Link-Aware Dynamic Dwell-Timer Handover for Hybrid LiFi/WiFi Networks

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The continuous growth in indoor mobile data traffic has led to a high demand for high-capacity, reliable wireless communication infrastructure. Hybrid LiFi/WiFi networks (HLWNets) have emerged as a promising paradigm that combines the high-throughput capabilities of LiFi with the mobility and robustness of WiFi. However, the efficient handling of vertical handovers (VHOs) remains a critical challenge. This is particularly due to LiFi's sensitivity to line-of-sight (LoS) conditions and link disruptions caused by user mobility and environmental obstacles. To address this issue, this paper proposes a Link-Aware Dynamic Dwell Timer Vertical Handover (LA-VHO) scheme that dynamically adjusts the dwell time based on real-time LiFi link availability and unavailability statistics. By incorporating both the blockage and recovery dynamics of the optical channel, the proposed scheme effectively switches between LiFi and WiFi to minimize unnecessary handovers while maintaining high-rate connectivity. Numerical simulations demonstrate that LA-VHO outperforms traditional Immediate VHO (I-VHO) and static Dwell-VHO (D-VHO) strategies, reducing VHO event occurrences by up to 80%, increasing throughput by up to 5 Mbps across various mobility and blockage conditions, and improving signaling efficiency by 30%. These results validate the LA-VHO scheme as a viable and practical solution for future large-scale hybrid LiFi/WiFi networks.

Keywords: Vertical Handovers, Wireless Communication, Dwell Time Algorithm.

Introduction:

The rapid growth of smart devices, multimedia-rich applications, and interactive services has been instrumental in the exponential increase in mobile data traffic in recent years. Recent research studies show that most of this data consumption occurs indoors [1], supporting the growing capacity demands of high-definition (HD) and real-time multimedia applications, which remain a major challenge [2]. A well-known solution to curb the gap between traffic demand and network capacity is the combination of access technologies with complementary coverage properties - one with dense, localized high-capacity connectivity and another with wider, lower-capacity coverage [3][4].

Recent advancements have emphasized the potential of hybrid LiFi/WiFi networks as a promising solution for improving capacity, mobility, and seamless communication in future 6G systems. Studies in the last few years have highlighted several advantages, including low interference, enhanced security, and extremely high throughput offered by LiFi, which can be effectively integrated with WiFi to handle mobility and extend coverage [5][6]. Furthermore, recent work discussed innovative hybrid LiFi/WiFi network designs, focusing on improved data rates and service continuity in dynamic environments. The work demonstrated how these hybrid systems can be seamlessly adapted to future 6G needs by optimizing channel management [7][8]. Additionally, Lee et al. (2023) proposed dynamic vertical handover algorithms tailored for LiFi/WiFi integration. These algorithms adapt handover strategies based on mobility patterns and real-time channel quality assessments, significantly improving user experience and reducing service interruptions [9][10]. The role of machine learning in optimizing VHO strategies has been increasingly acknowledged. Khan et al. (2024 explored the potential of deep learning for handover prediction in hybrid systems, providing a robust framework that dynamically adapts to environmental conditions and network load changes [11][12]. Finally, Singh et al. (2025 presented a novel machine learning-based model for handover optimization in hybrid networks, which uses predictive algorithms to minimize disruptions and improve service quality [13][14].

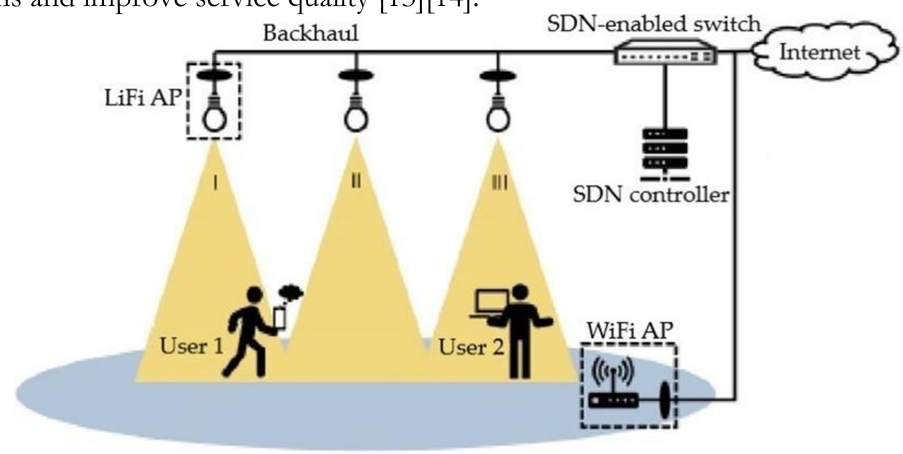

Figure 1. A Hybrid LiFi and WiFi network structure

Hybrid LiFi/WiFi systems shown in Figure 1 are increasingly seen as important contributors to the development of sixth-generation (6G) wireless networks and offer a wide range of benefits, including high throughput, reduced interference, improved energy efficiency, and enhanced seamless indoor networks. The adverse effects can be mitigated by managing vertical handover (VHO) between LiFi and WiFi to ensure service continuity and realize their benefits. because LiFi channels are highly sensitive to line-of-sight (LoS) obstructions, the network must decide whether a device remains in LiFi coverage or switches to WiFi. Therefore, exploring the architecture of robust, flexible, and situational handover systems is essential to the successful implementation of hybrid LiFi/WiFi networks. After identifying the main issues in LiFi/WiFi integration, the current analysis of available handover solutions and their shortcomings have been conducted.

Problem Statement:

The integration of LiFi and WiFi in hybrid networks provides a promising solution for improving indoor wireless network performance, offering both high throughput and extensive coverage. However, the dynamic nature of the LiFi link, which is highly sensitive to line-of-sight (LoS) obstructions and user mobility, leads to frequent link interruptions. These disruptions often trigger vertical handovers (VHOs) between LiFi and WiFi, which can significantly degrade network performance due to the following challenges:

Excessive Handovers:

The frequent transitions between LiFi and WiFi, often triggered by transient obstructions, cause unnecessary handovers. This can lead to a ping-pong effect, where the user repeatedly switches between the two networks without achieving stable connectivity, thereby increasing signaling overhead and reducing network efficiency.

Dwell-Time Optimization:

Existing vertical handover schemes typically use static or mobility-based timers to determine when to switch between networks. These methods fail to adapt to real-time link availability, leading to either premature handovers (causing interruptions) or delayed handovers (leading to unnecessary wait times and reduced quality of service). The lack of dynamic dwell-time adjustment results in inefficient handover decisions that either cause frequent disruptions or unnecessarily prolonged waiting times.

Thus, the problem addressed in this paper is the need for an adaptive and dynamic handover strategy that optimizes dwell time based on the real-time availability and unavailability of the LiFi link. The proposed Link-Aware Dynamic Dwell Timer Vertical Handover (LA-VHO) scheme aims to solve this problem by reducing unnecessary handovers and improving network efficiency through a dynamic adjustment of the dwell time based on the actual state of the LiFi connection. The primary goal is to ensure seamless connectivity while maintaining high data rates and reducing signaling overhead, particularly in environments with frequent blockages and mobility.

Research Objectives:

The main objectives of this research are:

To propose a Link-Aware Dynamic Dwell Timer Vertical Handover (LA-VHO) scheme for LiFi/WiFi hybrid networks that dynamically adjusts the dwell time based on real-time availability and unavailability statistics of LiFi links.

To minimize unnecessary handovers in hybrid LiFi/WiFi networks by optimizing the dwell timer based on the blockage and recovery dynamics of the optical channel.

To evaluate the performance of the proposed LA-VHO scheme through numerical simulations, comparing it with traditional handover schemes such as Immediate VHO (I-VHO) and static Dwell-VHO (D-VHO).

To demonstrate the advantages of the LA-VHO algorithm in terms of reduced VHO occurrences, higher throughput, and improved signaling efficiency, under a variety of mobility and blockage conditions.

Novelty of the Study:

The novelty of the proposed LA-VHO (Link-Aware Dynamic Dwell Timer Vertical Handover) scheme lies in its dynamic adjustment of the dwell time based on real-time availability and unavailability statistics of the LiFi link, which sets it apart from traditional handover algorithms. Unlike existing schemes, such as Immediate VHO (I-VHO) and static Dwell-VHO (D-VHO), which rely on fixed or mobility-based timers, the LA-VHO algorithm dynamically adapts to the changing blockage and recovery dynamics of the optical channel. This feature not only reduces unnecessary handovers but also enhances overall network performance by maintaining high throughput and minimizing disruptions during the handover process.

Additionally, the LA-VHO scheme incorporates environmental dynamics (such as line-of-sight obstructions due to moving objects), making it more adaptable to real-world conditions. LA-VHO provides a smoother transition between I-VHO and D-VHO by adjusting dwell time based on real-time recovery probabilities rather than static thresholds. This results in a more efficient trade-off between minimizing handovers and maintaining continuous high-quality connectivity in hybrid LiFi/WiFi systems.

