Outage Probability Analysis for Link Aggregation-Enabled Hybrid LiFi-WiFi Network

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***Abstract*—Li-Fi and Wi-Fi operate in non-overlapping spectrum, allowing users to receive data simultaneously from both access points (APs). Rising demand for high-speed, reliable indoor communication has spurred the development of hybrid Li-Fi/Wi-Fi networks. To assess the performance of link aggregation (LA) in such hybrid networks (LA-HLWNs), we propose an analytical model to derive rate outage probability. The model accounts for LA-overhead and benchmarks LA-HLWNs against standalone Li-Fi and Wi-Fi systems. Results show that LA-HLWNs consistently achieve lower outage probabilities across diverse scenarios, proving LA's effectiveness in combining Li-Fi and Wi-Fi strengths to meet growing indoor communication demands.**

***Index Terms*—Li-Fi, Wi-Fi, hybrid network, Link aggregation.**

I. INTRODUCTION

The exponential rise in wireless devices and demand for high-throughput communication has strained the radio frequency (RF) spectrum, which is projected to fall short by 2035 [1]. To address this, researchers are exploring alternatives such as the visible light spectrum. Visible Light Communication (VLC) uses LEDs to transmit data via modulated light, detected by photodiodes and converted into electrical signals.

Extending VLC, Light Fidelity (Li-Fi) offers high-speed, bidirectional, and secure indoor connectivity [2]. It benefits from the vast unlicensed visible spectrum, immunity to RF interference, inherent physical security, and compatibility with existing LED infrastructure, enabling gigabit rates in environments like hospitals and airplanes [3]. However, Li-Fi's dependence on line-of-sight limits coverage and throughput under blockages. In contrast, Wi-Fi provides broader, reliable coverage but at lower data rates. Hybrid Li-Fi/Wi-Fi networks thus emerge as a natural solution, combining Li-Fi's capacity with Wi-Fi's ubiquity [2], [3].

Performance can be further improved with load balancing (LB), which enhances rates, outage, and handover efficiency [3]. Yet, overlap in coverage and Wi-Fi's lower capacity complicate LB, which is modeled as a computationally challenging MINLP problem [2], [4]. Scalable LB methods are therefore required to ensure QoS.

Beyond LB, link aggregation (LA) enables simultaneous data reception from both Li-Fi and Wi-Fi APs, exploiting their non-overlapping spectra to boost capacity, reliability, and latency. Networks adopting this technique are termed LA-enabled hybrid Li-Fi/Wi-Fi networks (LA-HLWNs).

Although prior studies have investigated various aspects of LA-HLWNs across different protocol layers [2], [5]–[7], the literature remains fragmented. For example, [8] focused on optimizing power and bandwidth to improve energy efficiency, while [3] employed reinforcement learning for load balancing. However, neither work examined the impact of LA on QoS performance. Similarly, [2] provided only proof-of-concept demonstrations, whereas other efforts have concentrated primarily on physical- or data-link layer implementations [5]. In addition, Lyapunov optimization has been explored to provide throughput guarantees in RF–VLC hybrid systems [6]. Despite these contributions, a comprehensive framework that holistically addresses QoS under LA in HLWNs is still lacking.

Moreover, existing studies largely ignore the computational overhead of LA and lack a comparative analysis against conventional hybrid networks. More importantly, no analytical model yet evaluates the rate outage probability in LA-HLWNs, which is a key reliability metric under realistic conditions.

Research Gaps: Prior studies mainly focus on standalone Li-Fi, Wi-Fi, or basic hybrid networks, but do not model the distinct features of LA-enabled HLWNs at the physical layer. Approaches that approximate outage by multiplying standalone probabilities overlook the interactions and gains of link aggregation. To address this, we propose an analytical model for evaluating rate outage probability in LA-enabled HLWNs, validated against standalone systems. Our model advances beyond earlier approaches by explicitly accounting for LA overhead, ensuring results that align with real-world performance.

The key contributions of this work are as follows:

- **Analytical Modeling:** A new model for rate outage probability in LA-enabled HLWNs, overcoming limitations of conventional methods.
- **Comparative Analysis:** Performance evaluation of LA-enabled HLWNs against standalone Li-Fi and Wi-Fi, showing the advantages of link aggregation.
- **Practical Relevance:** Integration of LA overhead, improving the model's applicability to real-world deployments.

