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Mobility Management for Hybrid LiFi and WiFi Networks in the Presence of Light-path Blockage

Abstract

The escalating demand for mobile data has prompted a dire need for spectrum optimization due to the impending spectrum crunch in RF frequencies. In response, LiFi technology, leveraging visible light communication, has emerged as a promising alternative, offering a wider spectrum, heightened security, and gigabit-speed transmissions compared to conventional WiFi. This paper explores the fusion of LiFi and WiFi networks into Hybrid LiFi and WiFi Networks (HLWNets) to harness both LiFi's high-speed transmission and WiFi's widespread coverage. However, challenges such as access point selection (APS), load balancing (LB), and efficient handover strategies pose significant complexities in HLWNets, especially considering user mobility and light-path blockages.

The study introduces a novel approach that jointly optimizes load balancing and handover decisions in HLWNets. Unlike the conventional load balancing method, the proposed technique dynamically determines network access types for users over time, considering factors like user mobility and occurrences of light-path blockages. Monte Carlo simulations validate the proposed method's efficacy, showcasing a substantial system throughput improvement of up to 60% over the conventional approach.

Introduction

The proliferation of mobile devices and the surging demand for high-speed data services have propelled global mobile data traffic to unprecedented levels. Forecasts predict a fourfold increase in mobile data traffic within a mere four-year span, reaching an astounding 48.3 exabytes per month by the end of 2021 [1]. However, this meteoric rise in data consumption is coupled with a looming crisis— the potential spectrum crunch in radio-frequency (RF) bandwidths, foreboding an imminent scarcity of available frequencies to accommodate this escalating demand [2]. Novel approaches leveraging higher-frequency spectrums have garnered significant attention to alleviate this impending crisis, among which is the emerging technology of Light Fidelity (LiFi).

LiFi technology, an offshoot of visible light communication, presents a promising solution by utilizing light-emitting diodes (LEDs) to modulate light intensity, transmitting data and employing photodiodes (PDs) to receive the transmitted signals. LiFi holds several distinct advantages over traditional Wireless Fidelity (WiFi) technologies, offering access to a broader and unregulated spectrum, enhanced security in communications, and the potential for deployment in RF-restricted environments. Moreover, LiFi can deliver high-speed data transmissions, reaching the gigabit-per-second range [3].

To merge the advantages of LiFi's high-speed transmission and WiFi's ubiquitous coverage, researchers have proposed the concept of Hybrid LiFi and WiFi Networks (HLWNets). These hybrid networks aim to harness the strengths of both LiFi and WiFi technologies, augmenting throughput and extending coverage compared to standalone LiFi or WiFi networks [4].

However, integrating LiFi and WiFi technologies introduces intricate challenges in managing these hybrid networks. Access Point Selection (APS), Load Balancing (LB), and Handover have become complex issues in HLWNets for several reasons. WiFi access points possess broader coverage areas but limited capacities compared to their LiFi counterparts. Furthermore, the overlapping coverage areas of distinct networks exacerbate the challenge of APS. The conventional Signal Strength Strategy (SSS) for APS, which assigns users to access points based on received signal power, renders WiFi systems vulnerable to traffic overloads, necessitating effective load-balancing strategies [5].

This research aims to bridge this gap in the existing literature by presenting a novel approach that jointly optimizes Load Balancing (LB) and Handover decisions in HLWNets. Unlike conventional methods focusing on instantaneous APS, the proposed method dynamically determines network access types for users over time, considering user mobility, light-path blockages, and the associated handover costs.

Methodology

3.1 System Model of Indoor HLWNet:

An indoor Hybrid LiFi and WiFi Network (HLWNet) comprises one WiFi access point (AP) and multiple LiFi APs. The WiFi AP is centrally deployed on the ground, providing coverage to the entire room. Conversely, each LiFi AP is integrated into ceiling LED lamps, directing light downwards to cover a confined area. The network assumes that the LiFi APs operate on different spectra, preventing interference. Users follow a random waypoint model for mobility, assuming constant speeds within a given period. Time-division multiple access (TDMA) enables APs to serve multiple users concurrently.