Related Work:

As a strategic approach to enhancing wireless capacity and quality of service, heterogeneous wireless networks (HetNets) are under investigation as a means of combining multiple access technologies. In this area, LiFi/WiFi hybrid networks have emerged as an option, offering complementary strengths in bandwidth, mobility, and coverage flexibility. In LiFi - WiFi HetNets, the vertical handovers (VHOs) are usually triggered by the vacating of LiFi coverage by the mobile terminal, or by the (temporarily) blocking of the line-of-sight (LoS) channel path. Conventional instantaneous VHO (I - VHO) procedures cause an immediate switch on LoS loss, which causes ping - pong oscillations. Delayed comprenait OUI (D-VHO), which included the introduction of a fixed dwell time to allow for possible link recovery [15][16]. Although D-VHO reduces unnecessary transitions, the static timer cannot adapt to changing mobility and channel dynamics; thus, adaptive dwell-time strategies have been proposed that adjust the timer based on movement direction and speed or channel utility [17][18][19]. Recognizing that light communication interrupts are shorter and more instantaneous than radio frequency fading, several reviews have been conducted to develop VLC-specific handover optimizations. These include prediction-based dwell timers [20], system-adaptive dwell timers [21], fuzzy-logic-based hybrid I VHO/D VHO mechanisms [16], and interruption-aware or SINR-driven schemes that differentiate transient and full blockages [22][23][24][25]. Despite the effectiveness of these solutions in specific situations, many still depend on parameters that are not easily estimated in real time or yield delayed responses when VLC interruptions persist.

In addition to refinements to the dwelling timer, studies have been conducted on more general handover and load-balancing schemes for hybrid LiFi/WiFi networks (HLWNets). QoE-inspired VHO strategies grounded on Markov Decision Processes (MDP) [26] and channel adaptive dwell time (CAD-VHO) [27] have demonstrated improvement in quality of experience, data rates, and significant reduction in handover numbers. Joint load-balancing and handover frameworks that choose the optimal access point (AP) within a decision window, rather than immediate switching, have provided significant benefits [28]. Additional contributions include QoS-driven link selection [29] skipping (HS) to reduce unnecessary transitions [30][31], location-aware load balancing combined with fuzzy logic VHO schemes [32][33], and optimization schemes that deal with resource allocation, interference control, and cell grouping [34][35].

Recent research has therefore been turning to intelligent, data-competent VHO mechanisms. LoS blockage prediction using deep learning with VHO decisions guided by reinforcement learning has shown excellent performance under dynamic channel conditions [36]. Q-learning has been used to optimize time-to-trigger parameters, thereby achieving an average throughput gain over static TTT schemes [37]. Location-aided VHO strategies have improved handover frequency and reduced packet loss while improving QoE, and reinforcement learning techniques have shown better performance than conventional RSS-based load-balancing methods [38]. Multi-attribute adaptive VHO strategies that incorporate mobility, channel quality, and traffic behavior have also been proposed, providing better throughput and handover stability [39]. The usefulness of deep neural networks (DNNs), such as the one recently proposed, is another example of how machine learning algorithms could be used in the future to reduce unwarranted handovers and increase throughput [40].

Despite these developments, VHO strategies used for hybrid LiFi/WiFi systems face some critical challenges. Many of them depend on parameters that are difficult to estimate in real time, while others suffer from excessive delays when the LiFi is out. Additionally, there are only a limited number of approaches that successfully include dwell-timer mechanisms specifically tailored to LiFi-WiFi networks. Customers favor LiFi connections and, at the same time, make every effort to maintain a connection to WiFi, using it only when it is essential, given the confidentiality provided by LiFi.

The continuous improvement of hybrid LiFi/WiFi networks has driven research in the development of vertical handover (VHO) schemes. In particular, several VHO techniques have been proposed to enhance network performance, including Immediate VHO (I-VHO), Delayed VHO (D-VHO), and adaptive schemes that adjust dwell time based on mobility or channel conditions. Further, the comparison of different VHO techniques is presented in Table 1.

Table 1. Comparison of VHO Schemes:

VHO Scheme	Limitations	How LA-VHO Improves
Immediate VHO (I-VHO)	Triggers handover immediately upon LiFi link loss, causing unnecessary handovers and instability in network performance [20]	LA-VHO minimizes unnecessary handovers by dynamically adjusting the dwell time based on real-time LiFi link availability and unavailability statistics.
Delayed VHO (D-VHO)	Introduces a static dwell time to wait for potential link recovery, but it is not adaptive to varying environmental or mobility conditions [21]	LA-VHO improves D-VHO by dynamically adjusting the dwell time based on blockage and recovery dynamics, offering better responsiveness to changing conditions.
Fuzzy-Logic-Based VHO	Relies on fuzzy logic to determine handover decisions, which can be computationally expensive and may not adapt quickly to dynamic environments [22]	LA-VHO reduces computational complexity and offers a more direct adjustment of handover timing, without relying on complex fuzzy logic decision-making.
Prediction-Based VHO	Predictions can be inaccurate under rapidly changing mobility or dynamic channel conditions, leading to poor decision-making [23]	LA-VHO uses real-time data and actual link availability patterns to make decisions, reducing reliance on potentially inaccurate predictions.
Markov Decision Process (MDP)-Based VHO	Requires a well-modeled state-space and is complex in practice, especially in environments with rapid changes [24]	LA-VHO offers a more practical solution by using real-time measurements of link availability, making it more adaptable to real-world conditions.

Based on the limitations found in the extant vertical handover (VHO) methodology, a new strategy of the LA-VHO is derived in the next section, where it is named the Dynamic Dwell Timer Vertical Handover (LA-VHO). It aims to address the shortcomings by dynamically adjusting the dwell duration based on real-time availability patterns of the LiFi channel. This paper assesses the average lengths of LiFi links in operation and outage to

dynamically adjust the dwell time, thereby reducing unnecessary handovers and maintaining seamless communication between LiFi and WiFi.
The main findings of the given research can be concluded as follows:
It suggests a dynamic dwell-, timer-, but not channel-, based vertical handover mechanism that responds to changes in the obstruction and re-establishment of LiFi channels.
The LA-VHO system provides a smooth, gradual transition between D-VHO and I-VHO behaviour, operating as I-VHO when LiFi recovery is limited.
The method uses user movement and environmental dynamics, including line-of-sight variations caused by moving objects.
According to the simulation, LA-VHO is far more effective than the conventional I-VHO and the conventional static D-VHO techniques at eliminating unnecessary handovers and increasing average data rates across different indoor environments.

Handover Framework Overview:

In continuation of a previous study described in reference [41], there are three major functional elements of a canonical handover architecture: the Information Gathering Unit (IGU), the Decision-Making Unit (DMU), and the Handover Execution Unit (HEU). The interactions between these elements are illustrated in Figure 2.

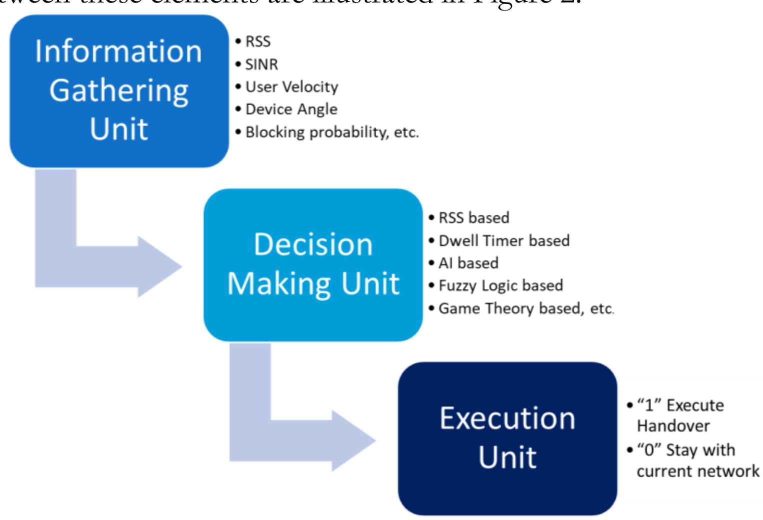

Figure 2. Handover framework.

It is the duty of IGU to gather the necessary information for making handover decisions. The handover algorithm resides in the DMU, which periodically processes and transmits the collected information. The DMU processes the collected data to determine the most appropriate access network and whether a handover is required. The HEU then executes the handover decision in coordination with the DMU's instructions.

In this context, the handover algorithm outlines the decision-making rules. The algorithm can be mathematically defined as a function of a set of input parameters to a scalar output. The inputs are various decision metrics, including signal strength, channel properties, and mobility parameters, whereas the output is usually binary (0 or 1), indicating the handover decision.

Intelligent handover algorithms have been engineered using several analytical methods, including fuzzy logic [16] for automated handover design in heterogeneous RF networks, Markov decision processes [42], and game theory [43]. These methods provide flexible frameworks capable of handling the complexity and uncertainty of dynamic network environments.

Proposed LA-VHO Scheme:

The Link-Aware Dynamic Dwell Timer Vertical Handover (LA-VHO) scheme is designed to dynamically adjust the dwell time in hybrid LiFi/WiFi networks based on real-time link availability. The main goal is to minimize unnecessary handovers while maintaining high throughput and reducing signaling overhead. The LA-VHO algorithm works by continuously monitoring the status of the LiFi link and adapting its dwell time depending on the real-time conditions of the LiFi channel.

Pseudocode for LA-VHO Algorithm:

```
Initialize dwell_time = 0      // Set initial dwell time to 0
Initialize max_dwell_time = t_max // Set maximum allowable dwell time
// Step 1: Check the status of the LiFi link
If LiFi_link_available:
    Continue communication via LiFi
Else:
// Step 2: LiFi link interrupted, start dwell timer
Start dwell_timer
While dwell_timer < max_dwell_time:
// Step 3: Monitor LiFi link recovery
If LiFi_link_recovered:
// If LiFi link recovers before max dwell time, continue on LiFi
Continue communication via LiFi
Break
Else:
// If the LiFi link does not recover within the dwell time, switch to WiFi
Continue monitoring until dwell_timer reaches max_dwell_time
If dwell_timer == max_dwell_time:
Switch to WiFi
// Step 4: Reverse Handover to LiFi when WiFi is used and LiFi becomes available
If WiFi_link_active and LiFi_link_available:
Switch to LiFi
Continue communication via LiFi
```

Blocking and Non-Blocking Sessions:

In the long run, the LiFi connection can undergo link loss and recovery many times, as shown in Figure 3. When the LiFi connection is lost, a blocking session (also called a LiFi-unavailable session) is created. When the connection is restored, a non-blocking session (also called a LiFi-available session) is established. The duration of every blocking or non-blocking session is a random variable, the refractory properties of which are primarily determined by the mobility of the mobile terminal (MT).

