Seamless Connectivity in Mobile Li-Fi: A Survey of Link Recovery Techniques for Dynamic Wireless Environments

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Abstract
Li-Fi (Light Fidelity) has become a prospective substitute to the conventional wireless technologies of wireless communication, and it allows transferring fast, safe, and spectrum-efficient data over visible light. Nonetheless, its

implementation in mobile and dynamic settings has been seen to be hampered by frequent link failure on account of the line-of-sight (LOS) requirement, the small coverage areas, and sensitivity with regards to user mobility. High-speed and helpful recovery of the links are thus a necessity to provide a smooth texting elucidation, as well as continuity of services, in real situations like smart towns, healthcare and Industry 5.0 scenarios. In this review, a complete investigation of the state-of-the-art methods of fast link recovery in Li-Fi systems was conducted, including adaptive handover strategy, load balancing algorithms, and access point changing schemes. Signal enhancement techniques and MAC-layer optimisations serving robust connectivity in scenarios based on mobility are also discussed in the paper. In addition, the potential of hybrid Li-Fi/Wi-Fi networks and smart algorithms, including solutions based on the AI and game theory, are addressed in providing an efficient handoff and dynamic resource control. Lastly, the future research directions are also drawn to develop Li-Fi technologies to define the mobility-resilient and scalable next-generation communication infrastructures.

Keywords: Li-Fi, Link Recovery, Mobility, Dynamic Environments, Handover, Load Balancing, Visible Light Communication (VLC), Hybrid Networks

1. Introduction

Li-Fi (Light Fidelity) is a new wireless communication technology that uses visible light of Light Emitting Diodes (LEDs) to transmit data over the air at high speeds. Being a part of Optical Wireless Communication (OWC), Li-Fi also has several advantages when compared to typical Radio Frequency (RF)-based systems, which include a wide unlicensed bandwidth range, high

data rates, enhanced security because of contained light transmission, and minimal electromagnetic interference. Such characteristics make Li-Fi a useful application as a solution in different areas associated with indoor broadband access to the Internet of Things (IoT) application in healthcare, transport, and smart cities [1]. Nevertheless, in spite of the possible benefits, Li-Fi encounters serious issues that prevent its proliferation, particularly in mobile and dynamic settings. Among the greatest flaws, we can mention its high reliance on online-of-sight (LOS) communication. Li-Fi messages can be easily knocked by an object and the range of a single illumination is usually limited. Consequently, users regularly exchange their locations between illumination areas, provoking connection interruptions and numerous handovers among the access points. In such real-world applications as hospitals, factories or urban transport systems where mobility is high and user density is very dynamic, such limitation heavily affects communication reliability and even user experience.

They require the provision of rapid, effective link recovery to counter such outages and ensure continuity of services. Link recovery in Li-Fi encompasses resumption of communication within a short period in case of loss, which may be occasioned by mobility, shadowing or change of light zone. With Li-Fi, as opposed to Wi-Fi, where propagation of signals can be somewhat resistant to the presence of small obstructions and provide wider coverage, the opposite is the case, where handovers (between signals) require receptive and smart mechanisms to maintain continuity. Thus, studies have been directed towards formulating adaptable handover protocols, load balancing algorithms and smooth access point switching strategies with respect to the individual properties of Li-Fi [2]. Besides, the development of the hybrid network architecture with the hybrid use of both Li-Fi and Wi-Fi has been a popular solution to the limitations it faces. When such a system is used, Wi-Fi could be used as a backup channel or an alternative channel just in case the Li-Fi coverage is unavailable at the

moment. However, these hybrid systems bring about some other issues in the form of handover decisions, management of the load and heterogeneity synchronisation issues.