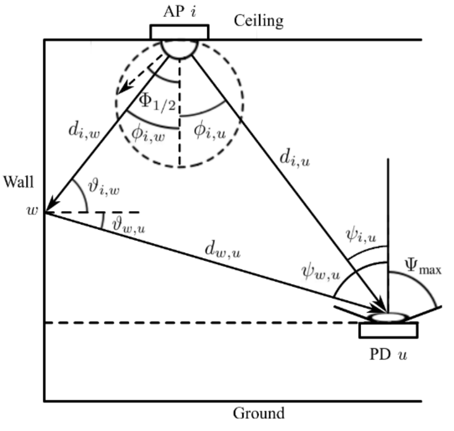


Fig. 1. The LoS and first-order NLoS paths of a LiFi channel.

3.2 Channel Models:

LiFi Channel Model: The LiFi channel includes Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) components. The LoS path's channel gain is expressed considering Euclidean distance, angles of irradiance and incidence, optical filter gain, and concentrator gain.

The channel gain (H)

$$H_{\mathrm{LoS}}^{i,u} = \frac{(m+1)A_{\mathrm{pd}}}{2\pi d_{i,u}^2} \cos^m(\phi_{i,u}) g_f g_c(\psi_{i,u}) \cos(\psi_{i,u}), \qquad (1)$$

where $m = -\ln 2/\ln(\cos \Phi_{1/2})$ is the Lambertian emission order, and $\Phi_{1/2}$ is the angle of half intensity; A_{pd} is the physical area of the PD; g_f denotes the gain of the optical filter; the optical concentrator gain $g_c(\psi_{i,u})$ is given by:

$$g_c(\psi_{i,u}) = \begin{cases} \dfrac{n^2}{\sin^2(\Psi_{\max})}, & 0 \le \psi_{i,u} \le \Psi_{\max} \\ 0, & \psi_{i,u} > \Psi_{\max} \end{cases}, \qquad (2)$$

where n stands for the refractive index, and $\Psi_{\max}$ denotes the semi-angle of the field of view (FoV) of the PD.

For NLoS paths, first-order reflections contribute to the overall channel gain.

The channel gain by NLoS path,

where A_w denotes a small area on the wall and ρ_w is the wall reflectivity. Adding (1) to (3), the total gain of a LiFi channel is given by:

$$H_{\mathrm{LiFi}}^{i,u} = H_{\mathrm{LoS}}^{i,u} + H_{\mathrm{NLoS}}^{i,u}. \tag{4}$$

At the receiver of user u, the PD gathers photons and converts them into an electric current:

$$I_{\mathrm{elec}} = R_{\mathrm{pd}} H_{\mathrm{LiFi}}^{i,u} P_{\mathrm{opt}} / \zeta, \tag{5}$$

where R_{pd} is the detector responsivity; P_{opt} is the transmitted optical power; and ζ is the ratio of the transmitted optical power to the optical signal power.

The signal-to-noise ratio (SNR) computation accounts for the impact of light-path blockages, representing the user's experience during connection interruptions.

$$I_{\mathrm{elec}} = (1 - \xi_u) R_{\mathrm{pd}} H_{\mathrm{LiFi}}^{i,u} P_{\mathrm{opt}} / \zeta. \tag{6}$$

The signal-to-noise ratio (SNR) of a LiFi user can be computed as:

$$\gamma_{\mathrm{LiFi}}^{i,u} = \frac{\left[(1 - \xi_u) R_{\mathrm{pd}} H_{\mathrm{LiFi}}^{i,u} P_{\mathrm{opt}} / \zeta \right]^2}{N_{\mathrm{LiFi}} B_{\mathrm{LiFi}}}, \tag{7}$$

where B_{LiFi} is the system bandwidth of the LiFi AP and N_{LiFi} is the power spectral density (PSD) of noise at the PD, including shot noise and thermal noise.