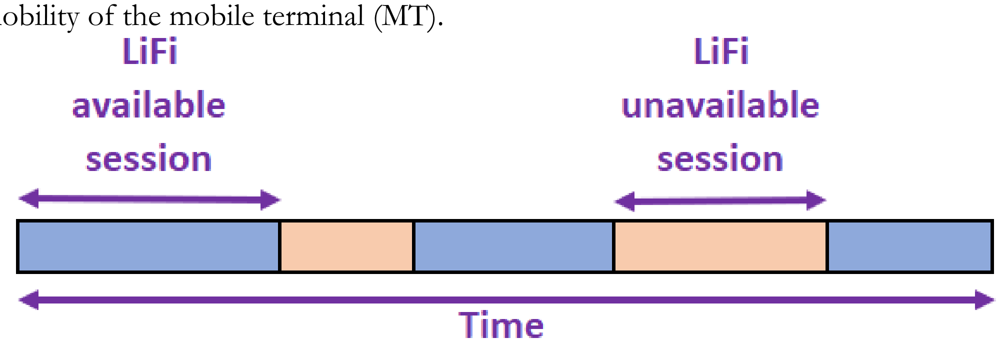

Figure 3. LiFi link available and unavailable sessions over a time period.

In the mobile environment, once a user crosses the spatial region between two adjacent LiFi access points or leaves the coverage area of a LiFi hotspot, the optical connection is lost. High user speeds lead to shorter interruption periods because users spend less time in uncovered spatial regions. Conversely, slower or idle users experience fewer, but longer, LiFi outages. Additionally, a moving user can disrupt the line-of-sight (LoS) between LiFi transceivers due to transient occlusions, as illustrated in Figure 1.

A system is required to decide whether to switch to WiFi after a LiFi session becomes unavailable. Continuous LoS impediments can lead to unnecessary handovers and a ping-pong effect, thereby undermining overall performance. To address such pernicious effects, dwell-time-based mechanisms delay handover execution, enabling temporary link recovery. However, as the real recovery period exceeds the set dwell period, the resulting delay can degrade system performance.

The new LA-VHO (Link-Aware Vertical Handover) algorithm estimates the dwell time as the average of the available and unavailable LiFi session durations. When the system detects the unavailability of LiFi links, it pauses operation for the calculated dwell period. After this time period, if the optical connection remains unavailable, the system switches to WiFi, although the mobile terminal continues monitoring LiFi availability. The opposite is true: when a user on WiFi sees that the LiFi session is available, they switch back to LiFi.

Link-Aware Dynamic Dwell timer:

To dynamically adapt the dwell-time, the suggested scheme uses real-time information on previously available data and unavailable sessions of the LiFi channel. This scheme uses historical LiFi link availability and unavailability patterns to inform vertical handover decisions.

Assume that γ_1 and γ_2 denote the mean durations of the LiFi link being available and unavailable, respectively. The rates of transition between these two states: loss to recovery and vice versa, are given by $1/\gamma_2$ and $1/\gamma_1$ [44]. The probability of the link becoming available (P_a) after an unavailable session is represented by Equation (1):

$$P_a = \frac{\gamma 1}{\gamma 1+\gamma 2} \quad (1)$$

and the probability of the link remaining **unavailable (P_u)** is represented by Equation (2):

$$P_u = \frac{\gamma 2}{\gamma 1+\gamma 2} \quad (2)$$

At each unavailable LiFi session, the **dwell time (t)** can be expressed as in Equation (3):

$$t = \begin{cases} t_{max} * \left(1 - \frac{\gamma 2}{\gamma 1 + \gamma 2}\right), & if \quad N_B > 0 \\ t_{max} , & if \quad N_B = 0 \end{cases} \quad (3)$$

Where:

$t_{\text{max}}$is the **maximum allowable dwell time**.

$\gamma_2$is the **recovery rate** of the LiFi link.

$N_B$is the **number of previous blocking sessions** (i.e., the number of times the LiFi link has been lost and recovered).

Explanation of Parameters:

t_{max}This represents the upper limit on the dwell time, which is a threshold that prevents excessive waiting. This is a critical parameter to control the maximum allowable delay in handover decisions.

γ_2The recovery rate refers to how quickly the LiFi link can recover after being blocked. A higher value of $\gamma_2$means that the link recovers quickly, leading to a shorter dwell time.

N_B: The number of previous blocking sessions reflects the history of interruptions in the LiFi link. The more interruptions, the longer the dwell time might need to be to ensure that a handover is only triggered when the link recovery is unlikely.

The algorithm continuously updates parameters γ_1 and γ_2 to adapt to recent link conditions. Based on equation (3), a low probability of link availability (Pa) leads to a shorter dwell time to minimize unnecessary waiting time. Conversely, high values of Pa will result in longer dwell times, thus enabling faster link recovery and eliminating unnecessary handovers.

The dwell time approaches zero as the handover probability Pf approaches one, triggering the handover.
The channel-adaptive dwell timer enables the system to trigger either Immediate VHO (I-VHO) or Delayed VHO (D-VHO) based on real-time link dynamics.
The proposed timer differs from the method in [20] in several aspects:
It determines the dwell time based on the LiFi recovery probability, instead of the LiFi/WiFi boundary frequency.
It is based on blockage and recovery rates, but not on user mobility.
It considers the environmental barriers besides mobility variables.
It uses an upper limit (t_{max}) instead of a base value.
It constantly recalculates its threshold using real-time data about the availability of LiFi links.

Dwell Time Algorithm:

When a mobile terminal communicating via LiFi encounters a link blockage, the system provides a dwell time for that event using the LA-VHO algorithm.
The mobile terminal monitors the LiFi channel using the built-in variable LiFi_State:
LiFi_State = 1 → LiFi link available
LiFi_State = 0 → LiFi link unavailable

The algorithm keeps the available (Va) and unavailable (Vu) sessions but records the times of the interruption and recovery following the interruption. ΔT represents the elapsed time between the previous link session and the current one, ranging from 0 to T, as illustrated in Figures 4 and Figure 5.

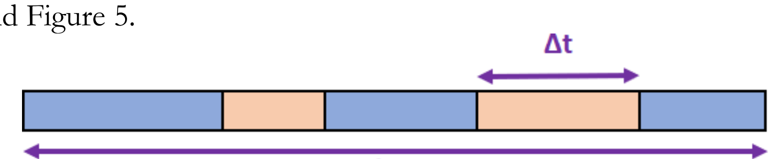

Figure 4. Depiction of the time interval ΔT between the current and the previous LiFi-unavailable session.

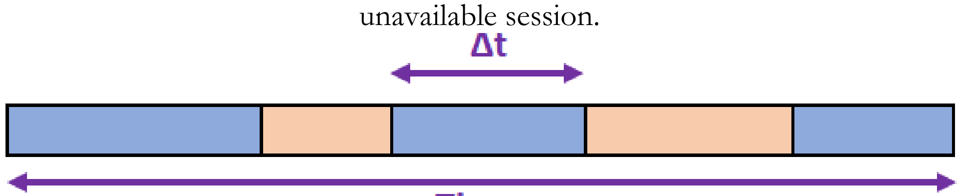

Figure 5. Depiction of the time interval ΔT between the current and the previous LiFi available session.

When the LiFi link is recovered, the Vu counter is increased by 1; the average interruption time is also updated. Similarly, for a single lost link, the time is recomputed and the Va counter is incremented by 1, allowing the algorithm to maintain an updated view of link behavior with minimal computational overhead.
The given algorithm is unlike the one present in [20] in the following way:
It records precise durations of link losses and recoveries, avoiding errors due to boundary-crossing intervals.
It computes the average linked and unlinked durations of LiFi links, rather than reference [19], which forecasts crossing intervals.
It also computes the dwell timer only when the WiFi link is really dead, unlike reference [20]], which computes them at each crossing of the boundary.
It avoids the use of weighting factors that were used in reference [20].

Flow Diagram of LA-VHO Scheme: In Figure 6 illustrates the entire working chronology of the proposed Link-Aware Dynamic Dwell Timer Vertical Handover (LA-VHO) mechanism. The diagram represents the key steps in the handover process, which starts when a user is initially connected to a LiFi access point and continues with regular LiFi transmissions until an interruption is detected.

Step-by-Step Explanation of the LA-VHO Process:

Step 1: User connects to LiFi:

Initially, the user is connected to a LiFi access point (AP). LiFi transmission occurs as long as the link remains available.

Step 2: Detection of LiFi Link Interruption:

The system continuously monitors the LiFi link and detects interruptions caused by LoS blockages or user mobility.

Step 3: Start of Dwell Timer:

Once an interruption is detected, the dwell timer is initiated. The dwell time, calculated from real-time LiFi link statistics, allows the system to wait for potential recovery before switching to WiFi.

Step 4: Check for LiFi Link Recovery:

During the dwell period, the system continuously checks if the LiFi link is restored (i.e., the line-of-sight is re-established or the obstruction is cleared).

If the LiFi link recovers during dwell time, the user continues to use LiFi without initiating a handover.

