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An Intelligent Management System for Hybrid Network between Visible Light Communication and Radio Frequency

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Abstract

This thesis investigates the challenges and potential solutions associated with hybrid Visible Light Communication (VLC) and Radio Frequency (RF) systems for indoor network environments. The rapid development of VLC technology, characterized by its high data rates, energy efficiency, and inherent security features, offers promising opportunities to complement RF networks in providing seamless connectivity and improved performance. However, integrating VLC and RF technologies effectively requires addressing a range of research and engineering challenges, including network coexistence, handover mechanisms, resource allocation, localization, and standardization.

We begin by conducting a comprehensive literature review encompassing existing research, technologies, and solutions related to hybrid VLC/RF architectures, handover management, indoor localization techniques, and the challenges faced by these systems. This background provides a solid foundation for understanding the current state-of-the-art and identifying research gaps in the field of hybrid VLC/RF networks.

Next, we propose a novel hybrid network architecture that integrates VLC and RF communication systems to enhance their strengths while mitigating their weaknesses. We discuss various types of hybrid VLC/RF architectures found in the literature and present our proposed design, which addresses the identified challenges through innovative strategies and mechanisms.

To improve system performance in our hybrid system, we develop an enhanced priority feedback channel that optimizes the traffic priority based on user preferences and network conditions. This approach minimizes service disruptions, reduces latency, and maintains user Quality of Experience (QoE).

Furthermore, we introduce a novel intelligent management system architecture tailored for hybrid VLC/RF networks. This system employs advanced algorithms and techniques to optimize resource allocation, load balancing, localization, and handover management, ensuring efficient operation and seamless connectivity.

We evaluate the performance of our proposed solutions through extensive simulations and testbed experiments, considering different network scenarios and metrics. The results demonstrate significant improvements in terms of data rate, latency, handover success rate, and localization accuracy, validating the effectiveness of our proposed architecture and management system.

Lastly, we explore several real-world applications and case studies of our intelligent management system in various indoor environments, such as retail stores, offices, and hospitals. These examples illustrate the practical benefits of our solution in enhancing customer experiences, optimizing operational efficiency, facilitating targeted marketing, and improving energy management.

In conclusion, this thesis contributes to the advancement of hybrid VLC/RF networks by proposing an innovative architecture and intelligent management system that address the key challenges faced by these systems in indoor environments. The findings and solutions presented in this work provided the backbone for the future research and development efforts aimed at fully harnessing the potential of VLC technology in combination with RF networks.

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List of Abbreviations

AIFS Arbitration Inter-Frame Space

AoA Angle-of-Arrival

APs Access Points

ARS Adaptive Resource Management System

AUVs Autonomous Underwater Vehicles

BER Bit error rate

CFR Channel Frequency Response

CIR Carrier to Interferences Ratio

CSMA/CA Carrier Sensing Multiple Collision-Avoidance

DCF Distributed Coordination Function

DDoS Distributed Denial-of-Service

DIFS Distributed Inter-Frame Space

EDCA-ACK Enhanced Distributed Channel Access - Acknowledgment

EEM Energy Efficiency Manager

EHM Energy Harvesting and Energy Efficiency Manager

FL Fuzzy Logic

HHO Horizontal Handover

IHC Intelligent Handover Controller

IoT Internet of Things

LEDs Light-Emitting-Diodes

LiFi Light Fidelity

LiRa Light-Radio Wireless Local Area Network

LoS Line-of-Sight

MIMO Multi-Input Multi-Output

mmWave Millimeter Waves

PRUs Processing Real-time Units

QoE Quality of Experience

RF Radio Frequency

ROVs Remotely Operated Vehicles

RSS Received Signal Strength

RSSI Received Signal Strength Indicator

SIFS Short Inter-Frame Space

SNR Signal to Noise Ratio

SPMS Security and Privacy Management System

ToA Time-of-Arrival

UE User Equipment

VHO Vertical Handover

VLC Visible Light Communication

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Chapter 1

Introduction

In recent years, there has been a tremendous increase in capacity demand for wireless networks. This growth can be largely attributed to the widespread proliferation of portable user devices and smart objects that require Internet connectivity. A recent Cisco report suggests that mobile data traffic will account for approximately 71% of total Internet protocol traffic by 2022, with over 80% of this mobile data traffic generated within indoor spaces [1]. The mounting demand for capacity, particularly in indoor scenarios, strains traditional RF-based technologies. As such, the development of advanced spectrum sharing solutions and innovative spectrum portions, including millimeter waves (mmWave) and Visible Light Communications (VLCs), have emerged as potential solutions.

Of these emerging technologies, VLC stands out as an especially promising alternative to complement the traditional radio frequency [2, 3]. In the design of next-generation 6G systems, it is explicitly considered due to its high bandwidth capabilities, immunity to interference from electromagnetic sources, and vast potential for spatial reuse [4, 5]. However, addressing the challenges posed by short-range wireless communication technology is critical for developing networks that can provide enhanced indoor services in the future [6, 7, 8]. Additionally, experts predict an imminent spectrum shortage due to the rapidly expanding wireless communications requirements. Consequently, either efficient communication protocols or alternative transmission resources must be developed to address the scarcity of radio frequency resources.

While spectrum sharing has been proposed to mitigate these issues [9, 10], legal complications and the fundamental problem of limited spectrum resources remain substantial hurdles. To overcome these challenges, further exploration of alternative spectrums for future communication networks is imperative. VLC has been designed to augment current communication networks in collaboration with 6G, ultimately enhancing users' quality of service.

The increasing adoption of VLC communications can also be attributed to the widespread use of Light-Emitting-Diodes (LEDs) for illumination purposes. LED lights boast several advantages over traditional incandescent lamps, such as a 75% reduction in power consumption and a 2500% increase in lifespan [11]. From 2020 to 2027, the market share of LED lighting is expected to grow at an annual rate of 13.4%. Exploiting LEDs deployed for illumination to modulate light signals and transmit data presents an intriguing opportunity.

However, designing an integrated infrastructure for both illumination and data distribution necessitates addressing several challenges. The limited coverage area of VLC links facilitates high-density spatial reuse but complicates node mobility management. Another issue arises from the difficulty of supporting uplink channels, as the light emitted for illumination purposes represents a high-power interference source for uplink signals. To circumvent this challenge, uplink channels can be implemented using different spectrum portions, including infrared signals [12] or RF signals [13].

This thesis seeks to provide a comprehensive analysis of hybrid VLC/RF systems as potential solutions to the aforementioned challenges associated with capacity demand and spectrum limitations in wireless networks. We begin by offering an overview of the present state of wireless networking, followed by a detailed discussion on the emergence and evolution of VLC technology as a viable alternative to RF-based systems. Additionally, we investigate the integration of VLC into next-generation networks, focusing on addressing the challenges related to coverage, uplink transmission, and spectrum shortages. Finally, we propose novel solutions based on hybrid VLC/RF systems and evaluate their potential impact on enhancing the performance and efficiency of indoor wireless networks

1.1 Background of VLC technology

VLC is an optical wireless communication technology that uses Light Emitting Diodes (LEDs) as both sources of illumination and data transmission. The widespread adoption of energy-efficient LED lighting presents an excellent opportunity for implementing VLC in indoor network environments. LEDs offer numerous advantages over traditional incandescent and fluorescent lamps, including lower power consumption, longer lifespan, and reduced environmental impact [14, 15]. These features render LEDs an ideal candidate for supporting VLC in indoor networks.

The use of VLC for indoor networking has several benefits over conventional RF-based technologies:

1. **High bandwidth:** The visible light spectrum offers a vast unregulated bandwidth, ranging from 400 THz to 800 THz, allowing for high-speed data transmission without the need for licensing or regulation.

2. **Immunity to electromagnetic interference:** VLC systems do not experience interference from RF sources such as WiFi, cellular networks, and electronic devices. This immunity to interference ensures reliable communication even in congested areas with multiple active devices.

3. **Spatial reuse:** The limited propagation of visible light allows for high-density spatial reuse, enabling multiple simultaneous users without significant interference, thereby increasing the overall network capacity.

4. **Energy efficiency:** VLC systems can piggyback on existing LED lighting infrastructure, resulting in minimal additional energy consumption for communication purposes.

5. **Enhanced security:** Since visible light does not penetrate walls or opaque materials, VLC systems provide inherent security against eavesdropping, ensuring secure communication within confined indoor spaces.

However, there are also certain challenges associated with using VLC for indoor network environments[16, 17]:

1. **Line-of-Sight (LoS) requirement:** VLC systems typically depend on direct LOS between transmitters and receivers, restricting communication when there is no clear path between devices.

2. **Limited range:** The range of VLC systems is often limited by the optical power of the LED transmitters and the sensitivity of the photodetector receivers.

3. **Mobility management:** The limited coverage area of VLC links makes node mobility management more complex, requiring efficient handover mechanisms and seamless integration with other technologies.

4. **Uplink channel support:** Establishing uplink channels in VLC systems is challenging due to the high-power interference caused by illumination purposes. Solutions include exploiting different spectrum portions, such as infrared signals or RF signals, for uplink transmissions.

Considering these challenges and benefits, this thesis aims to investigate the potential of VLC for improving indoor network environments. We provide an overview of the fundamental concepts and principles underlying VLC technology, followed by an in-depth analysis of its strengths and weaknesses. We address the challenges associated with deploying VLC systems in hybrid systems in indoor environments, focusing on issues such as handover, mobility management, coverage, and uplink channel support.

1.2 Motivation for Research in Indoor Network Environments

In today's digitally connected world, the demand for seamless and high-speed data transmission, as well as reliable connectivity within indoor environments, has increased tremendously. These environments, such as shopping malls, offices, hospitals, residential buildings, educational institutions, and transportation hubs, represent a significant portion of people's daily experiences, making robust communication networks essential to cater to various applications like multimedia streaming, real-time location-based services, smart automation, Internet of Things (IoT) devices, and public safety.

There are several reasons why conducting research on indoor network environments is of vital importance:

1. **Increasing Device Connectivity:** The rapid expansion of IoT and smart devices has led to an ever-growing number of connected gadgets in indoor spaces. This surge in device connectivity demands more efficient networking solutions that can handle high-traffic loads, minimize latency, optimize energy consumption, and provide seamless connectivity. By studying indoor network environments, researchers contribute to the development of adaptive and scalable wireless technologies that address these challenges.

2. **Complex Environment:** Indoor environments often pose unique challenges due to building materials, diverse layouts, and obstructions that can impact signal strength and quality. Additionally, users constantly move within these spaces, necessitating effective handover techniques, localization strategies, and interference management to ensure uninterrupted connectivity. Investigating these complexities helps researchers develop advanced mechanisms and algorithms that are tailored to indoor spaces and their specific requirements.

3. **User Experience:** Enhancing user experience is crucial in various settings such as retail, hospitality, healthcare, education, and transportation, where tailored experiences and personalized services are key aspects. By optimizing indoor networks, researchers contribute to improved location-based services, faster response times, targeted marketing, and ultimately, better user satisfaction. In-depth research into indoor networking techniques leads to innovations that benefit both businesses and end-users, adding value to everyday experiences in different settings.

4. **Security and Privacy:** The increase in connected devices, localization services, and data transmission within indoor environments raises concerns about security and privacy. Research in this area ensures secure communication channels, robust authentication mechanisms, encryption techniques, and privacy-preserving approaches to safeguard personal information, prevent unautho-

rized access, and maintain trust in digital systems. Understanding the security and privacy implications related to indoor networking drives the development of safer and more resilient technologies.

5. **Spectrum Congestion and Interference:** Traditional RF technologies, such as WiFi and Bluetooth, face spectrum congestion, interference issues, and limited bandwidth due to their widespread use. Exploring alternative or complementary wireless technologies, such as VLC, millimeter-wave, LiFi, or even 5G and beyond, can alleviate these problems and provide additional benefits like higher data rates, reduced interference, enhanced security, and accurate localization. Research aimed at integrating multiple communication technologies gives rise to novel hybrid network architectures that leverage each technology's strengths while mitigating its weaknesses.

6. **Energy Efficiency and Sustainability:** As energy consumption becomes an increasingly important concern, focusing on energy-efficient indoor networking solutions is paramount. Research in indoor network environments explores how to optimize power usage and minimize carbon footprints by integrating energy-efficient technologies, such as LED lighting for VLC, and developing smart algorithms that intelligently manage network resources. Sustainable networking solutions contribute to a greener future and reduce operational costs for businesses and users.

Considering the significance of indoor network environments and the challenges presented by traditional RF systems, it is essential to investigate alternative, complementary, and hybrid networking solutions that combine multiple communication technologies' strengths and overcome their individual limitations[18]. This thesis aims to explore advances in indoor networking, including hybrid VLC/RF systems, to address design challenges, improve priority feedback channels, develop intelligent management systems, and apply the proposed solutions to real-world scenarios. By doing so, this research will contribute to the development of efficient, secure, and sustainable indoor networking solutions, providing enhanced performance, security, and user experiences across various settings.

1.3 Handover Management in Heterogeneous Networks for Indoor Environments

Heterogeneous networks, consisting of various wireless communication technologies, offer great potential in addressing the challenges associated with indoor environments. However, to ensure seamless connectivity and optimal user experience, efficient handover management is crucial. This section delves into the importance of handover in heterogeneous networks, existing techniques, and proposed solutions specifically tailored for indoor scenarios.

1.3.1 Importance of Handover Management in Heterogeneous Networks

In heterogeneous networks, users often switch between different access points or network technologies as they move within indoor spaces. This transition process, known as handover, requires efficient management to maintain uninterrupted communication and avoid service degradation. Key factors that make handover management essential in heterogeneous networks for indoor environments include:

1. **User Mobility:** Users frequently move around indoor spaces, causing changes in signal strength and quality. Efficient handover mechanisms should ensure smooth transitions between access points or technologies while minimizing service disruption.

2. **Network Load Balancing:** In high-density areas, balancing user traffic across available resources is critical to optimizing network performance. Handover decisions should consider factors such as network load and capacity to distribute users effectively.

3. **Quality of Service (QoS) Maintenance:** Ensuring consistent QoS levels during handovers is vital, particularly for real-time applications like voice calls or video streaming. Handover mechanisms should minimize delays, packet loss, and service degradation.

4. **Energy Efficiency:** Battery-powered devices benefit from energy-aware handover strategies that prolong device lifetime by selecting the most energy-efficient network options available.

5. **Seamless Integration:** The integration of multiple wireless technologies necessitates standardized protocols and interfaces for seamless interoperation during handovers.

1.3.2 Existing Techniques for Handover Management

Various techniques have been proposed to optimize handover management in heterogeneous networks, including:

1. **Received Signal Strength Indicator (RSSI)-based Handover:** The most common approach relies on comparing the received signal strength from different access points or technologies. When the signal drops below a certain threshold or a stronger signal from another source becomes available, the handover process is initiated.

2. **Velocity-based Handover:** These techniques use user velocity information to predict future signal conditions and initiate a handover proactively, reducing service interruption for fast-moving users.

3. **Load-based Handover:** This approach considers network load and capacity when making handover decisions, aiming to balance user distribution across available resources for improved overall network performance.

4. **QoS-aware Handover:** Focusing on maintaining a consistent QoS level, these techniques prioritize connections that best meet specific application requirements, such as latency, bandwidth, or packet loss rate.

5. **Context-aware Handover:** These methods utilize contextual information, such as user preferences, device capabilities, or environmental factors, to make informed handover decisions and enhance user experience.

1.3.3 Proposed Handover Solutions for Indoor Heterogeneous Networks

This thesis aims to develop advanced handover management techniques explicitly designed for indoor environments with hybrid VLC/RF systems and other emerging communication technologies. Proposed solutions will address the unique challenges of indoor spaces, such as complex layouts, and diverse user mobility patterns, as well as consider security, privacy, and energy efficiency aspects.

Key components of the proposed handover solutions include:

1. Developing machine learning-based algorithms that model user mobility patterns and predict future movement trajectories, enabling proactive handover decisions that minimize service disruption.

2. Integrating network load, signal strength, and QoS parameters to create a comprehensive decision-making framework that dynamically adapts to changing indoor network conditions.

3. Proposed designing energy-aware handover strategies that consider both device battery life and network power consumption, ensuring sustainable connectivity solutions for indoor environments.

4. Incorporating security and privacy factors into handover decisions, prioritizing secure communication channels, and preserving user privacy throughout the handover process.

5. Evaluating the effectiveness of the proposed priority traffic flow and handover solutions through simulations and real-world experiments, respectively, validating their ability to improve network performance, user satisfaction, and resource utilization in indoor heterogeneous networks.

By developing advanced handover management techniques tailored to indoor environments, this research contributes to enhancing the overall performance, user experience, and sustainability of hybrid VLC/RF systems and other emerging indoor communication technologies.

1.4 Objectives and Scope of the Thesis

This thesis aims to investigate advanced networking solutions for indoor environments, specifically exploring alternative, complementary, and hybrid communication technologies that address the challenges associated with traditional RF systems. The objectives and scope encompass a detailed analysis of the state-of-the-art in indoor wireless networking technologies, focusing on their strengths, limitations, and potential use cases. Further, this research delves into handover management and user mobility, which are integral components of efficient indoor wireless networks.

1.4.1 Research Objectives

The specific objectives of this thesis include analyzing the challenges and requirements presented by diverse indoor environments, taking into consideration factors such as user mobility patterns, energy efficiency, security, and privacy concerns. The research aims to design and evaluate novel hybrid network architectures that combine the advantages of multiple wireless communication technologies (e.g., VLC/RF), ensuring seamless connectivity, enhanced performance, and efficient resource management. Furthermore, it seeks to develop intelligent algorithms and techniques for optimizing handover processes, interference mitigation, and localization accuracy within indoor network environments. The thesis also proposes optimized mechanisms to solve bottleneck issues in common uplink WiFi channels in hybrid systems for indoor networking systems.

In addition, the research investigates robust security and privacy-preserving measures that safeguard user data, ensure secure communication channels, and maintain trust in indoor networking systems. It assesses the energy efficiency of various networking solutions and explores methods to minimize power consumption and carbon footprint, contributing to sustainable indoor environments. Lastly, the thesis focuses on validating the proposed networking solutions through simulations and real-world experimentations, demonstrating their effectiveness in addressing the identified challenges and improving overall indoor network performance.

1.4.2 Scope of the Thesis

The scope of this thesis encompasses the following key aspects:

1. A comprehensive survey and comparative analysis of existing and emerging indoor wireless communication technologies, with a focus on alternative solutions such as VLC and Light Fidelity (LiFi), providing a detailed understanding of their features, advantages, and limitations.

2. The development of a future-proof architecture for heterogeneous indoor networks that is adaptable to system changes and mitigates the disadvantages of previous architectures, enabling seamless integration of various communication technologies.

3. An in-depth exploration of handover management techniques in heterogeneous indoor networks, emphasizing the creation of advanced algorithms that ensure smooth transitions between access points or network technologies, thus enhancing user experience.

4. Extensive simulation work in NS3 to demonstrate the effectiveness of our proposed algorithm in preventing bottleneck issues in hybrid networks, leading to a significant improvement in overall system performance.

5. The implementation and evaluation of a hybrid system testbed, employing various techniques to minimize the impact of handover procedures and enhance user experience in hybrid systems. Both Fuzzy logic and Machine Learning (ML) show promising results across different testing scenarios.

6. Empirical validation of the proposed networking solutions through a combination of simulation studies and experimental testbeds, offering valuable insights into their real-world feasibility, effectiveness, and potential influence on the development of future applications.

By pursuing these objectives and scope, this thesis contributes to advancing the field of indoor networking, ultimately leading to more efficient, secure, and sustainable communication systems for various indoor environments.

Chapter 2

Hybrid network architecture VLC and RF

This chapter delves into the concept of hybrid VLC/RF network architectures, which combine the advantages of both Visible Light Communication and Radio Frequency technologies to address the limitations inherent in each system. We provide a comprehensive understanding of hybrid networks, focusing on various integration strategies, resource allocation methods, handover mechanisms, and indoor estimation movement techniques. Our aim is to lay the groundwork for the development of innovative solutions that leverage the synergies between these communication technologies and present our proposed novel hybrid network architecture, designed to tackle the challenges associated with existing systems and optimize overall performance for indoor environments.

2.1 Related Work

In this section, we aim to provide a comprehensive overview of the current state-of-the-art in the field, as well as to identify research gaps that our proposed architecture seeks to address.

Several studies have explored different approaches for integrating VLC and RF networks to create hybrid systems designed for indoor environments. While some researchers have focused on parallel structures, where VLC and RF operate independently [19, 20], others have investigated more tightly coupled solutions, such as complementary, cooperative, or interworking structures [21, 22]. These works highlight the trade-offs between various architectural choices regarding complexity, performance, and implementation challenges.

Resource allocation and load balancing are critical aspects of hybrid VLC/RF network performance. Several studies have proposed algorithms and optimization techniques to distribute resources effectively among users while maintaining network stability and fairness [23, 24, 25]. Joint channel assignment, power control, and adaptive modulation schemes have been explored to optimize network capacity and energy efficiency in hybrid systems [26, 27, 28].

Handover management is a pivotal challenge in hybrid VLC/RF systems, ensuring seamless connectivity and minimal service disruption as users move within the coverage area. Researchers have developed various handover strategies and algorithms tailored to hybrid network requirements, including soft handover, context-aware handover, and make-before-break handover. These efforts aim to minimize latency, maintain user Quality of Experience, and reduce network overhead during the handover process. Accurate indoor localization and user mobility are essential for many applications in hybrid VLC/RF networks, such as navigation, asset tracking, or context-aware services. Several studies have investigated localization algorithms and techniques leveraging the complementary strengths of VLC and RF technologies, including fingerprinting, trilateration, and angle-of-arrival methods [29, 30]. The goal is to improve positioning accuracy, minimize localization errors, estimate movement direction, and reduce implementation complexity.

As hybrid VLC/RF systems gain traction, standardization becomes increasingly important to ensure interoperability and compatibility across different devices and vendors. Some standardization bodies, such as IEEE [31], have initiated efforts to define common protocols, interfaces, and functional specifications for hybrid VLC/RF networks. These initiatives seek to promote seamless integration and foster further innovation in the field.

In summary, the related work provides valuable insights into the challenges and opportunities associated with hybrid VLC/RF networks, laying the foundation for our proposed novel hybrid network architecture. In the next sections, we will present our innovative design, which addresses the identified issues and aims to provide an

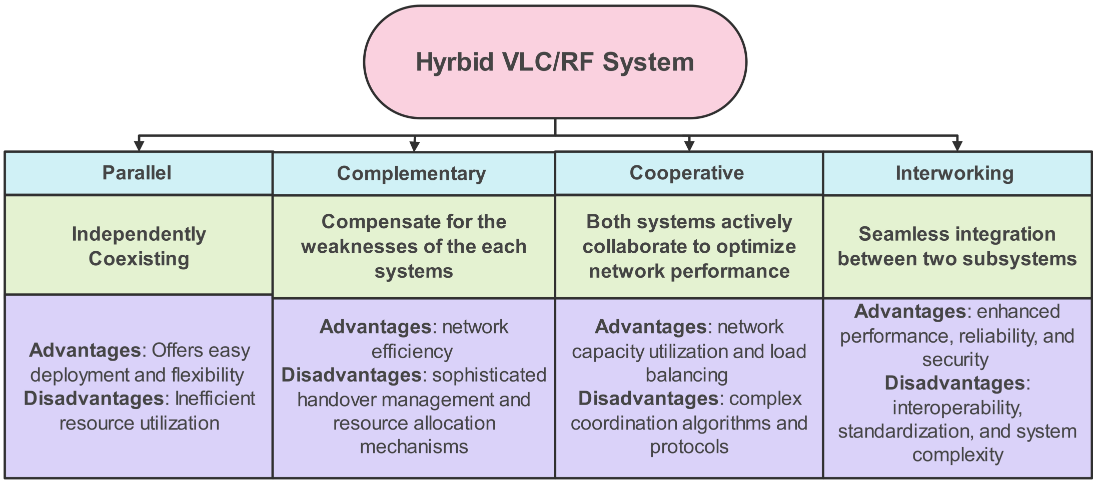

Figure 2.1: Different types of hybrid VLC/RF structures

efficient solution for indoor communication and localization applications.

2.2 Type of Hybrid VLC/RF Architecture

The integration of VLC with RF communication systems leads to the development of various hybrid VLC/RF architectures, each with unique design considerations and objectives similar in Figure 2.1. In this section, we provide an overview of different types of hybrid VLC/RF architectures, focusing on their characteristics, advantages, and limitations.

2.2.1 Parallel

In the parallel structure, VLC and RF communication systems coexist within the same environment without direct interaction or coordination. Both networks function independently, each with its own set of infrastructure, protocols, and devices. Users can seamlessly switch between the two networks based on various factors such as signal strength, data rate requirements, network load conditions, or system availability [19, 20]. The following sections provide a more detailed description of this architecture, along with its pros and cons.

Detailed Description

In a parallel structure, the VLC and RF systems are deployed alongside one another, providing complementary services to users. Each system operates using its respective communication medium − VLC leveraging visible light spectrum while RF relies on radio waves. As a result, both networks can offer redundant communication channels, allowing users to select the most appropriate option based on their specific needs and preferences at any given moment. The process of switching between the VLC and RF networks usually happens automatically, facilitated by user devices that are capable of accessing both communication modes. These devices continuously monitor the quality of the available networks and make decisions about when to switch for optimal performance.

Table 2.1: Pros and Cons of Parallel structure

	Pros
1	**Easy deployment:** One advantage of the parallel structure is that it requires minimal modifications to existing infrastructures. Since the VLC and RF systems operate independently, there is no need for complex integration procedures or extensive modifications to either technology.
2	**Flexibility:** Parallel structure provides flexibility in terms of connectivity options, giving users the choice to use either VLC or RF networks depending on their specific requirements and the prevailing network conditions. This ensures that users can always access the best-available network for their needs.
3	**Redundancy:** By offering two separate communication channels, the parallel structure enhances overall system reliability and resilience. In case of failures or disruptions in one network, users can still connect through the other, ensuring continuous communication.
	Cons

Continued on next page

Table 2.1 – continued from previous page

Cons	
1	**Inefficient resource utilization:** The main drawback of the parallel structure is that it may lead to inefficient resource utilization, as both VLC and RF networks operate without coordinating their actions. This lack of coordination can result in duplicated efforts and increased energy consumption, which could be minimized if the networks were integrated and managed collaboratively.
2	**Limitations in network optimization:** Since the VLC and RF systems operate independently in the parallel structure, opportunities for joint network optimization are limited. This could prevent organizations from maximizing the benefits of each technology and hinder the development of innovative solutions that leverage the unique strengths of both systems.

The table 2.1 presents the pros and cons of a parallel structure, which is a network architecture where VLC and RF systems operate independently. The pros include easy deployment, flexibility, and redundancy. Easy deployment is a result of minimal modifications needed to existing infrastructures, as there is no need for complex integration procedures. Flexibility is achieved by providing users with the choice to use either VLC or RF networks based on their requirements and network conditions. Redundancy is offered by having two separate communication channels, enhancing overall system reliability and resilience.

On the other hand, the cons consist of inefficient resource utilization and limitations in network optimization. Inefficient resource utilization occurs due to a lack of coordination between VLC and RF networks, leading to duplicated efforts and increased energy consumption. Limitations in network optimization arise because independent operation of VLC and RF systems hinders joint optimization opportunities, preventing organizations from maximizing the benefits of each technology.

In summary, while the parallel structure offers easy deployment and flexibility by allowing VLC and RF networks to coexist, it also has some drawbacks, including inefficient resource utilization. However, it still serves as a practical approach for organizations looking to explore the potential of hybrid VLC/RF communication systems without investing heavily in integration and coordination efforts.

2.2.2 Complementary

In the complementary structure, VLC and RF communication systems are designed to work together, leveraging the strengths of one technology to compensate for the weaknesses of the other. This approach aims to optimize overall system performance by utilizing each technology in scenarios where it performs best. For example, high-bandwidth data transmission can be offloaded to the VLC network within its limited coverage area, while RF technologies such as WiFi or LTE provide wider coverage and mobility support [21, 22]. The following sections further explore the detailed description of this architecture, along with its pros and cons.

Detailed Description

The complementary structure focuses on intelligently combining the capabilities of both VLC and RF systems to maximize their respective advantages. In this setup, devices can transparently switch between the two networks based on factors like signal quality, data rate requirements, or user preferences. A sophisticated handover management system is required to facilitate seamless transitions without disrupting ongoing communications.

Effective resource allocation mechanisms also play a crucial role in determining which technology should be employed for specific tasks at any given time. These mechanisms can consider factors such as network conditions, device capabilities, and application demands to make informed decisions that optimize overall system performance.

Table 2.2: Pros and Cons of Complementary structure

	Pros
1	**Enhanced network efficiency:** By leveraging the strengths of both VLC and RF technologies, the complementary structure enables improved network efficiency and performance, as each technology can be used in scenarios where it performs optimally.

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Table 2.2 – continued from previous page

Pros	
2	**Seamless connectivity:** With proper handover management and resource allocation mechanisms in place, this architecture provides seamless connectivity to users, ensuring uninterrupted communication even when transitioning between different networks.
3	**Flow control:** The complementary structure allows for dynamic flow control between VLC and RF networks, helping to reduce congestion and improve overall network performance for high-priority services, especially during periods of high demand.
Cons	
1	**Complex handover management:** Implementing a complementary structure necessitates sophisticated handover management systems capable of seamlessly transferring ongoing communications between VLC and RF networks. Developing and maintaining these systems can be challenging and resource-intensive.
2	**Advanced resource allocation mechanisms:** Ensuring optimal performance in a complementary structure requires the development of advanced resource allocation mechanisms that can intelligently allocate tasks to either VLC or RF networks based on various factors. This adds complexity to the system design, implementation, and maintenance processes.
3	**Potential compatibility issues:** Devices operating within a complementary structure must be equipped to handle both VLC and RF communication modes and switch between them as needed. This may result in higher manufacturing costs and potential compatibility issues across different devices.

The table 2.2 provided outlines the pros and cons of a Complementary network architecture, which combines the strengths of VLC and RF technologies. The pros of this architecture include enhanced network efficiency, seamless connectivity, and dynamic load balancing. By utilizing both VLC and RF technologies, the network can achieve improved efficiency and performance in various scenarios. Seamless connectivity is ensured through proper handover management and resource allocation mechanisms, providing users with uninterrupted communication. Additionally, dynamic load balancing between VLC and RF networks helps reduce congestion and improve overall network performance during high-demand periods.

