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Li-Fi Technology in Optical Communication Systems: A Review

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Abstract

This paper explores Light Fidelity (Li-Fi) technology, which uses light-emitting diodes (LEDs) to send data, providing an alternative to traditional WiFi that uses radio signals. Li-Fi takes advantage of the unused 300 Terahertz optical spectrum, helping to reduce overcrowding in radio frequency spectrums used by other technologies. The paper discusses the implementation of Li-Fi, compares it with WiFi, and describes some challenges and limitations. The goal is to provide clear insights into how Li-Fi performs, the applications, and the potential issues, showing how it could pave the way for wireless communication for various applications such as vehicles, hospitals, and smart lighting systems.

Keywords- Visible commutation, Li-Fi, LED, high speed, wireless technology.

I. INTRODUCTION

Light fidelity (Li-Fi) is a prominent technology in today's communication systems. Unlike conventional Wi-Fi, Li-Fi relies on light-emitting diodes (LEDs) for high-speed and efficient data transmissions. In contrast to radio waves, Li-Fi utilizes light and employs LED lamps with transceivers for information transmission and reception, diverging from the traditional use of wireless modems [1–4]. The increasing demand for high-data-rate applications pushes mobile communications technology to the ultimate edge every day, causing congestion in radio frequency (RF) spectrum limits. One solution to these challenges is Li-Fi technology, which utilizes the unlicensed and unused 300 Terahertz optical spectrum for wireless communications, as seen in Figure 1 [5,6].

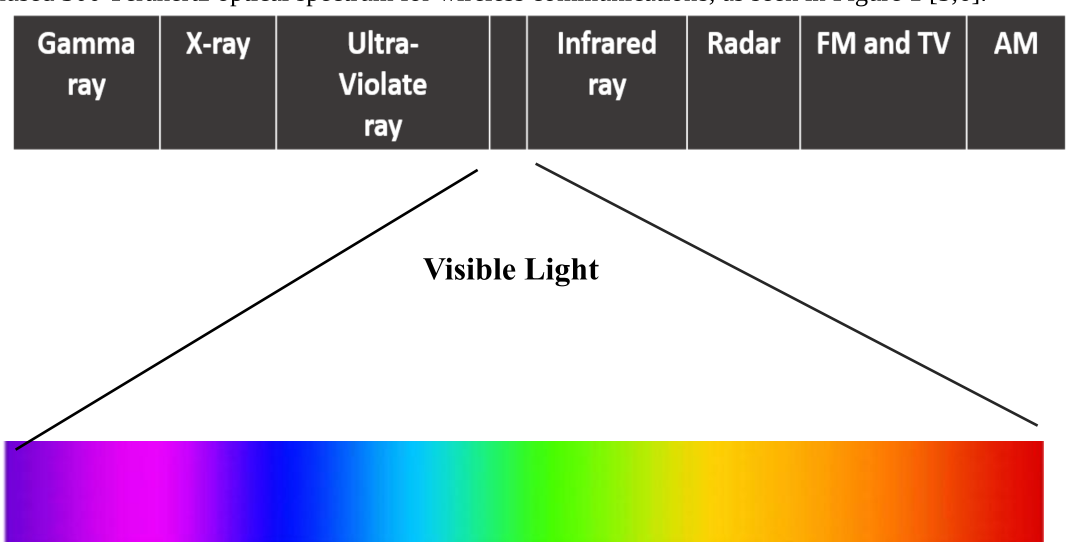

Figure .1 Frequency Spectrum with violet marked area for Li-Fi frequencies.

This technology will not only ease the challenges on conventional networks but also introduce a new dimension to the range of wireless communication systems to optimize the data rate and reduce the burden on traditional networks. A diverse application can be utilized out of Li-Fi technology, including vehicle-to-vehicle communications, health care, smart lighting, indoor positioning, and underwater communications. These applications and others will be discussed later in this paper.

This paper aims to clarify the installation processes of Li-Fi technology, followed by a comparative analysis between WiFi and Li-Fi, exploring their differences. Additionally, the paper addresses challenges inherent in applying Li-Fi technology and conducts analytical assessments. Then, the potential of the future will be discussed. Through this comprehensive examination, the study provides valuable insights into the deployment, comparative features, and challenges associated with Li-Fi technology across various contexts.