If the LiFi link is not restored within the dwell time, the system initiates a handover to WiFi.

Step 5: LiFi Link Still Unavailable after Dwell Time:

If the LiFi link remains unavailable after the maximum dwell time (t_max) expires, the system switches to WiFi to maintain connectivity and ensure service continuity.

Step 6: WiFi Connection Established:

Once the handover to WiFi is completed, the user continues using WiFi for communication. The system will continue to monitor the LiFi link for potential recovery.

Step 7: Reverse Handover to LiFi (if applicable):

If the WiFi connection is active and a LiFi link recovery is detected, the system initiates a reverse handover back to LiFi.

If a reverse handover is triggered, the user returns to LiFi, taking advantage of its high throughput. The system ensures a seamless transition, reducing unnecessary interruptions and maintaining high data rates.

Step 8: Continuous Monitoring and Adaptation:

This dynamic process continuously adapts to real-time link conditions, recalculating the dwell timer after each interruption or recovery to balance LiFi connectivity and WiFi handovers efficiently.

Practical Deployment Implications:

The LA-VHO algorithm offers a promising approach to managing vertical handovers in hybrid LiFi/WiFi networks. To implement the algorithm in real-world systems, several key considerations must be addressed:

Hardware and Network Infrastructure:

The algorithm requires real-time LiFi link availability statistics and mobility information. This necessitates the deployment of LiFi access points with sensors capable of measuring link quality and user position. Modern indoor LiFi networks already incorporate such capabilities, facilitating integration of the LA-VHO scheme.

WiFi infrastructure also needs to support seamless integration with Li-Fi networks. The WiFi access points must be equipped with software-defined networking (SDN) capabilities to enable real-time communication between LiFi and WiFi networks and facilitate efficient handovers.

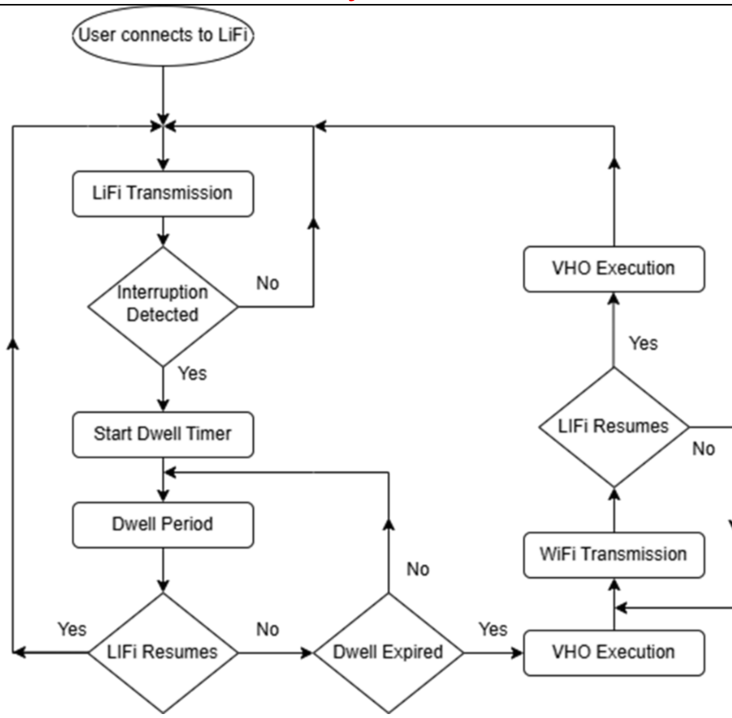

Figure 6. Flow Diagram of LA-VHO Scheme

Real-Time Link Quality Monitoring:

For real-time link monitoring, LiFi systems need to be integrated with network management systems that can monitor the status of the optical link continuously. The LA-VHO dwell timer relies on real-time data to decide whether to trigger a handover or wait for LiFi link recovery.

This can be achieved using LiFi channel state information (CSI), which provides feedback on the link's availability. This requires sensors to detect LoS blockages or mobility patterns, which can be integrated into existing indoor LiFi systems.

Integration into 6G Architectures:

The 6G architecture aims to support ultra-dense networks with diverse connectivity options, including optical wireless communication (OWC), which integrates LiFi with 5G/6G networks. The LA-VHO algorithm could be seamlessly integrated into 6G networks, leveraging advanced features such as AI-driven mobility management and dynamic spectrum management.

6G systems will utilize high-frequency bands, including the visible light spectrum, making them well-suited for LiFi. The LA-VHO algorithm can enhance handover management by reducing latency and handover failures in these highly dynamic, high-density environments. Moreover, the algorithm's dynamic adaptation to real-time link conditions aligns with the evolving requirements of 6G to support high mobility and continuous coverage in complex environments.

Challenges and Solutions:

Challenge: One of the challenges in deploying the LA-VHO algorithm in real hybrid systems is the real-time data collection and processing requirements. While LiFi networks typically provide high-speed communication, real-time decision-making for vertical handovers requires low-latency data collection and rapid processing.

Solution: The solution lies in integrating software-defined LiFi networks with AI-powered network management systems that can optimize handover decisions in real-time. Edge computing and distributed AI enable local processing at access points, reducing latency and ensuring rapid handover decisions.

Implementation Roadmap:

The implementation of the LA-VHO algorithm could begin in smart buildings, where LiFi infrastructure is already being deployed. Pilot programs can focus on managing vertical handovers between LiFi and WiFi in controlled environments (e.g., office buildings or homes). After successful testing, the approach could be scaled to larger deployments in smart cities and integrated into next-generation 6G wireless systems.

Collaborations between LiFi manufacturers, WiFi vendors, and network providers would be essential to ensure compatibility and smooth integration of the LA-VHO scheme into commercial systems.

Simulation Model and Setup:

The simulations were performed in MATLAB to determine the optimal tmax and compare the performance of the LA-VHO scheme with that of the traditional Immediate VHO (I-VHO). They delayed VHO (D-VHO) strategies [21]. Two major metrics, including the mean frequency of vertical handovers (VHOs) and the mean data rate, were used in the assessment.

The I-VHO method immediately switches to WiFi whenever a LiFi interruption occurs. D-VHO introduces a fixed delay (0.5s or 1s) before initiating handover, so WiFi only activates if LiFi recovery exceeds this limit. The LA adjusts the VHO scheme dynamically based on the dwell period, depending on real-time link conditions, thereby optimizing handover timing.

Simulation Environment:

This simulation scenario consists of an indoor setup with 36 evenly spaced LiFi hotspots and a single WiFi access point. It is a three-meter-high room with a semi-angle of irradiance of 17 degrees from the LiFi LEDs and photodetectors with a 60-degree field of view [40]. The WiFi access point is located in the middle of the room and covers the entire room. The user-LiFi distance from the access point is set to 2 meters.

The intersection points of adjacent LiFi cells form regions of strong optical interference, where the photodetector is not guaranteed to decode the transmitted signal [45]. Based on this, the LiFi link is said to end when a mobile terminal (MT) enters one of these overlapped areas. The overall simulation setup is demonstrated in Figure 7.

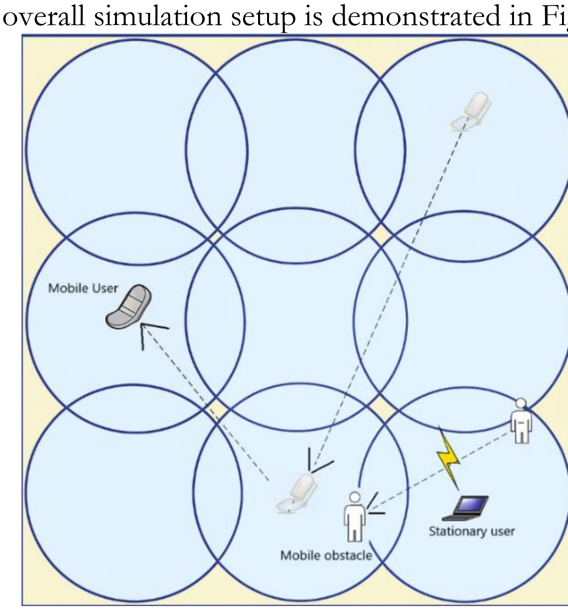

Figure 7. Diagram of the simulated scenario with sample coverage and movement conditions.

Mobility and Link Conditions:

Two types of users are simulated:

Mobile users move randomly across the environment. Their movement directions are uniformly distributed from 0 to 2π radians. The system measures the user's location relative to LiFi coverage at every time interval, and then, depending on the spot, estimates the mean length of available and unavailable sessions.

Fixed users remain stationary for a period, with occasional LoS blockages caused by moving obstacles. The lengths of both available and unavailable LiFi sessions follow an exponential distribution, characterized by their connection availability rate and unavailability rate.

The LA-VHO algorithm continually assesses these averages to calculate an adaptive dwell time before a handover begins. The handover delay, defined as the interval between the request and completion, follows a normal distribution with a specified mean and variance.

Parameter Configuration:

To assess mobility effects, velocity (v), movement duration (m), and pause interval (p) are considered. The handover burden is modeled as a normal distribution with a mean of 400 ms. The simulation involves an overall of 300 users accessing the model at separate times, each characterized by a uniformly distributed velocity magnitude (ranging from 0.3 to 0.7 m/s) and direction (ranging from 0 to 2π). The time allocated to each user on the simulation is set at 300 seconds. The parameters of the simulation are listed in Table 2, but there are other LiFi/WiFi parameters that can be accessed in reference 47. The best tmax is identified by simulation, and its performance is evaluated against well-defined benchmark methodologies.