II. OUTAGE PROBABILITY ANALYSIS

The primary focus of this section is the rate outage probability, which is directly influenced by the signal-to-interference-plus-noise ratio (SINR) received by the user. In the analysis, bandwidth is not explicitly included in the equations because

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it is assumed to be constant for all users within the network. Instead, the SINR, which encapsulates the impact of interference, noise, and signal strength, serves as the critical parameter for evaluating the outage probability.

A. Rate Outage Probability for Wi-Fi Only Network:

In a Wi-Fi-only network, user experience rate outages when the achieved data rates fall below the predefined rate threshold R_{th}. The rate outage probability is mathematically defined as:

$$P_{\text{outage, Wi-Fi}} = P(R_{\text{Wi-Fi}} < R_{\text{th}}), \tag{1}$$

where the user's normalized rate (with respect to the bandwidth) is given by:

$$R_{\text{Wi-Fi}} = \log_2(1 + \text{SINR}_{\text{Wi-Fi}}), \tag{2}$$

where $\text{SINR}_{\text{Wi-Fi}}$ is defined as SINR received by the user from Wi-Fi AP. Substituting $R_{\text{Wi-Fi}}$ into the outage probability definition, we have:

$$P_{\text{outage, Wi-Fi}} = P\left(\log_2(1 + \text{SINR}_{\text{Wi-Fi}}) < R_{\text{th}}\right). \tag{3}$$

This simplifies to:

$$P_{\text{outage, Wi-Fi}} = P\left(1 + \text{SINR}_{\text{Wi-Fi}} < 2^{R_{\text{th}}}\right). \tag{4}$$

Since the considered rate thresholds are expressed in Mbps and correspond to large system bandwidths, the resulting outage thresholds satisfy $2^{R_{\text{th}}} \gg 1$, which allows the approximation $2^{R_{\text{th}}} - 1 \approx 2^{R_{\text{th}}}$.

$$P_{\text{outage, Wi-Fi}} \approx P\left(\text{SINR}_{\text{Wi-Fi}} < 2^{R_{\text{th}}}\right). \tag{5}$$

For a Wi-Fi network operating under Rayleigh fading, the SINR follows an exponential distribution [9]. The probability density function (PDF) is expressed as:

$$f_{\text{SINR, Wi-Fi}}(x) = \frac{1}{\sigma_X^2} \exp\left(-\frac{x}{\sigma_X^2}\right), \tag{6}$$

where σ_X^2 represents the variance of the SINR.

Using the CDF, the rate outage probability for a Wi-Fi network is calculated as:

$$P_{\text{outage, Wi-Fi}} = 1 - \exp\left(-\frac{2^{R_{\text{th}}}}{\sigma_X^2}\right). \tag{7}$$

B. Rate Outage Probability for Li-Fi Only Network:

For a Li-Fi-only network, the rate outage probability follows a similar framework but considers the distinct propagation characteristics of Li-Fi, including its reliance on LoS communication. The outage probability is expressed as:

$$P_{\text{outage, Li-Fi}} = P\left(\log_2(1 + \text{SINR}_{Li-Fi}) < R_{\text{th}}\right), \tag{8}$$

where SINR_{Li-Fi} is defined as the SINR received at the user from Li-Fi AP. Simplifying further, we get:

$$P_{\text{outage, Li-Fi}} = P\left(\text{SINR}_{Li-Fi} < 2^{R_{\text{th}}} - 1\right), \tag{9}$$

$$P_{\text{outage, Li-Fi}} \approx P\left(\text{SINR}_{Li-Fi} < 2^{R_{\text{th}}}\right), \tag{10}$$

where Eq. (10) is valid for $R_{\text{th}} > 1$. In indoor Li-Fi systems, the received signal typically consists of a dominant line-of-sight (LoS) optical component along with weaker diffuse reflections. Accordingly, the Li-Fi SINR is modeled using a Rician distribution, which is a widely adopted assumption in indoor optical wireless communication and fading channel literature when the interference-plus-noise power varies slowly relative to the desired signal fluctuations [10], [11]. The PDF of the Rician distribution is given by:

$$f_{\text{SINR, Li-Fi}}(x) = \frac{x + K}{\sigma_X^2} \exp\left(-K_{\text{Rice}} - \frac{x + K_{\text{Rice}}}{\sigma_X^2}\right), \tag{11}$$

where K is the Rice factor representing the ratio of the line-of-sight (LoS) power to the scattered power, σ_X^2 denotes the average scattered-component SINR. Eq. (11) corresponds to a high-K (dominant LoS) approximation of the Rician distribution, which is appropriate for indoor Li-Fi channels where the LoS component strongly dominates the diffuse reflections [10]–[12].