2. Li-Fi Configurations:

In wireless communication, Li-Fi is considered the 5th Generation of wireless communication (5G) technology that has shown impressive progress, reaching peak speeds of 8 Gbps from a light source. This progress led to the creation of entire cellular networks based on Li-Fi technology [7].

Figure 2 shows that Li-Fi has some applications inside the house that will remove interference from the wifi network to provide better throughput and more resilience for feasible equipment.

Li-Fi has a symmetric and Asymmetric system. First, in the symmetric system, Li-Fi manages commutation in both directions, using visible light for the downlink and infrared for the uplink. Second, the asymmetric system uses Li-Fi for the downlink with visible light and WiFi for the uplink. This combined network of Li-Fi and WiFi brings benefits like consistent coverage, increased capacity, and faster response time [8-10]. For example, in the symmetric system, Li-Fi handles commutation in both directions with visible light, showcasing its versatility and potential to improve wireless networks by offering broad coverage and efficient data transfer.

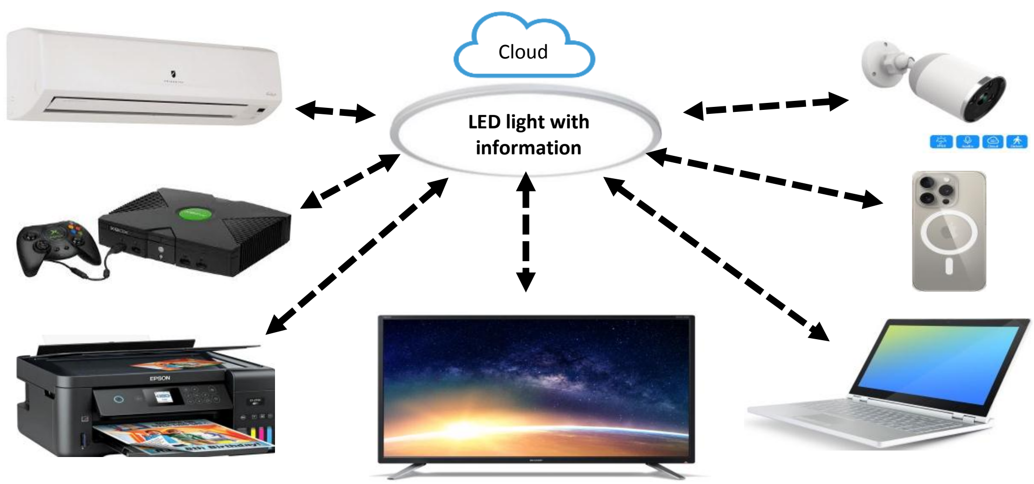

Figure .2 Some Visible light communications via Li-Fi technologies: air conditioning, smart printers, smart TVs, laptops, phones, etc.

II. COMPARISON BETWEEN LI-FI AND WI-FI

According to the article in [10], Li-Fi and Wi-Fi exhibit congestion, density, security, safety, and speed distinctions. Figure 3 shows the difference in terms of Wi-Fi and Wi-Fi connection range. Wi-Fi can reach up to 30 meters away from the access point. However, Li-Fi can connect up to 10 meters away.

Figure .3 Wifi and Li-Fi different ranges.

WiFi may encounter congestion as the number of connected devices increases, whereas Li-Fi can add more users simply by adding additional light sources. The contemporary emphasis on internet efficiency and safety underscores the significance of these technological differentiators. Notably, Li-Fi is supposed to exceed WiFi in terms of performance, with reported speeds allegedly 1000 times faster than traditional WiFi [10,12].

Regarding the security term, Li-Fi is considered more secure due to the confined propagation of the light signal, preventing penetration through walls advantage not shared by WiFi signals. In summary, Li-Fi offers enhanced communication security compared to WiFi. However, it is crucial to acknowledge that indoor Li-Fi communication may face vulnerabilities if there are leaks in the walls, potentially exposing intruders to security threats and data spoofing [12].

Table 1 shows detailed differences between Li-Fi and WiFi technologies, focusing on aspects such as capacitance, standards, transfer medium, data transfer rates, security, coverage range, and cost. Table 2 presents a comparative analysis of different types of networks and communication technologies, highlighting the main applications, fees, power requirements, and noise levels.