WiFi Channel Model: The WiFi channel's gain incorporates standard Rayleigh distribution and free-space path loss, considering the central carrier frequency and reference distance. SNR calculations in the WiFi model also account for noise power spectral density and signal transmission parameters.

$$G_{\mathrm{WiFi}}^{i,u} = \left| H_{\mathrm{WiFi}}^{i,u} \right|^2 10^{\frac{-L(d_{i,u})+X_\sigma}{10}}, \tag{8}$$

where $H_{\mathrm{WiFi}}^{i,u}$ describes the channel transfer function, which follows a standard Rayleigh distribution; the shadow fading X_σ is a zero-mean Gaussian random variable with a standard deviation of 10 dB; and $L(\cdot)$ represents the free-space path loss:

$$L(d) = \begin{cases} 20\log_{10}(f_c d) - 147.5, & d < d_{\mathrm{ref}} \\ 20\log_{10}\left(f_c \frac{d^{2.75}}{d_{\mathrm{ref}}^{1.75}}\right) - 147.5, & d \geq d_{\mathrm{ref}} \end{cases}, \tag{9}$$

where f_c is the central carrier frequency and $d_{\mathrm{ref}} = 10$ m is the reference distance. The SNR of a WiFi user is written as:

$$\gamma_{\mathrm{WiFi}}^{i,u} = \frac{G_{\mathrm{WiFi}}^{i,u} P_{\mathrm{WiFi}}}{N_{\mathrm{WiFi}} B_{\mathrm{WiFi}}}, \tag{10}$$

where N_{WiFi} is the PSD of noise at the receiver; B_{WiFi} and P_{WiFi} denote the system bandwidth and transmit power of the WiFi AP, respectively.

3.3 Conventional Load Balancing (LB) Method

The conventional approach employs proportional resource allocation based on the actual throughput obtained by users. It relies on instantaneous Load Balancing (ILB) solutions, allocating users to APs based on received signal power and Shannon capacity. However, ILB overlooks the dynamics of user mobility, light-path blockages, and handover costs, leading to suboptimal throughput.

$$R_u^{(t)} = \sum_i \chi_{i,u}^{(t)} \rho_{i,u}^{(t)} r_{i,u}^{(t)}, \tag{12}$$

where $\chi_{i,u}^{(t)} = 1$ means that a connection exists between AP i and user u, while $\chi_{i,u}^{(t)} = 0$ means otherwise; $\rho_{i,u}^{(t)}$ is a fraction variable between 0 and 1, which denotes the proportion of time that AP i allocates to user u; $r_{i,u}^{(t)}$ represents the Shannon capacity that AP i can provide to user u:

$$r_{i,u}^{(t)} = B_i \log_2\left(1 + \gamma_{i,u}^{(t)}\right). \tag{13}$$

3.4 Proposed Method for Joint Optimization:

The proposed method focuses on jointly optimizing Load Balancing and handover decisions in HLWNets over time. Unlike ILB's instantaneous decisions, the proposed method dynamically determines the network access type for each user. It accounts for the impact of user mobility and light-path blockages, adapting network access types to enhance overall throughput. The methodology ensures that users can switch between homogeneous APs, considering connectivity disruptions caused by light-path blockages and mobility.

$$\bar{R}_u = \sum_{\kappa} \chi_{\kappa,u} \sum_{\alpha} \rho_u^{\alpha} \tau_{\kappa,u}^{\alpha} r_u^{\alpha}, \tag{16}$$

where $\chi_{\kappa,u} = 1$ means that user u chooses κ-type of network access, while $\chi_{\kappa,u} = 0$ means otherwise; ρ_u^{α} denotes the proportion of time that α-type network allocates to user u; and r_u^{α} is the average Shannon capacity that the α-type network can provide to user u:

$$r_u^{\alpha} = \sum_{i \in \alpha} \chi_{i,u} \int_t B_i \log_2(1 + \gamma_{i,u}^{(t)}) dt. \tag{17}$$