The rate outage probability for the Li-Fi network is computed using the corresponding CDF:

$$P_{\text{outage, Li-Fi}} = 1 - \exp\left(-\frac{2^{R_{\text{th}}} + K}{\sigma_X^2}\right) I_0\left(\frac{\sqrt{2K \cdot 2^{R_{\text{th}}}}}{\sigma_X^2}\right), \tag{12}$$

where $I_0(\cdot)$ is the modified Bessel function of the first kind.

C. Rate outage probability for Link Aggregation enabled heterogeneous Li-Fi-Wi-Fi Network:

In link aggregation-enabled heterogeneous Li-Fi/Wi-Fi networks, the user concurrently receives data from both Li-Fi and Wi-Fi APs. The combined rate for a user in such network is expressed as:

$$R_{\text{LA}} = (1 - \beta)\left(R_{\text{Li-Fi}} + R_{\text{Wi-Fi}}\right), \tag{13}$$

where β accounts for the overhead introduced by packet reordering and synchronization in the link aggregation process. Substituting the rates in terms of SINR, the aggregated rate becomes:

$$R_{\text{LA}} = (1 - \beta)\left[\log_2(1 + \text{SINR}_{\text{Li-Fi}}) + \log_2(1 + \text{SINR}_{\text{Wi-Fi}})\right]. \tag{14}$$

A user in LA-HLWN is considered in outage if the aggregated rate falls below the threshold R_{th}. The outage probability is given by:

$$P_{\text{outage, LA}} = P\left[R_{\text{LA}} < R_{\text{th}}\right]. \tag{15}$$

To simplify the analysis, let $X = 1 + \text{SINR}_{\text{Li-Fi}}$, $Y = 1 + \text{SINR}_{\text{Wi-Fi}}$, and $C = 2^{\frac{R_{th}}{1-\beta}}$. The aggregated rate condition can be reformulated as:

$$P_{\text{outage, LA}} = P\left[X \cdot Y < 2^{\frac{R_{\text{th}}}{1-\beta}}\right]. \tag{16}$$

The outage probability is calculated by integrating over the joint probability distribution of X and Y, within the region defined by the outage condition $X \cdot Y < C$. This can be expressed as:

$$P_{\text{outage, LA}} = \int\int_{\Omega} f_X(x) f_Y(y)\, dx\, dy, \tag{17}$$

where:

- $f_X(x)$ and $f_Y(y)$ are the PDFs of X and Y, respectively,
- Ω is the region defined by $X \cdot Y < C$, i.e., $\Omega = \{(x, y) \mid x \cdot y < C\}$.

To solve this double integral, we split the computation into two steps:

1) For a fixed x, determine the limits of y such that $x \cdot y < C$, giving $y < \frac{C}{x}$.
2) Integrate over the PDFs of X and Y.

1) Inner Integration Over y: For a fixed x, the limits of y are from 0 to $y_{\max} = \frac{C}{x}$. The inner integral becomes:

$$\int_0^{\frac{C}{x}} f_Y(y)\, dy = F_Y\left(\frac{C}{x}\right), \tag{18}$$

where $F_Y(y)$ is the CDF of Y.

For a Wi-Fi network experiencing Rayleigh fading [13], the SINR (and hence Y) follows an exponential distribution. The PDF and CDF of Y are:

$$f_Y(y) = \frac{1}{\mu_Y} \exp\left(-\frac{y}{\mu_Y}\right), \quad F_Y(y) = 1 - \exp\left(-\frac{y}{\mu_Y}\right), \tag{19}$$

where μ_Y is the mean value of Y. For analytical tractability, and since the considered operating regime corresponds to sufficiently high SINR values, we adopt the approximation $1 + \text{SINR}_{\text{Wi-Fi}} \approx \text{SINR}_{\text{Wi-Fi}}$.