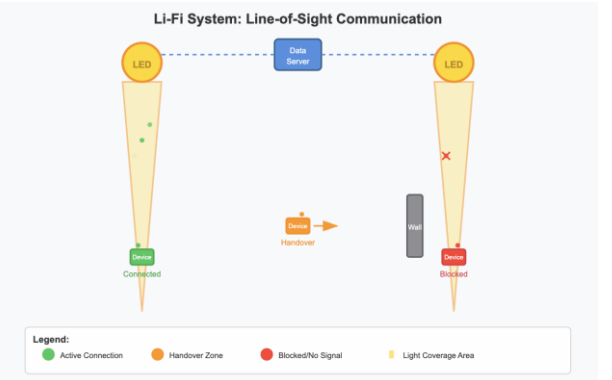


Fig.1: Li-Fi system architecture illustrating line-of-sight communication challenges

Fig. 1 proves the very problem of Li-Fi implementation in real-life conditions when mobile transmission and barriers have a severe influence on the reliability of communication. As shown in the diagram, LED-based access points provide a localised source of illumination and offer a smaller coverage area where the users must ensure they have a line-of-sight communication to enable effective transmission of data. As it has been demonstrated, mobile devices have periods of different levels of connection regulated by their proximity to the sources of light and the possible barriers. It is visually represented in the main limitation revealed in the literature, which is the frequent handovers between access points and signal blockage because of physical barriers, generating communication glitches that highly affect user experiences in dynamic contexts (such as hospitals, factories, and urban transportation systems).

The recent progress in Artificial Intelligence (AI), Machine Learning (ML) and the use of optimisation algorithms has further unleashed new realms to be applied to predictive mobility management and real-time handover implementation even in Li-Fi systems. Such smart ways can realise dynamic and application-adaptive resource allocation and enhance the Quality of Service (QoS) of the overall system with less latency in link recovery [3]. Considering the increasing need for reliable, low-latency, and high-capacity wireless channel communication, particularly in situations characterised by mobility, there is an urgent necessity to summarise the recent literature available on the recovery of link speed in Li-Fi networks. This literature review attempts to investigate and analyse existing solutions that are being offered to these problems, along with handover strategy, load-balancing mechanism, signal enhancement mechanism and hybrid networking. The paper also indicates areas of application that require swift restoration of links and their future scope to influence the development of mobile resiliency of the Li-Fi systems.

2. Challenges and Requirements for Link Recovery in Mobile Li-Fi Networks

Li-Fi networks, although with high rates and advantages of unlicensed spectrum, offer a different operational spectrum in mobile and dynamic settings. Compared to conventional RF-based systems, the availability of a line-of-sight (LOS) transmission route between the transmitter (generally LED) and receiver (generally photodiode) features is largely important in Li-Fi communications [4]. The fact that Li-Fi is also highly dependent on this and the low coverage area of individual Li-Fi cells exacerbates the sensitivity Li-Fi has to movement, shadowing, and obstacles. These conditions lead to the frequent interruption of the signals, and fast recovery mechanisms of the links are needed.

2.1 Key Challenges

- Opaque objects shield Li-Fi signals, and even a little obstruction can cause complete signal attenuation. In contrast to RF signals, visible light is unable to penetrate through human bodies or building walls, and it can lead to dropping the link very often [5].
- Li-Fi cells (or so-called attocells) usually occupy just several square meters. Since the users have to switch zones more often, the system will have to regularly conduct handovers, and, without ensuring its efficiency, this process will cause latency and packet loss.
- Signal degradation caused by mobility can be a bottleneck as in the case of hospitals, airports or industrial facilities where the users and equipment are continuously in motion.
- Load on access points (APs) will vary very quickly in a multi-user situation. Intelligent load balancing is the only way to avoid both crowded and underserved APs, as well as to use the picturesque resource efficiently.
- Signal interference can be caused by optical interference that occurs when several Li-Fi sources are in close contact. There is also the issue of user comfort and device reliability that may arise in some instances due to visible flickering caused by high-frequency modulation.