TABLE 1: outlines of major variations between LI-FI and WIFI [14–16]

variations	**Li-Fi**	**WiFi**
Capacitance	10^4 times bigger than WiFi	Less [13]
Standard	IEEE802.15.7	IEEE802.11b
Transfer medium	Visible Light	Radio wave
Data transfer rate	Faster transfer speed (>1 Gbps)	Data Transfer speed (150 Mbps)
Security	The signal's inability to pass through walls makes the network secure against outsider hacking.	good
Coverage Range	10 meters	20-100 meters
Cost	cheap	priced

TABLE 2: Wireless Network performance [17,18].

Type	**Application**	**Cost**	**Noise**	**Power**
PAN personal area network	Zigbee, Bluetooth	Low	Relative low	Low
LAN local area network	WiFi	High	Maybe high	High
WAN wide area network	Connecting cities, mobile phone communication	High	Can be high	High
optical wireless commutation	Longe range high bandwidth	Very low	Robust, limited by weather	In mW range
Li-Fi	Alternative office network	Low if used as illumination	Robust indoors interferes with sunlight	Low

To seek steamless coverage, both techniques can be combined to cover the internet for the entire area, knowing that overlapping both frequencies will not harm interferences as they are different spectrums, as seen in Figure 4 [41]. While WiFi surpasses in providing comprehensive wireless coverage for buildings, Li-Fi stands out for its ability to deliver dense wireless data convergence in confined spaces. Recognizing these points, the two technologies can be viewed as complementary. Li-Fi outperforms WiFi regarding bandwidth, efficiency, connectivity, and security, contributing to a comprehensive understanding of their respective strengths and applications [13].

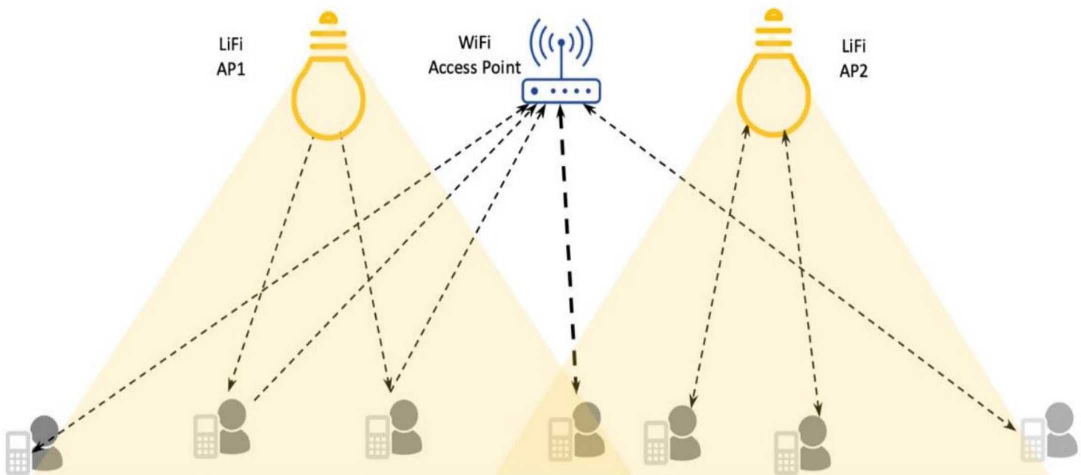

Figure .4 WiFi and Li-Fi overlap to ensure seamless coverage.

III. LI-FI APPLICATIONS

Li-Fi has many applications. This section will focus on Vehicle-to-Vehicle (V2V) communication, Li-Fi in Hospitals, smart lightning, indoor positioning, underwater communications, and wireless internet.