Substituting $y = \frac{C}{x}$ into the CDF:

$$F_Y\left(\frac{C}{x}\right) = 1 - \exp\left(-\frac{\frac{C}{x}}{\mu_Y}\right). \tag{20}$$

2) Outer Integration Over x: The outer integral is now:

$$P_{\text{outage, LA}} = \int_{x=0}^{\infty} \left[1 - \exp\left(-\frac{\frac{C}{x}}{\mu_Y}\right)\right] f_X(x)\, dx. \tag{21}$$

For a Li-Fi network, X follows a Rician distribution due to the presence of strong LoS. The PDF of X is given by:

$$f_X(x) = \frac{x + K}{\sigma_X^2} \exp\left(-K - \frac{x + K}{\sigma_X^2}\right) I_0\left(2\sqrt{\frac{K \cdot x}{\sigma_X^2}}\right), \tag{22}$$

The PDF in Eq. (22) is obtained by a variable transformation of the standard Rician distribution in Eq. (11) [11], where:

- K is the Rice factor representing the strength of LoS,
- σ_X^2 is the variance of the scattered components,
- $I_0(\cdot)$ is the modified Bessel function of the first kind.

3) Approximation Using Integral Identities: The double integral in Equation (17) can be simplified using known results for the product of independent random variables, where one variable follows an exponential distribution (Wi-Fi SINR) and the other follows a Rician distribution (Li-Fi SINR). Using such results, the outage probability simplifies to:

$$P_{\text{outage, LA}} = 1 - \left(\frac{C\mu_Y}{\sigma_X^2}\right) K_1\left(\frac{C}{\sigma_X \mu_Y}\right), \tag{23}$$

where $K_1(\cdot)$ is the modified Bessel function of the 2^{nd} kind.

TABLE I
SYSTEM PARAMETERS

System Parameter	**Value**
Room dimension	5 × 5 × 3 m^3
Number of APs	4 LiFi + 1 WiFi, 1 LiFi + 1 WiFi
WiFi AP location	(2.5, 2.5)
LiFi AP locations	(2.5±1.25 m, 2.5±1.25 m)
LA overhead (β)	0.2

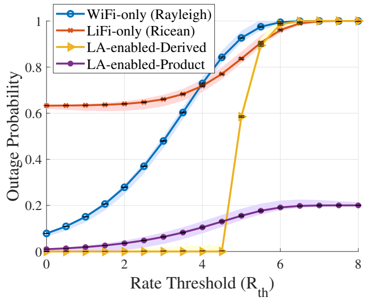

Fig. 1. Outage probabilities for LA-enabled HLWNs, Li-Fi-only, Wi-Fi-only networks, and direct product of $P_{outage,LiFi}$ and $P_{outage,WiFi}$ for various rate thresholds.

4) Final Expression: The outage probability is given by:

$$P_{\text{outage, LA}} = 1 - \left(\frac{2^{\frac{R_{\text{th}}}{1-\beta}} \mu_Y}{\sigma_X^2}\right) K_1\left(\frac{2^{\frac{R_{\text{th}}}{1-\beta}}}{\sigma_X \mu_Y}\right). \tag{24}$$

This result highlights the combined impact of the SINR distributions from both Li-Fi and Wi-Fi, the rate threshold R_{th}, and the link aggregation overhead β on the outage probability.

The derived outage model captures Li-Fi/Wi-Fi fading and aggregation overhead, demonstrating that link aggregation significantly enhances reliability over standalone networks.

III. RESULT ANALYSIS AND DISCUSSION

Table I summarizes the system parameters used, including AP placement and link aggregation (LA) overhead.

1) Outage Probability Comparison: Using the derived expressions (7), (12), and (24), Fig. 1 compares the outage probabilities of Li-Fi-only, Wi-Fi-only, and LA-HLWNs across different thresholds R_{th}. Results show that LA-HLWNs achieve zero outage up to $R_{th} = 5$ Mbps, after which outage rises (0.58 at $R_{th} = 5.5$ Mbps) due to the combined degradation of Li-Fi and Wi-Fi. Li-Fi-only networks face higher outage at low R_{th} because of limited coverage, while Wi-Fi-only networks deteriorate at high R_{th} due to capacity limits. At $R_{th} = 4$, Wi-Fi outage surpasses Li-Fi, highlighting their complementary behavior. Thus, LA-HLWNs consistently outperform standalone networks. Mathematically, outage under direct product approximation is:

$$P_{\text{outage,LA}}^{\text{prod}} = \Pr(\mathcal{O}_{\text{Li-Fi}} \cap \mathcal{O}_{\text{Wi-Fi}}) \quad \approx \Pr(\mathcal{O}_{\text{Li-Fi}})\, \Pr(\mathcal{O}_{\text{Wi-Fi}}), \tag{25}$$