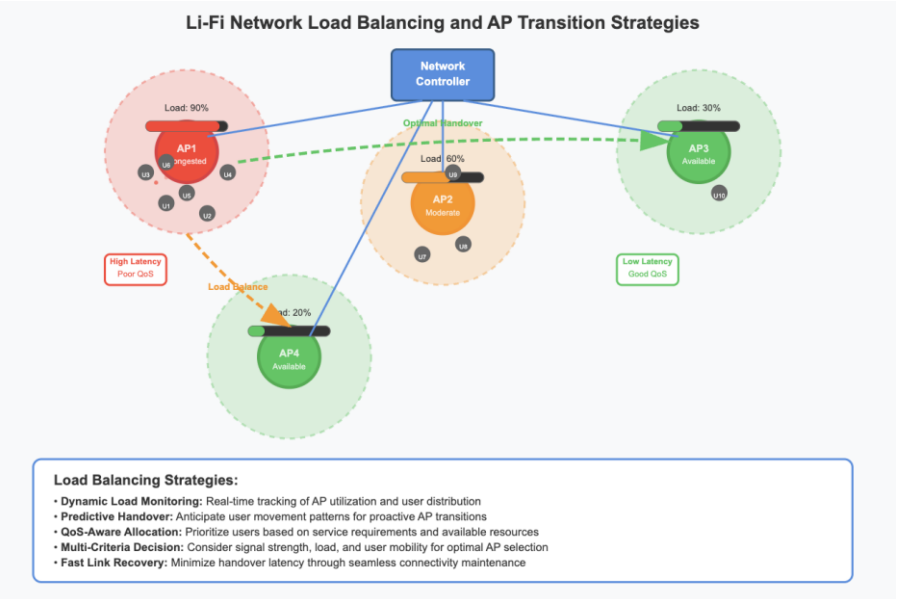


Fig.2: Load balancing challenges and AP transition strategies in mobile Li-Fi networks

The case of dynamic and heterogeneous traffic distributions across access points in a mobile Li-Fi network, presented in Figure 2, shows the paramount role of intelligent load balancing in mobile Li-Fi networks. Visualisation reveals a congestion which appears when the activity of the users around some APs is very high and therefore creates congestion in the network, consequently leading to decreased quality of service and high latencies, and yet other APs are not utilised. The suggested load balancing methods consist of real-time tracking of the AP usage, predictive handovers, which pre-determine user mobility, and multi-factored decision algorithms, which evaluate signal strength, current loads, and mobility patterns, providing the best AP choice. Such strategies would be vital in ensuring that high mobility environments have strong connectivity because it is proactive

in redistributing the network load and keep the service quality consistent through the quick recovery of the links in the AP transition process.

2.2 System Requirements for Fast Link Recovery

To ensure seamless communication in such scenarios, fast link recovery in Li-Fi networks must meet several technical and performance requirements:

- Low-latency Handover Mechanisms
- Load-aware Access Point Transition Protocols
- Real-time Monitoring and Signal Prediction
- Hybrid Support with Wi-Fi for Redundancy
- Energy-efficient Handover and Reconnection
- Cross-layer Optimisation to Reduce Protocol Overhead

Table 1: Summary of Challenges and Corresponding Recovery Requirements in Mobile Li-Fi Networks

Challenge	Description	Recovery Requirement
LOS Dependency	Signal blocked by obstacles	Real-time signal monitoring and fast reconnection
Small Cell Coverage	Frequent handovers due to small coverage zones	Seamless and predictive handover algorithms
High Mobility	Rapid signal loss during movement	Low-latency, adaptive AP switching
Dynamic Load	Uneven AP usage in multi-user scenarios	Load balancing and traffic-aware handover

Challenge	Description	Recovery Requirement
Optical Interference & Flicker Effects	Multiple Li-Fi sources causing signal degradation	Dynamic channel assignment and interference mitigation
Limited Penetration	No signal through walls or objects	Hybrid Li-Fi/Wi-Fi fallback integration

The interrelationship between the physical constraints and requirements at the network level, as presented in Table 1, showcases the requirement of combative, resilient, and smart link-recovery policies. Lack of a unified handover protocol is insufficient to accomplish seamless connection in these settings, but rather inclusion of predictive algorithms, as well as methods of load distribution and incorporation with hybrid systems. To bring forth the full capability of Li-Fi in mobile and dynamic applications, it is important to address them holistically.

3. Load Balancing and Access Point Transition Strategies

Dynamic, uneven network load is due to High mobility and changeable data requirements in mobile Li-Fi networks. It may cause bottlenecks at certain access points (APs), poor quality of service (QoS), and handovers become more latent [6]. To sustain strong and steady connectivity, particularly in operations where there is high user mobility and plenty of AP deployments, good load balancing policies and access point (AP) transition policies are essential ingredients of quick link recovery.