The coefficient $\tau_{\kappa,u}^{\alpha}$ in (16) denotes the proportion of time during which user u is served by the α-type network. Let T_{VHO} denote the VHO overhead. For different choices of κ, $\tau_{\kappa,u}^{\text{LiFi}}$ and $\tau_{\kappa,u}^{\text{WiFi}}$ are given by:

$$\tau_{\kappa,u}^{\text{LiFi}} = \begin{cases} 1 - \eta_u & \text{if } \kappa \text{ is 'LiFi only'} \\ 0 & \text{if } \kappa \text{ is 'WiFi only'} \\ \max\{1 - \eta_u - \lambda_u T_{\text{VHO}}, 0\} & \text{if } \kappa \text{ is 'LiFi/WiFi'} \end{cases} . \tag{18}$$

and:

$$\tau_{\kappa,u}^{\text{WiFi}} = \begin{cases} 0 & \text{if } \kappa \text{ is 'LiFi only'} \\ 1 & \text{if } \kappa \text{ is 'WiFi only'} \\ \max\{\eta_u - \lambda_u T_{\text{VHO}}, 0\} & \text{if } \kappa \text{ is 'LiFi/WiFi'} \end{cases} . \tag{19}$$

Now we take into account user mobility. For a user that is connected to the α-type network, the proportion of time taken up by HHOs is denoted by ϱ_u^{α}. Denoting the HHO overhead with respect to the α-type network by T_{HHO}^{α}, ϱ_u^{α} can be calculated by:

$$\varrho_u^{\alpha} = \begin{cases} \dfrac{T_{\text{HHO}}^{\alpha}}{T_u^{\alpha}} & \text{if } T_{\text{HHO}}^{\alpha} \le T_u^{\alpha} \\ 1 & \text{if } T_{\text{HHO}}^{\alpha} > T_u^{\alpha} \end{cases} , \tag{20}$$

where T_u^{α} is the average cell dwell time (CDT) of user u, which can be collected by statistics [16]. The average throughput in (16) is then modified to:

$$\bar{R}_u = \sum_{\kappa} \chi_{\kappa,u} \sum_{\alpha} \tau_{\kappa,u}^{\alpha} r_u^{\alpha} \min\{\rho_u^{\alpha}, 1 - \varrho_u^{\alpha}\}. \tag{21}$$

3.5 Simulation Setup, Parameters, and Assumptions:

Monte Carlo simulations are conducted to evaluate the performance of the proposed method. The simulation setup considers an indoor area with specific dimensions and positions of LiFi and WiFi APs. Parameters such as physical characteristics of PDs, transmitted powers, bandwidths, noise power spectral densities, handover overheads, and light-path blockage occurrences are configured based on experimental or standard assumptions. The simulations assess system throughput and network performance under varying user counts, speeds, and light-path blockage rates.

