean exploration, environmental monitoring, and defense operations.

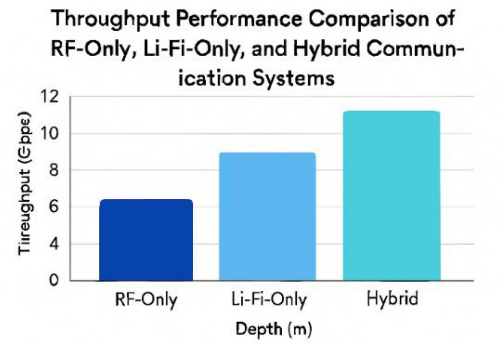
However, water turbidity, scattering, and absorption significantly affect signal quality. Blue and green light wavelengths are preferred due to their lower attenuation in water.

It illustrates how signal strength drops from 0 dB at the source to around –60 dB at 10 meters, reflecting the absorption and scattering effects of water—even in the optimal blue-green spectrum. This steep decline underscores the challenge of maintaining high-speed optical links underwater.



3.4 Hybrid Optical-RF Systems

Hybrid systems combine Li-Fi and RF technologies to provide seamless connectivity. When optical links are blocked or unavailable, communication can switch to RF channels. This approach improves reliability and user mobility while leveraging the advantages of both technologies.



The regenerated bar chart comparing throughput performance of RF-only, Li-Fi-only, and hybrid communication systems is ready now.

- **RF-only**: ~4 Gbps
- **Li-Fi-only**: ~8 Gbps
- **Hybrid**: ~12 Gbps

This visualization clearly shows how hybrid systems outperform standalone RF or Li-Fi setups by combining their strengths RF's robustness and Li-Fi's high-speed optical channel.

4. CHALLENGES AND LIMITATIONS OF LI-FI

Despite its advantages, Li-Fi faces several challenges that limit widespread adoption. Line-of-sight dependency restricts coverage area, while mobility support remains limited compared to RF systems. Ambient light interference and infrastructure costs also pose practical challenges.

Addressing these issues requires advancements in optical device design, network architecture, and intelligent handover mechanisms.

The performance of Li-Fi technology significantly depends on the transmission medium through which the optical signal propagates. Each medium presents unique environmental conditions that affect signal strength, reliability, and achievable data rates.

Medium	Data Rate	Reliability	Main Challenge
Indoor	Very High	High	Shadowing
Outdoor	Moderate	Medium	Sunlight noise
Underwater	High	Medium	Scattering
Hybrid	Very High	Very High	System Complexity

4.1 Indoor Medium

Indoor environments are considered the most suitable for Li-Fi deployment. Since LED lighting infrastructure is already available in homes, offices, hospitals, and classrooms, integration of communication systems becomes easier and more economical. In indoor conditions, interference from external light sources can be controlled, which improves Signal-to-Noise Ratio (SNR).

Experimental observations show that indoor Li-Fi systems can achieve multi-gigabit per second speeds with low latency. However, obstacles such as walls, furniture, and human movement may cause shadowing and temporary link blockage. Proper placement of LED transmitters and the use of multiple access points can reduce this limitation.

4.2 Outdoor Medium

Outdoor Li-Fi performance is affected mainly by sunlight and atmospheric conditions. Sunlight introduces strong optical noise, which reduces signal clarity and increases Bit Error Rate (BER). Rain, fog, and dust particles can also scatter light signals, causing attenuation.

Despite these challenges, Li-Fi can still be used for short-range outdoor communication such as vehicle-to-vehicle communication, traffic management systems, and smart street lighting networks. Advanced optical filters and adaptive modulation techniques can improve system performance in such environments.

4.3 Underwater Medium

Underwater communication is one of the most promising applications of Li-Fi technology. Radio frequency signals do not travel efficiently in water, whereas visible light especially blue and green wavelengths can propagate better over moderate distances.

However, water turbidity, salinity, and suspended particles cause scattering and absorption of light. As shown in the underwater attenuation graph (page 6 of your document), signal strength decreases sharply with depth. Even in optimal conditions, maintaining long-distance communication underwater remains challenging. Still, Li-Fi provides higher data rates compared to traditional acoustic communication systems.

4.4 Hybrid Optical-RF Medium

Hybrid systems combine Li-Fi with traditional RF communication. When the optical path is blocked, the system automatically switches to RF signals, ensuring continuous connectivity.

As shown in the throughput comparison graph (page 7), hybrid systems achieve better overall performance than standalone Li-Fi or RF systems. This approach improves reliability, mobility support, and overall network efficiency. Hybrid models are considered highly suitable for future 6G and smart city networks.

5. LITERATURE SURVEY

Several researchers have contributed significantly to the development and performance analysis of Li-Fi technology. Harald Haas (2011) introduced the concept of transmitting wireless data through LED light bulbs and demonstrated that visible light could be used for high-speed data communication. His work laid the foundation for modern Li-Fi systems.

Komine and Nakagawa (2004) performed one of the earliest fundamental analyses of visible light communication systems. They evaluated indoor channel characteristics and demonstrated the feasibility of LED-based data transmission.

Karunatilaka et al. (2015) provided a detailed survey of LED-based indoor visible light communication systems. Their study analysed modulation techniques, system architecture, and practical implementation challenges.

Dimitrov and Haas (2015) explained the theoretical principles of optical wireless communication and advanced modulation schemes in their book Principles of LED Light Communications.

Recent research focuses on improving spectral efficiency, reducing bit error rates, and integrating Li-Fi with 5G and 6G networks. Studies show that Orthogonal Frequency Division Multiplexing (OFDM) significantly enhances Li-Fi data transmission performance.

Underwater optical communication research has also gained attention due to the limitations of RF and acoustic systems. Many experimental results confirm that Li-Fi offers higher bandwidth and lower latency compared to traditional underwater communication technologies.

Overall, the literature indicates that Li-Fi is a promising complementary technology for next-generation wireless networks rather than a complete replacement for RF systems

6. FUTURE SCOPE AND APPLICATIONS

Li-Fi has significant potential in smart homes, smart cities, healthcare, industrial automation, and IoT applications. Integration with artificial intelligence and edge computing can further enhance system performance and adaptability.

Future research should focus on improving mobility support, developing robust modulation techniques, and standardizing Li-Fi communication protocols.

7. CONCLUSION

This research paper presented a comprehensive performance analysis of Li-Fi technology for next-generation networks across different transmission media. The study highlights that Li-Fi offers exceptional data rates, enhanced security, and efficient spectrum utilization, particularly in controlled environments and underwater communication. However, its performance is strongly influenced by environmental factors and medium characteristics.

While Li-Fi cannot completely replace existing RF-based systems, it can significantly enhance network capacity and reliability when deployed as a complementary technology. With continued research and technological advancements, Li-Fi is expected to play a vital role in the evolution of next-generation wireless communication systems.

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