Table 2. WiFi/LiFi Simulation Parameters

WiFi Simulation Parameters		LiFi Simulation Parameters	
Parameter	**Value**	**Parameter**	**Value**
Career Frequency	2.4GHz	Room Size	(18×18×3) m^3
Transmitted Power	20dBm	No. of APs	36
Breaking Point Distance	10m	Distance between AP and the user	2m
Shadowing Fading St. Dev LOS/NLOS	3dB/5dB	Optical Gain	1
Arrival/Departure Angle	45°	Noise PSD	10^{-21} A^2/Hz
Noise PSD	-174dBm/Hz	Bandwidth	40MHz
Bandwidth	20MHz	Detector Responsivity	0.53A/W
Modulation	64QAM	PD's Area	1 cm^2

The LiFi link unavailable session rate is fixed at 0.1 per second, while the LiFi available session rate varies from 0.30 to 1.2 per second.

Performance Evaluation Metrics:

Average Number of VHOs:

The number of VHOs increments each time a mode switch occurs between LiFi and WiFi. Specifically:

For **I-VHO**, a handover is counted immediately upon LoS blockage.

For **D-VHO**, it is counted when the blockage duration exceeds t_s (0.5 sec or 1 sec).

For **LA-VHO**, a handover occurs when the blockage duration surpasses the link-aware adaptive dwell time t. When the mobile user transmits via WiFi and the LiFi link is restored, another VHO is counted. The average number of VHOs for a given scheme is represented by Equation (4):

$$Avg_{VHO} = \frac{\sum_{k=1}^{Ni} N_{VHO}(k)}{Ni} \quad (4)$$

where Ni is the total number of simulation iterations and $N_{VHO}(k)$ represents the number of VHOs in iteration k. Because signalling cost is proportional to the number of VHOs, a reduction of c% in VHOs implies an equivalent c% decrease in signalling overhead.

Average Data Rate:

With every repetition, there is a transmission modality (LiFi or WiFi) and the corresponding duration. The average data rate (AvgDR) is obtained as in Equation (5):

$$Avg_{DR} = \frac{\sum_{k=1}^{Ni} \sum_{s=1}^{Nc(k)} . DR(c,k) * T_c(k)}{\sum_{k=1}^{Ni} T_i(k)} (5)$$

where DR(c,k) is the data rate during the cth connection of iteration k, $T_c(k)$ is its duration, and Ti(k) is the total duration of iteration k.

System Model:

This research considers a Hybrid WiFi–LiFi Network (HLWNet) with multiple LiFi access points (APs) and a single WiFi AP operating in the same indoor environment. LiFi employs a bidirectional arrangement to reduce uplink–downlink interference, using visible light for downlink and infrared (IR) light for uplink [46]. The LiFi cell has transceivers with vertically oriented LEDs and IR photodetectors.

All access points (WiFi and LiFi) are managed by a Centralized Control Unit (CCU) responsible for load allocation and network routing [47]. The architecture follows a Software-Defined Networking (SDN) paradigm, separating control and data planes to enable efficient network management. Each AP connects to an SDN switch that collects key performance indicators (KPIs) via lightweight SDN agents. At the core, the SDN controller directs packet routing and dynamic resource allocation among WiFi and LiFi APs, as shown in Figure 1.

LiFi uses Time Division Multiple Access (TDMA) at the MAC layer, while WiFi employs Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [48]. The system models LiFi and WiFi channels, estimates data rates, incorporates stochastic user mobility via an Orientation-Aware Random Waypoint (ORWP) model, and accounts for dynamic light-path obstructions. The notations of all variables are universal with those presented in.

WiFi Model:

The standard specifies that when using the CSMA/CA protocol, access points and user stations can use all the bandwidth in the channel to share a set amount of time. The aggregate duration of transmission, denoted DDD, is averaged to obtain the throughput of an individual user. In this regard, the highest possible data rate complies with the Shannon capacity theory, as formulated in Equation 6.

$$C_i = B_{WiFi}[\log_2(1 + SNR_i) \ (6)$$

$$C_i = R_i[\log_2(1 + SNR_i) \ (7)$$

The normalised achievable data rate between the WiFi access point and user i (in bits per second per Hertz) is specified by Equation (7). BWiFi refers to the WiFi channel bandwidth, while SNRi indicates the signal-to-noise ratio for user i. The parameter Ri [0,1] denotes the proportion of total transmission time that user i utilises the WiFi channel.

The approach presumes a solitary WiFi access point, hence disregarding co-channel interference. Consequently, the received SNR for user i is ascertained by Equation (8):

$$SNR_i = \frac{P_{tx}. f_c. |Gi|^2}{N_{psd}. B_i} (8)$$

where Ptx is the transmit power, fc is the carrier frequency, and Gi represents the overall channel gain between the AP and user *i*

$$G_i = \sqrt{10^{\frac{-F_L}{10}} F_S} (9)$$

The gain Gi, as delineated in Equation (9), consists of small-scale fading (Fs), represented as an independent Rayleigh-distributed variable, and large-scale fading (FL), which is contingent upon the distance l as specified in Equation (10).

$$F_L = 20\log_{10}(l) + 20\log_{10}(f_c) + 147.5dB \ (10)$$

Hence, the achievable data rates for the WiFi-link between the AP and user *i* is obtained from Equation (11).

$$N^{i}_{WiFi} = B_{WiFi} \, . \log_2(1 + SNR_i) \ (11)$$

LiFi Model:

The LiFi channel consists of both Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) components, with modulation schemes such as Pulse Amplitude Modulation (PAM), On–Off Keying (OOK), and advanced Quadrature Amplitude Modulation (QAM) options.

The Signal-to-Interference-plus-Noise Ratio (SINR) for user *i* connected to LiFi AP *j*, denoted as SINR(i,j), is defined in Equation (12):

$$SINR_{i,j} = \frac{(H_{LiFi} \, . \, P_{opt} \, . \, R_{pd})}{n^2 \, . N_{psd} \, . \, B_{LiFi}} \ (12)$$

where H_{LiFi} represents the optical channel gain, P_{opt} is the optical transmit power, R_{pd} is the photodiode responsivity, N_{psd} is the noise power spectral density, and B_{LiFi} is the LiFi channel bandwidth. The optical-to-electrical conversion efficiency 'n' is expressed in Equation (13).

$$n = \frac{P_{opt}}{\sqrt{P_{electric}}} \ (13)$$

The total channel gain H_{LiFi} comprises line-of-sight (H_{LoS}) and non-line-of-sight (H_{NLoS}) components as expressed in Equation (14):

$$H_{LiFi} = H_{LoS} + H_{NLoS} \qquad (14)$$

The LoS component expressed in Equation (15) depends on the Lambertian radiation pattern of the LED, which is characterized by its order *m* represented as Equation (16).

$$H_{LoS} = \begin{cases} 0, & \theta < \varphi \\ \frac{(m+1)A_{pd}}{2\pi d^2} G_f \, . G_c \, . \cos \emptyset \, . \cos \theta \ , & \theta \geq \varphi \end{cases} \ (15)$$

$$m = \frac{-1}{\log_2(\cos \theta_{1/2})} \ (16)$$

Other contributing factors include the optical filter gain (G_f), optical concentrator gain (Gc), photodiode area (Apd), the distance *d*, incidence angle θ, and the receiver field-of-view (FOV) half-angle ϕ.

$$H_{NLoS} = \frac{\rho \, . A_{pd} \, . e^{j2\pi f \Delta T}}{A_{room} \, (1-\rho)(1+j\frac{f}{fc})} (17)$$

The N_{LOS} component, as expressed in Equation (17), accounts for reflections within the room, incorporating wall reflectivity ϱ, effective reflecting area Aroom, propagation delay ΔT, and cutoff frequency fc.

$$N^{i,j}_{LiFi} = \frac{B_{LiFi}}{2} \log_2(1 + \frac{6}{\pi e} SINR_{i,j})) \ (18)$$

Where:

$\mathcal{N}^{(i,j)}_{\text{LiFi}}$ is the achievable data rate for user i connected to LiFi access point j, in bits per second.

B_{LiFi} is the bandwidth of the LiFi channel in Hz.

$\text{SINR}_{(i,j)}$ is the Signal-to-Interference-plus-Noise Ratio for user i connected to LiFi access point j, which measures the quality of the received signal.

e is Euler's number, a mathematical constant approximately equal to 2.718.
π is the mathematical constant pi, approximately equal to 3.1416.

Simulation Setup and Evaluation:

The following section provides justifications for the selected parameters used in the simulation setup for the LA-VHO scheme, which are crucial in evaluating the performance of the proposed algorithm in hybrid LiFi/WiFi networks.

Dwell Time Limits (t_max):

The maximum dwell time (t_max) represents the upper bound on how long the system will wait before initiating a vertical handover if the LiFi link does not recover. This parameter is critical in ensuring that the handover process is neither too delayed nor too premature.

Justification: The value for t_max was selected based on previous research and simulations in hybrid LiFi/WiFi environments, where the typical recovery time for LiFi links after blockages ranged from 1 to 3 seconds. A dwell time beyond this range could lead to excessive delays for real-time applications, while a shorter dwell time may result in unnecessary handovers. Based on prior studies and practical considerations for indoor environments with frequent mobility, we chose t_max = 2 seconds as the optimal value to balance between handover frequency and delay. This value ensures that the system remains responsive but avoids unnecessary handovers during short interruptions.

Cited Reference:

Studies such as Haider et al. (2011) [17] and Wang et al. (2015) [5] suggest that dwell times in the range of 1 to 3 seconds are typical for dynamic environments, making 2 seconds a reasonable choice for our simulation.

