Proceedings of CONF-FMCE 2025 Symposium: Semantic Communication for Media Compression and Transmission
DOI: 10.54254/2755-2721/2025.GL25194

Resource Allocation in Hybrid and Aggregated VLC-RF Systems

Zihang Shu

College of Electronic Information, Wuhan University, Wuhan, China
2022302121296@whu.edu.cn

Abstract. This paper comprehensively reviews resource allocation strategies in hybrid and aggregated visible light communication (VLC) and radio frequency (RF) systems. Leveraging the complementary characteristics of VLC and RF technologies, these systems aim to enhance data rates, energy efficiency, and system fairness. The study synthesizes recent advancements in optimization algorithms, including convex optimization, heuristic approaches, and emerging machine learning techniques, addressing critical challenges such as incomplete channel state information (CSI), user fairness, handover latency, and interference coordination. The analysis identifies the strengths and limitations of hybrid and aggregated systems under varying conditions by analysing key research contributions. The results demonstrate that hybrid systems offer greater adaptability in low-capacity environments, while aggregated systems are more energy-efficient when capacity is high. In addition, the study emphasizes the importance of using artificial intelligence to manage resources in a flexible way. This summary offers important information for the creation of future wireless communication systems.

Keywords: Hybrid VLC-RF systems, Aggregated VLC-RF systems, Resource allocation, Energy efficiency, Convex optimization.

1. Introduction

Wireless communication networks are evolving rapidly to meet the increasing demand for higher data rates, energy efficiency, and seamless connectivity. Visible light communication (VLC) and radio frequency (RF) technologies are two complementary solutions that address these demands. VLC boasts elevated data transmission speeds, diminished energy expenditure, and intrinsic security at the physical layer; however, its efficacy is hampered by restricted spatial range and vulnerability to obstruction. Conversely, RF communication furnishes broad spatial ubiquity and dependable connectivity, but is plagued by spectrum overcrowding and interference-related impediments [1-2].

Hybrid and aggregated VLC-RF systems combine the strengths of these technologies. Hybrid systems enable flexible switching between VLC and RF links, adapting to channel conditions and user demands. In contrast, integrated systems leverage concurrent links, thereby optimizing data throughput and energy conservation [3,4]. Despite their potential, these systems face challenges in resource allocation, including incomplete channel state information (CSI), fairness constraints, and energy efficiency optimization [5,6].

DOI: 10.54254/2755-2721/2025.GL25194

This paper reviews resource allocation in hybrid VLC-RF systems, focusing on optimization techniques and challenges. It contributes to understanding resource management in heterogeneous optical-radio networks, crucial for designing high-capacity, energy-efficient indoor wireless systems in smart environments.

2. Literature review

2.1. Hybrid VLC-RF systems

Hybrid systems allow dynamic switching between VLC and RF links. Wang explored application scenarios for hybrid systems, emphasizing their adaptability in environments with variable user demands and channel conditions [1]. Papanikolaou's research delved into the optimization of resource allocation within hybrid systems sharing a common backhaul, introducing fairness-driven methodologies aimed at maximizing data throughput while guaranteeing an equitable distribution of resources [7]. These studies underscore the versatility of hybrid systems but also highlight challenges related to handover and channel estimation.

Moreover, hybrid systems have been shown to benefit from robust handover mechanisms that reduce latency during transitions between VLC and RF links. This flexibility proves especially advantageous in mutable settings like offices and hospitals, where ambulatory users and fluctuating channel states are typical. A key challenge is ensuring a smooth handover without introducing significant latency or packet loss. Recent studies have proposed predictive handover algorithms that utilize historical CSI data to allocate resources, thus minimizing disruptions preemptively.