3.1 Load Balancing in Li-Fi Networks

Li-Fi networks are based on small-scale optical cells that can be called attocells and have minor coverage and capacity. Where the density is

high, many users can be connected to a single AP, resulting in the congestion of the network and low throughput. The concept of load balancing is to spread user connections among the APs such that the chances of congestion are minimised, as well as the resultant best use of resources. The traditional scheme of round-robin or signal-strength approach might not be adequate in Li-Fi owing to high signal attenuation and the disruption caused by mobility. The newer approaches include cooperative game theory [7], where different APs successively cooperate to assign users based on the cost-reward paradigm and optimisation algorithms using AI/ML, like Particle Swarm Optimisation (PSO) [8], which can dynamically examine the traffic patterns in a network and re-distribute users in an opportunistic way.

3.2 Access Point Transition Mechanisms

To keep the quality of such real-time apps as video streaming, remote monitoring, or interactive services, the Access Point (AP) transitions, also known as handovers, should be effortless and quick. Link outage, loss of packets or service disruption may occur due to poor management of the transitions. Recently, multi-phase protocols of handover have been proposed, like the three-phase handover with Load-awareness, which divides the handover process into three stages: preparation, execution, and completion. To ensure smoother transitioning, the target AP capacity would be pre-evaluated [9]. Equally, in the hybrid Li-Fi / Wi-Fi networks [10], both signal strength and network load are considered when defining the adaptive handover strategies, so when the Li-Fi connectivity is poor, a dynamic network switch to Wi-Fi can be produced. Table 2 provides an overview of several techniques of load balancing and AP transitions, indicates their major concepts, and identifies the advantages.

Table 2: Comparison of Load Balancing and Access Point Transition Strategies

Strategy	Key Principle	Benefits
Three-Phase Handover [1]	Preparation, execution, and completion phases	Smooth transition, reduced link failure risk
Adaptive Handover in Hybrid Networks [2]	Switch based on load and signal quality	Flexibility, improved continuity in dynamic environments
Game-Theory-Based Load Allocation [7]	Collaborative AP-user matching using utility functions	Optimized resource usage, fairness
Particle Swarm Optimization (PSO) [9]	Swarm intelligence for real-time load distribution	High accuracy, fast convergence
Signal-Strength-Based AP Selection	Connect to AP with strongest RSSI	Simple but may cause imbalance and congestion
Traffic-Aware Handover	Consider current AP load and user demand	Load-balanced, QoS-aware transitions

Smart AP transition and load balancing techniques greatly improve the performance of Li-Fi networks in a dynamic environment, as shown in Table 2. Even though the traditional approaches are simple, new procedures such as PSO and game theory allow smarter, context-aware decisions to be made, which can better respond to the complexity of the requirement of high mobility and heterogeneous demands. Such techniques not only guarantee equitable resource sharing but also minimise the latency of handover and enhance the user experience, which cannot be eliminated in a scalable deployment of Li-Fi.

4. Channel and Signal Enhancement for Stable Recovery

Li-Fi communication systems on mobile. To enable fast and effective link recovery, a stable, high-quality optical signal must be maintained in Li-Fi on mobile systems. Since Li-Fi is based on visible light, it is very sensitive to the conditions of the channel that are varied under the influence of mobility, the effects of the environment, interventions, and the rapid change of orientation of the receiver [11]. To tackle such shortcomings, some channel and signal improvement methods were investigated by scholars to improve the resistance of systems and reduce the time of recovery following disturbances.

4.1 Channel Modelling and Capacity Enhancement

The dimensions of modelling Li-Fi channel dynamically to predict the link degradation and preemptive recovery sequence are essential. Conventional channel models presuppose a static environment; when it comes to mobile environments, user movements, overshoot, and fading characteristics of multiple paths, as well as surface reflectivity, continue changing. Progressive modelling methods such as sparse coded mask modelling [12] improve the Discrete Multitone (DMT) modulation capacity by masking selective sub-channels dependent on the channel conditions. The technique adapts dynamically to changes in the channel; thus, it sustains throughput and minimises the error rates even in high-mobility settings. The flexibility of these models guarantees solid connection quality, faster link recovery and smaller packet loss.

4.2 Signal Modulation and Transmission Techniques

The strength of the signal being communicated is an important determinant in the speed with which a link will be restored when it breaks.