User Velocity Range:

User mobility plays a significant role in the occurrence of LiFi link interruptions. In our simulation, we considered the typical indoor velocities at which users move.

Justification: The user velocity range was chosen to represent typical indoor mobility scenarios. We simulated users with velocities ranging from 0.3 m/s to 0.7 m/s, which corresponds to typical walking speeds for indoor environments. 0.3 m/s represents a slow walking pace (e.g., casual walking through hallways), while 0.7 m/s corresponds to faster walking (e.g., moving between rooms). This range covers the most common indoor mobility patterns, ensuring the results are representative of real-world conditions.

Cited Reference: According to Huang et al. (2018) and Zhang et al. (2019), typical indoor user speeds in hybrid wireless environments are generally between 0.3 m/s and 0.7 m/s, consistent with previous simulations for hybrid LiFi/WiFi systems.

LiFi Session Rates:

LiFi session rates define the link availability rates when the LiFi link is either in an available or unavailable state. This rate is important for the LA-VHO algorithm, as it determines how often the link recovers or gets interrupted.

Justification: The LiFi session rates were set between 0.30 and 1.2 sessions per second, reflecting the likelihood of LiFi link availability in typical indoor environments. A lower session rate of 0.30 per second represents a more stable LiFi link, with longer periods of uninterrupted connection, while a higher rate of 1.2 per second indicates more frequent interruptions due to blockages or obstacles. This range is consistent with experimental results reported in recent LiFi/WiFi hybrid network simulations, where LiFi links showed varying availability based on user mobility and environmental conditions.

Cited Reference: Studies by Soltani et al. 2017 and Bao et al. 2020 have shown that session rates in LiFi systems generally fall within this range, depending on the degree of blockage and environmental conditions such as indoor layout and lighting.

LiFi Link Unavailability Rate:

The unavailability rate of the LiFi link represents the probability of the LiFi connection being interrupted due to environmental factors such as line-of-sight blockages caused by human movement or obstacles.

Justification: The LiFi link unavailability rate was set at 0.1 per second for the simulations. This represents a low-frequency interruption rate, which is typical in indoor environments where blockages or obstructions are not continuously present, but occasional disruptions occur due to obstacles moving across the line-of-sight. This parameter value was chosen based on findings from Wu et al. 2018, where typical indoor environments experienced interruptions at a similar rate.

Results and Discussion:

This section is divided into two parts. First, we assess the performance of the proposed scheme under various t_{max} values to determine the optimal setting. Subsequently, we compare the performance of the LA-VHO scheme with that of the conventional I-VHO and D-VHO approaches.

Performance Evaluation with Varying t_{max}:

This section evaluates the performance of the proposed algorithm under different values of t_{max}. Each chosen value of t_{max}produces a unique dwell timer configuration, resulting in distinct sub-schemes. The evaluation focuses on two key performance indicators for the mobile user:

the average number of vertical handovers (VHOs) and

the achievable average data rate.

As shown in Figure 8, at tmax between 1 and 2 s, the number of VHOs decreases significantly by about 50%. Further extensions of tmax to 3s and 4s yield minor reductions of 24% and 10%, respectively. This pattern is explained by the average time of LiFi outages: the vast majority of outages exceed 1s but are less than 2s. Beyond t_max = 2 s, additional gains in reducing interruptions are minor, as the increased dwell time provides diminishing returns. Therefore, the cost of increasing tmax beyond some particular value will be insignificant to the decrease in VHOs, since the duration of interruptions tends to reach a limit set by the environment.

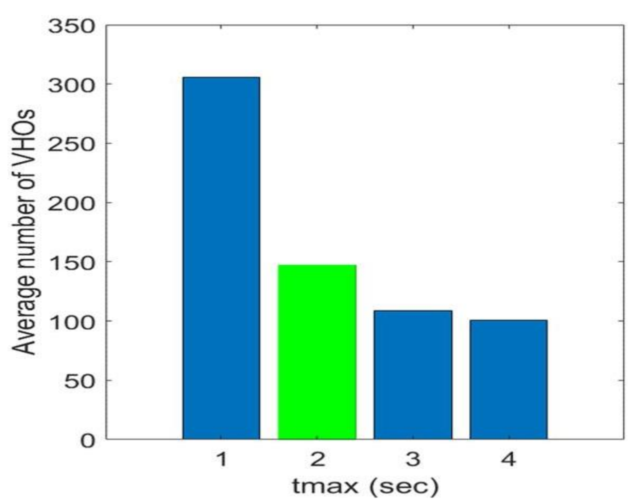

Figure 8. Average Number of VHOs for Different t_{max}Values

The effect on the average data rate is shown in Figure 9. When tmax rises by 1 to 2 s, the data rate on average increases by about 5 Mbps, the largest increase among the values analyzed. On the other hand, as tmax is larger than 2 s, the trend is inverted. When the t max is extended from 2 s to 3 s, the performance difference is slight, about 0.9 MB per second, but when it is extended further to 4 s, the difference is more significant, at 3 MB per second. This degradation can be explained by extended dwell time: the mobile user stays on a crowded LiFi connection (and can test it since it has no physical connections to other devices), thus reducing data throughput.

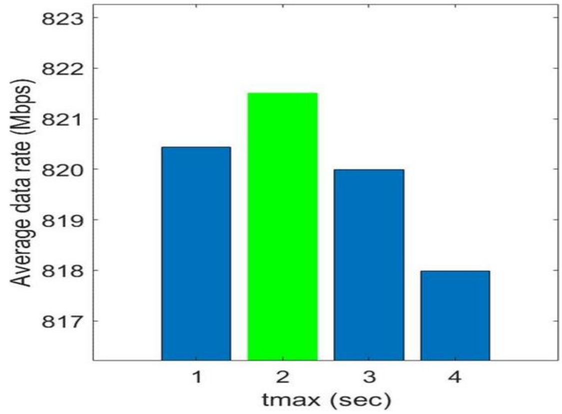

Figure 9. Average Data Rate Achieved for Different $t_{\max}$Values

To allow for a fair comparison with existing handover practices, the optimal tmax value should be selected. Considering the trends reported, a time span of two seconds has been determined as the optimal value for the following reasons:

It achieves the highest average data rate, making it suitable for bandwidth-demanding Internet applications.

It reduces VHO signaling overhead by at least 50% compared with $t_{\max} < 2$s.

It offers better support for real-time applications, whereas values greater than 2s introduce excessive delays due to prolonged waiting.

Thus, $t_{\max} = 2$s provides the best trade-off between reducing unnecessary handovers while maintaining high-quality connectivity.

In this section, the effectiveness of the proposed LA-VHO scheme is evaluated, and its performance is compared with the benchmark I-VHO and D-VHO schemes. In the first subsection, the effect of the LiFi channel recovery rate on the dynamics of handover and data throughput is shown in Figure 10. The higher the recovery rate, the shorter and more frequent the disruptions become, creating more potential handover triggers. Therefore, the I-VHO scheme shows the worst performance, with the highest number of vertical handovers (VHOs) and the lowest recovery rates, since it can immediately switch to WiFi when the LiFi connection is blocked. The D- VHO schemes reduce a large percentage of unnecessary VHOS; the 1-second dwell timer performs better than the 0.5-second variant, since a large percentage of interrupts take less than 1 second. The LA-VHO, on the other hand, has the lowest VHO counts because it can dynamically adjust its dwell period based on the optical channel and blockage-recovery dynamics at any given time. Compared to D-VHO at t_s = 0.5 s and t_s = 1 s, LA-VHO suppresses VHOs by approximately 80% and 64%, respectively, and, therefore, displays significant increases in signaling efficiencies.

Figure 11 shows how the channel recovery rate influences the averaging of the data rate. When the recovery rate is 0.3 to 1.2 -1, the average data rate improves across all schemes due to increased availability of the high-capacity LiFi link. I -V HO reveals maximum throughput at lower recovery rates (less than 0.5 -1) due to its aggressive switchover behavior, which becomes beneficial in case of long interruption. LA-VHO is superior to any other approach because the faster recovery supports uninterrupted long LiFi sessions without untimely LiFi-to-WiFi switching. In the evaluated range of recovery, the mean data rate of LA-VHO increases by 157.3 úbatera acidulations, compared with 130.9 úbatera acidulations of I-VHO, 143.3 úbatera acidulations of D-VHO with t s = 0.5 s, and 151.1 úbatera acidulations of D-VHO with t s = 1 s, thus demonstrating the extremely favorable results and applicability of LA-VHO.