On the other hand, the cons of a complementary structure involve complex handover management, advanced resource allocation mechanisms, and potential compatibility issues. Implementing this architecture requires sophisticated handover systems that can seamlessly transfer communications between VLC and RF networks, which can be challenging and resource-intensive. Moreover, achieving optimal performance necessitates the development of advanced resource allocation mechanisms, adding complexity to the system design, implementation, and maintenance processes. Lastly, devices operating within this architecture must be capable of handling both VLC and RF communication modes, potentially resulting in higher manufacturing costs and compatibility issues across different devices.

In summary, a Complementary network architecture offers the potential for improved network performance by leveraging the strengths of both VLC and RF technologies. However, it also introduces complexity and potential compatibility challenges that must be addressed during the design, implementation, and maintenance stages.

2.2.3 Cooperative

In the cooperative structure, VLC and RF communication systems work together actively to optimize network performance through resource sharing, information exchange, and joint decision-making. This collaboration enables improved network capacity utilization, interference mitigation, and load balancing [32]. However, implementing a cooperative structure requires complex coordination algorithms and protocols. The following sections delve into a more detailed description of this architecture, along with its pros and cons.

Detailed Description

cooperative structure focuses on integrating VLC and RF networks in such a way that they operate as a single unified system. This integration allows the networks to communicate and collaborate in real-time, improving overall performance and making the best use of available resources. Some examples of cooperative structures include joint channel assignment, load-aware resource allocation, and adaptive handover policies.

Joint channel assignment involves coordinating the use of channels between VLC and RF systems, allocating them based on factors such as interference levels, user demand, or other network conditions. Load-aware resource allocation dynamically balances the load between the two networks, helping to ensure efficient usage of both VLC and RF resources. Adaptive handover policies facilitate seamless transitions between the networks by considering various factors such as signal quality, user mobility, and network congestion.

Table 2.3: Pros and Cons of Cooperative structure

	Pros
1	**Optimal network performance:** The cooperative structure offers optimal network performance by leveraging the strengths of both VLC and RF technologies, while intelligently managing resources and mitigating interference.
2	**Efficient resource utilization:** By jointly allocating resources and balancing loads between the two networks, the cooperative structure ensures efficient utilization of network capacity, leading to improved performance and reduced energy consumption.
3	**Adaptive and flexible:** The cooperative structure can adapt to changing network conditions and user requirements, dynamically adjusting settings and allocations to maintain optimal performance throughout the entire system.
	Cons
1	**Complex coordination algorithms:** Implementing a cooperative structure requires the development and deployment of complex coordination algorithms and protocols to manage the interactions between VLC and RF systems. This can be challenging and require significant resources for design, implementation, and maintenance.
	Continued on next page

Table 2.3 – continued from previous page

Cons	
2	**Higher implementation costs:** Due to the complexity of cooperative structures, higher initial implementation costs may be incurred compared to parallel or complementary structures. These costs can stem from the need for additional hardware, software, or infrastructure modifications to enable seamless cooperation between VLC and RF systems.
3	**Potential scalability issues:** As the number of devices and users within a cooperative structure increases, the complexity of managing and coordinating interactions between VLC and RF systems may also rise, potentially leading to scalability concerns.

In summary, the cooperative structure offers significant advantages in terms of optimal network performance, efficient resource utilization, and adaptability. However, it also presents challenges related to the complexity of coordination algorithms, higher implementation costs, and potential scalability issues. Despite these drawbacks, the cooperative structure represents a promising approach for organizations seeking to maximize the benefits of both VLC and RF technologies while maintaining a highly efficient and adaptable communication system.

2.2.4 Interworking

Interworking structure focuses on tightly integrating VLC and RF subsystems at various layers of the protocol stack, enabling efficient data exchange and processing across both networks. This approach can lead to enhanced performance, reliability, and security but may present challenges related to interoperability, standardization, and system complexity. The interworking structures usually involve cross-layer optimization techniques and novel network protocols that enable seamless communication between VLC and RF components. The following sections provide a more detailed description of this architecture, along with its pros and cons.

Detailed Description

In an interworking structure, the VLC and RF systems are designed to closely interact and collaborate across different layers of the communication protocol stack. This tight integration allows for improved coordination and information sharing between the two technologies, resulting in more efficient communication overall. Cross-layer optimization techniques play a crucial role in interworking structures, as they help break down the traditional layer barriers within the protocol stack. This enables better resource allocation, data transmission, and management decisions that take into account the unique characteristics and capabilities of both VLC and RF technologies. Novel network protocols and algorithms are also developed to facilitate seamless communication and cooperation between the VLC and RF components, ensuring high-performance and reliable connectivity across the entire system.

Table 2.4: Pros and Cons of Interworking structure

	Pros
1	**Enhanced performance:** Interworking structure offers improved performance by allowing VLC and RF technologies to closely collaborate and share resources, leading to more efficient utilization and better overall system capabilities.
2	**Reliability and security:** The tight integration of VLC and RF subsystems in an interworking structure can enhance system reliability and security, as vulnerabilities or issues in one technology can be compensated for by the strengths of the other.
3	**Flexible and scalable:** Interworking structures can adapt to changing network conditions and user requirements, scaling up or down as needed to maintain optimal performance and resource usage across the entire system.
	Cons
1	**Interoperability challenges:** One of the major challenges of implementing an interworking structure is ensuring interoperability between the VLC and RF subsystems, which may have been developed independently and based on different standards.
	Continued on next page

Table 2.4 – continued from previous page

Cons	
2	**Standardization issues:** Due to the tight integration required between VLC and RF systems, the development and adoption of standardized protocols and interfaces are essential for the successful implementation of interworking structures. However, reaching consensus on these standards can be time-consuming and complex.
3	**Increased system complexity:** The close collaboration between VLC and RF subsystems in an interworking structure may lead to increased system complexity, making design, implementation, and maintenance processes more challenging and resource-intensive.

In summary, the interworking structure offers significant benefits in terms of enhanced performance, reliability, and security. However, it also presents challenges related to interoperability, standardization, and system complexity. Despite these drawbacks, the interworking structure represents a promising approach for organizations looking to harness the full potential of both VLC and RF technologies while maintaining a high-performance, reliable, and secure communication system.

Each of these hybrid VLC/RF architectures has its own set of merits and drawbacks, which need to be carefully considered when designing a network solution tailored to specific application requirements and environmental constraints. In the following sections, we will discuss the challenges associated with hybrid network architectures and present our proposed hybrid network design that addresses these issues.

Table 2.5 presents a comparison of four different network architectures: Parallel, Complementary, Cooperative, and Interworking. The comparison is based on various criteria that are essential for evaluating the performance and suitability of each architecture in different scenarios. The table uses checkmarks to indicate the presence of a specific feature or advantage in a particular architecture, while an asterisk (*) denotes drawbacks or challenges associated with that architecture. The parallel structure is easy to deploy but lacks flexibility. In contrast, the Complementary, Cooperative, and interworking structures offer better performance and seamless connectivity. The main differences lie in load balancing, coordination com-

Table 2.5: Comparison of Structures

Criteria	**Parallel**	**Complementary**	**Cooperative**	**Interworking**
Easy Deployment	✓			
Flexibility	✓	✓	✓	✓
Redundancy	✓	✓	✓	✓
Enhanced Performance		✓	✓	✓
Seamless Connectivity		✓	✓	✓
Dynamic Load Balancing	✓*		✓	✓
Resource Utilization	✓*	✓*		✓
Adaptive and Scalable				✓
Complex Coordination		✓*	✓*	✓*
Implementation Costs			✓*	✓*
Scalability Issues			✓*	✓*
Interoperability		✓*	✓*	✓*
Standardization Issues				✓*
System Complexity				✓*
* Indicates drawbacks or challenges in the specific architecture.				

plexity, and implementation costs. Both Cooperative and interworking structures support dynamic load balancing but require complex coordination and have higher costs. The interworking structure stands out with optimized resource utilization, adaptability, and scalability but faces challenges in standardization and increased system complexity.

2.3 Challenge for Hybrid System VLC and RF

While hybrid VLC/RF systems offer numerous advantages, they also introduce several challenges that must be addressed to ensure efficient performance and seamless connectivity. In this section, we discuss some of the principal challenges associated with hybrid VLC/RF network architectures.

2.3.1 Network Coexistence

One of the primary challenges in hybrid VLC/RF systems is ensuring effective coexistence between VLC and RF subsystems to maintain network stability and prevent interference. Although these communication technologies operate in different frequency bands, which means that their signals do not interact directly, designing a system that allows both networks to operate concurrently without causing performance degradation remains a non-trivial task. This challenge becomes even more complex when considering environments where other traditional RF systems already exist, such as WiFi, Bluetooth, and cellular networks.

Achieving seamless coexistence between VLC and RF networks requires careful consideration of various factors, including proper channel allocation, resource management, and signal processing techniques. Channel allocation strategies must take into account the spectrum availability and usage patterns of both VLC and RF systems to minimize interference and optimize network capacity. Resource management mechanisms should be designed to allocate resources dynamically between the two subsystems based on user requirements, network conditions, and load balancing objectives. Additionally, advanced signal processing techniques can help mitigate the effects of interference, multipath propagation, or shadowing, ensuring reliable and high-quality communication across the hybrid network.

Addressing these coexistence challenges is critical for realizing the full potential of hybrid VLC/RF systems, as it enables users to harness the complementary strengths of both communication technologies while providing robust, efficient, and seamless connectivity in indoor environments.

2.3.2 Handover Mechanisms

A critical challenge in hybrid VLC/RF systems is the seamless handover process, which enables users to switch between access points or communication technologies as they move within the coverage area [33]. The primary goal of handover mechanisms is to ensure minimal latency, service disruptions, and network overhead while maintaining user QoE. Developing effective handover algorithms and strategies demands a complex interplay of several factors, including accurate user location information, robust estimation of network conditions, and intelligent decision-making capabilities.

In the context of hybrid VLC/RF networks, designing efficient handover mechanisms becomes even more challenging due to the unique characteristics of each communication technology. For instance, VLC systems are typically sensitive to LOS constraints, physical obstructions, and mobility limitations, whereas RF systems exhibit more flexibility and wider coverage. Therefore, handover algorithms should be tailored to accommodate the specific requirements and constraints of both VLC and RF systems, ensuring smooth connectivity transitions without compromising performance.

Moreover, handover mechanisms must address issues such as load balancing, resource allocation, and interference management, taking into account the dynamic nature of indoor environments and user behavior patterns. This may entail leveraging machine learning techniques, predictive models, or context-aware algorithms that can adapt to changing conditions and make informed decisions on when and how to perform a handover.

By addressing these challenges in handover mechanisms, hybrid VLC/RF systems can deliver robust, efficient, and seamless connectivity for indoor communication applications, capitalizing on the complementary strengths of both visible light and radio frequency technologies.

2.3.3 Resource Allocation and Load Balancing

Efficient resource allocation and load balancing are vital for optimizing network performance in hybrid VLC/RF systems [34, 35]. However, the disparate characteristics of VLC and RF networks, such as data rate, coverage range, and path loss, pose significant challenges in allocating resources effectively among users and balancing network load. These differences require advanced optimization techniques and algorithms capable of addressing these issues while ensuring fair resource distribution among all users.

One particular challenge in resource allocation and load balancing within hybrid VLC/RF systems is achieving a seamless integration between the two communication technologies to maximize overall network efficiency. This requires the development of algorithms that can dynamically adapt resource allocation strategies based on factors such as user requirements, network conditions, and QoS constraints. Furthermore, these algorithms must be able to manage multiple objectives simultaneously, including maximizing data rates, minimizing latency, and reducing energy consumption.

Another challenge stems from the need to maintain network stability and fairness among users while accommodating the dynamic nature of indoor environments and user behavior patterns. This may involve incorporating context-awareness, predictive models, or machine learning techniques to analyze network parameters and make informed decisions on resource assignment and load balancing.

By tackling these challenges in resource allocation and load balancing, hybrid VLC/RF systems can capitalize on the complementary strengths of both visible light and radio frequency technologies, providing robust, efficient, and high-performing indoor communication solutions. By intelligently distributing resources and managing network load, these systems can cater to various applications with diverse requirements, ensuring an optimal user experience.

2.3.4 Localization and User Mobility

Indoor localization and positioning play a crucial role in hybrid VLC/RF systems, particularly for applications such as navigation, asset tracking, and context-aware services. Achieving high positioning accuracy and minimizing localization errors are challenging tasks, given the inherent limitations of VLC and RF technologies, such as multipath interference, signal attenuation, and LoS constraints. To address these challenges, innovative localization algorithms and techniques must be developed that exploit the complementary strengths of VLC and RF networks while considering user mobility patterns.

Developing effective localization mechanisms for hybrid systems involves integrating diverse measurement techniques available from both VLC and RF components. This may involve combining time-based, distance-based, or angle-based measurements, each with its own set of advantages and limitations. Designing fusion algorithms capable of merging these heterogeneous measurements can help improve overall positioning accuracy and robustness.

Another challenge is accounting for the dynamic nature of indoor environments and user mobility patterns, which often exhibit varying degrees of signal propagation and obstruction due to factors such as furniture arrangements, moving objects, or changing user density. Localization algorithms should be capable of adapting to these variations in real-time, ensuring consistent performance under different conditions and user movements.

Furthermore, localization and positioning techniques must consider the trade-off between complexity and precision, aiming to deliver accurate results while minimizing computational overhead and implementation cost. This might include leveraging machine learning approaches, such as neural networks or Bayesian filtering, to optimize localization performance while maintaining resource efficiency.

By addressing these challenges in localization and user mobility, hybrid VLC/RF systems can provide accurate and reliable indoor positioning information. This enables a wide range of applications and services that enhance the user experience and support innovative use cases across diverse scenarios.

2.3.5 System Integration and Standardization

The integration of VLC and RF networks into a unified system necessitates compatibility at various levels of the protocol stack, which poses challenges in terms of system complexity and interoperability [36]. Designing a hybrid architecture that effectively combines these communication technologies requires careful consideration of factors such as network planning, device configuration, and control mechanisms to ensure seamless operation and coexistence.

Furthermore, standardization efforts are required to define common protocols, interfaces, and functional specifications for hybrid VLC/RF systems, ensuring seamless integration across different devices and vendors. As hybrid VLC/RF systems gain traction, it becomes increasingly important for industry stakeholders and standardization bodies, such as IEEE to collaborate on developing consensus-based standards that promote interoperability, enhance performance, and foster innovation in the field.

Addressing these challenges in system integration and standardization is essential for realizing the full potential of hybrid VLC/RF network architectures and achieving optimal performance in indoor environments. By tackling issues related to compatibility, interoperability, and standardization, these systems can deliver robust, efficient, and high-performing communication solutions that capitalize on the complementary strengths of both visible light and radio frequency technologies.

In the next section, we will present our novel proposed hybrid network architecture that seeks to mitigate these challenges and provide an efficient solution for indoor communication and localization applications.

2.4 Conclusion

In this chapter, we delved into the intricacies of hybrid VLC and RF network architectures. We explored four distinct types of hybrid architectures: Parallel, Complementary, Cooperative, and Interworking, each with its unique advantages and challenges. The Parallel structure offers ease of deployment but may lead to inefficient resource utilization. The Complementary structure enhances network performance and ensures seamless connectivity but necessitates complex handover management. The Cooperative structure optimizes network performance and resource utilization but may face scalability issues. The Interworking structure, while enhancing performance and reliability, may grapple with standardization and increased system complexity.

We also identified and discussed five key challenges that hybrid VLC/RF systems face: network coexistence, handover mechanisms, resource allocation and load balancing, localization and user mobility, and system integration and standardization. These challenges range from ensuring stable and interference-free operation of VLC and RF subsystems in the same environment to achieving accurate indoor localization and positioning while considering user mobility patterns.

In conclusion, the development of a novel hybrid network architecture that effectively mitigates these challenges and optimizes performance for indoor communication and localization applications is crucial. Such an architecture would leverage the synergies between VLC and RF technologies, providing robust, efficient, and high-performing communication solutions that can meet diverse user needs and application requirements in indoor environments.

Chapter 3

A Novel Intelligent Management System Architecture for Hybrid VLC/RF Systems

3.1 Novelty of the Proposed Solution

The proposed architecture introduces several novel elements, distinguishing it from existing solutions:

- **Adaptive handover mechanism**: The Intelligent Handover Controller employs an adaptive handover mechanism that monitors changing user requirements, environmental factors, and network conditions [37, 38]. This feature minimizes disruptions and ensures consistent connectivity across different communication links, optimizing the overall user experience.

- **Energy Harvesting**: The Energy Harvesting component of the system focuses on harnessing ambient energy from various sources, such as solar radiation, vibrations, and thermal gradients [39, 40]. By incorporating flexible solar panels, piezoelectric transducers, and thermoelectric generators, this component efficiently converts these energy sources into electrical power, reducing reliance on traditional energy grids and extending the operational lifetime of devices [41, 42].

- **Resource Optimization**: The Adaptive Resource Management component optimizes resource usage by dynamically managing LED brightness based on environmental factors, selectively deactivating idle links when not in use, and reallocating resources across the hybrid VLC/RF network infrastructure based on real-time demand and energy availability [43, 44]. These capabilities ensure optimal energy usage, reduce operational costs, and contribute to the sustainability of the indoor communication system [45, 46].

- **Integration of federated learning algorithms for tracking and localization**: The Edge Tracking and Localization module utilizes federated learning algorithms that adapt to user movement patterns and network conditions. This approach preserves privacy while enabling accurate and efficient tracking and localization [47, 48, 49].

- **Unified security and privacy framework**: The proposed architecture integrates a comprehensive Security and Privacy Management System (SPMS) that addresses the unique challenges posed by hybrid VLC/RF networks. The SPMS encompasses advanced encryption techniques and secure handover mechanisms to protect user data during transitions between VLC and RF links. Additionally, it incorporates real-time threat detection and mitigation measures to ensure overall network integrity [50, 51]. By providing a cohesive layer of privacy and security across both VLC and RF domains, the system ensures a robust and reliable communication environment for users [52, 53].

These innovative features allow the intelligent management system to provide seamless communication with multiple receivers and traffic flows. At the same time, it balances the complexity of individual LED intelligence modules, offering a robust and versatile solution for diverse scenarios.

3.2 Architectural Components

The proposed system architecture comprises six main components in Figure 3.1:

1. Hybrid VLC/RF Communication Infrastructure: The foundation of the proposed architecture lies in the seamless integration of VLC and RF technolo-

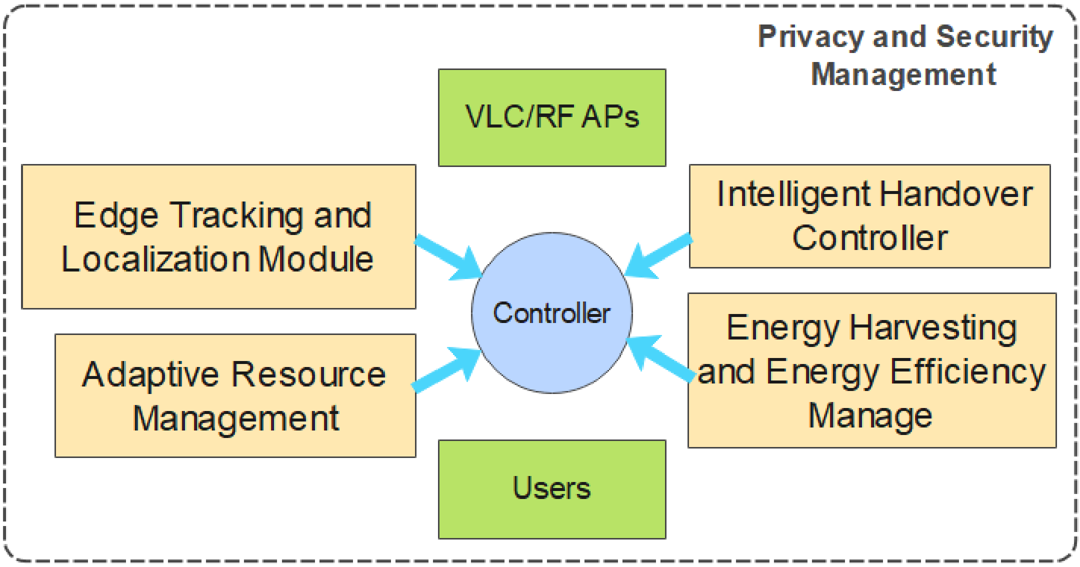

Figure 3.1: Hybrid VLC/WiFi system design framework

gies, enabling high-speed data transmission and wide-area coverage throughout the indoor environment. This hybrid approach combines the advantages of both communication methods, delivering a robust, efficient, and flexible networking solution. Key features of the hybrid VLC/RF communication infrastructure include:

- *Dual-mode VLC-enabled LED Lights*: By employing dual-mode VLC-enabled LED lights, the architecture supports simultaneous illumination and high-speed data transmission via visible light signals. This integration of VLC technology into the lighting infrastructure enables efficient resource utilization and reduces energy consumption, while offering increased capacity and reduced latency compared to traditional RF-based systems.

- *Wideband RF Access Points*: In addition to the VLC-enabled LED lights, the hybrid architecture incorporates wideband RF access points to provide broader wireless coverage and facilitate seamless handovers between VLC and RF links. These access points leverage advanced beamforming techniques and multi-input multi-output (MIMO) technology for improved signal strength, increased throughput, and enhanced link reliability.

- *Spatial Reuse and Spectrum Efficiency*: The hybrid VLC/RF communication infrastructure promotes spatial reuse of frequency bands and enhances spectrum efficiency by allowing multiple users to communicate simultaneously without causing interference. The coexistence of VLC and RF technologies within the same network environment facilitates the effective allocation of communication resources based on user requirements, network traffic conditions, and environmental factors.

- *Interference Mitigation*: By leveraging VLC technology, which operates in the visible light spectrum and has minimal interference with existing RF systems, the hybrid VLC/RF architecture mitigates co-channel and adjacent channel interference commonly encountered in crowded RF environments. Additionally, the system employs advanced interference management techniques, such as dynamic frequency selection and adaptive power control, to further minimize the impact of interference on network performance.

- *Adaptive Modulation and Coding Schemes*: The hybrid VLC/RF communication infrastructure supports adaptive modulation and coding schemes that dynamically adjust data rates and error-correction capabilities based on real-time link quality measurements. These adaptive techniques ensure reliable communication under varying channel conditions and enable the system to maintain high data rates and low-latency connections.

- *Scalability and Flexibility*: The hybrid VLC/RF architecture offers exceptional scalability and flexibility, enabling seamless integration with various network topologies, such as mesh networks, star networks, or hybrid configurations. This adaptability allows the system to accommodate a wide range of devices, applications, and user densities, catering to diverse indoor networking scenarios and requirements.

By integrating these advanced features, the hybrid VLC/RF communication infrastructure provides a powerful and versatile solution for indoor networking, effectively addressing key challenges, such as limited spectrum availability, interference issues, and high user density. The combination of VLC and RF technologies results in unprecedented levels of performance, reliability, and coverage, paving the way for innovative applications and services in the rapidly evolving field of indoor communications.

2. Intelligent Handover Controller (IHC): The IHC plays an essential role in orchestrating seamless handovers between the VLC and RF communication links within the hybrid network, ensuring a consistent and reliable user experience. By considering various factors such as user mobility patterns, localization accuracy, and link quality, the IHC dynamically manages the transitions between different communication mediums to maintain optimal network performance. Key features of the Intelligent Handover Controller (IHC) include:

- *Context-aware Handover Decision-making*: The IHC employs advanced machine learning algorithms to predict and adapt to the specific requirements and contextual information of individual users. This context-aware approach allows the IHC to make informed handover decisions based on a comprehensive understanding of each user's unique situation, including their location, speed, and communication preferences.

- *Dynamic Load-aware Handover Control*: To prevent congestion and uneven distribution of resources, the IHC intelligently monitors network traffic conditions and balances load among the available VLC and RF links. This dynamic load-aware handover control mechanism takes into account factors such as link capacity, user density, and data throughput when determining the most appropriate communication medium for each user, thereby maximizing overall network efficiency.

- *Proactive Handover Prediction*: The IHC incorporates predictive analytics to anticipate user movements and future handover events. By leveraging historical mobility data and real-time tracking information from the Edge Tracking and Localization (ETL) module, the IHC can proactively identify potential handover scenarios and initiate the necessary actions before users experience any disruptions in connectivity or service quality.

- *Multi-criteria Handover Optimization*: The IHC uses a multi-criteria optimization framework to evaluate several performance metrics, such as latency, signal strength, energy consumption, and security levels, when making handover decisions. This holistic approach ensures that all relevant factors are considered during the decision-making process, leading to more accurate and efficient handover management.

- *Seamless Vertical and Horizontal Handovers*: The IHC is designed to support both vertical and horizontal handovers, enabling seamless transitions between different access technologies (e.g., VLC-to-RF) and same-technology cells (e.g., VLC-to-VLC). This capability ensures uninterrupted connectivity, regardless of changes in user location or environmental conditions, and significantly enhances the overall user experience within the indoor environment.

- *Fault-tolerant Handover Mechanism*: The IHC incorporates a fault-tolerant handover mechanism that continuously monitors the health and performance of the hybrid VLC/RF system. In the event of hardware failures, software anomalies, or other unexpected issues, the IHC can rapidly detect and respond to these incidents by initiating fail-safe handover procedures and seamlessly redirecting users to alternative communication links.

By integrating these innovative capabilities, the Intelligent Handover Controller (IHC) ensures smooth, uninterrupted communication for users traversing the indoor environment with a diverse range of devices and applications. Its dynamic, proactive, and context-aware handover management techniques enable efficient coordination across the hybrid VLC/RF network infrastructure, providing a highly reliable and adaptive solution for various indoor networking scenarios.

3. Energy Harvesting and Energy Efficiency Manager (EHM) System: The EHM system is a groundbreaking feature of the proposed architecture that focuses on sustainability and energy efficiency. It integrates innovative energy harvesting techniques to convert ambient energy from various sources into usable power for the hybrid VLC/RF system [54, 55]. Simultaneously, the adaptive efficiency management component of EHM, known as the Energy Efficiency Manager (EEM), optimizes energy consumption based on real-time network demand and environmental factors. Key features of the EHM System include:

- *Multi-source Energy Harvesting*: The EHM system leverages diverse ambient energy sources, such as solar radiation, vibrations, and thermal gradients, to harvest energy. By incorporating flexible solar panels, piezoelectric transducers, and thermoelectric generators, the architecture can efficiently convert these energy sources into electrical power, thereby reducing its reliance on traditional energy grids and extending the operational lifetime of devices.

- *Energy Storage and Management*: To fully utilize the harvested energy, the EHM system includes an efficient energy storage and management subsystem. This subsystem comprises advanced energy storage components, such as supercapacitors or high-capacity batteries, which store excess energy generated during periods of low demand and release it when required. The energy management unit intelligently monitors energy levels and adjusts the charging and discharging processes to maximize energy utilization and minimize degradation of storage components.

- *Adaptive LED Brightness Control*: The EEM dynamically adjusts the brightness of VLC-enabled LED lights based on environmental factors, such as user presence and ambient light conditions, to optimize energy consumption without compromising communication performance. This adaptive control mechanism ensures that the LEDs operate at their most efficient levels while providing sufficient illumination and data transmission capabilities.

- *Selective Deactivation of Idle Links*: The EEM continuously monitors network traffic and selectively deactivates idle VLC or RF links when they are not in use, conserving energy and reducing overall power consumption. These inactive links can be rapidly reactivated upon detecting new user requests or changes in network conditions, ensuring seamless connectivity while maintaining energy efficiency.

- *Dynamic Resource Reallocation*: The EEM collaborates with the Adaptive Resource Management System to perform dynamic resource reallocation based on real-time demand and energy availability. By redistributing resources across the hybrid VLC/RF network infrastructure, the EEM ensures optimal energy usage and maintains service quality even under fluctuating energy constraints.

- *Energy-aware Handover Decisions*: The IHC takes energy efficiency into account when determining handovers between VLC and RF links. By considering factors such as link energy consumption rates, available energy reserves, and ongoing energy harvesting activities, the IHC can prioritize more energy-efficient communication channels without sacrificing user experience or connectivity quality.

Through the integration of cutting-edge energy harvesting methods and adaptive energy management features, the EHM System plays a crucial role in promoting the sustainability and long-term viability of the hybrid VLC/RF architecture. By reducing energy consumption and harnessing renewable energy sources, the EHM system enables a more environmentally friendly approach to indoor networking and communications.

4. Adaptive Resource Management System (ARS): This system manages load balancing, aggregated frequency, and overall resource optimization in the network by utilizing advanced algorithms and techniques to adaptively reconfigure the hybrid VLC/RF architecture according to changing user demands and network conditions. By doing so, it ensures efficient utilization of resources and maintains a high level of service quality while minimizing latency and bottlenecks. Key features of the Adaptive Resource Management System include:

- *Traffic Flow Prioritization*: The system intelligently prioritizes different types of traffic flows based on their specific requirements and characteristics (e.g., latency-sensitivity, bandwidth consumption) to ensure optimal QoS for each user. This approach allows critical or time-sensitive applications to be prioritized over less demanding ones, maximizing overall network performance.

- *Resource Pooling*: The adaptive resource management system consolidates available resources from both VLC and RF communication modules, creating a shared resource pool that can be dynamically allocated to users as required. This enables more efficient use of resources by allowing users to access the most suitable communication medium at any given time, depending on factors such as network congestion, signal strength, and mobility patterns.

- *Smart Resource Allocation*: The system employs machine learning-based algorithms to continuously analyze network state and user requirements, making informed decisions regarding resource allocation and adaptation. These algorithms take into account various factors such as user mobility, localization accuracy, link quality, and energy consumption when deciding how to allocate resources optimally across the hybrid network infrastructure.

- *Dynamic Load Balancing*: To prevent network congestion and uneven distribution of resources, the ARS continuously monitors network traffic and redistributes load among the available VLC and RF links. This dynamic load balancing mechanism adapts to changing network conditions and user demands, ensuring that no single link becomes overloaded and that the system operates efficiently even under high traffic loads.

- *Virtual Network Function Orchestration*: The ARS incorporates virtual network function orchestration techniques that allow for efficient management of the hybrid network's virtualized functions and resources. By automating and simplifying the deployment, scaling, and configuration of network functions, the system reduces operational complexity, increases flexibility, and improves overall efficiency.

By incorporating these innovative features, the ARS facilitates seamless communication with multiple receivers and diverse traffic flows, ensuring optimal network performance and QoS. Simultaneously, it balances the complexities of individual LED intelligence modules and efficiently manages resources within the hybrid VLC and RF network infrastructure, providing a robust and versatile solution for a wide range of indoor networking scenarios.