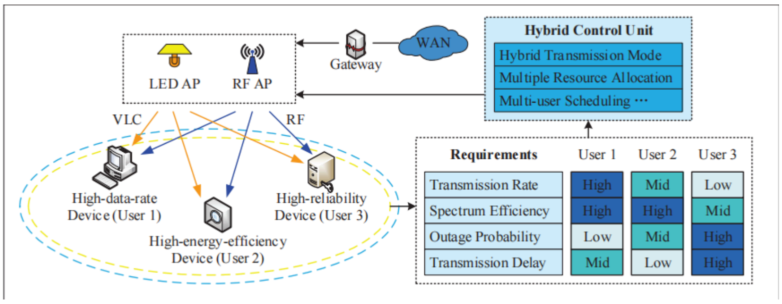


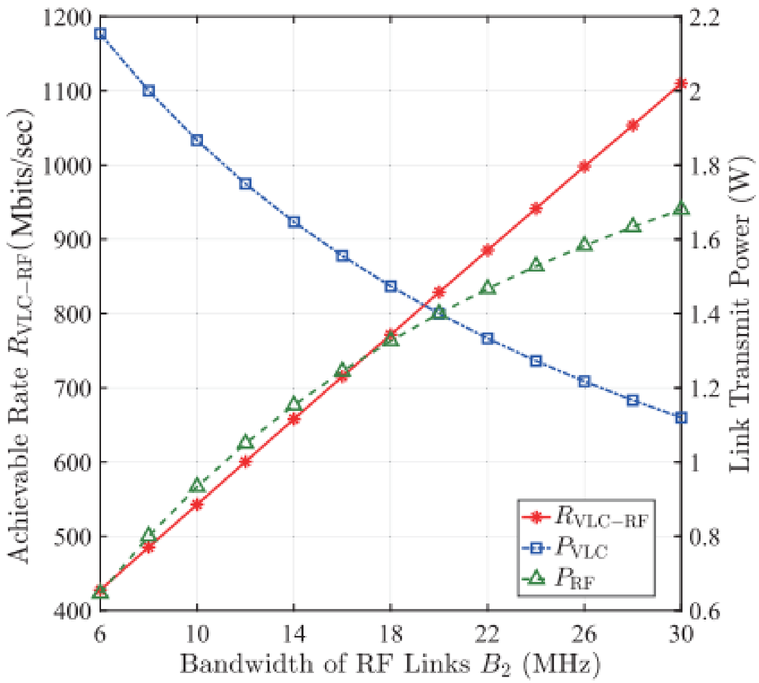
Figure 1. Different application scenarios for high data rate, high energy eff iciency, and high reliability from Wang [1]

Figure 1 shows that different application scenarios for high data rate, high energy eff iciency, and high reliability from Wang. Another area of interest in hybrid systems is using machine learning techniques to optimize resource allocation dynamically. By training models on real-world traffic patterns and environmental conditions, hybrid systems can better adapt to user demands and channel quality fluctuations. These approaches have shown promise in simulation studies, but their real-world implementation remains challenging due to computational overhead and hardware constraints.

2.2. Aggregated VLC-RF systems

Aggregated systems simultaneously leverage VLC and RF links for data transmission, maximizing spectral efficiency. Ma introduced power allocation strategies tailored for aggregated systems, attaining optimal global energy efficiency via iterative convex optimization techniques [2]. Rallis introduced cooperative non-orthogonal multiple access (NOMA) techniques, enhancing system performance for edge users [3]. These contributions demonstrate the potential of aggregated systems to outperform hybrid systems in high-capacity scenarios.

A unique advantage of aggregated systems is their ability to simultaneously exploit the complementary characteristics of VLC and RF links. For instance, while VLC provides high-speed data rates, RF ensures robust connectivity in areas with physical obstructions or poor lighting conditions. This dual-link utilization significantly enhances overall system performance in dense user environments. Ma provided detailed insights into the trade-off between data rates and energy efficiency as user density in increases.



(b)

Figure 2. (a) Achievable rate R(VLC−RF) and transmit power P(VLC) and P(RF) versus bandwidth of VLC link B1; (b) Achievable rate R(VLC−RF) and transmit power P(VLC) and P(RF) versus bandwidth of VLC link B2 from Rallis [2]

Figure 2 shows the performance of visible light communication (VLC) and radio frequency (RF) links under different bandwidth conditions when the user density increases. In addition to NOMA, other advanced multiplexing techniques like orthogonal frequency-division multiplexing (OFDM) have been integrated into aggregated systems to improve spectral efficiency further. These methods enable finer resource granularity, allowing for more precise power and bandwidth allocation across VLC and RF links. However, their implementation introduces additional computational complexity, which must be addressed through efficient algorithm design.

2.3. Energy efficiency and CSI challenges

In VLC-RF systems, energy efficiency is a paramount performance indicator. Aboagye et al. engineered energy-optimized resource allocation schemes, leveraging matching theory and quadratic transform methodologies, thereby realizing substantial gains in energy efficiency [4]. However, incomplete CSI remains a pervasive challenge. Accurate CSI is essential for effectively allocating

DOI: 10.54254/2755-2721/2025.GL25194

power and bandwidth, particularly in aggregated systems where simultaneous VLC and RF transmissions require precise coordination.

One promising approach to mitigating the impact of incomplete CSI is using robust optimization techniques. Bozanis proposed proactive resource allocation algorithms that account for the uncertainty in CSI, ensuring reliable performance under dynamic user mobility. Their simulation results demonstrated that proactive algorithms could improve system fairness up to 20% compared to conventional methods, even when CSI accuracy dropped by 30%.