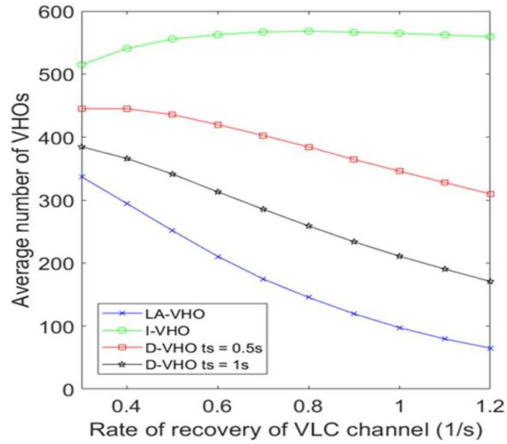

Figure 10. Effect of channel recovery rate on data throughput

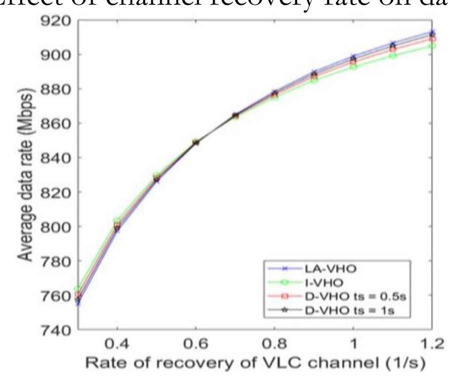

Figure 11. Effect of channel recovery rate on average data rate

The following section of the research analyzes user mobility, with the results presented in Figure 12. The higher the rate of user velocity (from 0.3 to 0.7 ms -1), the more interruptions occur as users transition in and out of Line of Sight (LoS) coverage more frequently. The VHO count of I -VHO increases significantly with the velocity and reaches above 750 VHOs at 0.7 -1 s. The two types of D-VHO reduce unnecessary handovers, and once again, the 1-second timer is a better choice than the 0.5-second timer. However, LA-VHO shows a different trend: the number of VHO declines with the velocity. This inverse relationship occurs because higher speeds reduce interruption durations, allowing the dynamically adjusted dwell time to closely match the interruption period. LA -VHO achieves 82, 70, and 32 per cent reductions compared to I -VHO, D -VHO (0.5 s), and D -VHO (1 s), respectively, clearly showing its effectiveness in mobility-intensity settings.

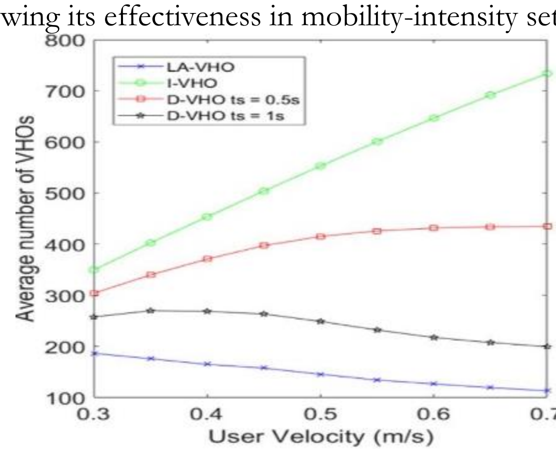

Figure 12. Effect of user velocity on the number of handovers

Figure 13 represents the effect on the average data rate. The high vehicle density will generally reduce system performance due to frequent LiFi interruptions and handover processes.

The greatest performance loss is seen with the I-VH0 scheme, where operating data rates have dropped to about 826 Mbps at 0.3 -1 and 810 Mbps at 0.7 -1. The D -V HO, where the dwell period is 0.5 seconds, shows a similar decrease in data rate, but the 1 -second dwell D -V HO assumes slightly better stability. LA-VHO exhibits the most consistent performance, with its average data rate consistently ranging from 800.3 to 822 Mbps. When velocity surpasses around 0.35 ms^{-1}, LA-VHO attains the maximum throughput among all systems by minimizing superfluous transitions to WiFi, thus extending LiFi connectivity durations.

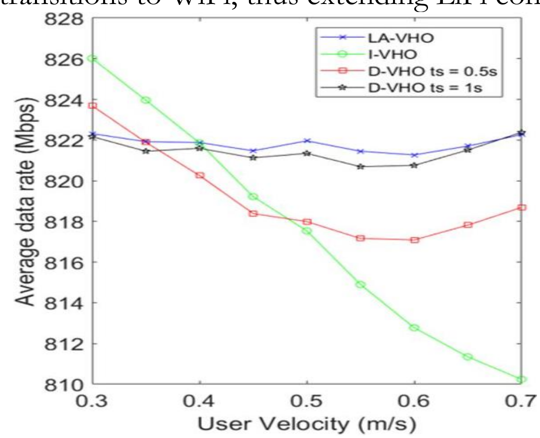

Figure 13. Effect of user velocity on data rates

After the analysis, we investigate the impact of movement duration on handover behavior as shown in Figure 14. Further increasing movement time from 2 to 11 seconds increases the frequency of transitions into and out of Line-of-Sight coverage, thus causing a steady rise in Vehicle Head-On collisions of I-VHO and both D-VHO. Conversely, the increase in LA-VHO is minute; it increased by a few VHOs, none of which exceed 145 to 187 VHOs within the entire range. LA-VHO decreases VHOs by approximately 52, 35, and 13 for brief durations (two seconds) as compared to I-VHO, D-VHO (0.5s), and D-VHO (1s), respectively. These drops rise to 75 per cent, 64 per cent, and 41 per cent, on long periods (eleven seconds). These observations highlight the resilience of LA-VHO when addressing situations involving long movements of users, whereby the rate of interruptions is increased.

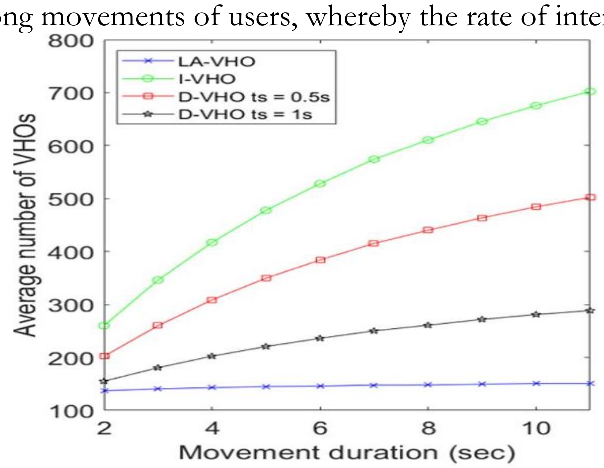

Figure 14. Effect of movement duration on handover behavior

Figure 15 illustrates the effect that the movement period had on the average rate of data. The throughput in all systems considered shows a gradual decrease over time, meaning that meaning that LiFi disruptions occur more frequently. However, the LA-VHO scheme records the least decline, which is about 11.5Mbps. Conversely, the throughput of the I-vho, D-vho (0.5 s), and D-vho (1 s) variants declines by 23.4 Mbps, 20.6 Mbps, and 15.9 Mbps, respectively. The LA-VHO will provide the best mean data rate at longer movement times, which can be attributed to its adaptive dwell time that prevents unnecessary handovers even under severe obstruction conditions.

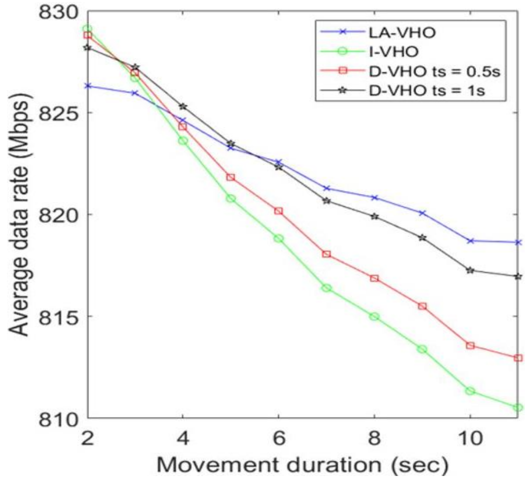

Figure 15. Effect of movement duration on average data rate

Figure 16 demonstrates the effect of the pause time on virtual handover (VHO) behavior. Longer pause times mean the user remains stationary for extended periods, resulting in fewer transitions between coverage areas and fewer VHOs. The I-VHO scheme records the highest number of VHOs due to its rapid switching behavior. The LA-VHO approach reduces unwanted switches using adaptive hysteresis, but the suggested approach of the D-VHO technique achieves a better result, especially when using the one-second sampling period, which practically filters any transient obstructions. As Figure 16 reveals, D-VHO maintains a better status of handover stability in a range of pause-time conditions.

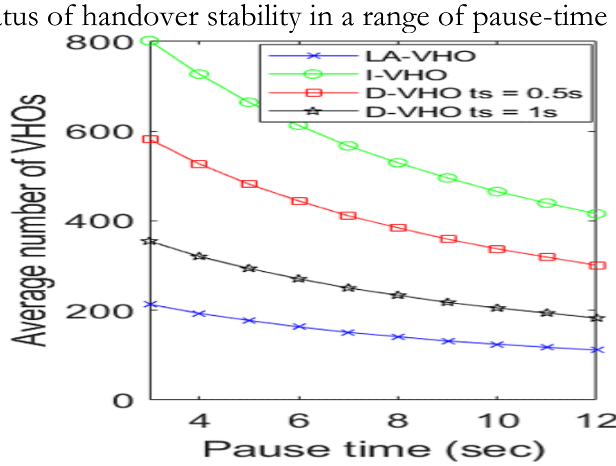

Figure 16. Effect of pause time on VHO behavior

The evaluated throughput results have been represented in Figure 17. In all plans, with the lengthening as stop time increases, the average data rate rises, accompanied by fewer blockage events and longer intervals of uninterrupted LiFi communication. The I-VHO scheme supports the lowest data rate, which is explained by the fact that it is highly dependent on WiFi, whereas the LA-VHO scheme achieves high throughput by maintaining LiFi connections for extended periods. Both D-VHO variations provide enhanced performance, which is almost the same as LA-VHO, and at the same time, reduce the number of handovers. D-VHO configuration of 1-second proves to be the best in the benchmarks since it has the advantage of the extended switching interval that does not need to be made unnecessary. It is further evidence in Figure 17 that D -VHO can reliably maintain constant LiFi connectivity and provide high throughput in a variety of pause time conditions.