5. Edge Tracking and Localization (ETL) Module: The ETL module revolutionizes tracking and localization by leveraging advanced edge computing and federated learning technologies, enabling real-time processing of data at the network periphery and significantly reducing latency [56, 57]. This approach results in improved response times and more accurate tracking and localization capabilities while preserving user privacy. Key features of the ETL module include:

- *Edge Computing Integration*: By integrating edge computing technology into the hybrid VLC/RF architecture, the ETL module enables localized processing of tracking and localization data closer to users. This reduces the need for transmitting large amounts of data to centralized servers, cutting down on latency, and ensuring faster response times. In turn, this enhances the overall user experience and allows the system to adapt rapidly to changing environmental conditions and user mobility patterns.

- *Federated Learning Algorithms*: The ETL module employs federated learning, a cutting-edge distributed machine learning technique that facilitates collaborative model training across multiple devices without sharing raw data. This innovative approach helps maintain privacy and security while reducing data exchange and associated latency. Federated learning ensures efficient and secure tracking and localization by allowing devices to learn from each other, improving their accuracy and effectiveness over time.

- *Dynamic Handover Prediction*: Leveraging machine learning algorithms, the ETL module can quickly and accurately predict user movements and anticipate handovers between VLC and RF links. This capability enables the IHC to initiate handovers proactively, minimizing service interruptions and maintaining seamless connectivity for users as they move within the indoor environment.

- *Real-time Adaptation*: The ETL module continuously analyzes and processes data related to user movements, localization accuracy, and environmental factors in real-time, allowing the system to adapt dynamically to various scenarios. This adaptation capability ensures that the hybrid VLC/RF system consistently delivers high-quality tracking and localization performance even under challenging conditions, such as moving objects, changing user density, or signal propagation variations.

- *Privacy-Preserving Techniques*: A key concern of any indoor tracking and localization system is protecting user privacy. By employing federated learning, the ETL module keeps raw data local to devices, significantly reducing the risk of privacy breaches. Additionally, the module incorporates advanced privacy-preserving techniques, such as differential privacy and secure multi-party computation, to ensure the confidentiality of user information during collaborative model training and decision-making processes.

Through these innovative features, the ETL module provides an efficient, secure, and highly accurate solution for indoor positioning needs. By anticipating user movements and adapting to dynamic environments in real-time, the ETL module enhances user experience and supports a wide range of innovative applications and services in diverse indoor networking scenarios.

6. Privacy and Security Management: The proposed architecture places a strong emphasis on maintaining user privacy and ensuring secure communication throughout the hybrid VLC/RF system. This is achieved through a combination of advanced cryptographic techniques, federated learning algorithms, and continuous monitoring for potential cyber threats. Key features of the privacy and security management component include:

- *Federated Learning Integration*: By incorporating federated learning algorithms into the ETL module, the solution allows devices to collaboratively train models without sharing raw data between them. This decentralized approach significantly reduces the risk of data breaches and maintains user confidentiality, thus enabling secure tracking and localization.

- *Advanced Encryption Techniques*: The IHC employs cutting-edge encryption methods to protect sensitive information during handovers between VLC and RF links. These methods may include quantum key distribution or post-quantum cryptography, which are resistant to potential attacks from quantum computers and provide long-term security guarantees.

- *Continuous Threat Monitoring*: To further enhance security, the architecture includes a threat detection and mitigation component that constantly monitors network activity for signs of potential cyber threats, such as Distributed Denial-of-Service (DDoS) attacks or unauthorized access attempts. By employing machine learning algorithms and network analytics, this component can detect anomalies in real-time and swiftly initiate countermeasures to address them.

- *Dynamic Isolation and Countermeasures*: In case of detected anomalies, the privacy and security management system takes immediate action by isolating affected nodes and deploying suitable countermeasures to minimize the impact on users. These countermeasures might involve IP filtering, traffic rate limiting, or temporarily deactivating compromised accounts to limit the spread of malicious activities within the network.

- *Security-aware Resource Allocation*: The ARS incorporates security considerations when allocating resources, ensuring that secure communication channels are prioritized and maintained for critical applications and sensitive data transmission. This approach provides an additional layer of protection against eavesdropping, interception, and other potential security breaches.

- *Privacy-preserving Data Processing and Storage*: The privacy and security management component ensures that user data is processed and stored securely, both at rest and in transit. This encompasses using technologies like homomorphic encryption, which enables computations on encrypted data without needing decryption, and secure enclaves, which store and process sensitive information within a protected environment isolated from the rest of the system.

These collective measures enable the hybrid VLC/RF architecture to offer robust privacy protection and a secure communication environment for all users. By integrating innovative techniques, such as federated learning, advanced encryption, and continuous threat detection, the proposed solution fosters trust and confidence among users, paving the way for widespread adoption of the technology in various indoor networking scenarios.

3.3 Operation scenario for Novel Hybrid Architecture

The proposed intelligent management system operates as follows:

1. Users connect to the hybrid VLC/RF access points (APs) using their preferred communication link. The ETL module tracks user movements, predicting their future locations and adjusting LED brightness accordingly to optimize energy consumption and maintain communication quality.

2. As users move within the coverage area, the IHC monitors changes in user requirements, environmental factors, and network conditions. If a handover is deemed necessary, the IHC prioritizes the appropriate link, taking into account energy efficiency, load balancing, and multi-criteria optimization, and initiates the handover process, ensuring minimal disruption to user experience.

3. During the handover process, the ETL module continues to track user movements, proactively identifying any additional changes that may require further handovers and enabling seamless transitions between VLC and RF links or within the same technology cells.

4. Throughout this process, the EHM system harvests energy from various ambient sources, such as solar radiation, vibrations, and thermal gradients. The energy is stored in advanced storage components and managed by the EEM, which adjusts LED brightness, deactivates idle links, and reallocates resources across the hybrid VLC/RF network infrastructure to optimize resource usage and enhance sustainability.

5. The Adaptive Resource Management System works in conjunction with the EHM system and IHC to maintain an efficient allocation of communication resources based on user demand, network traffic conditions, and environmental factors, resulting in optimal network performance and reduced operational costs.

6. The architecture ensures data privacy and security by incorporating robust encryption algorithms, secure authentication mechanisms, and stringent access control policies. This protection extends to both VLC and RF communication links, safeguarding user information and maintaining trust within the indoor communication environment.

3.4 Advantages of the Novel Hybrid Architecture

By incorporating a collaborative multi-agent approach in the intelligent management system architecture, our solution offers several advantages over existing architectures, such as:

- **Enhanced Connectivity**: The Hybrid VLC/RF Access Points offer seamless connectivity across different environments by leveraging both visible light communication and radio frequency technology. Users can enjoy uninterrupted, high-speed connections regardless of their location or device type, while benefiting from increased capacity and reduced interference.

- **Intelligent Handovers**: The IHC ensures smooth transitions between VLC and RF links, as well as within the same technology cells based on user movement patterns, contextual information, and network conditions. This feature minimizes connection disruptions, optimizes resource allocation, and enhances overall network performance.

- **Accurate Tracking and Localization**: The ETL module provides real-time, precise tracking and localization data with reduced latency and improved privacy. This capability enables dynamic handovers, proactive adjustments to the communication network, and enhanced user experience, all while ensuring optimal network operations.

- **Energy Efficiency and Sustainability**: The Energy Harvesting component effectively captures ambient energy and converts it into usable power, reducing reliance on traditional power sources and promoting sustainability. In conjunction with the ARS, the EEM optimizes energy consumption, adjusts LED brightness, and deactivates idle links, further contributing to lower operational costs and environmental impact.

- **Scalability and Flexibility**: The architecture's modular design allows for easy scalability to accommodate growing networks and changing requirements. Its adaptability makes it suitable for various use cases, from smart buildings and industrial environments to large public venues and transportation systems.

- **Privacy Preservation**: By employing federated learning in the ETL module, the architecture ensures that sensitive user data remains secure and private, enhancing data protection while maintaining the system's ability to perform tracking and localization tasks efficiently.

- **Improved Network Coordination**: The decentralized multi-agent nature of the architecture fosters better coordination among its components, leading to more efficient resource utilization, optimized handovers, and overall enhanced system performance.

- **Future-Proof Design**: The integration of cutting-edge technologies in this architecture ensures that it remains relevant and capable of adapting to the evolving needs of users and network operators. As new communication standards and techniques emerge, the system can be updated to incorporate these advancements while maintaining compatibility with existing infrastructure.

3.5 Disadvantages of the Novel Hybrid Architecture

Despite the numerous advantages, there are some potential drawbacks and challenges associated with the novel hybrid architecture. These disadvantages include:

- **Complexity**: Incorporating multiple advanced technologies, such as hybrid VLC/RF communication, edge computing, federated learning, and energy harvesting, increases the system complexity of this architecture. As a result, implementation costs may rise, development time may lengthen, and maintenance efforts may intensify.

- **Sensitivity to Environmental Factors**: External factors like ambient light intensity, temperature fluctuations, and vibrations can affect the performance of the energy harvesting component. This could lead to diminished energy efficiency and challenges in maintaining a consistent power supply for the system.

- **Security Concerns**: Although the architecture employs robust encryption algorithms and authentication mechanisms, the integration of multiple cutting-edge technologies and a decentralized multi-agent approach could introduce new vulnerabilities. Continuously updating security measures and addressing emerging threats is essential for preserving user trust and privacy.

- **Compatibility Issues**: Despite the modular design and adaptability of the proposed architecture, integrating it into existing infrastructures could still present compatibility challenges. Retrofitting older systems or incorporating legacy devices may necessitate additional effort and resources.

3.6 Conclusion

In conclusion, this chapter presents a groundbreaking intelligent management system architecture for hybrid VLC and RF systems. It innovatively integrates several features such as an adaptive mechanism, energy harvesting, resource optimization, and federated learning algorithms for tracking and localization, along with a comprehensive security and privacy framework. The architecture is composed of six main components: Hybrid VLC/RF Infrastructure, IHC, EHM System, ARS, ETL, and Privacy and Security Management system. Each component plays a pivotal role in ensuring seamless connectivity, intelligent handovers, accurate tracking and localization, optimal energy usage, and robust privacy and security measures.

A practical scenario of the architecture's operation is discussed, demonstrating the dynamic interaction of the different components and the architecture's adaptability to varying user requirements and network conditions. The architecture offers numerous advantages such as enhanced user experience, energy efficiency, scalability, privacy preservation, improved network coordination, and a future-proof design. However, potential challenges such as system complexity, sensitivity to environmental factors, security concerns, and compatibility issues are also recognized. These challenges form the basis for future research and development efforts aimed at refining the architecture and realizing its full potential. This novel architecture serves as a stepping stone towards the development of more intelligent, efficient, and sustainable indoor communication systems, paving the way for a new era of connectivity.

Chapter 4

Enhance Priority Feedback Channel in Hybrid Network

4.1 Related Work

Hybrid VLC and Radio Frequency systems have been proposed as state-of-the-art solutions to resolve both coverage and uplink transmission issues [58, 59, 60]. Numerous previous studies have applied hybrid VLC/RF connectivity schemes to enhance the performance of both technologies [61, 62, 63].

In [58], the authors propose an architecture incorporating WiFi links with several VLC downlinks through a combination of theoretical research and simulations. This proposed system demonstrates the potential to achieve high aggregate throughput. Additionally, the work in [64] illustrates how a hybrid VLC/RF architecture improves overall rate performance and delivers better per-user rate performance. Generally, the radio link serves as a backup channel in instances of VLC coverage gaps or as a feedback channel for VLC data and control information [13] (e.g., for sending signal strength reports to the transmitter).

In [13], the authors introduce a light-radio wireless local area network (LiRa) architecture and show promising results for LiRa architecture, such as reducing response delay up to a factor of 15 and reducing significant throughput degradation of legacy WiFi less than 3% compared to the transmission of VLC feedback. However, the authors do not consider the impact of congestion on the legacy WiFi network that may impact the performance of the associated VLC connection(s).

4.2 Scenarios and motivations

We assume that an integrated VLC/WiFi network is available in an indoor space, where VLC Access Points are embedded into the ceiling lamps of the illumination infrastructure and connected, together with WiFi Access Points, to a local area network. Therefore, the indoor space is covered by multiple Access Points employing both the VLC and WiFi technology for supporting high-density terminal nodes. The configuration of each AP, in terms of physical and access layer parameters, as well as the configuration of the internal routes are decided by a centralized controller, called Intelligent Control Unit. We also assume that mobile nodes equipped with a VLC receiver are also equipped with a WiFi interface exploiting the VLC links. In a similar fashion to what is reported in [58], we assume that each VLC receiver also features a WiFi device, which is used for uplink transmissions. In case the VLC receivers are downloading data from the VLC APs, the common WiFi interface provides a feedback channel for the VLC connections.

The VLC transmitters, for example, embedded in luminaries, share a local area network with the WiFi network access point, and with an Intelligent Control Unit whose purpose will be detailed in the following. Note that the WiFi channel is shared between the VLC-enabled nodes and legacy devices in Figure 4.1

The intelligent control unit is the central controller, where all decisions about network configurations are taken based on network conditions and other variable channel factors. Indeed, network performances can be optimized by opportunistically adapting the WiFi contention parameters and operating channels as a function of the network load. Moreover, the usage of a central controller simplifies the mobility management: while static nodes can exploit the high-bandwidth VLC links for downloading data, highly dynamic nodes can be switched to the WiFi network for avoiding service interruptions due to frequent handovers.

Figure 4.1 shows a schematic view of our reference network architecture. For simplicity, we assume that each lamp available on the illumination infrastructure is serving one mobile node. Each VLC link is unidirectional, from a VLC AP to a

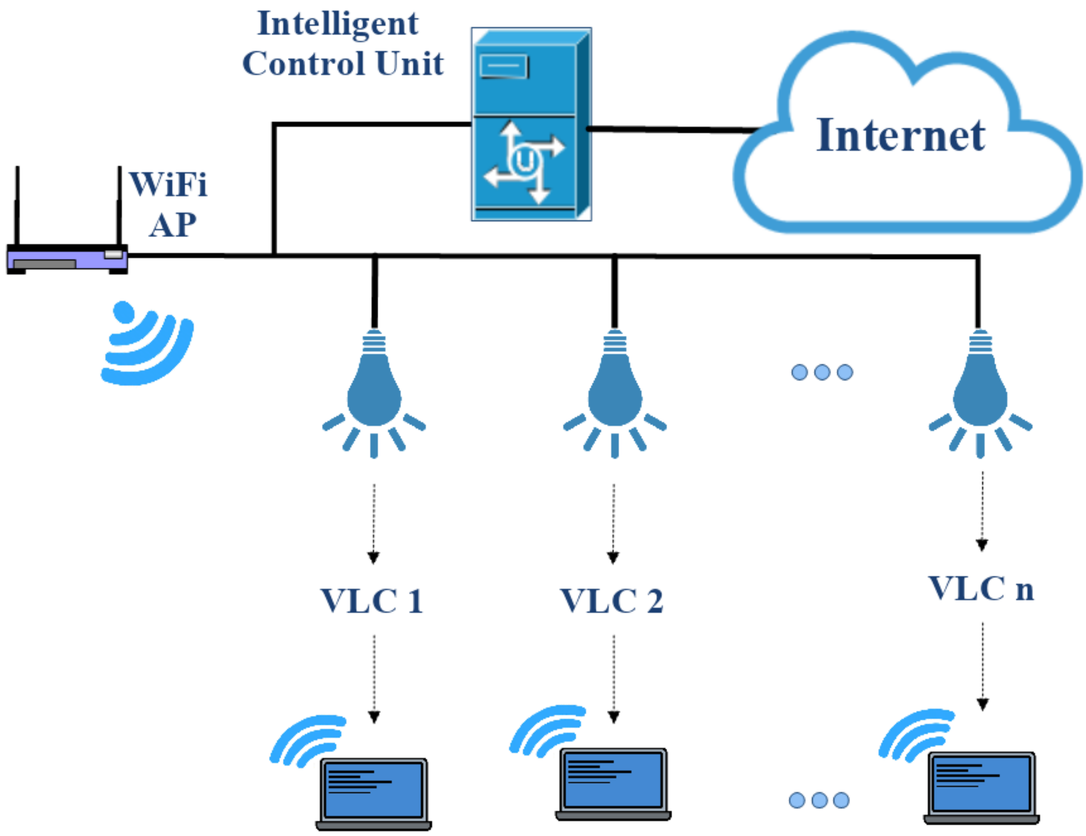

Figure 4.1: Hybrid VLC/WiFi reference architecture

mobile node also called VLC receiver, and it is labeled with a progressive identifier. No interference is generated between one VLC link and the neighbour ones. VLC receivers perform uplink transmissions towards the network infrastructure by means of the WiFi interface. A single WiFi Access Point covers the whole environment, where other (single-interface) WiFi nodes can be present.

4.2.1 Congestion impact on inter-technology performance

In our reference scenario, mobile nodes receive and transmit data by means of two different technologies, thus introducing some coupling effects between the performance of the coexisting VLC and WiFi networks. In particular, it is evident that uplink WiFi transmissions performed by neighbor mobile nodes may interfere each other, while downlink VLC transmissions are orthogonal. Since most applications generate bidirectional traffic flows, even when the dominant flow is in the downlink, it is important to understand in which conditions the WiFi network can act as a bottleneck for the whole system. In particular, we consider the case in which mobile nodes are involved in a file download from the network, by using a TCP transport protocol. All the TCP acknowledgements generated by each VLC link contend in the same WiFi network. Therefore, the number of coexisting VLC links cannot be arbitrarily large, because the delays and losses of TCP acknowledgements will force VLC transmitters to reduce their transmission rate. Moreover, in presence of background WiFi traffic, the rate reduction due to TCP congestion control can occur even in presence of a single VLC link.

In order to demonstrate the impact of such a phenomenon, we run a simple experiment in our lab at the University of Palermo, by using the OpenVLC platform for implementing the VLC link. OpenVLC is an open-source, flexible and low-cost VLC system [65] developed for testing innovative protocols exploiting the VLC technology. We implemented our mobile nodes on a Beaglebone Black (BBB), used as embedded computer running the VLC access protocol and integrating a visible-light TX/RX front-end. The details on the hardware and software architecture are presented in [65]. We also integrated a WiFi interface on the same Beaglebone and configured the routing rules needed to send the uplink data through the WiFi interface. Although the OpenVLC interface can achieve a maximum throughput of 400 kbps (much lower than state-of-art VLC data rates), we were able to reproduce the above mentioned phenomenon by tuning the WiFi data rate to a fixed value of 6 Mbps.

In figure 4.2, the blue line shows the TCP throughput of the OpenVLC link configured between one node acting as VLC Access Point and one node acting as mobile node, when the number of coexisting WiFi nodes varies from 0 to 5. VLC packets have a fixed size of 1500 bytes. Each coexisting WiFi node generates an UDP traffic flow towards the common WiFi Access Point at a source rate of 800 kbps. Packets are transmitted with a physical transmission rate of 6 Mbps. From the figure, we can observe that, when no WiFi coexisting node is active, the VLC link achieves a maximum rate slightly lower than 400 kbps. As the congestion level on the WiFi network increases, due to the activation of multiple WiFi nodes, such a throughput is progressively reduced down to almost zero (when 5 nodes

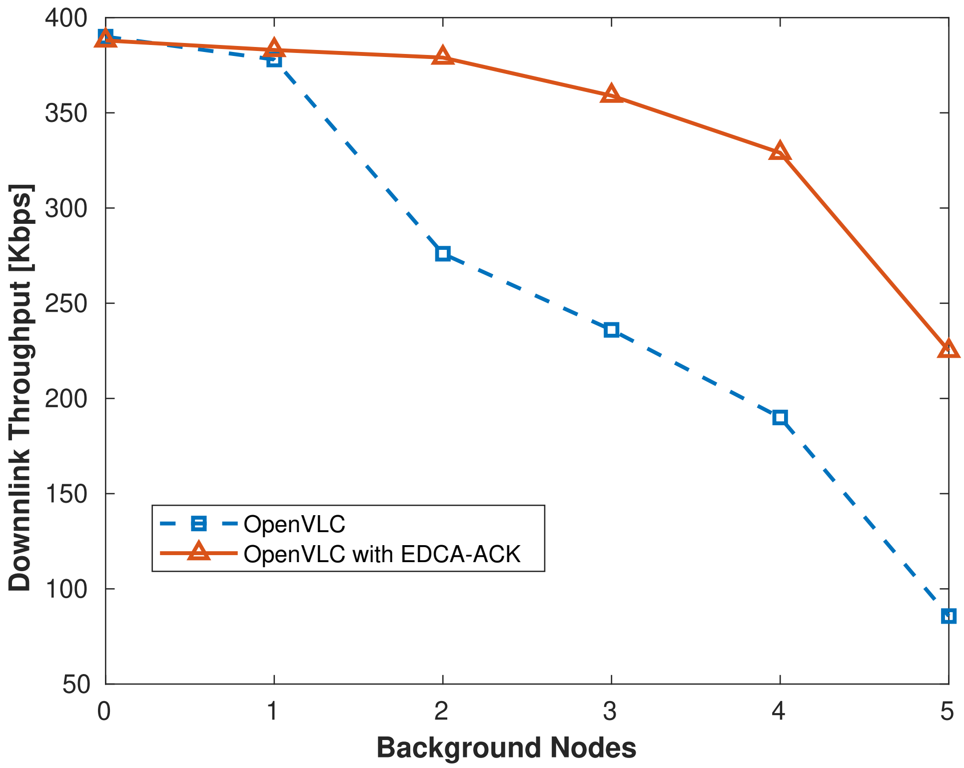

Figure 4.2: Throughput of a real VLC link, when TCP acknowledgements are sent on a WiFi network with a varying number of contending nodes.

are active). This happens despite the fact that the uplink traffic flow generated by the VLC receiver has a maximum rate of about 10 kbps (by considering that each TCP data frame will generate one acknowledgment, whose size is 40 bytes only). The figure also reports the observed minimum and maximum values for our experimental results, observed when repeating the experiments five times. The orange line in figure 4.2 shows the performance when the scheme proposed in the following section is employed.

Enhanced Distributed Channel Access - Acknowledgment *EDCA-ACK* is the upgrade version of EDCA, which is designed with one more category on the list, namely, *AC_ACK*, to solve the background noise traffic in the shared WiFi networks in hybrid VLC/RF architecture. In *EDCA-ACK*, as shown in Figure 4.3, packets from the upper layer are classified into five ACs according to their priority, respec-

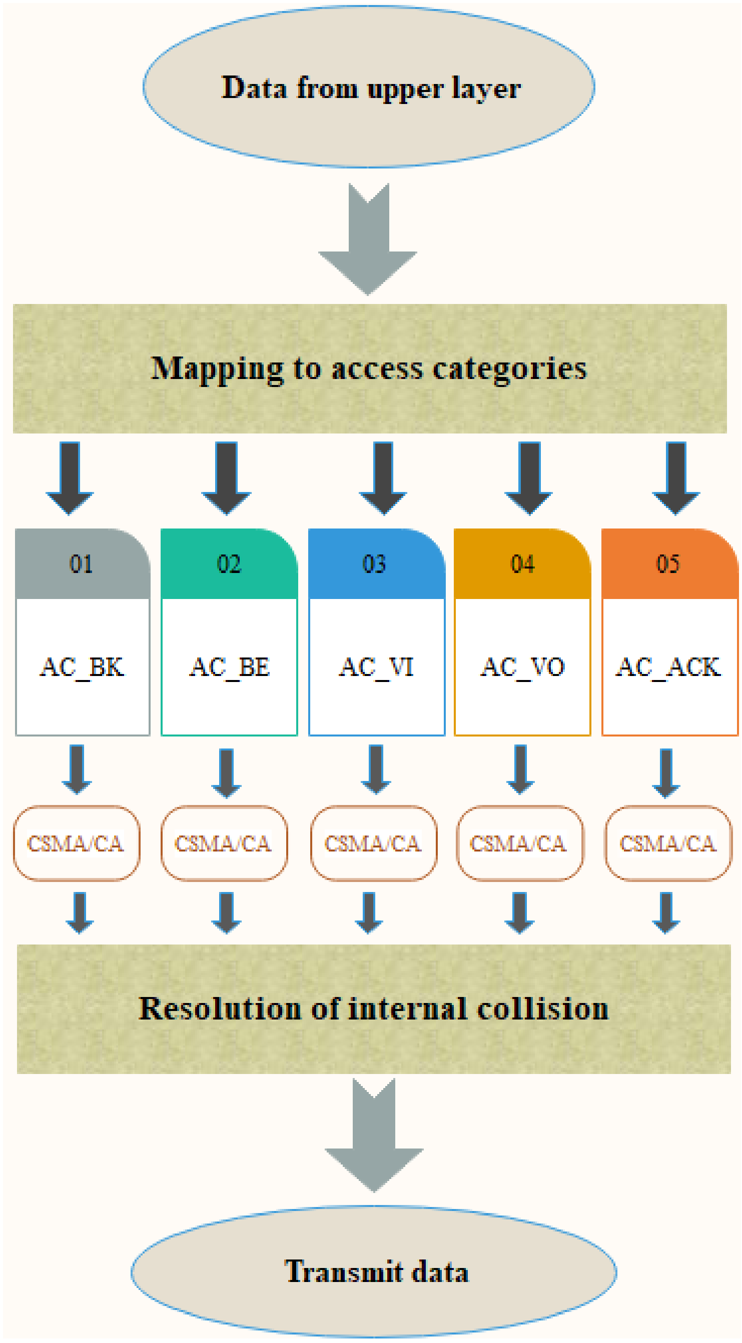

Figure 4.3: The priority control scheme of EDCA-A

tively: background *(AC_BK)*, best-effort *(AC_BE)*, video *(AC_VI)*, voice *(AC_VO)*, and acknowledge packet *(AC_ACK)*. The type of service field in the IP header or the virtual LAN suffix, as defined in 802.1Q, is used to categorize the packets. Each AC has its own *EDCA-ACK* access criteria, which specify the priority of the AC. After classification, the data packets are stored in the ACs queues. Each AC then conducts a carrier sensing multiple collision-avoidance (CSMA/CA) protocol, which is the basic procedure for transmitting a frame to IEEE 802.11 WLANs to address internal collisions between ACs.

In legacy WLANs, the STA with frames to transmit starts the carrier sense procedure and checks whether the channel is available or occupied by using distributed coordination function (DCF). Then, the STA only begins to transmit the frame after a fixed waiting time equal to the total of the distributed inter-frame space (DIFS) interval. In *EDCA-ACK*, these procedures are accomplished independently in all ACs with some modifications. The AC with a waiting time reaches zero faster, it will gets the priority to transmit first. The contention window is established to prevent the collision of multiple frames transmitted from different ACs simultaneously. The contention window size is computed from the number of slots randomly between CWmin and CWmax. The CWmin is applied when the frame is transmitted for the first time. In the case, the frame is retransmitted because of a collision or error. The contention window size is increased to reduce the probability of collision by extending the number of selective slots. The contention windows should not be bigger than CWmax, specified as the maximum window size. The *EDCA-ACK* frame transmission method is based on CSMA/CA. DIFS is a fixed waiting time solution, which is an inflexible solution. The arbitration inter-frame space (AIFS) is introduced and provides a different waiting time for each AC. The ACs with higher priority give lower AIFSs value. Consequently, the ACs with higher-priority are likely to get more transmission opportunities than the ACs with lower-priority. Besides, CWmin and CWmax values are lower for higher-priority ACs. Therefore, we give the *AC_ACK* a higher priority than any other ACs; hence the acknowledgment packet has a shorter waiting time and more likely to transmit first in the standard WiFi uplink. Moreover, *EDCA-ACK* provides a short inter-frame space (SIFS) function, which is the shortest waiting time defined in any IEEE 802.11 standard. The STA with the right of transmission can transmit several frames continuously during the transmission opportunity (TXOP). The TXOP value is defined in access parameters for *EDCA-ACK*. For example, with TXOP limit = 0, the AC can only send a single frame per transmission phase. AIFS, CWmin/CWmax, and TXOP are essential access parameters for *EDCA-ACK*, and these values are established in each STA in advance. The access point's *EDCA-ACK* parameter field broadcasts in a beacon frame simultaneously, and then the access point can inform STAs of whatever parameters suitable to use. Finally, an STA received an updated beacon frame with the *EDCA-ACK* parameters and used them to transmit frames. Hence, the AP can control the *EDCA-ACK* parameters of STAs in transmission.

4.3 Optimized EDCA Feedback channel

In this section, we focus on the limits of VLC/WiFi integrated architectures. In particular, we consider the possibility of supporting a technology-based duplexing scheme, in which downlink and uplink transmissions are performed, separately, on the VLC and WiFi interfaces deployed on the same node. Since WiFi links have a much wider coverage areas than VLC ones, in presence of high-density VLC links or other background WiFi traffic, the WiFi network may be congested. Congestion on the WiFi network, in turn, has an impact on the performance of the VLC links.

4.3.1 Simulation with NS-3

The most exciting advantage of using a real-time network simulator is that it reduces the expense of building a testbed. NS3 is a real-time network emulator that is powered by several advantages [66]. The discreteness function of NS3 was a key factor in its selection. NS3 gives the researcher the advantage of integrating each network layer separately and without interrupting the other layer. NS3 is a real-time network simulation platform that uses two programming languages: C++ and Python, further develop step-by-step to incorporate different models [67, 68]. Furthermore, NS3 is an open-source simulator that gives network engineers and researchers a free space to work. As a result, NS3 was chosen for the following reasons: NS3 is an open-source program that allows researchers to review and test system-level network implementations.

- NS3 is a comprehensive set of library files that facilitates large-area network simulations and evaluations.
- The NS3 protocol structures are configured similarly to individual hardware devices, incorporating the most commonly used performance criteria for reliable evaluations.
- NS3-based models provide network functionalities. The mobility model offers the orientations and angular mobility of the devices. This makes the implementation of hybrid architecture VLC/RF very straightforward and effective.
- The NS3 simulation runs in real-time and is designed specifically for research work.

NS3 is built with an extensive library, which can be flexibly linked to the main program that defines the simulation topology. Both C++ and Python are suitable as programming languages for NS3, which is a distinct advantage not easily found in other network simulators. Furthermore, NS3 offers some key "add-on" software like `NetAnim` - providing visual animations of network topologies - and `GNUplot` - generating graphical representations of system performance parameters.

4.3.2 Hybrid system with Downlink VLC

We study the impact of such congestion on the performance of multiple high-density VLC links. We consider a scenario in which VLC-links are used for a reliable data transfer towards smart objects. We assume a congestion-control transport protocol as TCP is used for data transfers. With this assumption, TCP acknowledgements are sent in uplink on the WiFi network and can result in a bottleneck for the whole integrated system. We then propose the use of EDCA access categories for giving priority to the WiFi feedback channel of the integrated nodes. The benefits of the proposed approach is shown by means of NS-3 simulations and a simple experiment.