4.1 **V2V communication:** Li-Fi technologies integrated into V2V communication systems offer novel avenues for enhancing traffic efficiency, promoting road safety, and enabling cutting-edge applications [19]. The integration can either be as a standalone communication system within vehicles or as part of an overreaching V2V communication framework. Li-Fi can be used as an early accident detection system by utilizing driver and vehicle speed sensors, sending notifications when the driver is unaware, or the distance between vehicles is too close [20]. Such technology can prevent collisions at the front and rear of vehicles, employing LED and photodiodes as receivers and circuits directly connected to brake sensors to ensure cost-effectiveness [21].
The car front headlights can function as transmitters and photodiodes as receivers, achieving high data rates with a transmission distance of 4.5 meters. Some modulation techniques, like pulse width modulation (PWM), can extend the broadcast range to 40 meters [23].
LED displays facilitate vehicle communication due to high frequency and flexibility in electromagnetic interference. This approach requires less transmission power than traditional car lamps, ensuring effectiveness and safety. The chosen transmission method is Manchester encoding, with a 20 m distance between cars [24].
The Li-Fi-based V2V communication system aims to prevent collision by sending emergency text messages to nearby vehicles. The system demonstrates high bit rate capabilities and cost-effectiveness, utilizing GPS for driver tracking and GSM for alerts. Implementation involves Arduino, with future considerations for Raspberry Pi and a camera for more comprehensive monitoring [25].
Challenges in vehicle communication systems include different spatial distributions, path losses, and channel characteristics. Global positioning struggles with vehicle obstruction recognition, leading to delays in the V2V system's response [26]. A study in [28] explores the use of Li-Fi communication for sending text messages via the GSM system, incorporating Arduino for implementation.
To address vehicle blockages in V2V communication, a backpropagation neural network (BPNN) is trained using measurements as training datasets, achieving an identification accuracy of about 97%. This effectively identifies obstacles and ensures the system's correctness in the V2V communication system [27].
An IoT-based system aims to reduce road accidents by addressing causes such as poor road visibility, false estimation of nearby vehicles, and driver delay in hitting the brake. Visual and audio alerts and distance measurement features contribute to safer driving practices [29].
4.2 **Hospital:** Efficient medical data management within a hospital setting necessitates thoughtful consideration of data streaming and storage. As shown in Figure. 5, when transmitting patient data to adjacent rooms or the cloud, employing specialized software becomes imperative to discern and organize information entry. Utilizing a centralized database for patient files is pivotal, especially when distributing files to other rooms or healthcare professionals. Each file captures comprehensive health parameters specific to an individual patient by uploading patient data to the cloud in a file. This approach facilitates targeted access for concerned authorities or doctors, streamlining the retrieval process and enabling prompt actions or interventions. The hospital repository retains these files, providing a valuable resource for recurrent health issues. This system enhances treatment efficacy and responsiveness by providing doctors with real-time access to patient data before their physical presence, minimizing delays during emergencies. Periodic monitoring and cloud storage ensure that health parameters are consistently updated, appended, and secured, with rigorous data correction and privacy algorithms in place [29-32].

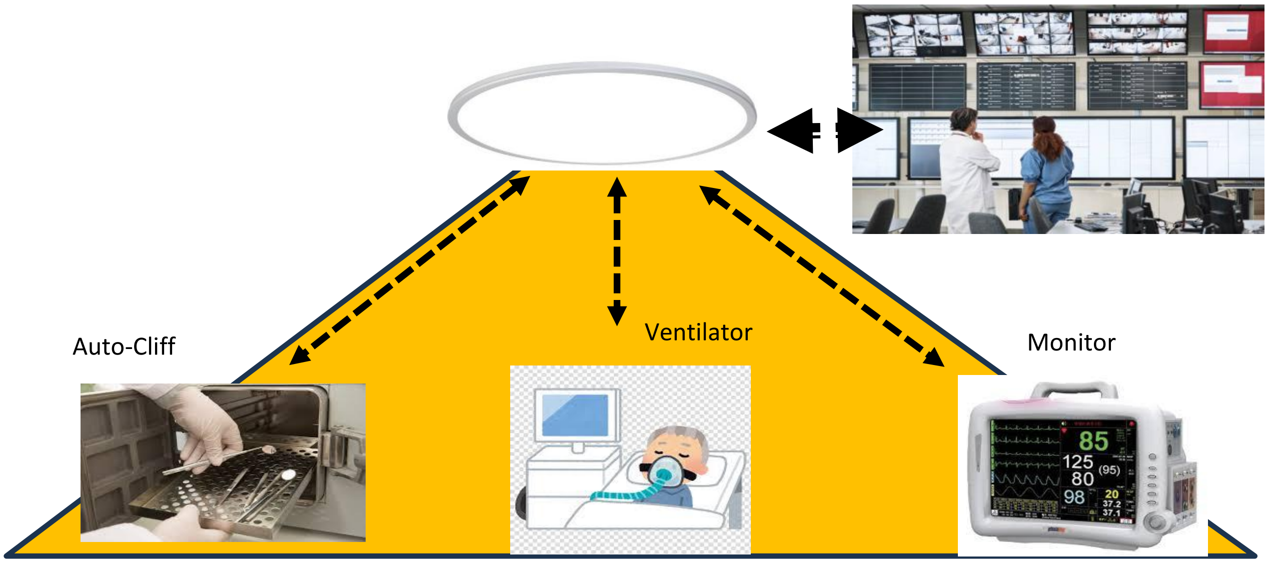

Figure .5 Overview of Li-Fi applications.