Another critical challenge is energy efficiency under incomplete CSI conditions. Papanikolaou explored the integration of energy-harvesting techniques to supplement traditional power sources. Integrating ambient light energy harvesting with sophisticated resource management protocols, their innovative architecture demonstrated energy efficiency gains of up to 25%, even under conditions of substantial Channel State Information (CSI) impairment.

Machine learning techniques like reinforcement learning have also been explored to solve CSI-related challenges. Reinforcement learning algorithms can dynamically adapt resource allocation decisions based on real-time feedback from the environment, effectively compensating for incomplete or outdated CSI. Although these approaches are computationally intensive, recent advancements in hardware acceleration have made their deployment increasingly feasible.

Future research should focus on integrating these robust optimization and energy-harvesting techniques with machine learning frameworks to create a holistic approach to addressing incomplete CSI challenges. Such an approach would improve energy efficiency and enhance overall system robustness and adaptability in dynamic environments.

3. Discussion

3.1. Challenges in resource allocation

The primary challenges in resource allocation for VLC-RF systems include:

- Incomplete CSI: Imperfect channel estimation leads to suboptimal resource allocation, reducing system performance [9]. For example, simulations conducted by Bozanis revealed that a 20% deviation in CSI accuracy can lead to a 15% reduction in overall data rates.

- Fairness Constraints: Balancing resource allocation among users with varying demands is critical to ensuring equity and avoiding user dissatisfaction [7]. Aggregated systems, in particular, face fairness challenges when serving users at the edge of both VLC and RF coverage zones.

-Energy Efficiency:For energy-efficient systems, a central challenge persists in optimizing power and bandwidth allocation to ensure sustained high performance [4] [6]. Hybrid systems often experience energy inefficiencies during frequent handovers, highlighting the need for more robust handover algorithms.

3.2. Optimization frameworks

Resource allocation frameworks for hybrid and aggregated VLC-RF systems rely on advanced optimization techniques to maximize energy efficiency and system performance. This section discusses key methods and their applications in hybrid and aggregated systems, focusing on their strengths, limitations, and future directions.

DOI: 10.54254/2755-2721/2025.GL25194

3.2.1. Hybrid systems

Resource allocation in hybrid systems is typically modeled as a convex optimization problem. The main goal is to ensure fairness among users while maintaining high data rates. Several approaches have been proposed:

(1) Fairness-Oriented Algorithms: Iterative fairness-aware algorithms dynamically adjust resource allocation based on channel conditions [1] [7]. These algorithms give precedence to users experiencing less favorable channel conditions, thereby guaranteeing a baseline quality of service (QoS) for all subscribers. To illustrate, Wang's simulations revealed a 15% enhancement in fairness indices through the implementation of these algorithms.

(2) Predictive Handover Mechanisms: To minimize disruptions during link switching, predictive models are employed to anticipate user movements and preallocate resources [5]. Bozanis proposed a proactive handover strategy that reduces latency by 30% compared to traditional reactive methods.

(3) Machine Learning-Assisted Allocation: Recent advancements in machine learning have introduced reinforcement learning algorithms for adaptive resource allocation. These techniques exhibit dynamic learning capabilities, adapting to network states and user actions to enhance allocation efficacy. Nevertheless, the computational demands pose obstacles to their implementation in real-time scenarios.

3.2.2. Aggregated systems

Aggregated VLC-RF systems utilize simultaneous transmissions to maximize throughput and energy efficiency. Non-convex optimization problems, such as energy efficiency maximization, are often solved using Dinkelbach-type algorithms and other heuristic methods.

(1) Dinkelbach-Type Optimization: This approach adeptly tackles the inherent non-linearity present in energy efficiency maximization challenges. Ma demonstrated that Dinkelbach algorithms yield a 25% enhancement in energy efficiency when contrasted with traditional convex optimization methodologies [2]..

(2) Coordinated Resource Management: Addressing inter-cell interference is critical in aggregated systems, especially in dense user environments. Papanikolaou proposed game theory-based coordination techniques that ensure optimal power and bandwidth sharing among cells [7]. Simulation studies reveal a 20% increase in system capacity using these methods.

(3) Energy Harvesting Integration: Aggregated systems can leverage light energy harvesting to supplement power sources, improving energy efficiency under constrained scenarios. Papanikolaou demonstrated that integrating energy harvesting mechanisms into resource allocation frameworks could achieve a 30% reduction in total power consumption without compromising performance [8].