Explicitly consider the problem of congestion with simple *EDCA-ACK* priority scheme, which does not require a great deal of network reconfiguration and is effective in dealing with the background traffic on the legacy WiFi network. In addition, *EDCA-ACK* is compatible with the legacy WiFi networks since it is based on the EDCA standard in WiFi 802.11e. Finally, we tested the effectiveness of our proposed scheme by implementing it in the ns-3 network simulator, evaluating the impact of congestion on the WiFi network on a hybrid VLC/WiFi system, and evaluating how our proposed scheme outperforms the plain hybrid scenario. The measured throughput and mean delay metrics are used to evaluate the performance of the VLC connections. EDCA reduces the mean delay by a factor of 16 compared to a standard VLC link and decreases the VLC throughput degradation by an order of magnitude compared to a standard hybrid VLC/RF connection.

In this section, we evaluate the VLC performance using the system described above to see the impact of background nodes on VLC performance with standard, soft QoS and hard QoS. We study both uplink and downlink performance for WiFi and VLC connection and mean delay for uplink in this case.

Simulation platform and setup

We used NS-3 for simulating our hybrid VLC/WiFi network. NS-3 is widely adopted for simulating the performance of large-scale networks. Moreover, it provides an extensive library with many standard network protocols and local access technologies and an easy interface for defining the network topology. The configuration of each network node requires installation of protocol stacks and can mimic every aspect of real nodes. Several tools are included in the simulator for visualizing the behavior of the networks, debugging through analysis of the event log and collecting results for performance evaluation.

Figure 4.4 summarizes the simulation scenario created in NS-3. There are two types of nodes in the simulation: nodes employing only a single WiFi interface (STA 1 to STA M), and nodes integrating one WiFi and one VLC interface (VLC 1 to VLC N). The first group of nodes will act as background traffic for studying the impact of WiFi congestion on the VLC links. The shared WiFi network is configured in infrastructure mode, with QoS support, and a physical layer based on 802.11a (configured with a fixed rate of 6Mbps). Since NS-3 is lacking support for high-speed VLC simulation, we also employed WiFi links in order to emulate those. Specifically, we configured IEEE 802.11ac orthogonal channels with a fixed VHT MCS with a measured maximum throughput of 60 Mbps. The VLC-emulating

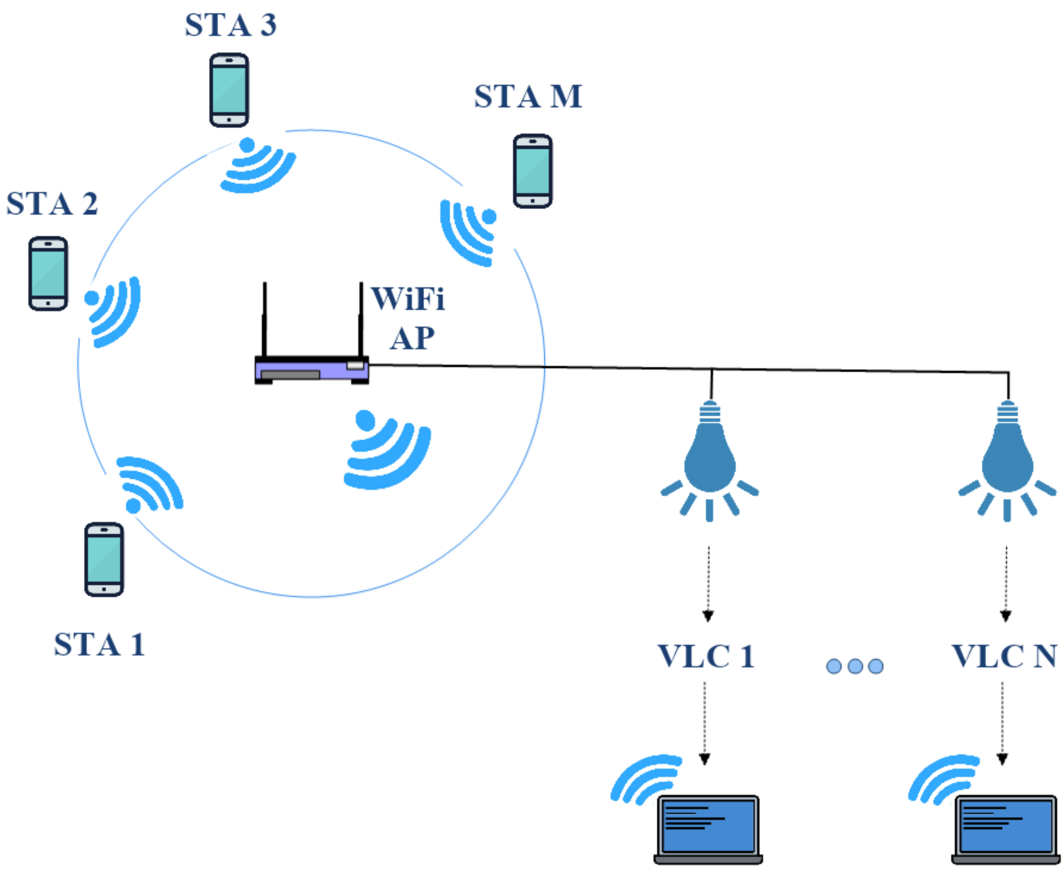

Figure 4.4: Simulation scenarios with several background nodes in the network

access points were placed close to their respective mobile node (with no mobility model in this experiment), in order to guarantee high-quality channel conditions. And all of the STAs are stay in the same distance to the AP.

Experimental results

For simulating the orthogonal VLC links, since the VLC technology is not natively included in NS-3 libraries, we used the WiFi library. In particular, we created a physical layer with the propagation characteristics of VLC links and a data rate of 10 Mbps, working on an independent per-link channel (i.e. working in isolation conditions, without perceiving any interference by the neighbor links). We also left the random access scheme for VLC emulated links, with the minimum possible contention window, but we disabled the MAC layer acknowledgements. Since each emulated VLC link has a single active transmitter, which is the VLC AP, no packet loss due to collision may happen. Moreover, VLC receivers are very close to the VLC corresponding APs, so that channel conditions are also very good.

Emulation of the simplex links was carried out by setting up static routes on the mobile nodes, so that the uplink data is forwarded through the common WiFi network. Regarding the QoS setting, we implemented the *EDCA-ACK* priority solution with soft EDCA and hard EDCA, by configuring all the uplink traffic generated by VLC receivers with the *AC_VO* class. Other configuration parameters are listed in Table 4.1.

Table 4.1: Simulation Parameters

Parameters	**Values**
Simulation duration	10–100 seconds
MTU	1500 bytes
Number of VLC nodes	1–4
Source rate for each VLC flow	10 Mbps
Transport protocol for the VLC flows	TCP
Mobility model	Constant position
Number of background nodes	1–8
Source rate for each background node	800 kbps
Transport protocol for the background flows	UDP
Soft quality of services	CWmin, AIFS
Hard quality of services	CWmin=CWmax, AIFS

Downlink and Uplink throughput VLC/WiFi performance

We started from the same scenario that we considered in our simple experiment. More into detail, in this simulation, we deployed only one VLC connection and several WiFi connections in the background. We used the flow monitor function in NS-3 to monitor and compute the throughput of the hybrid VLC/RF TCP flow.

To assess the impact of the TCP ACK priority mechanism, figure 4.5 compares the downlink throughput performance of our reference VLC links coexisting and WiFi links with a varying number of background WiFi nodes without and with priority for the WiFi return-channel traffic generated by the VLC receiver. The throughput performance of the VLC link is slightly reduced when the network has one or two background nodes. However, the VLC throughput dramatically decreases when the background nodes increasing in the network in the standard case. The downlink throughput reduce approximately 45% with 8 nodes in the background in this case. In contrast, the downlink throughput of the TCP flow through the VLC link using the *EDCA-ACK* priority scheme remains stable. The downlink throughput for WiFi channel improve signification in hard QoS case.

The downlink throughput for VLC and WiFi for two, three and four VLC connection show in figure 4.6, 4.7, 4.8, respectively. We can see the consistent performance improvement for both soft QoS and hard QoS. Regarding WiFi performance, the hard QoS performs slightly better than the soft QoS and standard method.

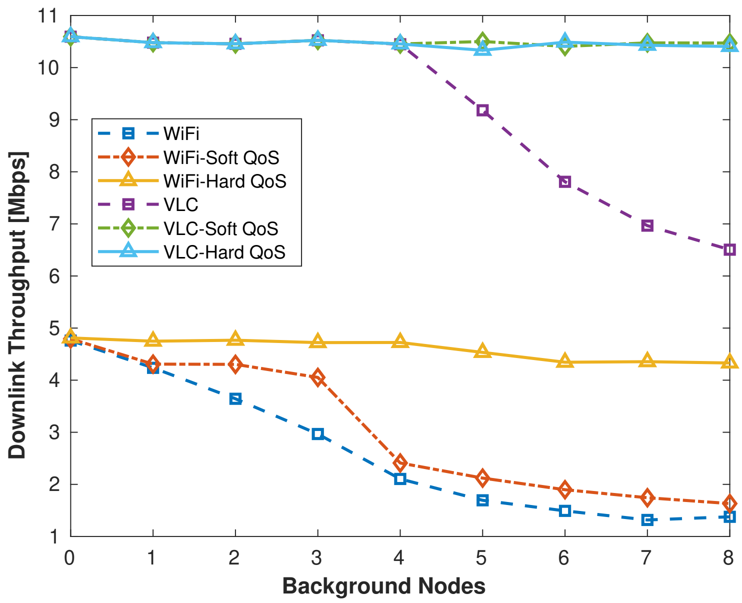

Figure 4.5: Comparison downlink throughput of a RF and VLC link with standard, soft QoS and hard QoS with N=1

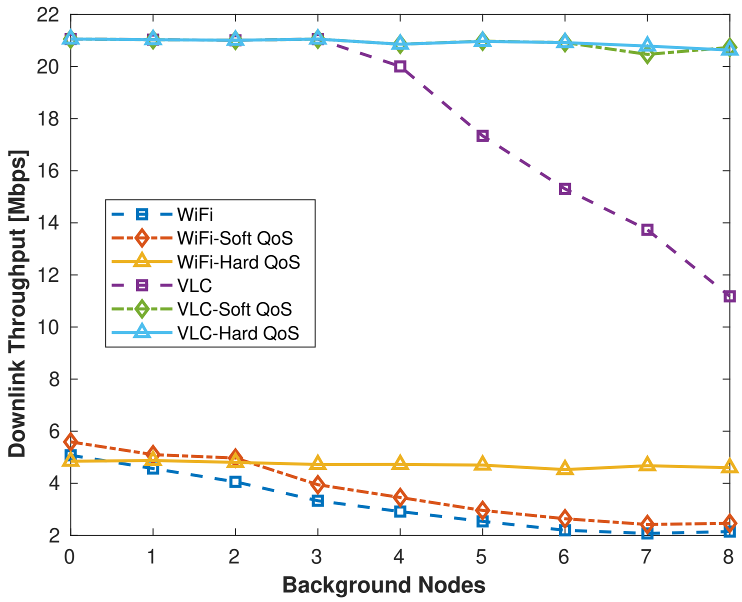

Figure 4.6: Comparison downlink throughput of a RF and VLC link with standard, soft QoS and hard QoS with N=2

In the second set of simulations, we evaluate the impact of the *EDCA-ACK* prioritization scheme when multiple VLC links are simultaneously active. In such a case, we consider a constant background WiFi traffic. Obviously, in this scenario the uplink traffic flows contend not only with the background WiFi traffic but also with the other priority flows generated by the coexisting VLC links. Priority *AC_VO* flows can be particularly sensitive to collisions in case of congestion generated by the same access category, because of the small contention window values used in contention. However, we want to remark that the rate of each uplink flow is a small percentage of the VLC link capacity (e.g. about 200 Kbps for a VLC link at 10 Mbps) and therefore the WiFi network can accommodate several coexisting VLC links before saturating.

In figure 4.9, the graph present the uplink throughput performance for VLC link and WiFi link. Both soft QoS and hard QoS show consistently better performance in the high number of background node in the network. The soft QoS show slightly better compare to hard QoS in this case, however, hard QoS still more effectively in WiFi channel.

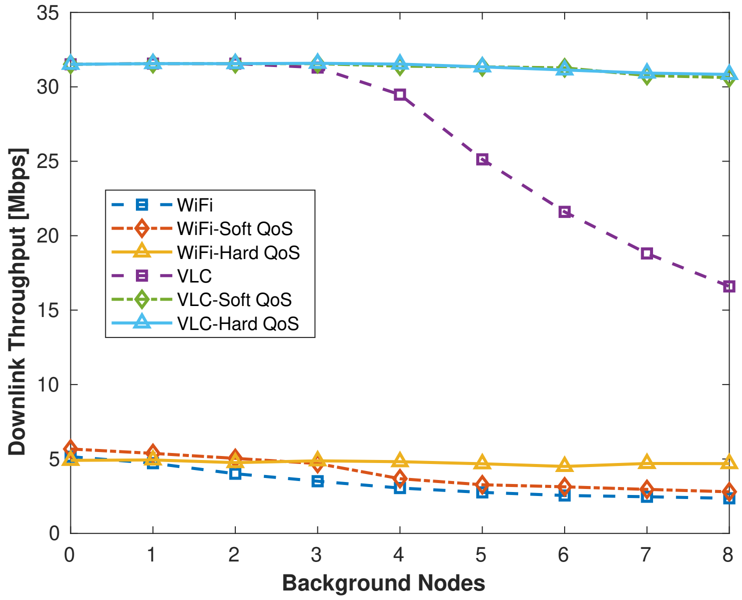

Figure 4.7: Comparison downlink throughput of a WiFi and VLC link with standard, soft QoS and hard QoS with N=3

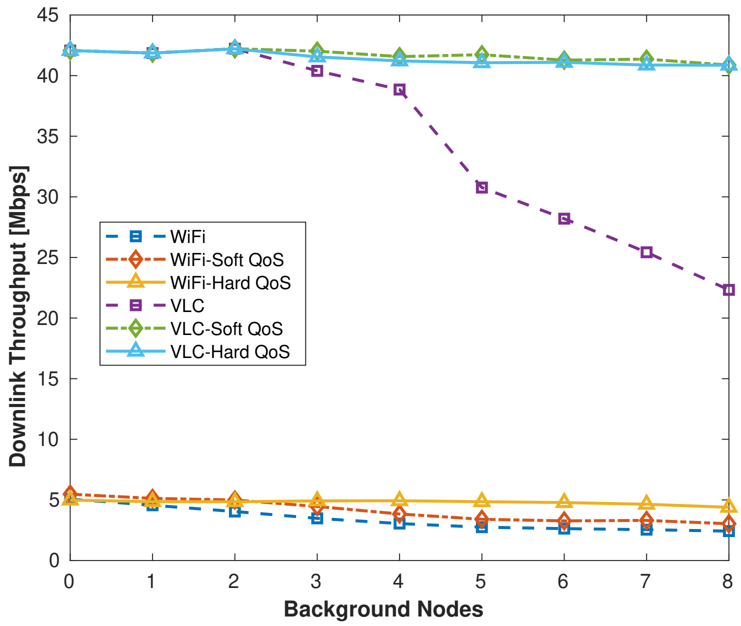

Figure 4.8: Comparison downlink throughput of a WiFi and VLC link with standard, soft QoS and hard QoS with N=4

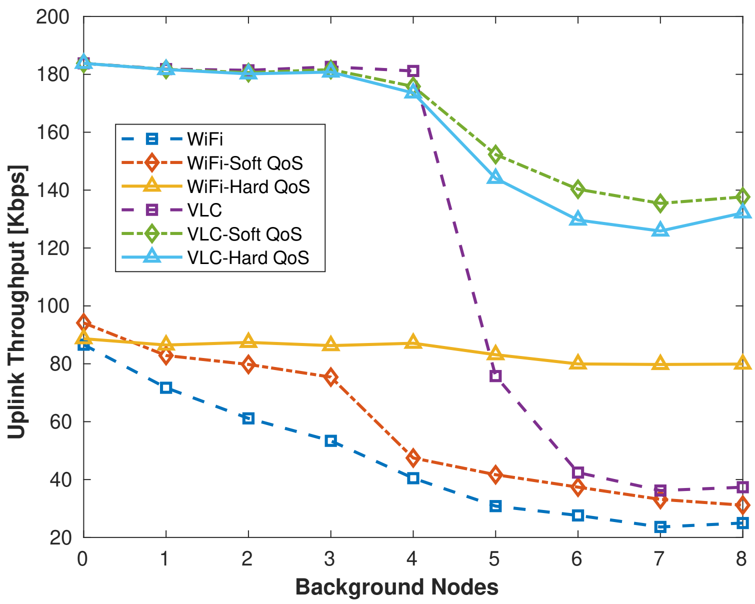

Figure 4.9: Comparison uplink throughput of a WiFi and VLC link with standard, soft QoS and hard QoS with N=1

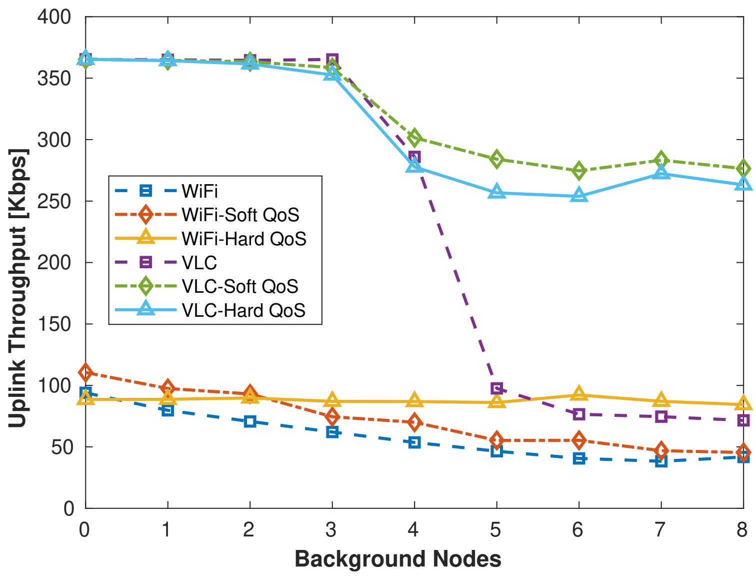

Figure 4.10: Comparison uplink throughput of a WiFi and VLC link with standard, soft QoS and hard QoS with N=2

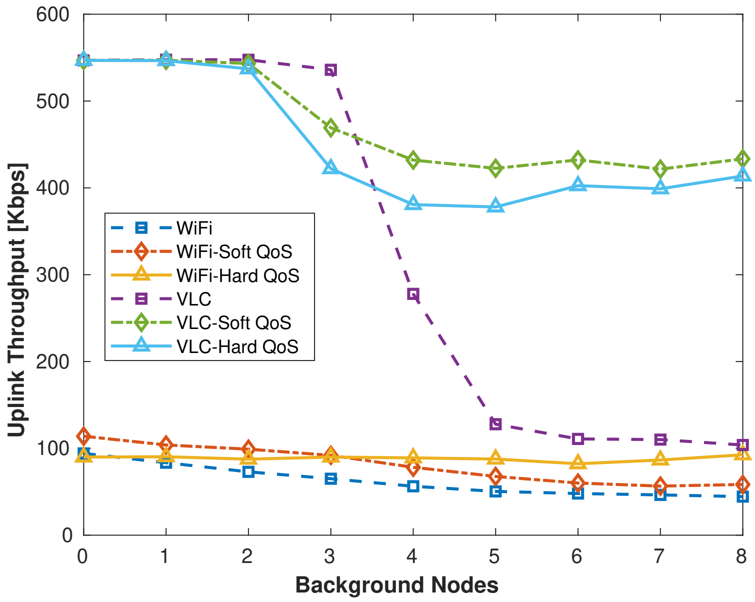

Figure 4.11: Comparison uplink throughput of a WiFi and VLC link with standard, soft QoS and hard QoS with N=3

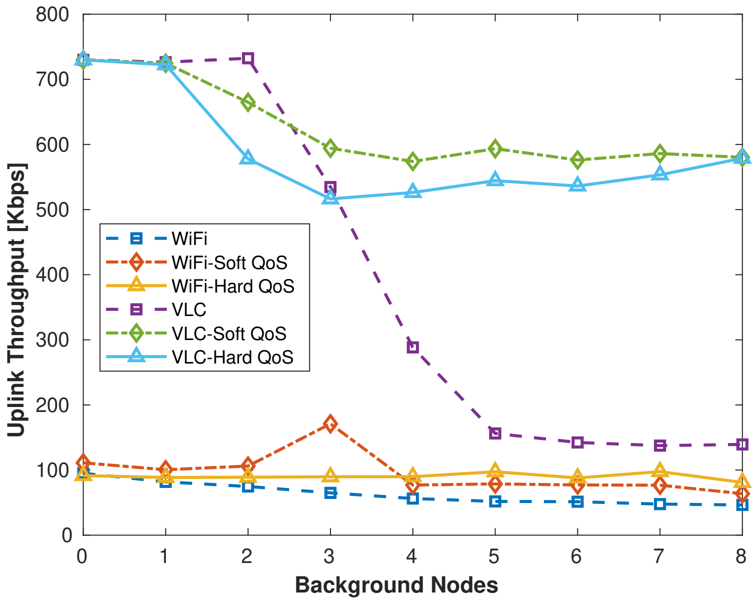

Figure 4.12: Comparison uplink throughput of a WiFi and VLC link with standard, soft QoS and hard QoS with N=4

Similar to downlink performance, the performance for VLC uplink significant better with *EDCA-ACK* than uplink performance with standard method in several background nodes, which show in figure 4.10, 4.11 and 4.12 . With soft QoS and hard QoS, the uplink channel for WiFi channel also perform better than WiFi link without *EDCA-ACK* support.

Mean delay in Uplink for WiFi and VLC connection

In our analysis, we focused on the mean delay performance metric for both WiFi and VLC connections, taking into account varying numbers of background nodes. This is illustrated in figures 4.13, 4.14, 4.15, and 4.16. As anticipated, the primary impact of the background traffic is an increase in access delay, which consequently leads to a longer measured Round-Trip Time (RTT) for the TCP flow. This effect becomes more pronounced as the number of background nodes increases. By employing the *EDCA-ACK* mechanism in our hybrid architecture, we were able to effectively mitigate this substantial time delay. In particular, our observations revealed that the access delay was reduced by an order of magnitude when using the *EDCA-ACK* scheme, as compared to the mean delay experienced in the default setup. Remarkably, both hard QoS and soft QoS demonstrated equivalent performance in this aspect, significantly outperforming the standard setup.

It is important to note that our simulations were conducted under various network conditions, which allowed us to validate the effectiveness of the *EDCA-ACK* mechanism across a range of scenarios. The results consistently indicated that the hybrid system's performance was substantially enhanced when utilizing the *EDCA-ACK* scheme. This improvement was observed not only in terms of reduced access delay but also in the overall reliability and stability of the network. Furthermore, the *EDCA-ACK* mechanism is standards-compliant, ensuring seamless integration with existing network protocols and devices.

In conclusion, our simulation results demonstrate that the *EDCA-ACK* mechanism provides a reliable, standards-compliant solution that significantly improves the performance of the hybrid WiFi and VLC system under various network conditions. This compatibility makes it an attractive solution for real-world implementation, as it can be readily adopted by network operators without the need for extensive

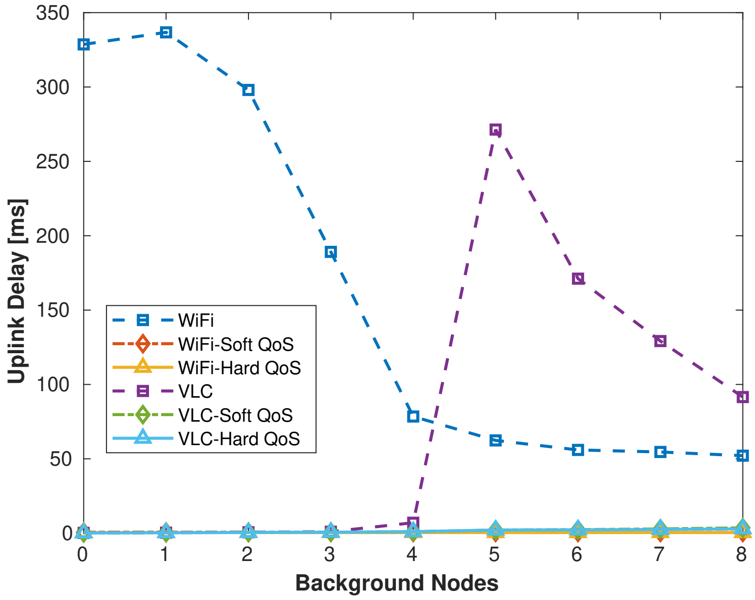

Figure 4.13: Mean delay between standard hybrid system and hybrid system with *EDCA-ACK* with N=1

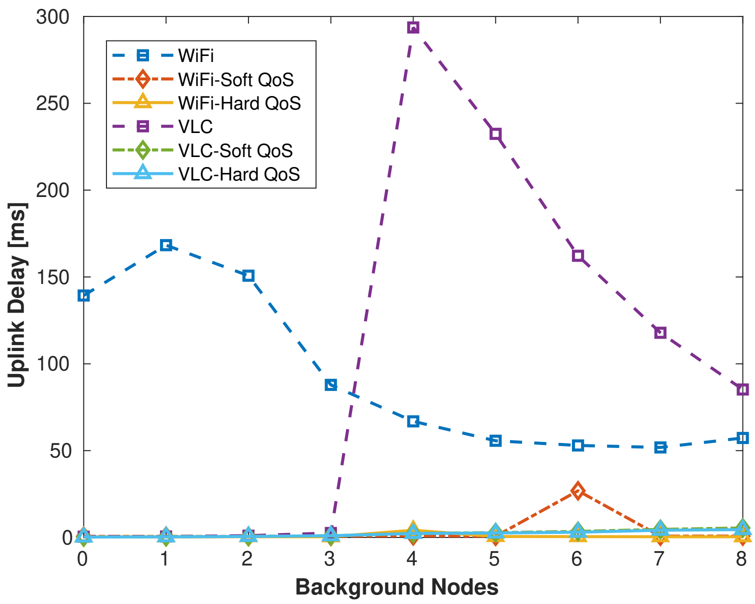

Figure 4.14: Mean delay between standard hybrid system and hybrid system with *EDCA-ACK* with N=2

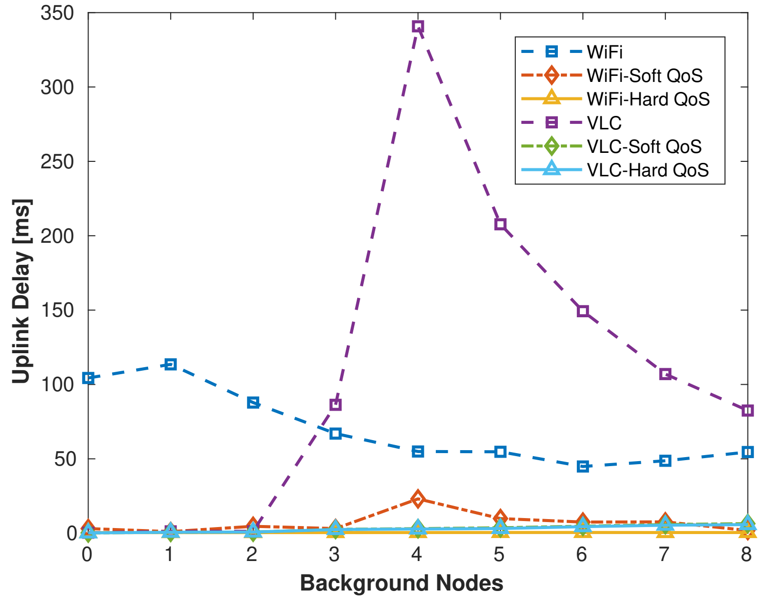

Figure 4.15: Mean delay between standard hybrid system and hybrid system with *EDCA-ACK* with N=3

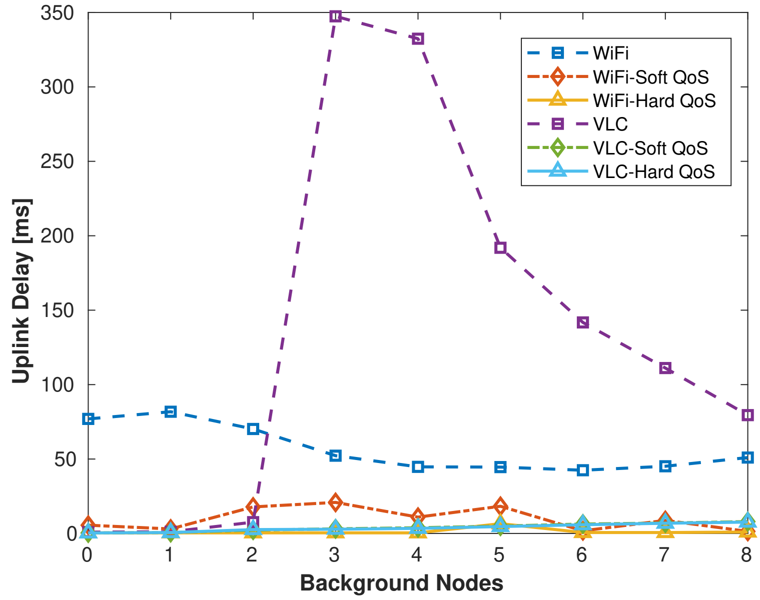

Figure 4.16: Mean delay between standard hybrid system and hybrid system with *EDCA-ACK* with N=4

modifications to their existing infrastructure. By reducing access delay and enhancing both hard and soft QoS, the *EDCA-ACK* scheme offers a promising approach to address the challenges faced by today's increasingly congested and demanding wireless networks.

4.3.3 Hybrid system with Uplink VLC

The reference scenario of our hybrid VLC/WiFi network is shown in Figure 4.17 for the VLC uplink case. For simplicity, we assume that VLC connections are isolated (i.e., no VLC nodes interfere with each other), unidirectional (i.e., from VLC transmitter to VLC receiver), and VLC receivers relay feedback via the WiFi interface. A single WiFi Access Point can cover the entire surroundings, even if there are other (single-interface) WiFi nodes.