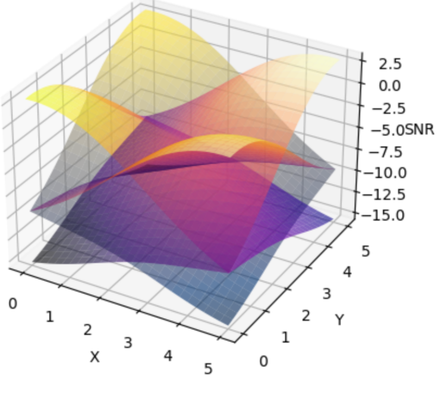
TABLE I
SIMULATION PARAMETERS

Parameter	Value
Room size (length by width by height)	$5 \times 5 \times 3$ m
The physical area of the PD, A_{pd}	1 cm^2
The gain of the optical filter, g_f	1
Refractive index, n	1.5
Half-intensity radiation angle, $\Phi_{1/2}$	60°
FoV semi-angle of PD, $\Psi_{\max}$	90°
The ratio of P_{opt} to the optical signal power, ζ	3
Detector responsivity, R_{pd}	0.53 A/W
Wall reflectivity, ρ_w	0.8
Transmitted optical power per LiFi AP, P_{opt}	3 Watt
Transmitted power per WiFi AP, P_{WiFi}	20 dBm
Bandwidth per LiFi AP, B_{LiFi}	20 MHz
Bandwidth per WiFi AP, B_{WiFi}	20 MHz
PSD of noise in LiFi, N_{LiFi}	10^{-21} A^2/Hz
PSD of noise in WiFi, N_{WiFi}	-174 dBm/Hz
The HHO overhead, T_{HHO}	200 ms [18]
The VHO overhead, T_{VHO}	500 ms [8]

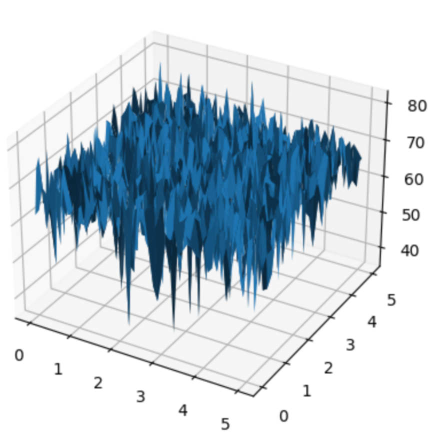
Simulation

The performance evaluation of the proposed methodology is carried out using Monte Carlo simulations. These simulations are designed to assess the system throughput and network performance concerning varying factors such as the number of users, user speed, and the occurrence rate of light-path blockages. The results are presented through a series of figures, charts, and tables showcasing the system throughput under different scenarios.

SNR Plot for LiFI



SNR Plot for WiFi



We ran the simulation for 10 users with some changes in parameters for step size, and average user speed to see the performance of users in the network.

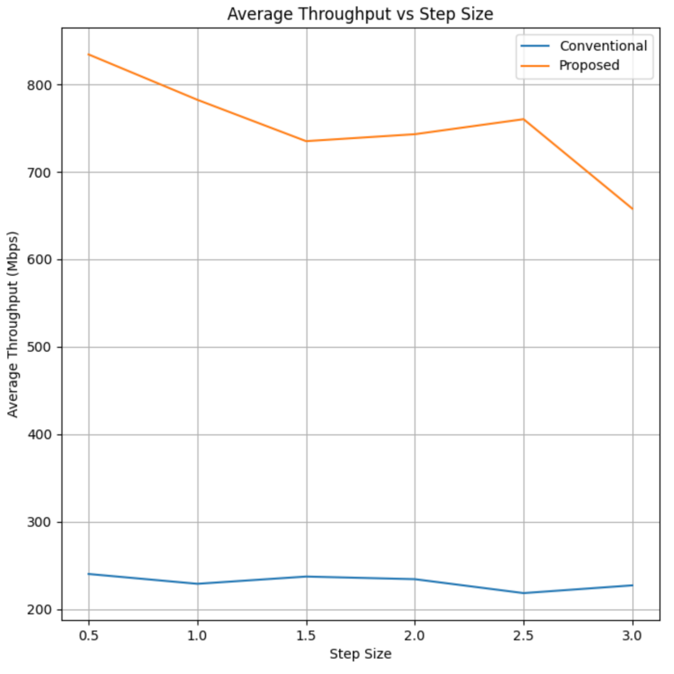
We also calculated the average throughputs using the conventional load balancing and the proposed method for load balancing in the paper.