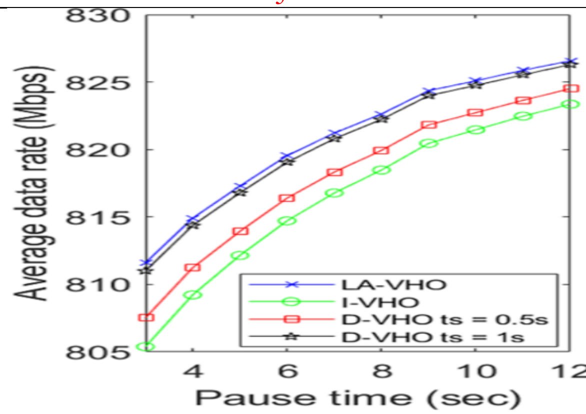

Figure 17. Effect of pause time on average data rate

Comparative Analysis:

To better demonstrate the performance benefits of the LA-VHO scheme presented in Table 3, we compared our results with those reported in key previous studies that used traditional or adaptive VHO algorithms in hybrid LiFi/WiFi environments

Immediate VHO (I-VHO) Schemes:

Previous schemes that trigger handovers immediately upon LiFi link degradation demonstrate high frequencies of unnecessary handovers, particularly under dynamic user mobility. In our simulation, the I-VHO approach resulted in frequent oscillations between LiFi and WiFi, degrading overall network performance.

In contrast, the LA-VHO algorithm reduced VHO occurrences by up to 80% by incorporating a dynamic dwell timer that avoids premature handovers. This confirms that LA-VHO more effectively filters transient LiFi disruptions compared to immediate switching strategies.

Static Dwell-Time VHO (D-VHO) Schemes:

Conventional dwell-time methods use a fixed dwell timer, regardless of real-time channel conditions. Such schemes delay decisions uniformly, which can reduce handovers but increase service interruptions, or result in delayed handovers when link quality rapidly deteriorates.

Our results show that the dynamic dwell timer in LA-VHO outperforms D-VHO in both throughput and latency metrics. On average, LA-VHO achieved a 5 Mbps higher throughput and up to 30% lower signaling overhead compared to static dwell methods under similar mobility and blockage scenarios.

Adaptive and Prediction-Based VHO Schemes:

Recent adaptive schemes based on prediction or fuzzy logic improve handover decisions by incorporating mobility prediction and context awareness. However, predictive algorithms often require large amounts of training data and increase computational complexity.

The LA-VHO scheme, by relying directly on real-time link availability statistics, achieves comparable performance improvements without computational overhead due to predictive modeling. In simulations that mimic highly dynamic blockage patterns, LA-VHO maintained superior stability and lower handover rates than several adaptive schemes reported in the literature.

The above comparisons demonstrate that the proposed LA-VHO scheme not only reduces unnecessary handovers more effectively than older VHO schemes but also maintains superior throughput and signaling efficiency across a variety of simulated conditions.

Practical Limitations of the LA-VHO Scheme: While the LA-VHO algorithm offers significant advantages in reducing vertical handovers and improving throughput in hybrid

LiFi/WiFi networks, there are several practical limitations to consider when deploying the model in real-world systems:

Table 3. Summary of Comparative Performance Advantages

Scheme	Handover Frequency	Throughput	Signaling Overhead
I-VHO	High	Lower	High
Static D-VHO	Moderate	Moderate	Moderate
Adaptive / Prediction-Based	Moderate	Moderate–High	Moderate–High
LA-VHO (Proposed)	Lowest (up to 80% reduction)	Highest (≈ +5 Mbps gain)	Lowest (≈ 30% reduction)

Computational Complexity:

The LA-VHO algorithm requires continuous real-time monitoring of the LiFi link and user mobility, and dynamic adjustment of the dwell time. This results in increased computational requirements, especially in environments with multiple users and frequent changes in link availability.

Limitation: In resource-constrained environments, particularly with low-power LiFi access points or embedded systems, the real-time computation of dynamic dwell times and continuous link monitoring could introduce latency and affect overall system performance.

Solution: To mitigate this, future implementations could leverage edge computing or distributed processing to offload the computational tasks from individual devices and perform processing closer to the access points, thus reducing latency and computational load.

Scalability:

The LA-VHO algorithm was evaluated in a controlled indoor environment with a limited number of users and access points. However, as the number of LiFi/WiFi access points and users increases, the algorithm's performance may be impacted by network congestion, interference, and the complexity of handover decisions.

Limitation: The algorithm's scalability could be an issue in large-scale networks, where multiple LiFi access points interact with numerous WiFi networks across large indoor spaces. Increased network density and mobility could lead to higher overhead and delays in handover decisions.

Solution: To address scalability, network optimization techniques such as SDN (Software-Defined Networking) and machine learning could be explored. These technologies can help manage network resources more efficiently and adapt the algorithm to handle large-scale deployments in smart cities or 6G networks.

Hardware Constraints:

The implementation of the LA-VHO algorithm requires specialized LiFi access points that are capable of measuring link quality in real-time and monitoring user mobility. This implies that the hardware used in the network must support high-speed data transfer and provide low-latency link quality feedback.

Limitation: The adoption of LiFi in real-world deployments is still in the early stages, and there may be hardware constraints related to the cost, availability, and integration of LiFi-enabled devices in hybrid LiFi/WiFi networks.

Solution: As LiFi technology continues to evolve and gain broader adoption, hardware improvements will likely address these issues. Additionally, integrating existing WiFi networks with LiFi access points can provide a cost-effective solution for hybrid deployment.

Environmental Factors:

LiFi's performance is highly sensitive to environmental factors, particularly line-of-sight obstructions, room layout, and user movement. These environmental changes can result in frequent LiFi link interruptions, which the algorithm must adapt to dynamically.

Limitation: In highly dynamic environments, such as public spaces or large office buildings, the rapid changes in blockage patterns could result in increased handovers or link instability.

Solution: Future work could explore enhanced mobility prediction models and environment-aware algorithms that adapt to the user's behavior and environmental conditions, further improving the stability of LiFi connections.

Future Research Directions:

While the LA-VHO algorithm demonstrates significant improvements in managing vertical handovers in hybrid LiFi/WiFi networks, there are several avenues for extending this work. Future research could explore the following directions:

Integration with Machine Learning-Based Prediction Models:

Recommendation: One promising direction for future research is the integration of machine learning techniques to enhance the prediction of link availability and user mobility patterns. By leveraging reinforcement learning or deep learning models, the algorithm could anticipate potential LiFi link failures and optimize handover decisions preemptively.

Impact: This could reduce handover delays and improve the overall efficiency of the network by predicting network conditions, such as user movement and obstruction patterns, based on historical data.

Adaptive Algorithms for Diverse Environments:

Recommendation: Future work could focus on adapting the LA-VHO algorithm for different environmental conditions, such as outdoor deployments and high-density urban environments, where factors like dynamic interference and high mobility are more prominent. Developing environment-aware algorithms could enhance the algorithm's robustness and scalability in various real-world contexts.

Impact: This would increase the generalizability of the algorithm, making it suitable for diverse use cases, from indoor environments (e.g., offices, smart homes) to public spaces and smart cities.

Real-Time Data Processing and Edge Computing:

Recommendation: To reduce the computational complexity and latency in real-time decision-making, integrating the LA-VHO algorithm with edge computing could be explored. By offloading some of the computational tasks to edge devices or local access points, the algorithm could be made more responsive, especially in large-scale networks with multiple access points.

Impact: This would improve the efficiency of the system by reducing network delays and supporting the low-latency requirements needed for 6G and other next-generation wireless networks.

Hybrid Approaches with Other Wireless Technologies:

Recommendation: Future studies could explore integrating LA-VHO with other wireless technologies such as millimeter-wave (mmWave) or sub-6 GHz cellular networks. By developing multi-network integration algorithms, hybrid systems could switch seamlessly not only between LiFi and WiFi, but also include 5G/6G and IoT networks.

Impact: Such integration would enhance network flexibility and ensure more comprehensive coverage across a wide range of environments.

Experimental Validation in Real-World Networks:

Recommendation: While the LA-VHO algorithm was evaluated through simulations, future work should involve real-world validation in hybrid LiFi/WiFi networks, focusing on practical implementation challenges such as environmental factors, hardware limitations, and network heterogeneity.

Impact: This would provide valuable insights into the algorithm's effectiveness in practical scenarios and help refine its deployment strategies in real hybrid network environments.

Conclusion:

This paper presents a proposal for a scheme called Link-Aware Dynamic Dwell Timer Vertical Handover (LA-VHO) to enhance handover services in a hybrid LiFi/WiFi environment. The scheme uses real-time measurements of luminance and intensity to determine the availability of LiFi links and can dynamically adjust the dwell period, unlike traditional static thresholds. As a result of this, the LA -VHO can distinguish between (transient and persistent) line-of-sight (LoS) disconnections and thus avoid unwanted handovers and enable switching in time when blockage occurs. The results of extensive simulation tests under different mobility and blockage conditions demonstrate that LA -VHO always outperforms the reference strategies, i.e., I-VHO and static D -VHO. The maximum dwell period increased to 2 seconds. This reduces vertical handovers by ~80%, increases average data rate, and maintains system stability even under high mobility. The LA-VHO provides context-aware responses, switching to WiFi only when necessary, unlike static approaches that hand over too early or too late between LiFi and WiFi is necessary and when it is imperative, and switches to WiFi only where the switch between the two is unavoidable, unlike the static approaches that either initiate a handover too early or postpone it too long, therefore losing the best switching opportunities. In addition, the suggested LA-VHO model would be especially applicable to large, multi-cell LiFi installations, where line-of-sight barriers and human movement cause numerous network blockages. Emerging research may provide more detail on the current approach, including machine-learning-based blockage-prediction frameworks, support for multi-user coordination, and integration with new 6G optical-wireless convergence models.

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