Congestion impact on inter-technology performance

In our reference scenario, mobile nodes receive and transmit data by means of two different technologies, thus introducing some coupling effects between the performance of the coexisting VLC and WiFi networks. In particular, it is evident that WiFi transmissions performed by neighbor mobile nodes may interfere with each other, while VLC transmissions are orthogonal. Since most applications generate bidirectional traffic flows, even when the dominant flow is in one direction only (i.e. downlink or uplink), it is important to understand in which conditions the WiFi network can act as a bottleneck for the whole system. For example, consider the case in which mobile nodes are involved in a file download from the Internet, by using the TCP transport protocol. All the TCP acknowledgements generated by each VLC link contend in the same WiFi network. Therefore, the number of coexisting VLC links cannot be arbitrarily large, because the delays and losses of TCP acknowledgements will force VLC transmitters to reduce their transmission rate. Moreover, in presence of background WiFi traffic, the rate reduction due to TCP congestion control can occur even in presence of a single VLC link. Similar considerations can be done in the reverse direction, for uplink data transfers. Since mobile nodes transfer data using both WiFi and VLC technologies, coupling effects between the two coexisting networks might appear. In general, neighboring mobile

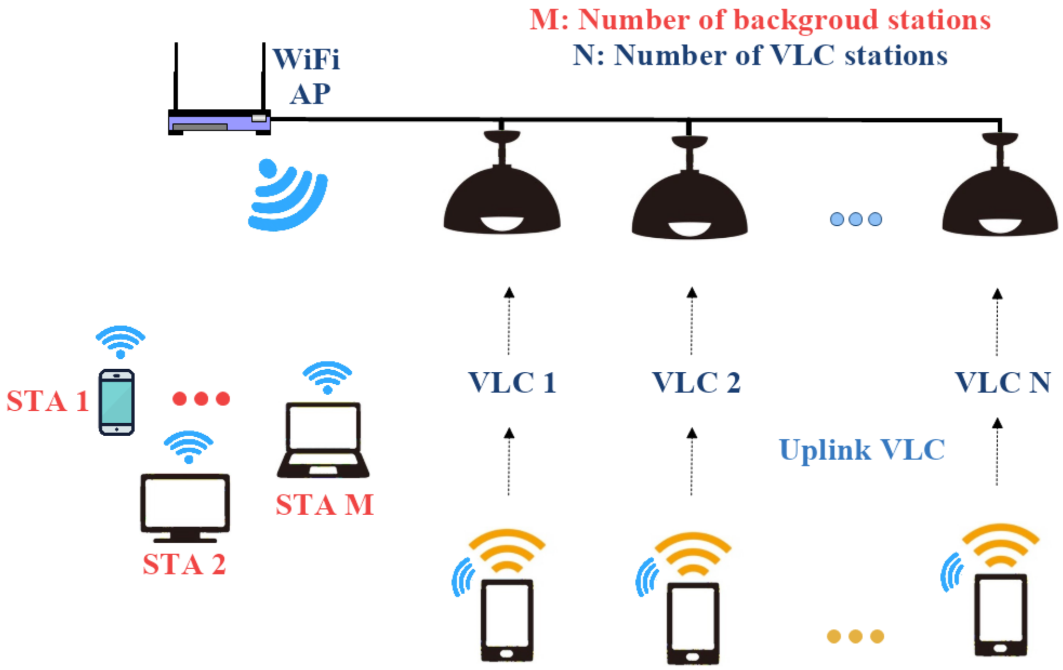

Figure 4.17: The reference scenario in hybrid VLC/WiFi network with uplink VLC data transfers.

WiFi node transmissions may collide, but VLC signals are orthogonal. Because most services have bidirectional flows, even if the majority of the data is transmitted in one direction only (i.e. downlink VLC or uplink VLC), it is vital to determine when the feedback WiFi links become a limitation for the performance of the VLC links.

For example, consider a scenario where mobile devices download data from the Internet with the TCP protocol. Each VLC link generates TCP acknowledgements that compete in the same WiFi network. As a result, the number of VLC connections cannot be exceedingly high, otherwise TCP ACK delays or losses on the feedback WiFi links might cause VLC transmitters to restrict their transmission rate. Furthermore, even in the presence of a single VLC link, rate degradation caused by TCP congestion control could still happen in presence of background WiFi traffic. Similar considerations can be done for uplink VLC data transfers.

Experimental results

We now present the results obtained both in the VLC download scenario and in the VLC upload scenario, in presence of several WiFi background streams in saturation. Considering a single VLC link and a source data rate of 10Mbps and a packet size of 1500 bytes, the reverse traffic flow caused by TCP ACKs is estimated to be 190 kbps at the maximum VLC download rate.

Download Scenario

In this scenario, we considered a network similar to [22]. Figure 4.18 shows the download throughput (solid lines) of a single VLC node when varying background WiFi nodes from 0 to 8, with or without WiFi contention priority for the uplink TCP ACKs. When the TCP ACKs are transmitted with AC_BE (blue line), few active WiFi background nodes provide significant throughput reduction. The figure also shows the ACK throughput (dashed lines, right y-axis scale), has a sudden reduction already with 2 background stations. This is due to the fact that the WiFi shared channel capacity is not enough for allocating a flow of 190 kbps. Indeed, with several TCP ACK colliding on the WiFi link, the transmission rate on the VLC link is decreased in response to the TCP congestion control.

Since the reference VLC link functions effectively up to M = 8 background nodes, different results are obtained when the AC_VI priority for the TCP ACKs is established (red dashed line). When M is within the range $[3, 8]$, with this access mode we can guarantee a rate of 140 kbps for TCP ACK transmission. It should be noted that TCP ACKs can be supported in a single TXOP with the default AC_VI value of 15. Thus, the improvement in VLC performance is due both to the increased channel utilization and the channel access priority together.

Figure 4.19 shows the results in a similar scenario with $N = 4$ VLC/WiFi nodes, and a variable number of background STAs. Although multiple TCP ACK flows are contending at the same time in this scenario, the behavior is similar to the previous case. Although the ACK flows use a small contention window (priority AC_VI is especially vulnerable to collisions in the same access category), the WiFi network still supports multiple coexisting VLC feedback flows before becoming saturated. This is due to the fact that the TCP ACK flow rate is low (note that for $M = 0$ the

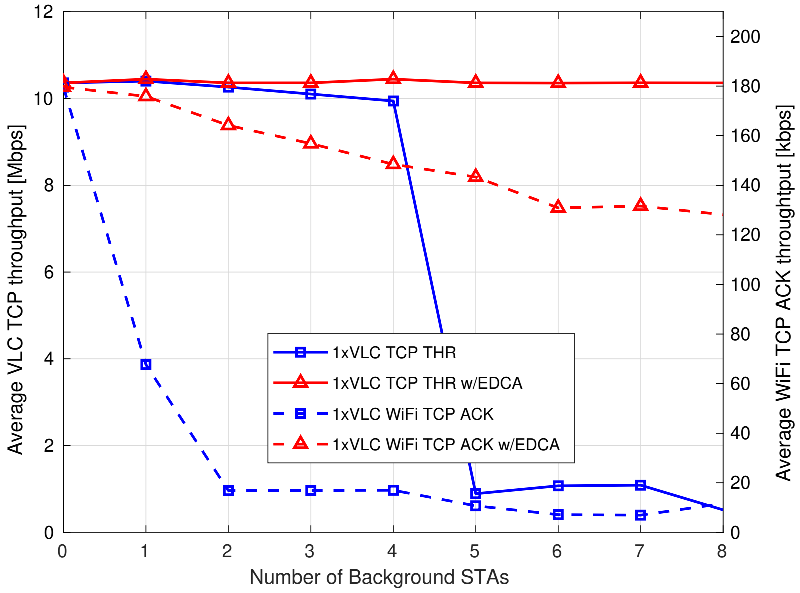

Figure 4.18: Comparison of VLC downlink (solid)/WiFi uplink (dashed) throughput, for N=1 Hybrid VLC/WiFi station

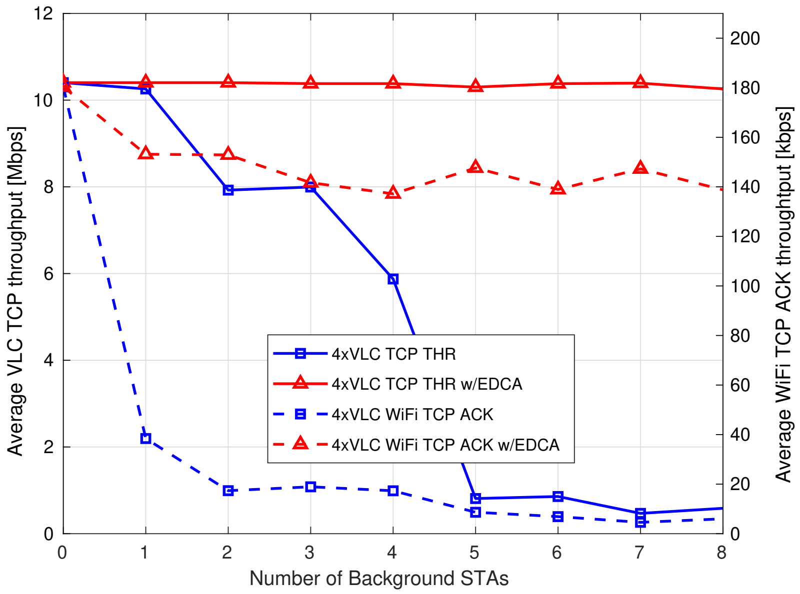

Figure 4.19: Comparison of VLC downlink (solid)/WiFi uplink (dashed) throughput, for N=4 Hybrid VLC/WiFi stations

reference VLC link operates at the maximum rate despite the absence of *EDCA-ACK* priority). While using prioritization throughput reduction is only 20% for the worst congested case $M = 8$, the degradation is more dramatic when TCP ACKs are transmitted without EDCA.

The behavior in this scenario is similar to the previous one, although in such a case multiple TCP ACK flows are contending simultaneously. Indeed, priority *AC_VI* is particularly sensitive to collisions in the same access category, because of the small contention window adopted. Nevertheless, since the rate of the TCP ACK flows is small, the WiFi network can accommodate several coexisting VLC links before saturating (note that, for $M = 0$ the reference VLC link work at the maximum rate even without using *EDCA-ACK* priority). When the number of background node increases, the throughput degradation is more relevant when TCP ACKs are transmitted without EDCA, while the usage of prioritization leads to a throughput reduction of only 20% for the worst congested case $M = 8$.

Figure 4.20 shows average delay measurements for TCP ACK transmissions with and without priority for single VLC (solid lines) and N=4 VLC links (dashed lines). We can observe that the delay is significantly reduced with priority compared to TCP ACKs transmitted with best effort access category. Indeed, prioritization mechanism allows to reduce delays by one order of magnitude compared to the ones transmitted with *AC_BE* (red curves vs. blue curves).

Finally, the WiFi background nodes' throughput is displayed in Figure 4.21, in both the scenarios of a single VLC link (solid line) and four VLC links (dashed lines). As expected, when the VLC links use a prioritization mechanism (red curves), the throughput reduction for WiFi background nodes is more noticeable, especially when multiple priority flows are active (dashed red curve).

Finally, figure 4.21 shows the throughput achieved by the WiFi background nodes, in both the scenarios of a single VLC link (solid line) and four VLC links (dashed lines). As expected, the throughput reduction for WiFi background nodes is more evident in case the VLC links employ a prioritization mechanism (red curves), especially when multiple priority flows are active (dashed red curve).

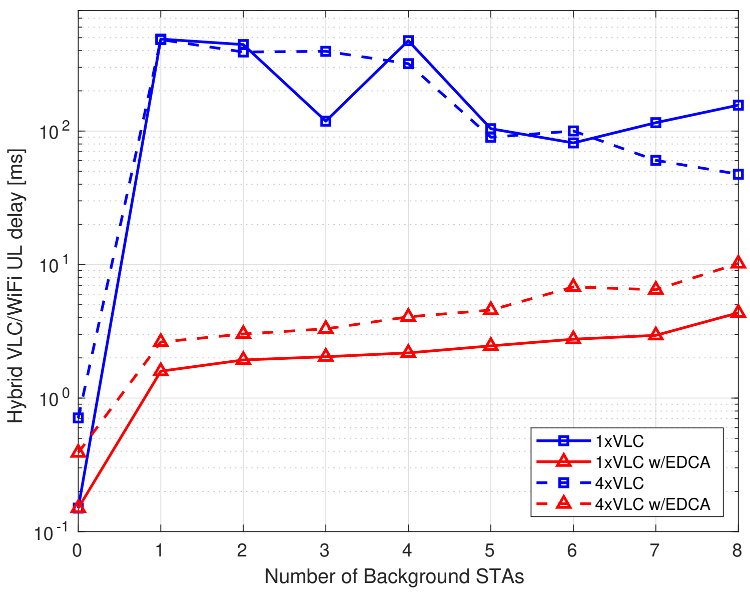

Figure 4.20: Comparison of VLC downlink (solid)/WiFi uplink (dashed) throughput, for N=1 Hybrid VLC/WiFi station

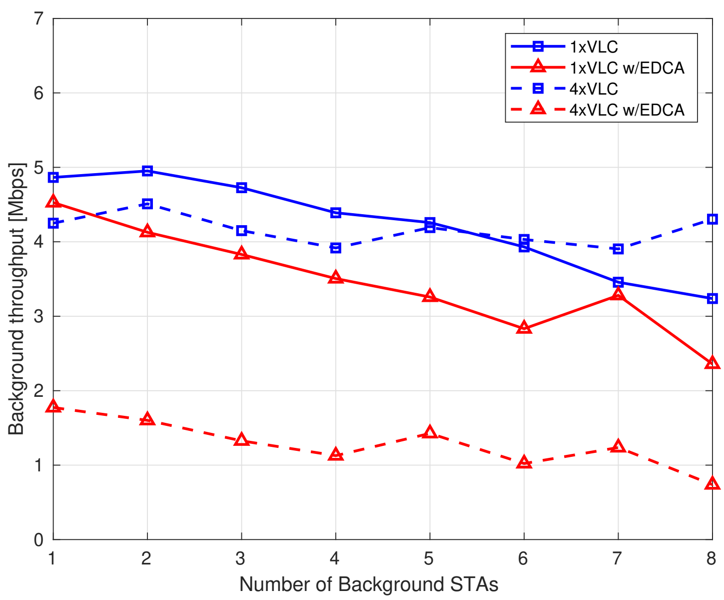

Figure 4.21: Comparison of VLC downlink (solid)/WiFi uplink (dashed) throughput, for N=4 Hybrid VLC/WiFi stations

Upload Scenario

We performed upload simulations by exchanging the direction of the flows, in the scenario depicted in Figure 4.17. In 4.22 and 4.23, we analyze VLC upload traffic (with TCP ACKs traffic flowing on the WiFi downlink) for a number of VLC nodes equal to N=1 and N=4, respectively. In figure 4.22, solid blue lines shows the uplink VLC data throughput which is comparable and close to the maximum application data rate, even in case of severe background traffic. This means that the number of received TCP ACKs is still enough to avoid timeouts (e.g. thanks to Selective acknowledgements) accommodating for lost ACK segments. Instead, dashed lines show that without TCP ACK priority the throughput of the ACK flows quickly drops under 30Kbps, while priority allows a throughput close to 120 kbps even with 8 background nodes.

Figure 4.23 shows a different performance behavior in case of N=4 VLC nodes. In this case, uplink traffic on VLC link is stable when priority is enabled, while in case of legacy WiFi for the TCP ACK flows, throughput becomes less than 3 Mbps already with a single background node. Indeed, without priority the ACK throughput on the WiFi link becomes unstable, causing TCP timeouts. Regarding the delay of the ACKs and the performance of the background nodes, similar results have been obtained as in the previous download scenario and are omitted for brevity.

In conclusion, our simulation results demonstrate that *EDCA-ACK* offers a promising, standards-compliant way to enhance the performance of hybrid VLC/WiFi systems. Summarizing, our simulation results show that *EDCA-ACK* provides a standards compliant, reliable system, which improves the performance of the hybrid VLC/WiFi system we simulated. In order to better support our results, we added the EDCA AC_VI priority class on the WiFi device used for the VLC return channel in the OpenVLC experiment reported in Fig.4.2. (but with a transmission opportunity value set to zero). The measured throughput is presented by the red line in the figure, which shows how the system throughput exhibits a significant improvement.

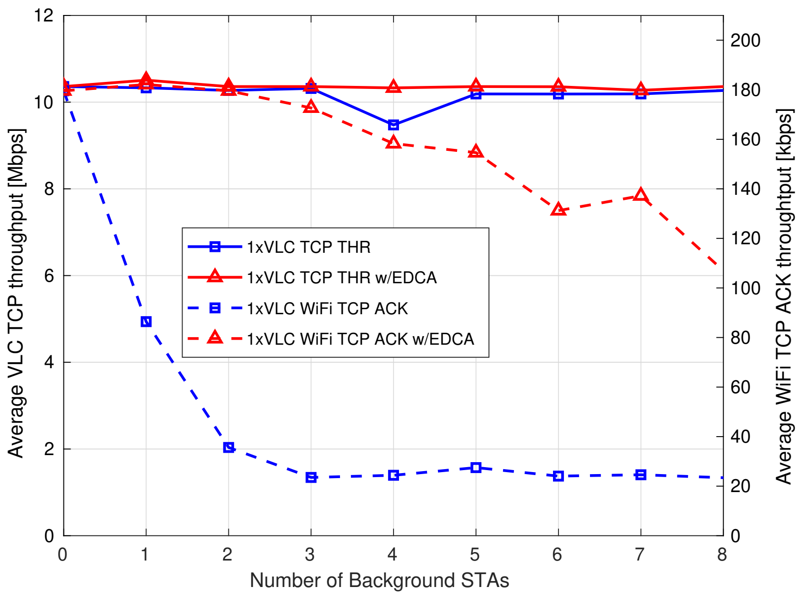

Figure 4.22: Comparison of VLC Uplink (solid)/WiFi Downlink (dashed) throughput, for N=1 Hybrid VLC/WiFi stations

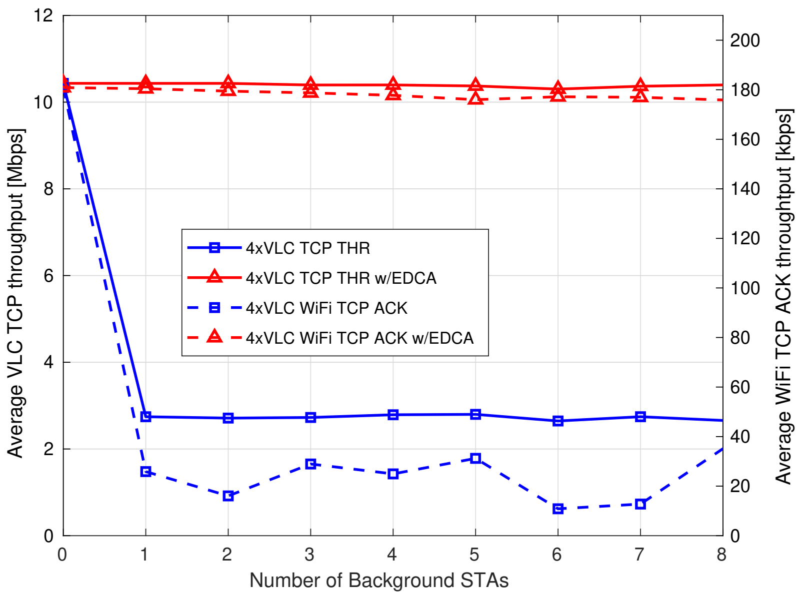

Figure 4.23: Comparison of VLC Uplink (solid)/WiFi Downlink (dashed) throughput, for N=4 Hybrid VLC/WiFi stations

4.4 Conclusion

In this chapter, we have evaluated how a hybrid VLC/WiFi communication system can be impaired by the wireless channel congestion conditions, and proposed a simple standards-compliant method to enhance the performance of transport flows by giving priority to the return channel control information sent on the shared wireless channel. In order to deploy this mechanism, an intelligent control unit system is required for coordinating the update of the routing tables and dynamically adjusting the EDCA parameters of the wireless stations. The hybrid architecture is designed with a simplex VLC downlink and bi-directional WiFi connection. The VLC links have experienced a massive delay and throughput degradation with some traffic nodes in the WiFi uplink. We have shown, through simulations and a simple experiment, that our method provides a significant improvement for the throughput of TCP flows transported through the hybrid heterogeneous network architecture. In this chapter, we studied WiFi priority mechanisms to improve hybrid VLC/WiFi networks. We considered a scenario in which the WiFi network is congested, causing significant delay and jitter to the feedback channel used for TCP ACKs, with a reduction in the overall network performance. We analyzed different options at the WiFi MAC level to improve the VLC/WiFi nodes. While it is not possible to assign fixed portions of WiFi channels for VLC feedback, aggregation of TCP packets in a single WiFi frame (or TXOP) could improve spectrum use significantly. Moreover, MAC priority based on EDCA parameters can be exploited to prioritize the TCP ACKs of the hybrid VLC/WiFi nodes and therefore increase the performance of the VLC links. In this direction, we quantified the gain achieved by the VLC segment with or without ACK priority on the WiFi link, both in download and upload scenarios, using the NS-3 simulator and demonstrating the effectiveness of the proposed solutions.

Chapter 5

Intelligent Management System in testbed scenario

In today's rapidly evolving technological landscape, intelligent management systems have become increasingly vital in optimizing the performance, reliability, and energy efficiency of hybrid VLC and RF networks. This introduction aims to provide a comprehensive overview of IMS for the cutting-edge hybrid system, delving into their respective advantages and limitations, as well as exploring the challenges and opportunities associated with integrating them into a robust and efficient hybrid network.

The integration of VLC and RF technologies into a seamless and efficient hybrid network presents its own set of unique challenges. To address these challenges, intelligent management systems have emerged as a key component in ensuring smooth operation and seamless communication within such networks. These systems are responsible for managing resources, optimizing network performance, and enhancing overall user experience by intelligently allocating and load balancing between VLC and WiFi connections.

We will not only discuss the importance of intelligent management systems in the context of hybrid VLC and WiFi networks but also explore the different implementations of various techniques and approaches employed to achieve optimal network performance. By examining the role of machine learning, and other advanced algorithms in the design and implementation of these systems, we will highlight the critical role that intelligent management systems play in shaping the future of wireless communication and the potential benefits that can be derived from the successful integration of VLC and WiFi technologies.

5.1 Related Work

In a hybrid network, horizontal and vertical handovers are the two main types of handovers. Horizontal handover (HHO) occurs within the domain of a single technology, while vertical handover (VHO) occurs between different wireless access technologies. During a VHO, the air interface is modified while keeping the destination's path constant. There are mainly three types of research related to handovers in a hybrid network: i) HHO in VLC, which focuses on improving performance within the VLC domain; ii) VHO between VLC and WiFi, which aims to optimize handovers between these two wireless access technologies; and iii) studies that work on both VHO and HHO, providing a more comprehensive approach to addressing handover challenges in hybrid networks. The most recent literature review concerning handover processes in hybrid VLC and RF systems is presented in Table 5.1.

Table 5.1: Summary of the Handover Approaches

Ref	Outcome	Remark
[69]	Considered mobility in VLC and HO based on RSSI in both overlap and non-overlap coverage	Simulation, HHO
[70]	A novel handover skipping scheme based on reference signal received power (RSRP) and their changed rate to determine the handover target.	Simulation, HHO
[71]	Proposed HO considers a handover skipping scheme and aims to tackle the negative impact of the handover rate	Simulation, HHO
[72]	Handover based on RSSI and studied handover probability based on a Markov chain model.	Simulation, VHO

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Ref	Outcome	Remark
[73]	A Markov decision process adopts a dynamic approach to obtain a trade-off between the switching cost and the delay features.	Simulation, VHO
[74]	Fuzzy logic (FL) algorithm with dynamic handover scheme for dynamic HO. Channel state information, user speed and desired data rate are considered.	Simulation, VHO and HHO
[75]	Adopts a dynamic coefficient via machine learning. Adaptive handover mechanism and selection algorithm optimization are the main focus.	Simulation, VHO and HHO
[76]	HO is based on link aggregation and MPTCP tools. The main focus is lower handover outage duration and a high network throughput.	Experiments, VHO and HHO

Handover metrics are critical in determining when, where, and how to perform handovers in a hybrid network. To ensure seamless user connectivity, various quality of service elements that impact handover must be considered. For example, factors like RSSI, CSI, network load, handover delay/latency, user preferences, and so are all essential considerations. The duration of handovers can also vary depending on the type of handover. However, minimizing handover time is crucial to prevent disruption to user services, and therefore, choosing between HHO and VHO is vital for the hybrid system. Overall, effective handover mechanisms should consider multiple factors, including QoS elements, handover duration, and user preferences. In this chapter, we have presented the most recent handover mechanisms for hybrid systems. However, it is worth noting that previous studies on HHO or VHO are also relevant to our work and can be found in reference [77]. Many of them lack implementation, which is crucial for verifying their effectiveness in a testbed environment. To address this gap, we have developed and implemented our handover mechanism in an open platform. By doing so, we can verify the effectiveness of our proposed handover mechanism in a real-world setting and ensure that it provides superior performance compared to existing solutions.

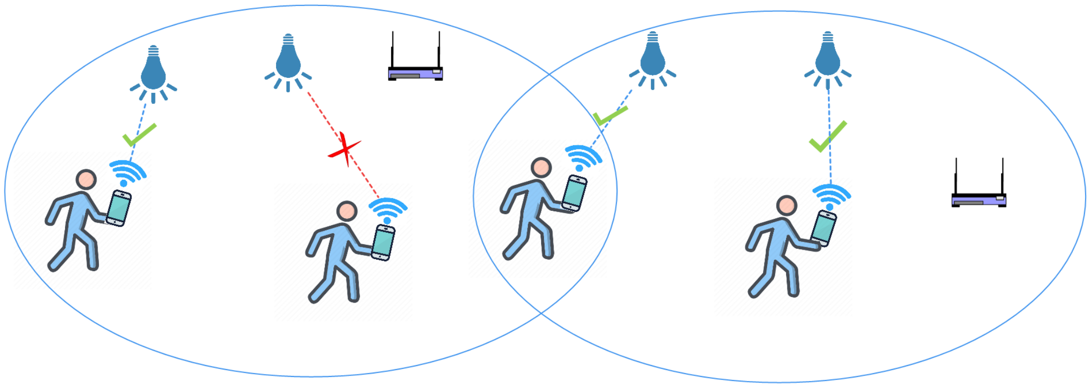

Figure 5.1: Simple scenario of handover.

5.2 Handover

Handover phases

In a mobile network, handover takes place when the user is transferred from one access point to another AP without experiencing loss of connectivity similar to Figure 5.1. Achieving a reduced network outage duration during handover in an indoor industrial environment network and identify localization are essential and very critical, especially in indoor scenarios such as industrial and logistic plants with different types of robots or devices moving around. The hybrid VLC/WiFi network with smooth handover it is essential to adopt techniques to achieve the minimum handover outage duration. In VLC/WiFi network, horizontal handover is carried out within the VLC network, and it is associated with the next available LAP in the same network in an industrial environment. However, there are some cases where the delay is longer than expected and may require vertical handover with better coverage technology like WiFi. Therefore, the high demand for a complementary alternative hybrid wireless technology solution.

Types of handovers

The handover process involves moving an active wireless communication from one AP that is currently serving users to another AP. A handover request is made when a user device leaves the range of coverage of a neighboring AP. If the present cell is fully loaded or the transmission channel becomes unusable due to interference, another handover will be required. There are two types of handover: vertical and horizontal. When mobile equipment is moved from one AP to another inside the same network, it is said to be in a horizontal handover situation. Vertical handover, however, happens when a mobile device is moved from one AP to another that has a different access technology (e.g from WiFi to VLC or VLC to LTE).

Because users walk about constantly or randomly, LiFi and WiFi channel status information in real life is time-varying. A user will switch to a VLC network if they are currently connected to a WiFi network and they notice a better VLC signal. Users in a hybrid VLC/WiFi network will consequently encounter continuous handovers based on user movement and strong signal recognized by the user. In a hybrid system, a dynamic load-balancing strategy with the handover was presented. Hard and soft handovers are the two fundamental types of handover. The user equipment (UE) is essentially unplugged from its serving AP before it is linked to the new AP in a hard handover scenario. Although it is simple to build and less complex, the user still experiences service disruption. When a handover is soft, the UE stays connected to the AP that is currently serving it until it connects to the new AP. Better user experiences are achieved through this approach, but more wireless transmission resources are required. Making decisions during the handover process is essential. It aids in both improving network use and satisfying the needs of users. The handover decision involves several different factors.

Handover metrics aid in determining when, where, and how to perform handovers, among other things. To maintain user connectivity, many QoS elements that impact vertical handover are considered. In order to enable vertical handover factors, like received signal strength indicator (RSSI), network load, financial service cost, handover delay/latency, user preferences, number of unnecessary handovers, handover failure probability, security control throughput, Bit error rate (BER), and Signal to Noise Ratio (SNR), should be taken into account.

Figure 5.2 show the three main type of handover in the hybrid system: HHO, VHO and Selection HHO/VHO and their sub-categories in each type. Due to the change of air interfaces, a VHO usually needs a much longer processing time than a HHO. Also, the WiFi system has a lower system capacity than VLC, and an excessive number of WiFi users would cause a substantial decrease in throughput. Thus, the

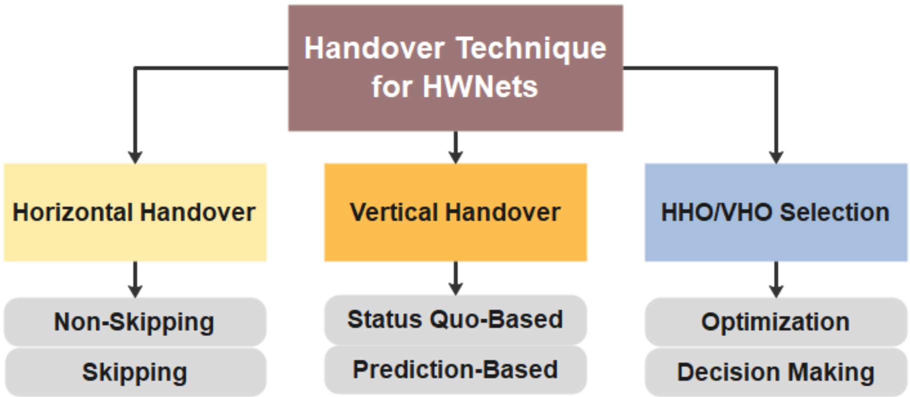

Figure 5.2: Handover Type.

choice between HHO and VHO is critical to the hybrid network. Specifically, not all of the users that lose VLC connectivity should be switched to WiFi, e.g., the users encountering a transient light-path blockage. Apart from that, the user's velocity is also an important factor in deciding whether a user should be served by VLC or WiFi. In general, fast-moving users prefer WiFi, since they would experience frequent HHOs in VLC. To solve the complicated problem of choosing between HHO and VHO, we proposed a handover scheme based on fuzzy logic. This method makes handover decisions by measuring parameters including not only CSI but also the user's speed and data rate requirement.