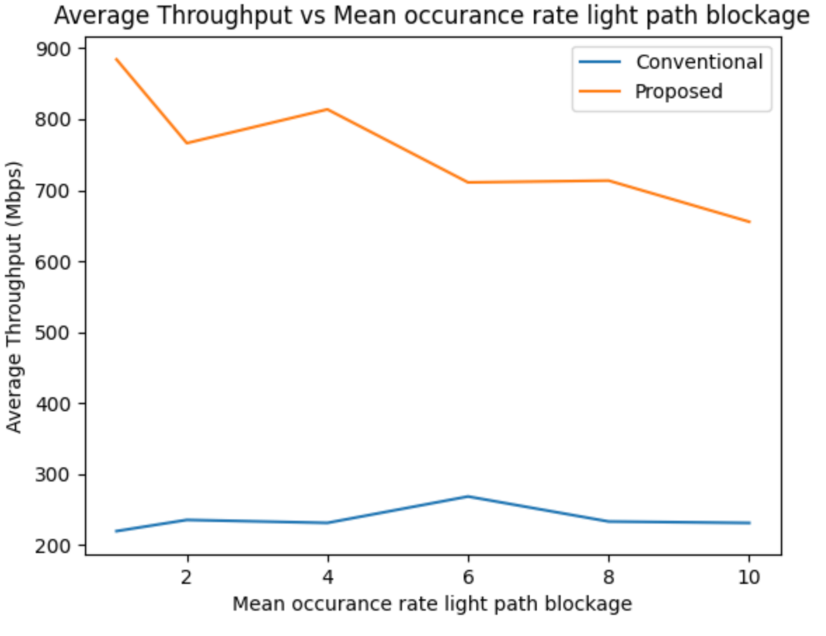
See Results for the Graphs.

Results

The outcomes derived from the Monte Carlo simulations provide significant insights into the performance of the proposed Access Point Selection (APS) method in Hybrid LiFi and WiFi Networks (HLWNets). Analysis of the simulation results reveals a notable enhancement in system throughput compared to conventional approaches, namely Instant Load Balancing (ILB) and Signal Strength Strategy (SSS).

Detailed comparative analyses demonstrate that the proposed APS method consistently outperforms ILB and SSS across various network scenarios. The system throughput achieved by the proposed method exhibits significant improvements, particularly under high user density, varying user mobility, and in the presence of light-path blockages. Specifically, in scenarios with a high occurrence of light-path blockages, the proposed method showcases remarkable resilience and achieves superior throughput compared to conventional approaches.





Conclusion

In conclusion, this research has presented a novel Access Point Selection (APS) method tailored for Hybrid LiFi and WiFi Networks (HLWNets) to address the challenges of load balancing, handover, and user mobility. The study's key findings indicate the significant performance improvements achieved by the proposed APS method compared to traditional approaches.

While the proposed APS method exhibits promising results, it's important to acknowledge certain limitations and areas for further research. Future investigations could focus on practical implementations, real-world validations, and the development of adaptive algorithms to handle dynamic network conditions more efficiently. Additionally, exploring the impact of diverse network topologies and heterogeneous environments would enrich the understanding the proposed method's applicability and scalability.

References

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2. Modeling of the Handover Dwell Time in Cellular Mobile Communications Systems by M. Ruggieri; F. Graziosi; F. Santucci (https://ieeexplore.ieee.org/document/669087)
3. Shadowing and Blockage in Indoor Optical Wireless Communications by S. Jivkova; M. Kavehrad (https://ieeexplore.ieee.org/document/1258840)

Contributions

1. Deeksha Singh Duvesh (2020049)
    a. User Mobility Implemented
    b. Simulator
2. Pragyan Yadav (2020226)
    a. Conventional and Proposal Load Balancing Implemented
    b. Graphs and Interpretations
3. Sumit Kumar (2020249)
    a. WiFi Channel Model Implemented
    b. Light Path Blockage Implemented
4. Khushdev Pandit (2020211)
    a. Lifi Channel Model Implemented
    b. Light Path Blockage Implemented