Conventional modulation systems are good in a stable environment but perform poorly in a fluctuating environment. As a solution to this, hybrid modulation techniques have been proposed to overcome the effect of this [10], including Hybrid Frequency Shift Keying with Pulse Width Modulation (FSK-PWM). The advantage of this method is that it integrates the effect of both of the schemes, as it has the ability to deal with tolerant noise and channel fading that arise in high-motion and obstacle-rich environments. The data integrity is improved with the use of these hybrid methods, which are especially useful in places with high mobility, such as public transportation or factory automation.

4.3 MAC Layer Optimisations for Fast Recovery

At the data link layer, the Medium Access Control (MAC) protocols are enhanced in a manner that is critical towards reducing the downtime in recovery. The protocols associated with the MAC layer that are specific to Optical Wireless Communication (OWC) address adaptive behaviour to the channel dynamics. As a case in point, the adaptive superframe scheme presented by Bhutani et al. [8] wherein beacon and contention duration are adaptively changed corresponding to real-time network data and mobility trends. This enables a switch to be accessed quickly upon link failures, and it gives priority to important data transmissions. On the same note, energy-efficient MAC will guarantee that communication is achieved with low latency and that it consumes minimal power, which is vital in wearable or mobile Li-Fi products that have limited batteries. Table 3 includes some methods of channel and signal strengthening, as well as the benefits.

Table 3: Summary of Channel and Signal Enhancement Techniques for Li-Fi Recovery

Technique	Description	Benefits
Sparse Coded Mask Modeling [3]	Adaptive subchannel masking in DMT	Improved capacity and error resilience
Hybrid FSK-PWM Modulation [10]	Combines FSK and PWM for robust signaling	Better tolerance to noise, suitable for mobility scenarios
Adaptive Superframe Structure [8]	Dynamic MAC scheduling based on network and user conditions	Faster channel access, reduced latency
Energy-Efficient MAC Layer [5]	Optimizes energy use while maintaining QoS	Extended device life, low-latency recovery
VLC Transmission Optimization [6]	High-efficiency data transmission using LED modulation improvements	Enhanced data rates and reduced retransmission

Table 3 demonstrates that the improvement of both physical and data link layers of the Li-Fi system plays a serious role in providing link recovery with high stability and in a reasonable time. All these methods together make it possible to guarantee and assure that in case of rapid mobility or environmental changes, the Li-Fi systems would be able to respond to such changes as fast as possible and sustain the quality of connection, considering real-time applications, cause minimal interference or disruption.

5. Smart Environment Applications and Future Trends

The capabilities of Li-Fi are not limited to the conventional communication system, and it changes the smart environment with potential, including healthcare, transportation and industrial automation. Hospitals' Li-Fi allows high-security, high-speed wireless connection of the patient monitoring systems with minimal medical equipment interference

[4]. Li-Fi is especially involved in the smart transportation systems, which provide an opportunity to support the vehicle-infrastructure (V2I) communication leading to improved traffic safety and real-time data exchange [11]. With the emergence of cities as smart ecosystems, the idea is to have Li-Fi paired with AIoT (Artificial Intelligence of Things) to provide predictive mobility management and to have efficient data dissemination in high-density urban areas. In the future, the combination of Li-Fi and Wi-Fi systems will be a central focus in the provision of a smooth service amid changing circumstances. Further resiliency of Li-Fi networks will be provided by the standardisation that is happening to IEEE 802.15.7r1 [12] and the introduction of AI and machine learning to predict mobility and perform intelligent handover. The convergence of 6G, the optimisation of cross-layer, and energy-efficient recovery are likely to be the future study direction to allow scalable, mobility-aware Li-Fi deployments.

6. Conclusion

The most influential methods of accomplishing rapid link reconstruction in Li-Fi communication systems in dynamic mobile settings were reviewed in this paper. We studied issues like LOS dependency, frequent hand-offs and dynamic traffic loads and examined countermeasures like adaptive handover protocols, load balancing strategies and enhancement strategies on signals. Noise and spectral efficiency can be fixed with the help of a combination of Li-Fi/Wi-Fi networks and smart algorithms. With the development of Li-Fi, future studies should be carried out on AI-based mobility prediction, standardisation and energy-efficient framing control methods to ensure the performance and resilience of the next-generation smart environments.

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