Handovers can be distinguished into horizontal handovers and vertical handoffs according to the access technologies involved in. On the one hand, horizontal handovers occur within a single type of network interface that involves only one wireless access technology. In a cellular network, there are two types of horizontal handovers: intra-cell handovers and inter-cell handovers. Intracell handovers only change radio channels within a cell in order to minimize the inter-channel interference. Inter-cell handovers change all the connections from the source BS to the target BS when the MS moves between two adjacent cells. On the other hand, vertical handoffs change the connection between a variety of different network interfaces which typically have different wireless access technologies, such as 3GPP (3rd Generation Partnership Project), 802.11, and 802.16, etc. Handover management is a critical aspect of developing solutions and supporting mobility scenarios. It is the process by which the user maintains its active connection while moving from one point of attachment to another. This section describes the handover process features and provides the handover decision problem in a heterogeneous network.

Many works describe the handover process in three phases. Firstly, handover information gathering refers to the process of collecting all the essential information needed to identify when a handover is necessary and to initiate it if required. This phase is also known as the handover initiation or system discovery phase. By gathering critical information, such as signal strength and available bandwidth, this phase helps determine when a handover is necessary and triggers the subsequent steps in the handover process. Secondly, the handover decision phase is responsible for determining whether and how a handover should be performed. This involves selecting the most appropriate access network based on specific criteria, such as user preferences, and providing instructions for the execution phase. Also known as network or system selection, this phase is crucial in ensuring a seamless and efficient handover process. By making informed decisions about which network to connect to next, the handover process can help maximize network performance while minimizing disruptions to the user experience. Thirdly, the handover execution phase involves changing channels in accordance with the details determined during the decision-making phase. Once the appropriate access network has been selected, this phase takes action to execute the handover, ensuring that the user's connection is smoothly transferred from one base station or access router to another. By performing the handover promptly and effectively, this phase helps maintain continuous connectivity for users as they move across different attachment points.

5.3 Handover management in hybrid system

Handover management is the key aspect in the development of solutions supporting mobility scenarios. It is the process by which MT maintains its active connection while moving from one point of attachment (base station or access router) to another. In this section, we describe the handover process features and we provide the motivation for analyzing the vertical handover decision problem in a heterogeneous environment. Fig shows the handover management concept features: mobility scenarios, handover process, types, control, and performance. The highlighted grey box represents the features closely related to the handover decision issue.

Many works describe the handover process in three phases:

- Handover Information Gathering: used to collect all the information required to identify the need for handover and can subsequently initiate it. It can be called also handover initiation phase or system discovery.
- Handover Decision: used to determine whether and how to perform the handover by selecting the most suitable access network (taking into account some criteria such as user preferences) and by giving instructions to the execution phase. It is also called network or system selection.
- Handover Execution: used to change channels conforming to the details resolved during the decision phase.

5.3.1 Handover decision criteria

Handover criteria play a crucial role in determining the need for a handover in hybrid VLC and WiFi networks. These criteria can be broadly categorized into network-related and terminal-related factors, which help in maintaining seamless communication and optimal resource allocation in hybrid networks.

Network-related criteria include factors such as coverage, bandwidth, latency, and link quality. Link quality can be further assessed using metrics like (RSS (Received Signal Strength), CIR (Carrier to Interferences Ratio), SIR (Signal to Interferences Ratio), BER, etc.). Other network-related factors to consider are monetary cost and security level. Terminal-related criteria, on the other hand, are associated

Figure 5.3: Different handover criteria.

with the user's device and its characteristics. These factors include the device's velocity, battery power, and location information. These terminal-related criteria are essential in ensuring a smooth user experience and minimizing disruptions during handovers.

Figure 5.3 illustrates six main criteria that are typically considered when evaluating the handover cost. These criteria can be adapted and utilized depending on the specific system and various scenarios. The three primary criteria among these are channel quality, network performance, and resources availability. Intelligent management systems, incorporating artificial intelligence and machine learning algorithms, can effectively analyze these handover criteria to facilitate seamless communication and efficient resource allocation in hybrid VLC and WiFi networks. By considering both network-related and terminal-related factors, these systems can optimize the overall performance, reliability, and energy efficiency of the integrated networks, thereby shaping the future of wireless communication and unlocking the potential benefits of VLC and WiFi technology integration.

User-related: user profile and preferences. Service-related: service capabilities, QoS, etc. These criteria can be classified into static and dynamic depending on the frequency and causes of changes. Typically static criteria are user profile and the cost of the different access networks, whereas the MT's velocity and RSS are typically dynamic criteria

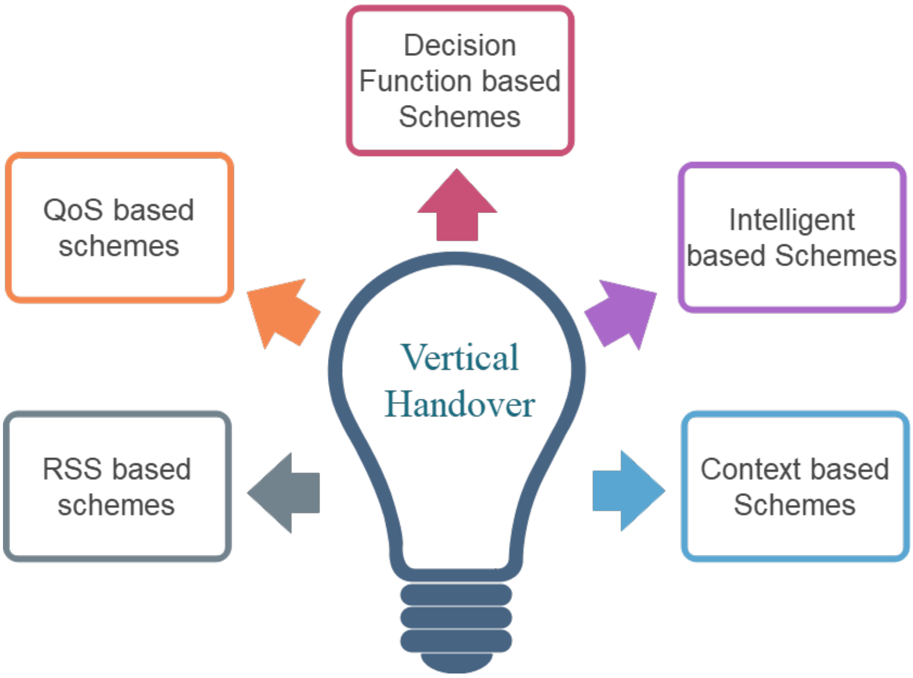

Figure 5.4: Key decision-making criteria for VHO in hybrid networks.

In Figure 5.4, we delve deeper into the key decision-making process for vertical handover in hybrid networks. Five criteria are taken into account when determining the optimal handover strategy: RSS, QoS, decision-making function, intelligence, and context. The Received Signal Strength criterion evaluates the signal strength of each available network and plays a crucial role in maintaining seamless communication. A higher RSS value indicates a stronger connection, which can lead to better overall network performance.

The QoS criterion encompasses various network performance metrics, such as bandwidth, latency, and link quality. Ensuring optimal QoS is essential for maintaining a satisfactory user experience, especially for applications with strict performance requirements, like video streaming or online gaming. The decision-making function is a mathematical model that takes into account multiple factors to determine the most suitable network for handover. By considering network-related and terminal-related factors, the decision-making function helps optimize resource allocation and maintain seamless connectivity.

Intelligence refers to the use of artificial intelligence and machine learning algorithms in the handover process. These algorithms can effectively analyze various criteria to optimize performance, reliability, and energy efficiency in hybrid networks. By leveraging AI and ML, the handover process can be more adaptive and responsive to changing network conditions. Finally, the context criterion considers the user's location, velocity, and other environmental factors that may affect the handover decision. By taking these factors into account, the handover process can be tailored to better suit the user's specific needs and preferences.

In conclusion, these five criteria play a critical role in the decision-making process for VHO in hybrid networks. By effectively analyzing and utilizing these criteria, the potential benefits of integrating VLC and WiFi technology can be fully realized, shaping the future of wireless communication.

5.3.2 Handover decision policy

To improve the efficiency of handover decisions in hybrid networks integrating VLC and WiFi technology, additional criteria can be incorporated into the handover decision policy. These extended policies take into account QoS, decision-making functions, intelligence, and context-awareness.

- QoS-based Policy: considering multiple network performance metrics such as delay, throughput, and packet loss rate. The new BS is chosen if it provides better overall QoS.
- Decision-making Function-based Policy: using mathematical models such as utility functions, fuzzy logic, and game theory to optimize resource allocation

and connectivity. The new BS is chosen based on the output of the decision-making function.

- Intelligent Handover Policy: employing AI and ML algorithms to analyze historical data and learn from previous handovers. The new BS is chosen based on the predictions and recommendations provided by the intelligent algorithm.
- Context-aware Policy: taking into account user location, velocity, and environmental factors such as signal interference and obstacles. The new BS is chosen based on the context-specific requirements and conditions.

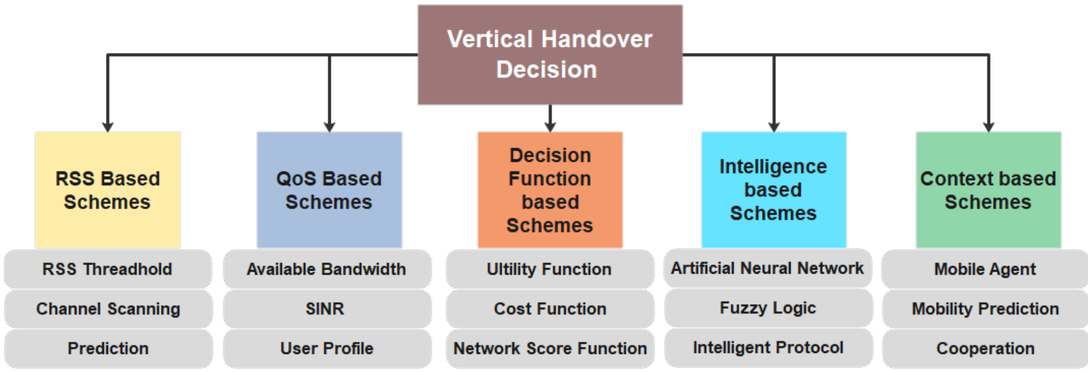

Figure 5.5: Vertical Handover Decision policies.

Handover decision rules can be classified based on threshold and hysteresis values. In every policy, a crucial factor plays a significant role in influencing the decision-making process. Figure 5.5 illustrates the key factors contributing to handover decisions across various schemes. Traditional handover decision policies depend primarily on RSSI values. And the rule can be explain like this:

- **RSSI Value Rule:** Transition to the new base station (BS) if $\text{RSSI}_{\text{new}} > \text{RSSI}_{\text{old}}$.
- **RSSI with Threshold T Rule:** Select the new BS if $\text{RSSI}_{\text{new}} > \text{RSSI}_{\text{old}}$ and $\text{RSSI}_{\text{old}} < T$.
- **RSSI with Hysteresis H Rule:** Choose the new BS if $\text{RSSI}_{\text{new}} > \text{RSSI}_{\text{old}} + H$.

- **RSSI Hysteresis and Threshold Rule:** Opt for the new BS if $\text{RSSI}_{\text{new}} > \text{RSSI}_{\text{old}} + H$ and $\text{RSSI}_{\text{old}} < T$.

5.3.3 The challenge for handover management

The discussion revolves around the challenges in handover management for hybrid VLC and WiFi systems. The integration of these two technologies presents numerous obstacles that must be addressed to ensure seamless connectivity, mobility, and user experience in hybrid networks.

One of the primary challenges is the heterogeneity of network technologies. VLC and WiFi operate on different frequency bands and have distinct physical layer characteristics, which can complicate the handover process. Moreover, the performance of these networks can be influenced by various factors, such as the presence of obstacles, interference, and signal quality. As a result, handover management algorithms must be capable of adapting to the dynamic changes in network conditions to maintain seamless connectivity.

User mobility is another significant challenge, as it can lead to frequent handovers between VLC and WiFi networks. This can result in increased energy consumption, latency, and degradation of QoS. Handover management algorithms need to consider user mobility patterns and make intelligent decisions to minimize the impact on energy consumption and QoS. This may involve predicting user movement and selecting the most appropriate network based on factors such as signal strength, network load, and user preferences.

Scalability is also an essential aspect to consider in hybrid VLC and WiFi networks. As the number of users and devices increases, handover management algorithms must be capable of handling the increased complexity and ensuring efficient resource allocation. This requires the development of scalable algorithms that can adapt to the evolving network conditions and user demands.

Security and privacy concerns are another critical aspect of handover management in hybrid networks. Transferring data between VLC and WiFi networks can expose users to potential security risks, such as eavesdropping, data tampering, and unauthorized access. Handover management algorithms must incorporate robust security mechanisms to protect user data and privacy during the handover process.

In conclusion, addressing the challenges in handover management for hybrid VLC and WiFi systems is vital for ensuring seamless connectivity, mobility, and user experience in these networks. The development of efficient handover management algorithms, collaboration between industry stakeholders, researchers, and standardization bodies, and the adoption of common standards and protocols are necessary steps towards overcoming these challenges and enabling the successful integration of VLC and WiFi technologies.

5.4 Intelligent Management System in Testbed

In today's rapidly evolving communication landscape, ensuring seamless connectivity and efficient handover management is of utmost importance [78]. This section introduces an intelligent management system in a testbed environment, which leverages the strengths of both VLC and WiFi technologies. By utilizing RSS based schemes and user mobility (context based schemes) as a key factor in the handover process, this system aims to provide more accurate and efficient handovers. Advanced techniques, such as indoor localization based on neural networks, are potential to predict the receiver's location, enabling a more robust and reliable communication experience. This intelligent management system demonstrates the potential for improved connectivity and performance in hybrid VLC and WiFi networks.

We investigate the implementation of an IMS as depicted in Figure 5.6. The system features multiple downlink VLC connections, complemented by a common WiFi network, catering to the needs of various users, including VLC receivers. The IMS acts as a central control unit responsible for gathering and processing information, with decision-making based on different techniques tailored to specific situations. The experimental setup for the hybrid network is illustrated in Figure 5.7.

5.4.1 Handover Information Gathering in VLC

Our testbed is built on OpenVLC 1.3, an open platform that enables researchers to develop their prototypes [79]. The OpenVLC system comprises three components: the OpenVLC cape, which is the front-end transceiver connected to the Beaglebone Black; the OpenVLC firmware, which runs on the Processing Real-time

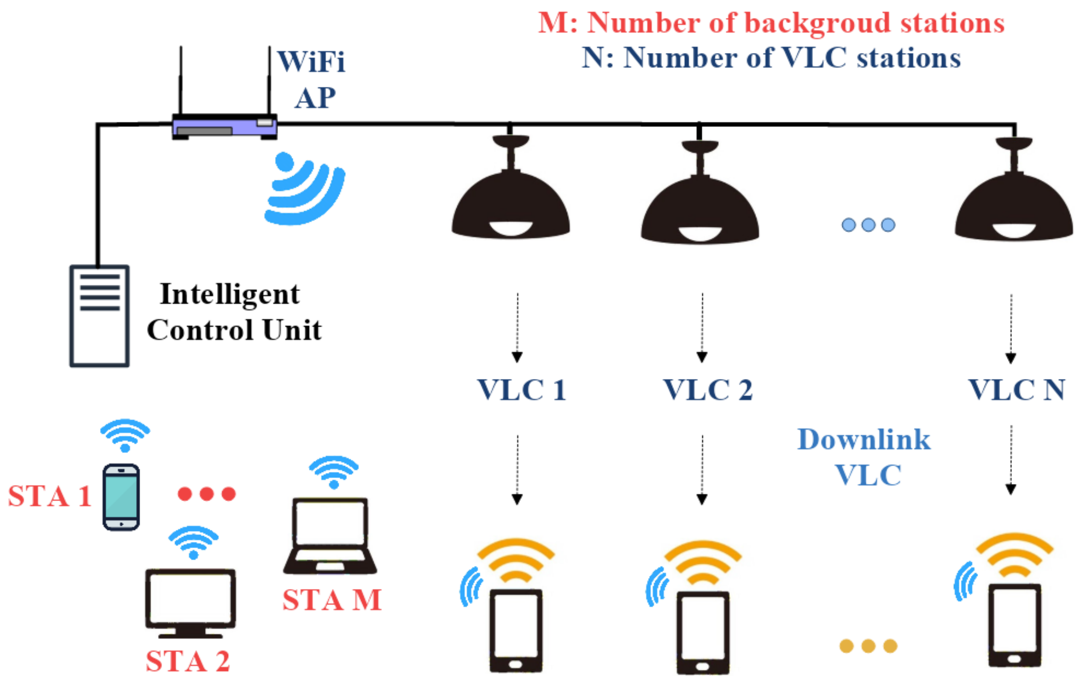

Figure 5.6: Intelligent Management System in Hybrid VLC/WiFi scenario.

Units (PRUs) that function as microprocessors for the BBB and performs real-time processing; and the OpenVLC driver, which is a module in the Linux kernel that implements the VLC MAC and PHY layers, as well as sampling, symbol identification, coding/decoding, and Internet protocol interoperability. However, the current state of the OpenVLC platform does not provide RSSI to a Linux environment. The OpenVLC firmware stores each of the 16 bits of the current RSSI value in the register of PRU0. Once read, this RSSI is compared with a threshold for decoding. After decoded, a new RSSI value is started to be read, so the previous one is lost. The process shows in Figure 5.8. To extract the RSSI value and integrate it into our handover mechanism, we utilized a prudebug-bbb tool to gain insight into the registers used by the OpenVLC firmware. With this knowledge, we modified the firmware to search for the register containing the RSSI value. Our efforts led us to identify r3 as the essential register for storing the RSSI value from PRU0. By successfully retrieving the RSSI value on the receiver side, we have taken a significant step toward implementing our handover mechanism. In Figure 5.9, the graph

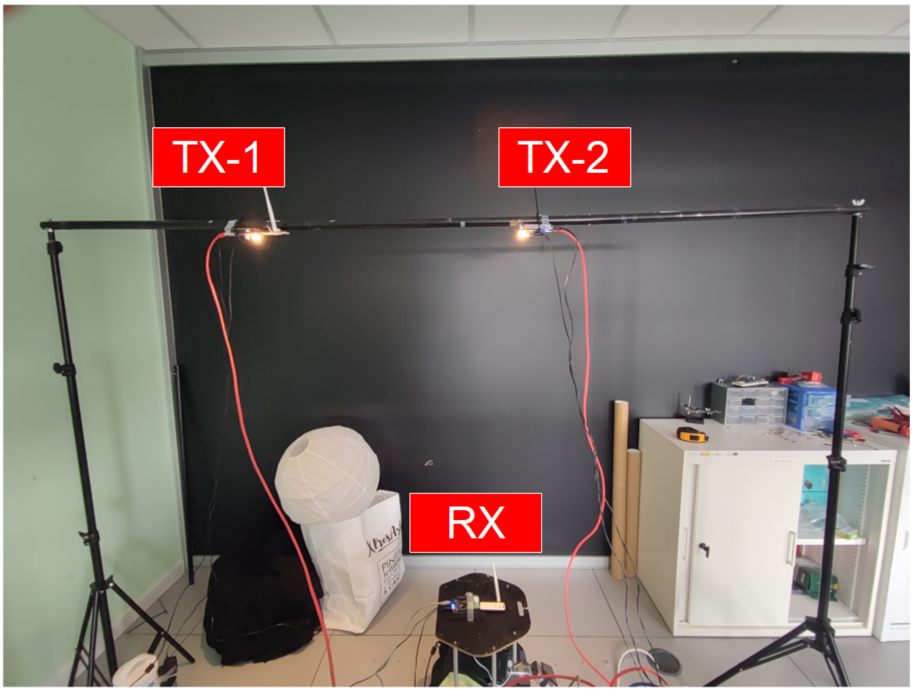

Figure 5.7: The scenario for handover for hybrid VLC/WiFi system.

displays a sample of data collected in relation to the distance between Tx-1 and Rx as the Rx moves along the path between the two transceivers. The results in Figure 5.10 become more apparent when focusing solely on the maximum RSSI values corresponding to varying distances between transceivers.

The conversation emphasizes the advantages of a hybrid VLC and WiFi system, which overcomes the limitations of traditional localization methods and provides more accurate and secure positioning solutions. VLC network localization offers a unique approach with short-range communication capabilities and triangulation algorithms for accuracy. Integrating VLC networks with WiFi in a hybrid system allows for the creation of cutting-edge applications and services that depend on exact indoor positioning information, revolutionizing our interaction with the environment.

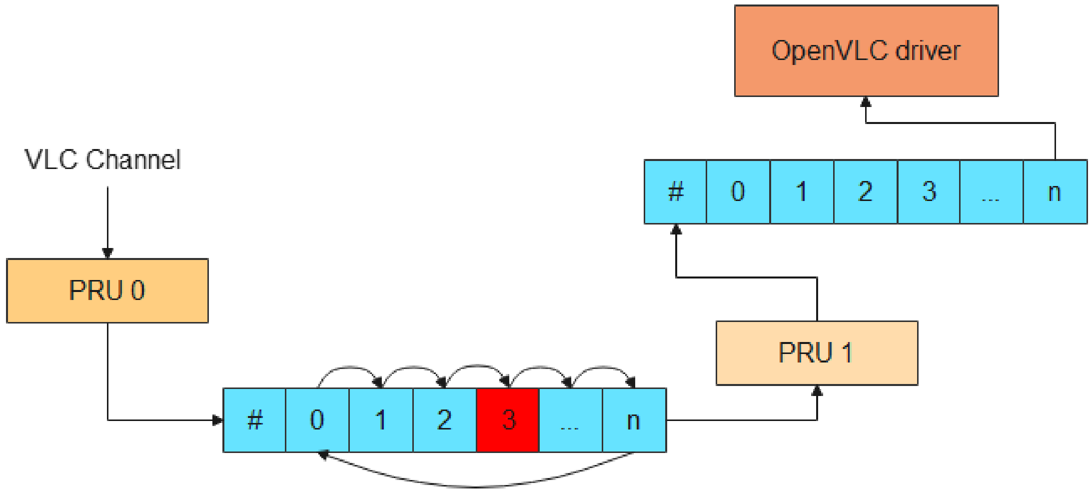

Figure 5.8: Memory sharing between PRUs and OpenVLC driver receiver.

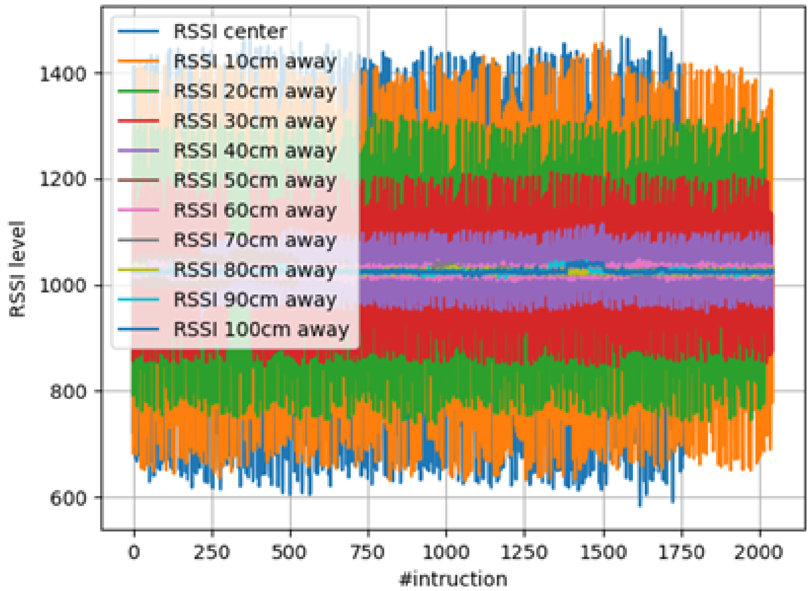

Figure 5.9: The RSSI sample collected for hybrid VLC/WiFi system in relation to the distance between Tx and Rx.

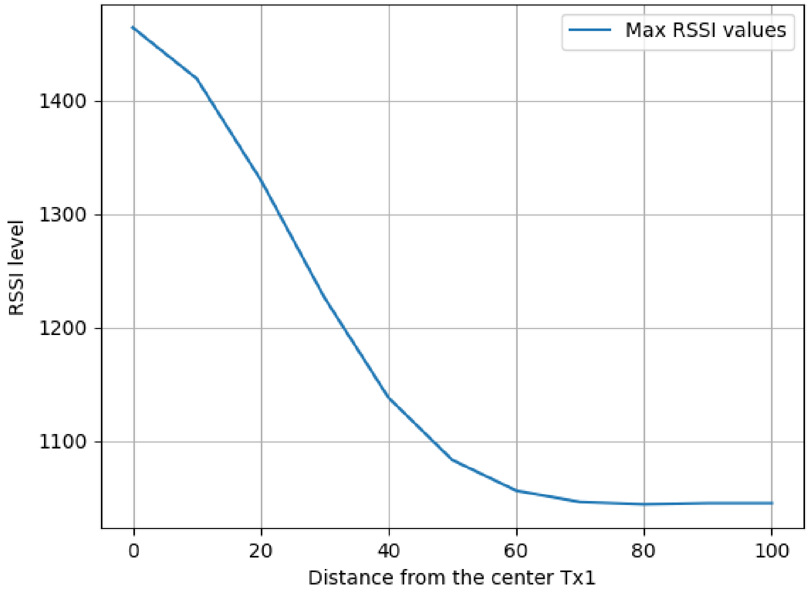

Figure 5.10: The Max RSSI sample capture with different distance between VLC Tx and Rx.

5.4.2 Handover Information Gathering in WiFi

It is not easy to monitor users without a device using standard WiFi devices. The reflection signals used for device-free tracking are much weaker than the direct-path signal compared to device-based monitoring, making extracting accurate and usable tracking information from the reflection signals more challenging. Additionally, the restricted bandwidth and a limited number of antennas found on the majority of commodity WiFi cards make angle-of-arrival (AoA) and time-of-arrival (ToA) based passive tracking too insensitive. With Doppler information, whose resolution is unaffected by the number of antennas or bandwidth, we hope to solve the tracking movement problem in this section.

In an indoor environment, human movements alter the path length of the WiFi signal reflected from the human body for each pair of transceivers, causing a Doppler frequency shift of the signal. This is the fundamental concept and theoretical basis of our WiFi based device-free tracking system. The phase information of the CSI available at the common WiFi receiver can be used to determine the amplitude and direction of the Doppler frequency shift. The velocity and location of the human target are thus linked to the amount of Doppler frequency shift because they affect how quickly the reflection path length shifts. Additionally, we can get the AoA spectrum from CSI, which shows the object's location (angle) probability. We can then estimate the human velocity, location, and consequently moving trajectory by fusing Doppler frequency shift with the AoA spectrum, accomplishing our objective of precise device-free human tracking with common WiFi devices.

Using CSI information to calculate the doppler velocity is more useful and accurate compared to using CSI to detect the user's location. For the main function of IMS, we want it to provide the best services for users. By accouting user's movement speed, we can optimize the handover mechanism to provide better services for all users inside the network.

Channel State Information (CSI)

WiFi Interface Cards (NICs) persistently observe changes in the wireless channel using CSI, which characterizes the frequency response of the wireless channel [80, 81]. Suppose $X(f,t)$ and $Y(f,t)$ denote the frequency domain representations of transmitted and received signals, respectively, with carrier frequency f. The connection between these two signals can be expressed as $Y(f,t) = H(f,t) \times X(f,t)$, where $H(f,t)$ is the complex-valued Channel Frequency Response (CFR) for carrier frequency f measured at time t. In essence, CSI measurements contain these CFR values. Let N_{Tx} and N_{Rx} represent the number of transmitting and receiving antennas, respectively. Since CSI is measured on 30 selected OFDM subcarriers for a received 802.11 frame, each CSI measurement consists of 30 matrices with dimensions $N_{Tx} \times N_{Rx}$. Each entry in any matrix is a CFR value between an antenna pair at a specific OFDM subcarrier frequency at a particular time.

CSI-Mobility Model

Although directly measuring the phase of a path is challenging, it is possible to infer the phase of a path using the CFR power, i.e., $|H(f,t)|^2$. Our approach is based on the principle that when the lengths of multi-paths change, the CFR power varies according to the path length change.

To understand the relationship between CFR power and the length change of a path, we first express CFR as a sum of dynamic CFR and static CFR and then calculate the power. Dynamic CFR, denoted by $H_d(f,t)$, is the sum of CFRs for paths whose lengths change with human movement and is given by

$$H_d(f,t) = \sum_{k \in P_d} a_k(f,t) e^{-j2\pi d_k(t)/\lambda} \tag{5.1}$$

where P_d is the set of dynamic paths whose lengths change. Static CFR, denoted by $H_s(f)$, is the sum of CFRs for static paths. Thus, the total CFR can be expressed as follows.

$$H(f,t) = e^{-j2\pi \Delta f t} \left(H_s(f) + \sum_{k \in P_d} a_k(f,t) e^{-j2\pi d_k(t)/\lambda} \right) \tag{5.2}$$

The total CFR has time-varying power because, in the complex plane, the static component $H_s(f)$ is a constant vector while the dynamic component $H_d(f,t)$ is a superposition of vectors with time-varying phases and amplitudes. When the phase of the dynamic component changes, the magnitude of the combined CFR changes accordingly.

Now, consider how CFR power changes with an object moving around. Suppose an object moves at a constant speed such that the length of the kth path changes at a constant speed v_k for a short time period, e.g., 100 milliseconds. Let $d_k(t)$ represent the length of the kth path at time t. Thus, $d_k(t) = d_k(0) + v_k t$. The instantaneous CFR power at time t can be derived as follows (detailed derivations are omitted due to space constraints).

$$\begin{aligned} |H(f,t)|^2 = & \sum_{k \in P_d} 2|H_s(f) a_k(f,t)| \cos\left(\frac{2\pi v_k t}{\lambda} + \frac{2\pi d_k(0)}{\lambda} + \phi_{sk} \right) \\ & + \sum_{\substack{k,l \in P_d \\ k \neq l}} 2|a_k(f,t) a_l(f,t)| \cos\left(\frac{2\pi (v_k - v_l) t}{\lambda} + \frac{2\pi (d_k(0) - d_l(0))}{\lambda} + \phi_{kl} \right) \\ & + \sum_{k \in P_d} |a_k(f,t)|^2 + |H_s(f)|^2 \end{aligned} \tag{5.3}$$

where $\frac{2\pi d_k(0)}{\lambda} + \phi_{sk}$ and $\frac{2\pi(d_k(0)-d_l(0))}{\lambda} + \phi_{kl}$ are constant values representing initial phase offsets.