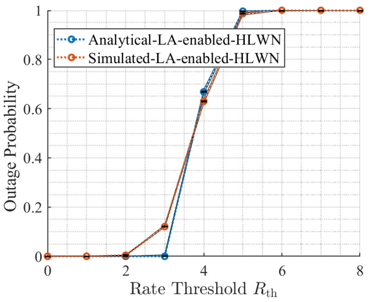

Fig. 2. Comparison of analytical and simulated outage probability for LA-enabled HLWN with one Li-Fi AP and one Wi-Fi AP.

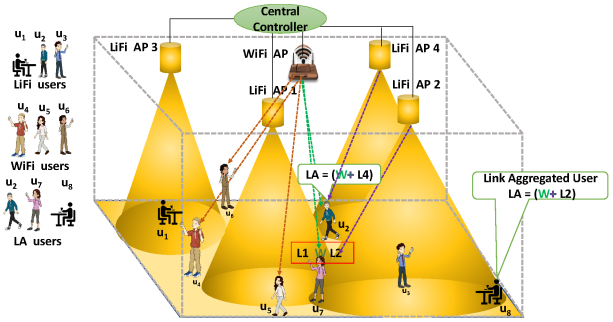

Fig. 3. System model with four Li-Fi and one Wi-Fi AP for LA-HLWN evaluation.

where, $\mathcal{O}_{\text{Li-Fi}} = \{\text{SINR}_{\text{Li-Fi}} < \gamma_{\text{th}}\}$ and $\mathcal{O}_{\text{Wi-Fi}} = \{\text{SINR}_{\text{Wi-Fi}} < \gamma_{\text{th}}\}$ denote the individual outage events. where $\gamma_{\text{th}} = 2^{R_{\text{th}}} - 1 \approx 2^{R_{\text{th}}}$ denotes the SINR threshold associated with the target rate R_{th}. This fails to represent actual performance trends, validating the need for the proposed derivation in (24).

2) Analytical vs. Simulation Validation: The proposed model is validated via simulations under two scenarios: (i) one Li-Fi and one Wi-Fi AP (Fig. 2), and (ii) four Li-Fi and one Wi-Fi AP (Figs. 3, 4). All results are based on 10^6 Monte Carlo realizations. The corresponding 95% confidence intervals, computed assuming a binomial outage process, are extremely tight and hence not visually distinguishable in Figs. 1 and 2, while in Fig. 3 they are further compressed by the logarithmic scale.

In the single-AP case, analytical and simulation results closely match, with minor deviations arising from SINR approximations in the analytical model. In the multi-AP scenario, users within overlapping coverage regions benefit from link aggregation (e.g., u_7 combining Li-Fi AP2 and Wi-Fi), leading to improved rates and reduced outage. Again, strong agreement is observed, with small discrepancies attributable to location-dependent SINR variations captured only in simulations.

Overall, the strong agreement across scenarios validates the proposed analytical framework for accurately characterizing outage behavior in LA-enabled HLWNs.

IV. CONCLUSION

In this paper, we analyze the rate outage probability of LA-enabled HLWNs through analytical modeling and simulation.

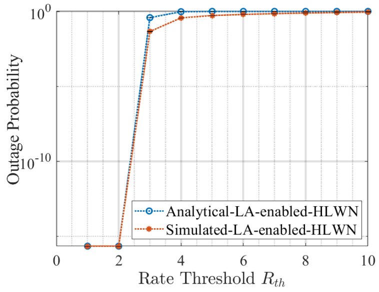

Fig. 4. Comparison of analytical and simulated outage probability for LA-enabled HLWN with four Li-Fi APs and one Wi-Fi AP.

The proposed model closely matches simulation results and shows that LA-enabled HLWNs consistently outperform standalone Li-Fi and Wi-Fi networks across a wide range of rate thresholds. While Li-Fi offers high capacity and Wi-Fi provides broad coverage, Wi-Fi-only systems experience higher outage at elevated rates due to capacity limitations. Prior studies that rely on simple probability multiplication, the proposed framework accurately captures link interactions and aggregation effects, enabling a more reliable evaluation of throughput, reliability, and scalability in future indoor wireless systems.

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