4.3 Smart lightning: Integration with smart lighting systems presents an innovative path for enabling data communication while simultaneously providing light. This interaction not only enhances energy efficiency but also contributes to improved connectivity. By leveraging visible light communication (VLC), smart lighting systems become multifunctional, serving both lighting and data transmission purposes [33,34]

4.4 Indoor Positioning: Integrating VLC into indoor positioning systems introduces a breakthrough in accurate tracking and location services within enclosed spaces. This technology utilizes light signals to enable precise indoor positioning, offering advantages in various applications such as navigation and object tracking [35,36].

4.5 Underwater Communications: Li-Fi unique ability to transmit data through water using light signals presents a transformative solution for underwater sensor networks and insea applications. This capability opens new possibilities for reliable, high-speed communication in aquatic environments [37,38].

4.6 Wireless Internet: Li-Fi technology stands out as a provider of high-speed wireless communication, offering an alternative or complement to traditional wireless internet solutions. With its potential for increased bandwidth, efficiency, and security, Li-Fi contributes to advancing wireless communication [39,40].

IV. CHALLENGES AND LIMITATIONS

In the real world, Li-Fi technology faces challenges and limitations that may obstruct its widespread adoption and deployment. As we said earlier, limited Range is one of the primary limitations of Li-Fi due to its relatively short range compared to traditional WiFi. Li-Fi signals can only travel as far as light can, which means they are typically restricted to the range of the light source. This can restrain the practical application of Li-Fi in larger indoor spaces or outdoor environments [42].

Another limitation is the Line-of-Sight Requirement for Li-Fi communication, which typically requires a direct line of sight between the transmitter (LED light source) and the receiver (photo-detector). Any obstruction between the transmitter and the receiver can disrupt the signal, leading to potential connectivity issues [43].

Furthermore, interference from ambient light such as sunlight or other artificial lighting in the environment can degrade signal quality and impact the reliability of commutation. Particularly in environments with fluctuating light conditions [44].

Unlike radio waves in WiFi, light waves in Li-Fi cannot penetrate through solid objects that the receiver may be behind. This limitation restricts the ability of Li-Fi signals to pass through walls or obstacles, thereby limiting its applicability in scenarios requiring seamless connectivity across different rooms or floors [45].

In terms of cost-effectiveness, deploying a Li-Fi structure may include high upfront costs, including installing LED lighting fixtures equipped with Li-Fi transmitters and photodetectors. Additionally, specialized Li-Fi-enabled devices may be required, which can further increase the overall implementation costs.

Scaling Li-Fi networks to accommodate many users in densely populated areas may pose scalability challenges. As the number of connected devices increases, managing network congestion and ensuring consistent performance becomes more complex [46].

Lastly, the limitation of security concerns will be discussed in the next section.

V. SECURITY AND PRIVACY CONSIDERATIONS

Security and privacy considerations are crucial aspects of any wireless technology. In Li-Fi technology implementation, ensuring that transmitted over light waves remains confidential is not an easy task. Below are some key security and privacy considerations for Li-Fi:

a) Encryption: employing robust encryption algorithms such as advanced encryption standards (AES) is essential to protect data transmitted over Li-Fi networks. Encryption ensures that data is securely encoded, making it unreadable to unauthorized entities attempting to intercept or eavesdrop on the commutation.

b) Authentication and key management: implementing strong authentication mechanisms helps verify the identity of devices attempting to connect to the Li-Fi network. This prevents unauthorized access and ensures that only authenticated devices can access the network resources [47].

c) Physical security and interference mitigation: since Li-Fi signals are confined to the range of the light source, physical security measures are crucial to prevent unauthorized access to a transmission medium. Li-Fi depends on visible light, which can be received through a window glass. Therefore, the implementation of such technology needs to be addressed via techniques such as beamforming to minimize interference intercept with other users and improve protection [48].

d) Monitoring and auditing: implementing a robust monitoring and auditing mechanism enables continuous network activity monitoring and detection of irregular behavior or security incidents [49]. Regular security audits help identify vulnerabilities and ensure devotion to security best practices

VI. RESEARCH TRENDS AND FUTURE DIRECTIONS

Researchers are exploring the integration of Li-Fi with existing wireless commutation technologies such as WiFi to create hybrid Li-Fi systems [50,51]. The hybrid systems leverage the strengths of both Li-Fi and WiFi, offering enhanced coverage, reliability, and flexibility in communication.