From Equation 5.3, we can observe a key insight: the total *CFR power* is the sum of a constant offset and a set of sinusoids, where the frequencies of the sinusoids are functions of the speeds of path length changes. By measuring the frequencies of these sinusoids and multiplying them with the carrier wavelength, we can obtain the speeds of path length change. In this way, we can construct a *CSI-mobility model* that relates the variations in *CSI power* to movement speeds.

5.5 Handover Testbed

Our testbed, as illustrated in Figure 5.7, incorporates two OpenVLC transmitters integrated with WiFi, facilitating effective data transmission via visible light. On the receiver side, we have one OpenVLC unit with customized firmware, which is mounted on a robot that can move freely between the two access points. One critical feature of the VLC channel condition is the RSSI value, which measures the signal strength between the transmitter and receiver. To better understand this aspect of the OpenVLC platform, we conducted experiments to observe how the RSSI value changes as the receiver moves further away from the center point of the OpenVLC AP. With all knowledge about OpenVLC, we successfully retrieved the RSSI value on the receiver side, enabling us to integrate it into our handover mechanism, which determines the most effective base station for seamless handover. By conducting experiments to monitor the RSSI value as the receiver moved away from the center point of the OpenVLC AP, we gained insight into the performance of the VLC channel under different conditions. Our results showed that the maximum RSSI value decreased as the receiver moved further away from the center point, indicating a degradation in signal strength like in Figure 5.10 . These observations may also lead to advancements in the performance of VLC systems, as a better understanding of channel conditions can result in more robust systems that deliver higher data rates and improved reliability.

5.6 Results and Discussion

After careful consideration, we used the sample standard deviation of RSSI values (sRSSI) to measure RSSI channel variability similar like in Figure 5.11. We choose sRSSI because it provides a comprehensive view of the RSSI channel and is less prone to bias than other standard deviation estimates. Overestimating variability in samples is preferable to underestimating it, which could potentially lead to inaccurate results. Therefore, sRSSI is a reliable way to gauge RSSI variation in our study.

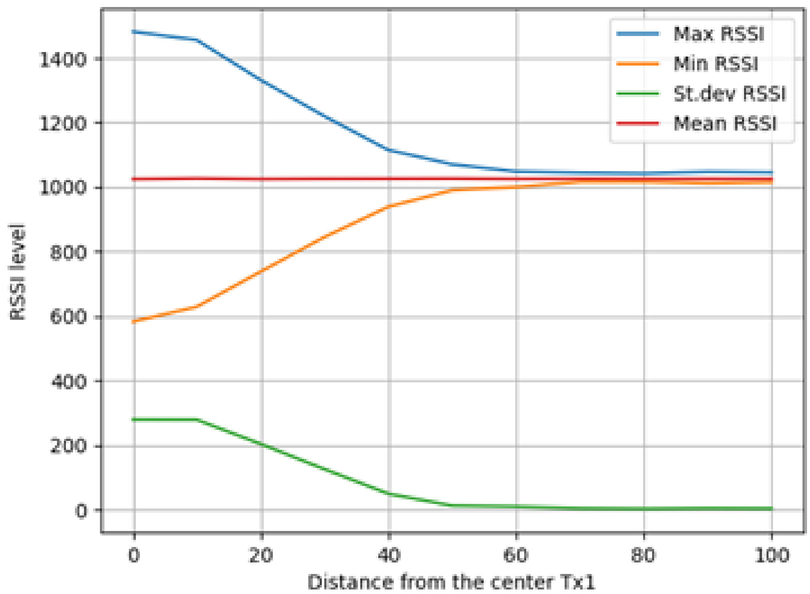

Figure 5.11: The maximum, minimum, mean, and standard deviation RSSI values with different distances between Tx1 and Rx.

To investigate user mobility in a WiFi environment, we collected CSI data and extracted doppler velocity components, as depicted in Figure 5.12. The experimental setup involved linear movements of a receiver at different velocities. The sequence is the receiver moves at high speeds for the first 10 seconds, followed by a slow movement for the next 10 seconds, with a 10-second pause in between. This cycle was repeated for 120 seconds. Our analysis revealed a strong correlation between the doppler velocity and the rate of user mobility, allowing us to categorize it into three levels based on our predetermined thresholds: slow movement (green), moderate movement (blue), and fast movement (red). We plan to leverage this information in our ML algorithms.

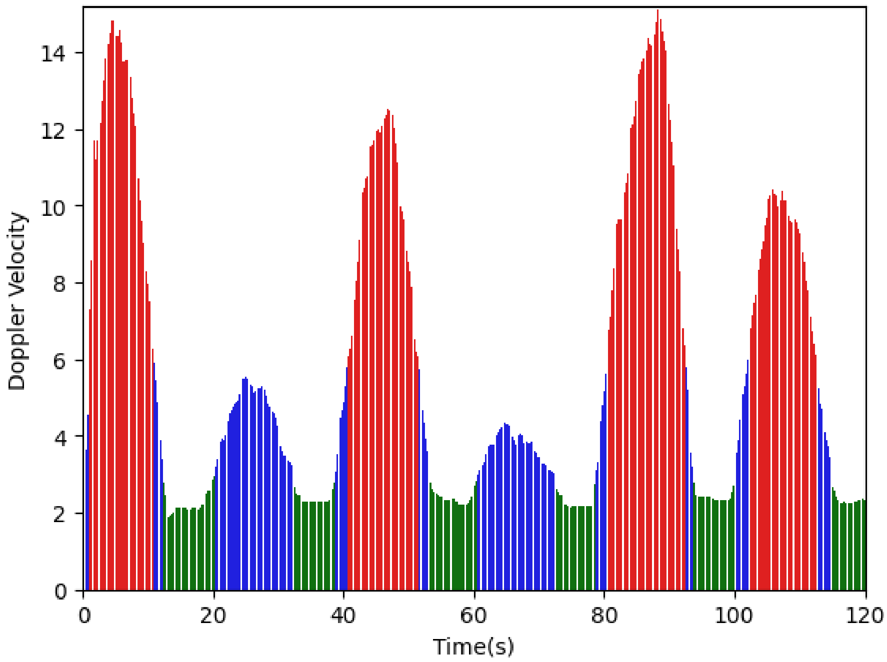

Figure 5.12: Doppler velocity envelope extracted from a testbed scenario.

Handover Decision

Handover decisions are crucial in the handover process, especially when developing a handover mechanism between VLC and WiFi networks. However, this can be challenging due to differences in physical layers, communication protocols, and network architectures. Therefore, selecting appropriate handover criteria is of utmost importance. In our study, we experimented with various combinations of techniques and features that can be collected from both networks. After careful consideration, we decided to employ fuzzy logic for our small-scale testbed, which allowed us to achieve fast handover times while meeting our requirements.

In our fuzzy logic approach, we consider the sRSSI 1 and sRSSI 2 values for two

Table 5.2: Fuzzy Logic Rules for handovers

Rule No.	**Features**			**AP Allocation**
	sRSSI 1	**sRSSI 2**	**WiFi data rate**	
1	not Low	-	-	VLC1
2	-	not Low	-	VLC2
3	Low	High	-	VLC2
4	High	Low	-	VLC1
5	Low	Low	not Low	WiFi

OpenVLC access points, respectively. We chose the WiFi data rate as the most convenient feature to learn about WiFi channel conditions. In our testbed, in case the VLC channel is appropriate for transmitting data, we prioritize it over the WiFi channel, which serves as a backup network. The algorithm show in Algorithm 1.

Algorithm 1 Handover Decision Algorithm

procedure HANDOVERDECISION($sRSSI_1$, $sRSSI_2$, $WiFiDataRate$)
    Sensing environment
    if $sRSSI_1 \neq Low$ **then**
        return VLC1
    else if $sRSSI_2 \neq Low$ **then**
        return VLC2
    else if $sRSSI_1 = Low$ **and** $sRSSI_2 = High$ **then**
        return VLC2
    else if $sRSSI_1 = High$ **and** $sRSSI_2 = Low$ **then**
        return VLC1
    else if $sRSSI_1 = Low$ **and** $sRSSI_2 = Low$ **and** $WiFiDataRate \neq Low$ **then**
        return WiFi
    end if
end procedure

This approach helps reduce the likelihood of bottleneck issues in the WiFi channel. In our OpenVLC platform, the maximum achievable data rate is 400 kbps. We observed that when sRSSI is low, traffic drops below 50 kbps, which led us to define the sRSSI threshold at this level as a handover procedure that should take place. We demonstrate the fuzzy logic rules in TABLE 5.2 and Algorithm 1.

Handover Execution

As part of our experimental study, we conducted tests in several indoor environments to evaluate the effectiveness of our proposed hybrid handover solution. We collected data for five minutes while the receiver moved in the same cycle as we collected CSI data for doppler velocity. These tests assessed the system's ability to handle handovers seamlessly between VLC and WiFi networks.

Table 5.3: Vertical handover times

Handover	**VLC to WiFi (s)**	**WiFi to VLC (s)**
1	0.431	0.488
2	0.421	0.320
3	0.503	0.287
...	...	...
10	0.386	0.311
Average	0.436	0.401

Our experiments generated valuable data, presented in table 5.3 and 5.4, which showcases the handover times execution for VHO and HHO, respectively. As predicted, the experimental results indicate that the handover time for VHO is typically more than double compared to the handover time in HHO.

For HHO, the minimum handover time observed ranges from 0.043 s to 0.105 s, while for VHO, it ranges from 0.287 s to 0.401 s. Although the handover time has not yet been defined in VLC standardization, these results meet the standard

Table 5.4: Horizontal handover times

Handover	**VLC 1 - VLC2**
1	0.045
2	0.115
3	0.043
...	... .
10	0.172
Average	0.105

for handover time in other radio frequency technologies. Our results demonstrate better performance than the latest reported handover time for the Li-Wi network in [76]. In that study, the author employed MPTCP and link aggregation tools to develop handover mechanisms, only achieving a minimum handover time of 0.2 s to 0.35 s.

In Table 5.5, we evaluate the effectiveness of our system by implementing both HHO and VHO and recording the time duration for each handover session. The results clearly demonstrate that the IMS system remains efficient in these scenarios.

Handover with User Mobility and Machine Learning

Our experiment aims to scale up our operations in a massive IoT system by utilizing machine learning techniques to develop robust handover systems. Gathering more information about our testbed is crucial before fine-tuning the ML model. Moreover, our approach prioritizes decisions based on maintaining a minimum throughput, which guarantees that the quality of service remains consistently high across all user scenarios and movement patterns. To achieve this, we have identified seven features - maximum RSSI, minimum RSSI, sRSSI, WiFi link quality, WiFi noise level, and

Table 5.5: Handover process

	Horizontal HO (s)	**Vertical HO (s)**
Sensing	3	3
Decision	0.02	0.04
Execution	0.107	0.401

WiFi data rate, current network - that can provide valuable insights into network performance. In addition, we have incorporated user mobility as an essential feature by extracting it from doppler velocity data. This information has been categorized into three distinct movement patterns - slow, moderate, and fast - as illustrated in Figure 5.12 . By integrating user mobility data with other relevant features, we aim to improve the accuracy and reliability of our ML model for predicting handovers in different scenarios.

To identify the most effective algorithms for enhancing our machine learning model, we experimented with various supervised learning techniques, including Logistic Regression, Support Vector Machine Classifier, Gradient Boosting, Naive Bayes Classifier, and others. Based on our initial analysis, we selected the four methods that exhibited the greatest potential for improving the accuracy of our model while requiring a fast-training time. These techniques were K-Nearest Neighbors, Random Forest, AdaBoost C4.5, and Logistic Model Tree. We proceeded to fine-tune these models and evaluated their accuracy results, which are presented in Table 5.6.

Our analysis indicates that when 80% of our dataset is used to train the model, the accuracy of predicting handovers exceeds 93%. During the tuning process, we found that the AdaBoost C4.5 algorithm displayed the most significant potential with an impressive 97.5% accuracy. We selected AdaBoost.C4.5 because it employs Decision Trees as its base classifiers, which are widely recognized for their effectiveness in machine learning applications. Specifically, AdaBoost.C4.5 incorporates

Table 5.6: Performance of Classifiers

Classifier	**Training Size** (%)	**Accuracy** (%)	**Training Time (s)**
KNN	40	85.4	0.01
	60	90.5	0.01
	80	93.1	0.01
Random Forest	40	87.6	1.01
	60	90.5	1.21
	80	95.3	1.52
AdaBoost C4.5	40	85.2	0.03
	60	90.1	0.03
	80	97.5	0.03
LMT	40	85.2	0.05
	60	90.1	0.05
	80	93.6	0.05

the C4.5 decision tree algorithm into the AdaBoost framework. Unlike AdaBoost, which uses weak learners, AdaBoost.C4.5 builds a forest of decision trees and selects the best one to add to the ensemble at each iteration. This approach allows AdaBoost.C4.5 to identify more complex relationships in the data than AdaBoost alone, leading to improved predictive accuracy.

Our machine learning model for the handover system was optimized by utilizing two essential hyperparameters, namely n_estimators and learning_rate. The hyperparameter n_estimators was set to 100 and 200, indicating the maximum number of estimators utilized before the AdaBoost.C4.5 algorithm terminated the boosting process. By increasing this value from the default 50, we could reduce the model's variance while preventing overfitting on the training data. Furthermore, we could determine the number of expanding rounds executed before the algorithm stops by utilizing n_estimators. The second hyperparameter, learning_rate, was tuned from 0.001 to 0.5. This parameter controls the weight update during each iteration of the boosting process. A lower value of learning_rate leads to a slower adaptation of the model to the gradient of the loss function, while a higher value results in a faster adaptation. It is crucial to strike a balance between the two hyperparameters since using a small learning_rate and many estimators might not lead to better results and can increase computational costs.

In conclusion, selecting appropriate values for these hyperparameters is paramount in influencing the model's performance. As such, we paid keen attention to tuning both hyperparameters to strike a balance between model accuracy and computational efficiency. There is potential to expand this research further by incorporating more transmitter and receiver access points with different hybrid VLC and RF technology. Additionally, we can further boost the performance of our ML models by increasing the size of the data available through the hybrid system.

5.7 Discussion and future research directions

This work will be open-source with OpenVLC, which can help other researchers to implement their research in OpenVLC and also our Center Control Unit. There are several research directions for researchers based on this IMS.

The discussion highlights the potential of system control based on localization information in enhancing user experiences and optimizing various applications. WiFi network localization benefits from widespread adoption, existing infrastructure, and the RSSI method for distance measurement. Combining WiFi with other localization methods in a hybrid system enables the development of innovative applications and services that rely on precise indoor positioning data, ultimately transforming how we interact with our surroundings.

5.7.1 Access Point placement

Access point placement is a crucial aspect in VLC networks. The placement of access points, also known as light sources, directly affects the coverage and performance of the VLC network. There are several factors that need to be considered when placing access points in a VLC network. Firstly, the light sources need to be positioned in such a way that they provide adequate coverage to the target areas. This requires careful consideration of the light transmission properties of the environment, such as the presence of obstacles and reflections. Another factor to consider is the quality of the received signal. To ensure a high-quality signal, the light sources should be placed in such a way that they are not obstructed by other objects [82, 83]. This is particularly important when considering multi-floor buildings where there are likely to be many obstacles between the light sources and the receivers.

In addition, it is important to consider the power of light sources. High-power light sources can increase the coverage of the VLC network, but they can also cause interference with other optical devices and increase the cost of the network. On the other hand, low-power light sources can reduce the cost of the network but can also reduce the coverage area and the quality of the received signal. Finally, the placement of the access points should be optimized to reduce the overall network cost. This can be achieved by reducing the number of light sources required to cover the target area, or by reducing the power requirements of the light sources. In conclusion, the placement of access points in a VLC network is a crucial aspect that can develop in IMS which requires careful consideration of several factors, such as coverage, signal quality, power requirements and cost. By optimizing the placement of access points, it is possible to achieve a high-performing, cost-effective VLC network.

5.7.2 Handover Skipping

Handover skipping is a technique used in VLC networks to improve the overall performance and efficiency of the network. In VLC networks, handover events can cause significant overhead, and handover skipping aims to reduce the number of these events, and the associated overhead, by skipping over less optimal APs and directly switching to a more optimal AP. Handover skipping is achieved through the use of advanced signal processing algorithms that can accurately predict the future position of a device and determine the most optimal AP for the device to connect to. The algorithms consider various factors such as the device's movement speed, the signal strength and quality of each AP, and the availability of resources on each AP [70, 71]. Handover skipping aims to minimize the number of handover events and ensure that the device is always connected to the most optimal AP, resulting in a more efficient and stable VLC network. In addition to improving the overall performance of the VLC network, handover skipping also has the potential to reduce power consumption and increase the battery life of devices, as less time is spent searching for and connecting to new APs. Furthermore, handover skipping can improve the quality of the communication link, as the device is always connected to the best AP, resulting in improved signal strength and quality.

In conclusion, handover skipping is a key technique in optimizing VLC/WiFi networks and can help improve the overall performance, efficiency, and stability of the network. With the continued development of VLC technology, it is expected that handover skipping will become an increasingly important component of VLC networks and play a crucial role in the future of communication technology.

5.7.3 Transfer Learning

IMS is crucial for hybrid system, but in the future we can put all the management function into each transceiver. Transfer learning might be a future direction to moving forward in IMS. Transfer learning is a machine learning technique that allows a model that has been trained on one task to be reused and fine-tuned for another related task. In the context of hybrid VLC/WiFi, transfer learning can be used to improve the performance of the systems by leveraging the knowledge obtained from previous VLC/WiFi studies and experiments. The use of transfer learning in hybrid system can help to overcome some of the challenges associated with designing and implementing VLC systems and WiFi [84, 85]. For example, the availability of labeled data for VLC is often limited, which makes it difficult to train machine learning models from scratch. Transfer learning enables VLC systems to take advantage of pre-existing models trained on large amounts of data, thus improving the accuracy and performance of VLC systems.

Furthermore, transfer learning can also help to address the differences in channel characteristics that exist between different VLC systems. Different VLC systems have different channel characteristics, such as different distances between the transmitter and receiver, different angles of view, and different channel impairments. Transfer learning can be used to fine-tune pre-existing models to the specific channel characteristics of each VLC system, which can help to improve the performance of the VLC system. In conclusion, transfer learning is a promising technique that can be used to improve the performance of hybrid VLC/WiFi systems by leveraging existing knowledge and overcoming some of the challenges associated with designing and implementing VLC systems.

5.8 Conclusion

Developing a seamless handover mechanism between the two systems is crucial to explore VLC and WiFi integration's full potential. Our proposed testbed serves as a platform for researchers to address the challenges associated with handover mechanisms and develop more efficient, reliable, and secure communication systems across different industries and applications. To achieve seamless integration between VLC and WiFi systems, we proposed a hybrid handover solution based on RSSI and CSI values for both HHO and VHO. Our experimental results indicate that the proposed solution achieves maximum handover times of around 100 ms and 400 ms for HHO and VHO, respectively. Additionally, our machine learning algorithm for handover decision-making provides remarkable accuracy, with a score of 97.5%. The results demonstrate that our proposed solution can achieve efficient handover times in diverse indoor environments. This underscores the importance of developing a seamless handover mechanism to enable other researchers working on hybrid systems to implement their work in a similar testbed environment. In the future, several extension ideas warrant further investigation. Integration of tracking and localization into our machine learning model could lead to more efficient handovers by dynamically adapting to user movement patterns and changing network conditions. Developing an architectural solution for managing strip-LED systems allows seamless communication with multiple receivers and traffic flows while balancing the complexity of individual LED intelligence modules. Exploring resource allocation trade-offs between traffic load in each cell and dwell time during handovers may optimize overall system performance. Additionally, investigating adaptive node-association strategies based on anticipated user movement could minimize handover dwell times, even in cell-free systems. By pursuing these research directions, we aim to enhance the applicability and efficiency of our proposed handover mechanism, ultimately contributing to improved user experiences and more robust large-scale networks.

Chapter 6

Application for Intelligent Management System in Hybrid System

The extensive advantages offered by our Novel Intelligent Management System Architecture for Hybrid VLC/RF Systems demonstrate its capacity to transform numerous industries, ushering in a new era of technological advancements and improved quality of life.

- **Agriculture:** By employing our hybrid VLC/RF architecture, farmers can access real-time data on variables such as soil moisture levels, nutrient content, and plant growth. This enables them to make informed decisions about irrigation, fertilization, and pest control, ultimately leading to higher crop yields and reduced waste. Additionally, the architecture facilitates remote monitoring of livestock health and location, offering opportunities for improved animal welfare and farm management shows in Figure 6.1.

- **Retail:** The integration of VLC and RF technologies in retail settings can enhance customer experiences by enabling context-aware promotions and personalized recommendations, based on individual preferences and shopping history. Further, this architecture can assist in streamlining inventory management through real-time tracking of item locations and quantities, reducing

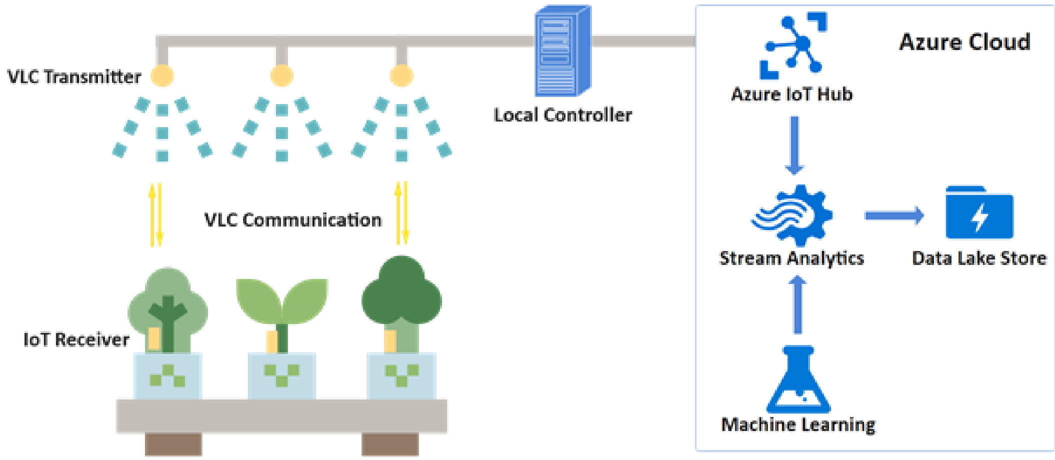

Figure 6.1: Smart agriculture application for a hybrid system.

the likelihood of stockouts and overstocking. Finally, the secure, high-speed connectivity empowers retailers to offer seamless contactless payment options, increasing transaction efficiency and convenience for customers show in Figure 6.1.

- **Smart Homes:** Our proposed system facilitates the seamless interconnectivity of various smart home devices and appliances, making it possible for homeowners to create a truly integrated living environment. Homeowners can easily manage their lighting, temperature, and security systems remotely or through automated schedules, resulting in enhanced comfort and energy savings. Moreover, the privacy-preserving capabilities of our architecture ensure that sensitive household data remains protected from unauthorized access illustrate in Figure 6.2.

- **Entertainment:** The high-speed, low-latency characteristics of our hybrid architecture are critical for delivering next-generation entertainment experiences. This includes uninterrupted streaming of ultra-high-definition media content, fully immersive virtual reality and augmented reality gaming experiences, and responsive multiplayer online gaming sessions. The architecture also caters to multi-user environments, allowing simultaneous device connections without compromising performance shows in 6.3 .

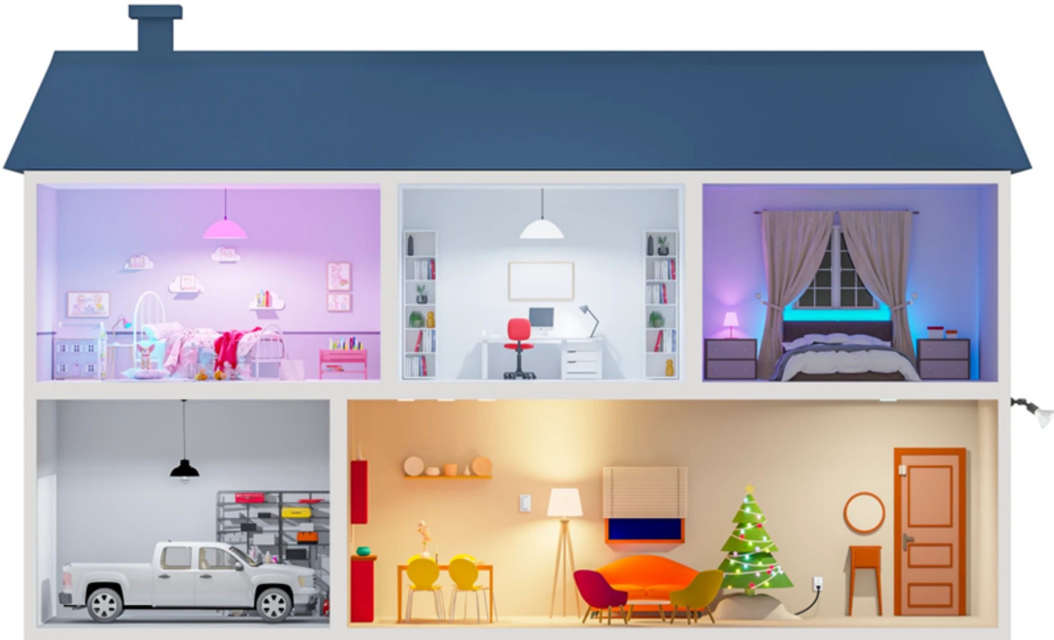

Figure 6.2: Smart homes application for a hybrid system.

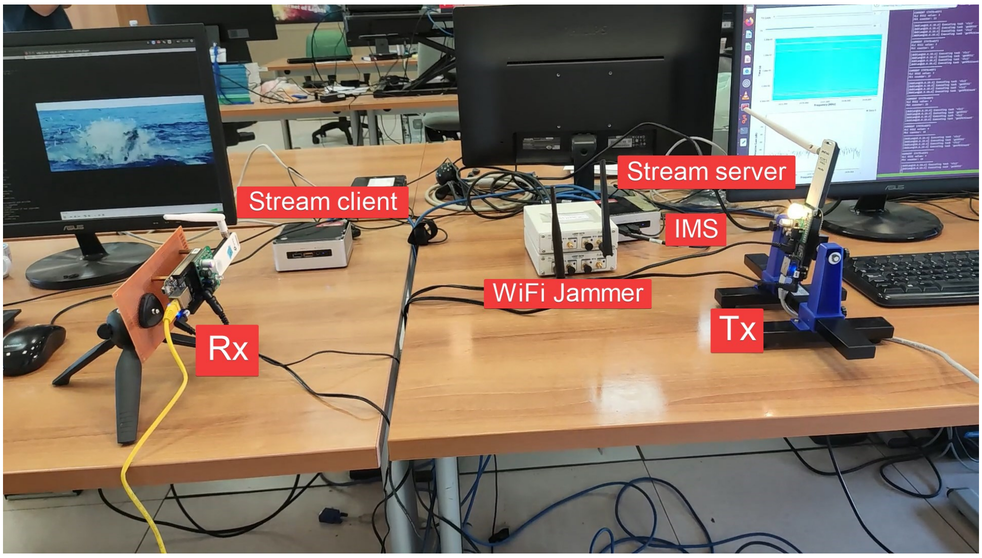

Figure 6.3: Entertainment demo for a hybrid system.

- **Public Safety:** In emergency situations, the robust and reliable communication enabled by our hybrid architecture is vital for effective coordination between first responders, law enforcement agencies, and rescue teams. The system allows rapid transmission of mission-critical information, such as live video feeds, GPS coordinates, and important updates, ensuring that resources are deployed efficiently and lives are saved. Furthermore, during disaster relief operations, our architecture can provide crucial support for establishing temporary communication networks in affected areas, facilitating search and rescue efforts, and aiding in resource distribution.

- **Hospital Environments:** The implementation of our intelligent management system for hybrid VLC/RF communication in hospitals can significantly enhance patient care and overall healthcare efficiency [86]. The architecture supports real-time monitoring of patients' vital signs and location, allowing healthcare providers to respond quickly in emergency situations. Furthermore, the system can streamline the management of medical equipment and supplies, ensuring that necessary resources are readily available when needed. The high-speed, reliable connectivity also enables seamless data transfer and communication between healthcare professionals, facilitating informed decision-making and collaboration. All of these benefits contribute to a safer, more efficient hospital environment, as depicted in Figure 6.4.

- **Underwater Communication:** The hybrid VLC/RF communication system holds great potential for underwater applications, such as oceanographic research, environmental monitoring, and marine life tracking. By leveraging the unique characteristics of both VLC and RF technologies, our intelligent management system can overcome the connectivity and performance challenges typically associated with underwater communication. This enables real-time data collection and transmission from underwater sensors, autonomous underwater vehicles (AUVs), and remotely operated vehicles (ROVs), supporting a wide range of scientific and industrial applications. An illustration of underwater communication using the hybrid system is shown in Figure 6.5.

In conclusion, the proposed intelligent management system for hybrid VLC/RF

Figure 6.4: Hospital application for a hybrid system.

Figure 6.5: Underwater communication application for a hybrid system.

communication has the potential to revolutionize various industries by providing secure, high-speed, and reliable connectivity solutions. By addressing the unique challenges and requirements of each application, our architecture can pave the way for innovative use cases and enhanced quality of life in the digital era.

6.1 Smart Retail Environment

The proposed intelligent management system architecture is in smart retail environments, where store owners and managers can leverage the seamless integration of VLC and RF technologies to enhance customer experiences, optimize store operations, and facilitate targeted marketing. In this setting, customers can connect to hybrid VLC/RF APs as they move throughout the store, enjoying uninterrupted connectivity and receiving real-time promotions and product information based on their location. The ETL module enables accurate tracking of customer movement patterns, enabling store owners to optimize store layouts and product placements accordingly. Additionally, the EEM ensures efficient energy usage by dynamically adjusting LED brightness levels and selectively deactivating idle links based on customer presence and store requirements.

The scalability and adaptability of the proposed intelligent management system architecture make it particularly suited for application in smart retail environments. In these settings, store owners and managers can leverage the seamless integration of VLC and RF technologies to achieve improved customer experiences, more efficient store operations, and targeted marketing strategies. This chapter provides a comprehensive overview of the potential benefits and applications of our architecture in smart retail environments, as well as an exploration of its integration with other emerging technologies.