(4) Proactive Resource Allocation: Proactive resource allocation strategies, as proposed by Bozanis, account for the uncertainty in channel conditions, particularly under outdated CSI scenarios. These strategies improve system robustness by pre-allocating resources based on predicted CSI trends. The simulation outcomes reveal a 15% enhancement in mean data throughput relative to reactive allocation techniques [9].

3.2.3. Future directions

To further enhance the adaptability and scalability of these frameworks:

-Integration with AI: Reinforcement learning and neural networks should be explored to adjust resource allocation in real time dynamically.

-Scalability: To ensure practical deployment, frameworks must be tested and refined for large-scale multi-cell networks.

-Hardware Constraints: Future research should also consider the implications of hardware limitations on resource allocation performance.

By leveraging these optimization techniques, hybrid and aggregated VLC-RF systems can address existing challenges and achieve superior performance in next-generation wireless communication networks.

4. Conclusion

This review has comprehensively analyzed the state-of-the-art resource allocation strategies in hybrid and aggregated VLC-RF systems. Our investigation indicates that hybrid systems offer unparalleled agility and versatility in low-throughput contexts. They sustain consistent operation via active VLC-RF link transitioning, though they are vulnerable due to their dependence on precise channel estimation and handover delay. In contrast, aggregated systems are highly effective in high-throughput settings, delivering enhanced data transfer rates and energy conservation through concurrent VLC-RF employment. Sophisticated methodologies such as NOMA and OFDM further amplify efficiency, albeit at the expense of greater computational demands. Pervasive challenges persist across both paradigms, notably incomplete channel state information (CSI) and fairness constraints, where the integration of machine learning and real-time feedback mechanisms shows significant promise yet demands deeper investigation.

Looking ahead, future research should prioritize three critical directions: AI-driven resource allocation using adaptive machine learning techniques, rigorous exploration of hardware constraints on algorithmic performance, and scalability validation for multi-cell network deployments. The insights derived herein collectively establish a foundational framework for advancing VLC-RF systems, ultimately driving innovations that address the escalating demands of next-generation wireless networks in critical domains such as smart cities, industrial IoT, and immersive communications.

References

[1] Wang, F., Yang, F., Song, J., & Han, Z. (2022). Access frameworks and application scenarios for hybrid VLC and RF systems: State of the art, challenges, and trends. IEEE Communications Magazine, 60(3), 55-61.

[2] Ma, S., Zhang, F., Li, H., Zhou, F., Alouini, M. S., & Li, S. (2020). Aggregated VLC-RF systems: Achievable rates, optimal power allocation, and energy efficiency. IEEE Transactions on Wireless Communications, 19(11), 7265-7278.

[3] Rallis, K. G., Papanikolaou, V. K., Diamantoulakis, P. D., Tegos, S. A., & Karagiannidis, G. K. (2023). Energy-efficient cooperative communications in aggregated VLC/RF networks with NOMA. IEEE Transactions on Communications, 71(9), 5408-5418.

[4] Aboagye, S., Ngatched, T. M. N., Dobre, O. A., & Poor, H. V. (2023). Energy-efficient resource allocation for aggregated RF/VLC systems. IEEE Transactions on Wireless Communications, 22(10), 6624-6641.

[5] Papanikolaou, V. K., Diamantoulakis, P. D., Sofotasios, P. C., & Karagiannidis, G. K. (2020). On optimal resource allocation for hybrid VLC/RF networks with common backhaul. IEEE Transactions on Cognitive Communications and Networking, 6(1), 352-365.

[6] Fahim Raouf, A. H., Anjinappa, C. K., & Guvenc, I. (2024). Optimizing energy-harvesting hybrid VLC/RF networks with random receiver orientation. IEEE Access, 12, 147574-147589.

[7] Bozanis, D., Evgenidis, N. G., Papanikolaou, V. K., & Tegos, S. A. (2024). Proactive resource allocation for aggregated VLC/RF networks with outdated CSI. IEEE Wireless Communications Letters, 13(4), 944-948.

[8] Zargari, S., Kolivand, M., Nezamalhosseini, S. A., & Chen, L. R. (2022). Resource allocation of hybrid VLC/RF systems with light energy harvesting. IEEE Transactions on Green Communications and Networking, 6(1), 600-

DOI: 10.54254/2755-2721/2025.GL25194

610.
[9] An, N., Yang, F., Cheng, L., Song, J., & Han, Z. (2024). IRS-assisted aggregated VLC-RF system: Resource allocation for energy efficiency maximization. IEEE Transactions on Wireless Communications, 23(10), 12578-12590.