Another trend called high-speed Li-Fi is underway to improve the data transmission rates of Li-Fi systems, enabling faster commutation speeds comparable to even passing those of traditional WiFi networks. Advancements in modulation techniques, signal processing algorithms, and hardware components contribute to achieving higher throughput in Li-Fi systems [52]. Li-Fi technology shows promise for indoor positioning and navigation applications, offering high-accuracy location tracking capabilities in environments where GPS signals are unreliable or unenviable. Research focuses on developing Li-Fi-based position algorithms and infrastructure for applications such as asset tracking, indoor navigation, and augmented reality [53].

Further, Li-Fi is being utilized as a wireless connectivity solution for Internet of Things (IoT) devices, enabling high-speed data exchange and low-latency commutation in IOT ecosystems. Research efforts include developing energy-efficient Li-Fi transceivers, protocols, and network architectures optimized for IoT applications [54]. Integration of Li-Fi with 5G cellular networks, especially the mmWave [55], is another trend that is increasing the demand for high-speed data transmission in dense urban environments. Hybrid Li-Fi/5G systems offer complementary benefits, including increased capacity, coverage, and spectrum efficiency.

The future direction for Li-Fi technology is characterized by continued innovation, widespread adoption, and transformative applications across various domains. Some of the key future directions and potential outcomes for Li-Fi include

I. **Li-Fi for beyond 5G (B5G) applications:** as the demand for ultra-high-speed, low-latency communication continues to grow, Li-Fi technology may play a significant role in beyond 5G (B5G) and 6G communication systems, future Li-Fi systems may support massive connectivity, tactile internet, holographic communication, and other advanced B5G use cases, enabling transformative applications in healthcare, entertainment and beyond [56].

II. **Li-Fi for space communication:** Li-Fi technology holds promise for space communication applications, offering high-speed data transmission and reliable connectivity in space missions, satellite communications, and space habitats. Further developments may involve deploying Li-Fi systems on spacecraft, lunar bases, and interplanetary missions, enabling real-time data exchange and communication in space environments [57].

III. **Li-Fi for next-generation display technologies**: Li-Fi technology can be integrated with next-generation display technologies such as micro-LEDs and OLEDs to enable high-speed data communication display capabilities. Future-enabled displays may support wireless video streaming, augmented reality(AR), virtual reality (VR) [58-60], and immersive gaming experiences, enhancing user interaction and entertainment.

VII. CONCLUSIONS

Our paper studies the Li-Fi technology and investigates different applications of this technology in our lives. We explore V2V communication systems, healthcare, smart lighting, indoor positioning, fiber internet, and underwater communications. Firstly, V2V communication emphasizes how Li-Fi can help detect and prevent accidents early on, making roads safer using simple LED and photodiodes. Different hybrid systems can work together with other communication technologies for better connections.

In healthcare, our paper explores how Li-Fi can streamline patient data management within hospital settings. We discuss the advantages of uploading standardized files to the cloud, providing real-time access to doctors, and ensuring prompt responses to medical emergencies. The emphasis on data security and correction algorithms underscores the e importance of safeguarding patient privacy. Integrating Li-Fi with smart lighting systems is another focal point, showcasing how this combination enhances energy efficiency and opens up new possibilities for data communication within illuminated spaces. We analyze how VLC transforms smart lighting into a multifunctional tool. Indoor positioning systems utilizing Li-Fi are examined for their potential to provide highly accurate tracking and location services. We explore t the advantages of employing visible light communication for navigation and asset tracking within enclosed spaces.

Furthermore, our paper highlights Li-Fi's unique capability to transmit data through water, addressing the specific needs of f underwater sensor networks and subsea applications. Additionally, we discuss Li-Fi as a high-speed wireless internet, emphasizing its potential contributions to the evolution of the paper; we rely on wireless alternative communication systems. Throughout, we acknowledge the transformative impact of Li-Fi technology while recognizing challenges that need to be addressed for its widespread adoption. By critically reviewing the literature and synthesizing findings from various studies, our paper contributes to a comprehensive understanding of Li-Fi, its applications, and its potential implications for the future of wireless communication.

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