6.1.1 Enhancing Customer Experiences

Uninterrupted Connectivity

A key feature of the proposed architecture is the ability to ensure uninterrupted connectivity for customers as they move throughout the store. By maintaining a consistent connection to hybrid VLC/RF Access Points, customers can enjoy a smooth shopping experience that includes real-time access to promotions, product information, and other digital resources. This uninterrupted connectivity also supports interactions with digital signs, augmented reality applications, IoT devices, and other components of the smart retail environment.

Location-Based Services

The location-aware capabilities of the proposed architecture allow retailers to offer a range of location-based services tailored to individual customers. For example, by tracking a customer's location within the store, the retailer can provide targeted promotions or personalized product recommendations based on the customer's browsing history and preferences. These location-based services can be delivered through a variety of platforms, such as mobile apps, digital signage, or in-store PA systems.

Improved In-Store Navigation

By leveraging the accurate tracking and localization features of the ETL module, retailers can provide enhanced in-store navigation for customers. Interactive maps, turn-by-turn directions, and other location-based services can help guide customers to their desired products or sections of the store, streamlining the shopping experience and reducing frustration caused by difficulty locating specific items.

6.1.2 Optimizing Store Operations

Data-Driven Layout Optimization

The data generated by the ETL module allows store owners and managers to gain valuable insights into customer movement patterns within the store. By analyzing this data, retailers can identify areas with high traffic, discover opportunities for improvement in store layouts, and optimize product placements to maximize customer flow and encourage impulse purchases. The result is a more efficient and customer-centric layout that can lead to increased sales and overall customer satisfaction.

Inventory Management

The proposed architecture's tracking capabilities can also play a vital role in enhancing inventory management processes. Knowing which products are popular and understanding customer movement patterns can help store owners ensure sufficient stock levels for in-demand items while identifying opportunities to strategically place promotional items or products needing a boost in visibility. This data-driven approach to inventory management can help reduce out-of-stock situations, improve turnover rates, and streamline supply chain operations like shows in 6.6

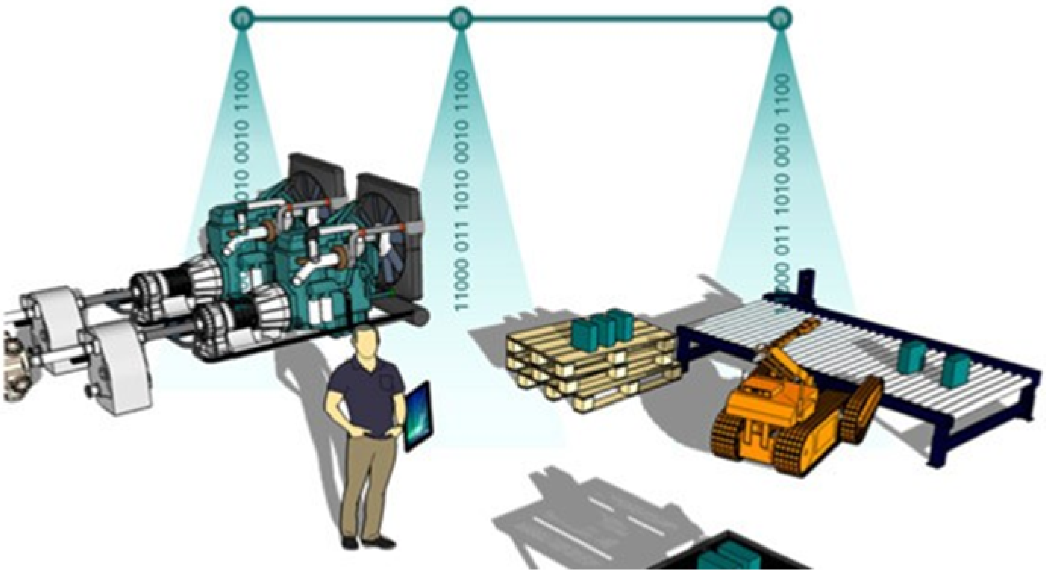

Figure 6.6: Smart factory application for a hybrid system.

Staff Allocation

In addition to optimizing store layouts and inventory management, the insights gained from the ETL module can be used to inform staff allocation decisions. By understanding peak hours, high-traffic areas, and other trends in customer behavior, store managers can allocate staff more effectively to provide better customer service, manage queues, and maintain optimal staffing levels during busy periods. This increased efficiency in staff allocation can lead to improved customer satisfaction and reduced labor costs.

6.1.3 Facilitating Targeted Marketing

In-Store Promotions and Advertising

One of the key advantages of the proposed intelligent management system architecture is its ability to facilitate targeted marketing efforts within the store. Using the wealth of data gathered on customer behavior and preferences, retailers can create highly targeted in-store promotions and advertisements, maximizing their effectiveness and relevance to individual customers. This targeted approach can lead to higher conversion rates, increased return on investment for marketing efforts, and greater customer loyalty.

Personalized Multi-Channel Marketing

Beyond in-store promotions, the data collected by the intelligent management system can be leveraged to inform personalized marketing strategies across multiple channels, such as email newsletters, social media campaigns, and mobile app notifications. By tailoring marketing messages to individual customer preferences, demographics, and purchasing habits, retailers can foster stronger connections with their customer base and drive repeat business.

6.1.4 Integration with Other Technologies

Machine Learning and Big Data Analytics

The intelligent management system architecture can be combined with machine learning algorithms and big data analytics to further enhance its value in smart retail environments. These technologies can provide deeper insights into customer preferences, behavior patterns, and sales trends, allowing retailers to refine their sales strategies, improve supply chain management, and ultimately, increase customer satisfaction.

IoT Devices and Sensors

Our proposed architecture can also be integrated with various IoT devices and sensors to create a more comprehensive smart retail environment. For example, by connecting to smart shelves, electronic price tags, or inventory management systems, the architecture can help store owners automate and optimize various aspects of in-store operations. Additionally, integration with environmental sensors, such as those monitoring temperature or humidity, can ensure optimal conditions for product storage and customer comfort.

Augmented Reality

The seamless connectivity provided by our architecture can facilitate the implementation of augmented reality applications within the smart retail setting. AR can enhance customer experiences by providing additional layers of information about products, such as user reviews, nutritional information, or virtual fitting rooms. By integrating AR into the shopping experience, retailers can drive customer engagement and provide unique value propositions that differentiate them from competitors.

6.2 Case Studies and Real-World Applications

To further illustrate the potential benefits and applications of the proposed intelligent management system architecture in smart retail environments, this section provides several case studies and real-world examples of how the technology could be implemented.

6.2.1 Case Study 1: Supermarket

In a supermarket setting, our proposed architecture can be employed to improve various aspects of the customer shopping experience. For instance, customers can access personalized promotions through their smartphones as they move through different sections of the store. Store layouts can be optimized based on data collected from customer movement patterns, ensuring popular items are easily accessible and impulse purchases are encouraged. Moreover, staff allocation can be informed by real-time data on customer traffic and queue length, enabling efficient customer assistance and reducing wait times at checkout counters.

6.2.2 Case Study 2: Clothing Store

In a clothing store, the architecture can support enhanced customer experiences with the integration of AR applications, such as virtual fitting rooms, which allow customers to "try on" clothes without physically changing. Accurate tracking of customer movement patterns can inform store layout optimization, ensuring popular items are prominently displayed and easy to find. Furthermore, targeted marketing efforts can be facilitated through personalized product recommendations and promotions delivered via customers' smartphones or digital signage throughout the store.

6.2.3 Case Study 3: Electronics Store

In an electronics store, our architecture can enable seamless interactions between customers and IoT devices, such as smart TVs, home automation gadgets, or wearable devices. The ETL module's tracking capabilities can help retailers understand customer interests and preferences, allowing them to personalize marketing messages and product demonstrations accordingly. In addition, real-time inventory management can be achieved by integrating the architecture with smart shelves and electronic price tags, ensuring popular items are consistently well-stocked and accurately priced.

6.2.4 Case Study 4: Automotive Showroom

In an automotive showroom, our proposed architecture can be employed to elevate the customer experience by providing interactive and immersive demonstrations of vehicle features. For instance, AR applications can be used to project visualizations of car interiors, exteriors, and engine components onto physical models, allowing customers to explore customization options. The system's localization and tracking capabilities can facilitate personalized marketing efforts, tailoring promotional content on digital displays or smartphones based on individual preferences and browsing history. Moreover, staff allocation and assistance can be optimized through real-time monitoring of customer traffic patterns and engagement levels, ensuring timely support and efficient customer service.

6.2.5 Case Study 5: Smart Library

In a smart library setting, our hybrid VLC/RF architecture can be utilized to enhance user experiences and streamline operations. Seamless connectivity allows patrons to access digital resources and services, such as e-books, audiobooks, and research databases, on their personal devices while navigating the physical library space. Indoor localization and tracking technologies can guide users to specific bookshelves or reading areas, and provide personalized recommendations based on prior borrowing history. Additionally, librarians can utilize data collected from user movement patterns and resource usage to optimize the library layout, ensuring that popular materials are easily accessible and quiet study areas remain undisturbed.

6.2.6 Case Study 6: Exhibition Center

In an exhibition center, our novel intelligent management system architecture can empower event organizers to create engaging and personalized experiences for attendees. High-speed, low-latency connectivity can support the integration of VR and AR applications, enabling immersive presentations and interactive product demonstrations. Accurate indoor localization and navigation systems can aid attendees in locating specific booths, conference rooms, or facilities, while exhibitors can leverage real-time analytics on visitor traffic patterns to optimize booth layouts and staffing. Furthermore, the architecture's privacy-preserving features ensure that attendee data remains protected, fostering trust in the digital services provided.

These case studies demonstrate the versatility and potential impact of our Novel Intelligent Management System Architecture for Hybrid VLC/RF Systems across various sectors. By embracing this technology, businesses and organizations can unlock new opportunities for growth, efficiency, and customer satisfaction.

6.3 Conclusion

In conclusion, the proposed intelligent management system architecture holds significant promise for application in smart retail environments. By leveraging the seamless integration of VLC and RF technologies, store owners and managers can enhance customer experiences, optimize store operations, and facilitate targeted marketing efforts. The incorporation of additional features, such as the ETL module and EEM, serves to further improve the retail environment by enabling data-driven decision-making and promoting energy efficiency. Integration with emerging technologies, such as machine learning, big data analytics, IoT devices, and augmented reality, offers even greater potential for innovation and differentiation in the competitive retail landscape.

Chapter 7

Conclusions

In conclusion, this thesis has presented a Novel Intelligent Management System Architecture for Hybrid VLC/RF Systems that aims to revolutionize communication and connectivity across a multitude of industries. By leveraging the strengths of both visible light communication and radio frequency technologies, our proposed architecture addresses limitations in existing systems while offering enhanced efficiency, reliability, and security.

Initially, an in-depth literature review on hybrid systems is presented, including various architectures such as parallel, complementary, cooperative, and interworking, along with their respective advantages and disadvantages. We also discuss the challenges associated with hybrid VLC and RF systems. After extensive research, we present a state-of-the-art hybrid architecture that incorporates all the benefits of these systems.

Subsequently, we conduct both simulation and experimental work to implement our vision for the hybrid network. Our advanced algorithm demonstrates significant improvement in hybrid system performance, addressing the bottleneck issue commonly associated with WiFi uplink channels. We simulate various scenarios and test different conditions, showing that EDCA-ACK provides a standards-compliant, reliable system, which improves the performance of the hybrid system. This results in increased system throughput, reduced delay for TCP ACK packets, and enhanced priority mechanisms for VLC uplink scenarios. The prioritization mechanism supports multiple priority flows that are active and improves throughput and delay in multiple scenarios.

On the experimental side, we implement an actual testbed with OpenVLC, showcasing the immense potential of our intelligent management system for controlling operations in hybrid networks, particularly during handover procedures. We deploy algorithms using fuzzy logic and ML to help the IMS adapt to different scenarios. The results clearly demonstrate that the management system is essential for improving robustness and seamless user experiences when dealing with handover in hybrid networks. Fuzzy logic is up to standard for handover procedures, while ML algorithms based on the AdaBoost C4.5 algorithm prove to be the most promising after the tuning process, achieving 97.5% accuracy in predicting handover decisions.

Various applications and case studies discussed in this thesis underscore the far-reaching implications of our hybrid VLC/RF architecture. From smart cities and industrial IoT to retail, healthcare, agriculture, and entertainment sectors, the deployment of this technology holds tremendous potential to transform the way we live, work, and engage with one another.

Through the integration of advanced features such as energy-efficient communication, seamless connectivity, accurate tracking and localization, and privacy-preserving data processing, our proposed architecture sets the stage for a new era of technological advancements. As demonstrated in the diverse case studies, businesses and organizations can harness the benefits of this novel system to optimize operations, enhance customer experiences, and streamline decision-making processes. Moreover, the adoption of our intelligent management system architecture contributes to global sustainability efforts by promoting energy efficiency and enabling smarter resource allocation. This is particularly significant given the rising demand for energy and the need to reduce greenhouse gas emissions in order to mitigate climate change.

Future research for hybrid networks should focus on enhancing the energy harvesting component by exploring more efficient techniques and a broader range of ambient energy sources. This could lead to extended device lifetimes and reduced reliance on traditional energy grids. Additionally, the development of advanced algorithms for dynamic resource optimization could increase energy savings and system sustainability. Further exploration into federated learning algorithms for tracking and localization could improve system efficiency and accuracy. Security advancements, such as sophisticated encryption techniques, secure handover mechanisms, and real-time threat detection, could provide a more robust and reliable communication environment. Lastly, continuous assessment and optimization of the system's overall architecture will ensure it effectively adapts to changing user needs and technological advancements.

List of Publications

[1] Kien Trung Ngo, Stefano Mangione, and Ilenia Tinnirello. 2021. *Exploiting EDCA for feedback channels in hybrid VLC/WiFi architectures*. In *19th Mediterranean Communication and Computer Networking Conference (MedComNet)*, IEEE, 2021.

[2] Kien Trung Ngo, et al. 2022. *Hybrid VLC/WiFi Architectures with Priority Feedback Channels*. In *61st FITCE International Congress Future Telecommunications: Infrastructure and Sustainability (FITCE)*, IEEE, 2022.

[3] Kien Trung Ngo, et al. 2023. *Seamless Handover in Hybrid VLC and WiFi Network: A Testbed Scenario*. In *12th International Conference on Communications, Circuits, and Systems (ICCCAS)*, IEEE, 2023.

(Best Oral Presentations Award)

[4] Kien Trung Ngo, Stefano Mangione, and Ilenia Tinnirello. 2023. *A Novel Intelligent Management System Architecture for Hybrid VLC/RF Systems in Smart Retail Environment*. In *The 29th Annual International Conference on Mobile Computing and Networking (ACM MobiCom '23)*, October 2–6, 2023, Madrid, Spain. ACM, New York, NY, USA, 3 pages. `https://doi.org/10.1145/3570361.3615725`.

(Best Poster Award at the MobiCom 2023)

(Third-Place winner for Mobicom 2023 Student Research Competition)

[5] Kien Trung Ngo, et al. *Intelligent Management System for Hybrid Network VLC and RF: Architecture and Applications*. To be submitted.

Bibliography

[1] Cisco. *Cisco visual networking index: Forecast and Trends, 2017-2022.* Tech. rep. Nov. 2018.

[2] Toni Besjedica, Krešimir Fertalj, Vlatko Lipovac, and Ivona Zakarija. "Evolution of Hybrid LiFi–WiFi Networks: A Survey". In: *Sensors* 23.9 (2023), p. 4252.

[3] Lisandra Bravo Alvarez, Samuel Montejo-Sánchez, Lien Rodríguez-López, Cesar Azurdia-Meza, and Gabriel Saavedra. "A Review of Hybrid VLC/RF Networks: Features, Applications, and Future Directions". In: *Sensors* 23.17 (2023), p. 7545.

[4] Saeed Ur Rehman, Shakir Ullah, Peter Han Joo Chong, Sira Yongchareon, and Dan Komosny. "Visible Light Communication: A System PerspectiveâOverview and Challenges". In: *Sensors* 19.5 (2019), p. 1153.

[5] Mostafa Zaman Chowdhury, Moh Khalid Hasan, Md Shahjalal, Md Tanvir Hossan, and Yeong Min Jang. "Optical Wireless Hybrid Networks: Trends, Opportunities, Challenges, and Research Directions". In: *IEEE Communications Surveys & Tutorials* 22.2 (2020), pp. 930–966.

[6] Harald Burchardt, Nikola Serafimovski, Dobroslav Tsonev, Stefan Videv, and Harald Haas. "VLC: Beyond point-to-point communication". In: *IEEE Communications Magazine* 52.7 (2014), pp. 98–105.

[7] Dhurgham Abdulridha Jawad Al-Khaffaf and Ali M Alsahlany. "A cloud VLC access point design for 5G and beyond". In: *Optical and Quantum Electronics* 53.8 (2021), p. 472.

[8] W Zhang and Mohsen Kavehrad. "Comparison of VLC-based indoor positioning techniques". In: *Broadband access communication technologies VII*. Vol. 8645. SPIE. 2013, pp. 152–157.

[9] Kien Trung Ngo, Mika Hoppari, Jani Suomalainen, and Marko Höyhtyä. "Distributed LSA Controller for Public Safety Communications". In: *2018 IEEE 4th International Conference on Computer and Communications (ICCC)*. IEEE. 2018, pp. 1134–1138.

[10] Marko Höyhtyä, Kalle Lähetkangas, Jani Suomalainen, Mika Hoppari, Kaisa Kujanpää, Kien Trung Ngo, Tero Kippola, Marjo Heikkilä, Harri Posti, Jari Mäki, et al. "Critical Communications Over Mobile Operatorsâ Networks: 5G Use Cases Enabled by Licensed Spectrum Sharing, Network Slicing and QoS Control". In: *IEEE Access* 6 (2018), pp. 73572–73582.

[11] Grandviewresearch. *LED Lighting Market Size, Share and Trends Analysis Report By End Use (Residential, Commercial, Industrial, Others), By Product (Lamps, Luminaires), By Application (Indoor, Outdoor), And Segment Forecasts, 2020 - 2027*. Tech. rep. Jun, 2020.

[12] PureLiFi. *PureLiFi technology overview*. https://purelifi.com/technology. May 2021.

[13] Sharan Naribole, Shuqing Chen, Ethan Heng, and Edward Knightly. "LiRa: A WLAN architecture for visible light communication with a Wi-Fi uplink". In: *2017 14th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON)*. IEEE. 2017, pp. 1–9.

[14] Shlomi Arnon. *Visible light communication*. Cambridge University Press, 2015.

[15] Luiz Eduardo Mendes Matheus, Alex Borges Vieira, Luiz FM Vieira, Marcos AM Vieira, and Omprakash Gnawali. "Visible light communication: concepts, applications and challenges". In: *IEEE Communications Surveys & Tutorials* 21.4 (2019), pp. 3204–3237.

[16] Dominic C O'brien, Lubin Zeng, Hoa Le-Minh, Grahame Faulkner, Joachim W Walewski, and Sebastian Randel. "Visible light communications: Challenges and possibilities". In: *2008 IEEE 19th International Symposium on Personal, Indoor and Mobile Radio Communications*. IEEE. 2008, pp. 1–5.

[17] Parth H Pathak, Xiaotao Feng, Pengfei Hu, and Prasant Mohapatra. "Visible light communication, networking, and sensing: A survey, potential and challenges". In: *IEEE communications surveys & tutorials* 17.4 (2015), pp. 2047–2077.

[18] Irina Stefan and Harald Haas. "Hybrid visible light and radio frequency communication systems". In: *2014 IEEE 80th Vehicular Technology Conference (VTC2014-Fall)*. IEEE. 2014, pp. 1–5.

[19] Wei Guo, Qing Li, Hong-Yi Yu, and Jian-hui Liu. "A Parallel Transmission MAC Protocol in Hybrid VLC-RF Network." In: *J. Commun.* 10.1 (2015), pp. 80–85.

[20] Jacob Chakareski and Mahmudur Khan. "Wifi-VLC Dual Connectivity Streaming System for 6DOF Multi-User Virtual Reality". In: *Proceedings of the 31st ACM Workshop on Network and Operating Systems Support for Digital Audio and Video*. NOSSDAV '21. Istanbul, Turkey: Association for Computing Machinery, 2021, 106â113. ISBN: 9781450384353. DOI: 10.1145/3458306.3460999. URL: https://doi.org/10.1145/3458306.3460999.

[21] Kien Trung Ngo, Fabrizio Giuliano, Daniele Croce, Stefano Mangione, Ilenia Tinnirello, and Giovanni Garbo. "Hybrid VLC/WiFi Architectures with Priority Feedback Channels". In: *2022 61st FITCE International Congress Future Telecommunications: Infrastructure and Sustainability (FITCE)*. 2022, pp. 1–6. DOI: 10.23919/FITCE56290.2022.9934522.

[22] Kien Trung Ngo, Stefano Mangione, and Ilenia Tinnirello. "Exploiting EDCA for Feedback Channels in Hybrid VLC/WiFi Architectures". In: *2021 19th Mediterranean Communication and Computer Networking Conference (MedComNet)*. 2021, pp. 1–6. DOI: 10.1109/MedComNet52149.2021.9501241.

[23] Abdulmajeed M Alenezi and Khairi A Hamdi. "Reinforcement learning approach for content-aware resource allocation in hybrid WiFi-VLC networks". In: *2021 IEEE 93rd Vehicular Technology Conference (VTC2021-Spring)*. IEEE. 2021, pp. 1–5.

[24] Liwei Yang, Lu Yang, Jianming Wang, Tiancheng Huang, Xin Tian, Langnima Suo, and Qi Zhang. "Resource allocation for hybrid visible light communications (VLC)-WiFi networks". In: *2021 9th International Conference on Communications and Broadband Networking*. 2021, pp. 310–313.

[25] Xuan Li, Rong Zhang, and Lajos Hanzo. "Cooperative load balancing in hybrid visible light communications and WiFi". In: *IEEE Transactions on Communications* 63.4 (2015), pp. 1319–1329.

[26] Abdallah Khreishah, Sihua Shao, Ammar Gharaibeh, Moussa Ayyash, Hany Elgala, and Nirwan Ansari. "A hybrid RF-VLC system for energy efficient wireless access". In: *IEEE Transactions on Green Communications and Networking* 2.4 (2018), pp. 932–944.

[27] Shuai Ma, Fan Zhang, Hang Li, Fuhui Zhou, Mohamed-Slim Alouini, and Shiyin Li. "Aggregated VLC-RF systems: Achievable rates, optimal power allocation, and energy efficiency". In: *IEEE Transactions on Wireless Communications* 19.11 (2020), pp. 7265–7278.

[28] Weihua Wu, Fen Zhou, and Qinghai Yang. "Adaptive network resource optimization for heterogeneous VLC/RF wireless networks". In: *IEEE Transactions on Communications* 66.11 (2018), pp. 5568–5581.

[29] Jialiang Zhang, Chi Zhang, Xinyu Zhang, and Suman Banerjee. "Towards a visible light network architecture for continuous communication and localization". In: *Proceedings of the 3rd Workshop on Visible Light Communication Systems*. 2016, pp. 49–54.

[30] Qing Liang and Ming Liu. "Plugo: a vlc systematic perspective of large-scale indoor localization". In: *arXiv preprint arXiv:1709.06926* (2017).

[31] Richard D Roberts, Sridhar Rajagopal, and Sang-Kyu Lim. "IEEE 802.15. 7 physical layer summary". In: *2011 IEEE GLOBECOM Workshops (GC Wkshps)*. IEEE. 2011, pp. 772–776.

[32] Changyuan Yu, Xiaodi You, Zhongxu Liu, and Jian Chen. "Conceptual design for indoor visible light communication and positioning cooperative systems". In: *2020 22nd International Conference on Transparent Optical Networks (ICTON)*. IEEE. 2020, pp. 1–4.

[33] Oluwaseyi Paul Babalola and Vipin Balyan. "Vertical handover prediction based on hidden markov model in heterogeneous VLC-WiFi system". In: *Sensors* 22.7 (2022), p. 2473.

[34] Fubin Wang, Fang Yang, Changyong Pan, Jian Song, and Zhu Han. "Hybrid VLC-RF Systems with Multi-users for Achievable Rate and Energy Efficiency Maximization". In: *IEEE Transactions on Wireless Communications* (2023).

[35] Shengnan Shi, Guan Gui, Yun Lin, Chau Yuen, Octavia A Dobre, and Fumiyuki Adachi. "Joint Beamformer Design and Power Allocation Method for Hybrid RF-VLCP System". In: *IEEE Internet of Things Journal* (2023).

[36] Fubin Wang, Fang Yang, Jian Song, and Zhu Han. "Access frameworks and application scenarios for hybrid VLC and RF systems: state of the art, challenges, and trends". In: *IEEE Communications Magazine* 60.3 (2022), pp. 55–61.

[37] Mohanad Obeed, Anas M Salhab, Mohamed-Slim Alouini, and Salam A Zummo. "On optimizing VLC networks for downlink multi-user transmission: A survey". In: *IEEE Communications Surveys & Tutorials* 21.3 (2019), pp. 2947–2976.

[38] Abu Jahid, Mohammed H Alsharif, and Trevor J Hall. "A contemporary survey on free space optical communication: Potentials, technical challenges, recent advances and research direction". In: *Journal of Network and Computer Applications* 200 (2022), p. 103311.

[39] Gaofeng Pan, Jia Ye, and Zhiguo Ding. "Secure hybrid VLC-RF systems with light energy harvesting". In: *IEEE Transactions on Communications* 65.10 (2017), pp. 4348–4359.

[40] Cheng-Xiang Wang, Xiaohu You, Xiqi Gao, Xiuming Zhu, Zixin Li, Chuan Zhang, Haiming Wang, Yongming Huang, Yunfei Chen, Harald Haas, et al. "On the road to 6G: Visions, requirements, key technologies and testbeds". In: *IEEE Communications Surveys & Tutorials* (2023).

[41] Sylvester Aboagye, Ahmed Ibrahim, Telex MN Ngatched, Alain R Ndjiongue, and Octavia A Dobre. "Design of energy efficient hybrid VLC/RF/PLC communication system for indoor networks". In: *IEEE Wireless Communications Letters* 9.2 (2019), pp. 143–147.

[42] Mohamed Kashef, Mohamed Abdallah, and Naofal Al-Dhahir. "Transmit power optimization for a hybrid PLC/VLC/RF communication system". In: *IEEE Transactions on Green Communications and Networking* 2.1 (2017), pp. 234–245.

[43] Weihua Wu, Fen Zhou, and Qinghai Yang. "Dynamic network resource optimization in hybrid VLC and radio frequency networks". In: *2017 International Conference on Selected Topics in Mobile and Wireless Networking (MoWNeT)*. IEEE. 2017, pp. 1–7.

[44] Shivanshu Shrivastava, Bin Chen, Chen Chen, Hui Wang, and Mingjun Dai. "Deep Q-network learning based downlink resource allocation for hybrid RF/VLC systems". In: *IEEE Access* 8 (2020), pp. 149412–149434.

[45] Mohanad Obeed, Anas M Salhab, Salam A Zummo, and Mohamed-Slim Alouini. "Joint optimization of power allocation and load balancing for hybrid VLC/RF networks". In: *Journal of Optical Communications and Networking* 10.5 (2018), pp. 553–562.

[46] Yangbo Guo, Ke Xiong, Yang Lu, Duohua Wang, Pingyi Fan, and Khaled Ben Letaief. "Achievable information rate in hybrid VLC-RF networks with lighting energy harvesting". In: *IEEE Transactions on Communications* 69.10 (2021), pp. 6852–6864.

[47] Yusuf Said Eroglu, Ismail Guvenc, Nezih Pala, and Murat Yuksel. "AOA-based localization and tracking in multi-element VLC systems". In: *2015 IEEE 16th annual wireless and microwave technology conference (WAMICON)*. IEEE. 2015, pp. 1–5.

[48] Wessam M Salama, Moustafa H Aly, and Eman S Amer. "VLC localization: Deep learning models by Kalman filter algorithm combined with RSS". In: *Optical and Quantum Electronics* 54.9 (2022), p. 584.

[49] Gaofeng Pan, Hongjiang Lei, Zhiguo Ding, and Qiang Ni. "3-D hybrid VLC-RF indoor IoT systems with light energy harvesting". In: *IEEE Transactions on Green Communications and Networking* 3.3 (2019), pp. 853–865.

[50] Ali Hassan Sodhro, Ali Ismail Awad, Jaap van de Beek, and George Nikolakopoulos. "Intelligent authentication of 5G healthcare devices: A survey". In: *Internet of Things* (2022), p. 100610.

[51] Gaofeng Pan, Jia Ye, Chao Zhang, Jianping An, Hongjiang Lei, Zhiguo Ding, and Mohamed Slim Alouini. "Secure cooperative hybrid VLC-RF systems". In: *IEEE Transactions on Wireless Communications* 19.11 (2020), pp. 7097–7107.

[52] Mohamed Amine Arfaoui, Mohammad Dehghani Soltani, Iman Tavakkolnia, Ali Ghrayeb, Majid Safari, Chadi M Assi, and Harald Haas. "Physical layer security for visible light communication systems: A survey". In: *IEEE Communications Surveys & Tutorials* 22.3 (2020), pp. 1887–1908.

[53] Pawani Porambage, Gürkan Gür, Diana Pamela Moya Osorio, Madhusanka Liyanage, and Mika Ylianttila. "6G security challenges and potential solutions". In: *2021 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*. IEEE. 2021, pp. 622–627.

[54] Amir Hossein Fahim Raouf, Chethan Kumar Anjinappa, and Ismail Guvenc. "Optimal Design of Energy-Harvesting Hybrid VLC/RF Networks". In: *2022 IEEE Globecom Workshops (GC Wkshps)*. IEEE. 2022, pp. 705–710.

[55] Qiuyue Hu, Chaoqin Gan, Xuefeng Liu, Guiyu Gong, and Yifan Zhu. "Dynamic handover cost modeling in hybrid VLC/RF networks". In: *Ad Hoc Networks* 146 (2023), p. 103174.

[56] Seyed Mohammad Sheikholeslami, Arash Rasti-Meymandi, Seyed Jamal Seyed-Mohammadi, Jamshid Abouei, and Konstantinos N Plataniotis. "Communication-Efficient Federated Learning for Hybrid VLC/RF Indoor Systems". In: *IEEE Access* 10 (2022), pp. 126479–126493.

[57] Sherief Hashima, Mostafa M Fouda, Sadman Sakib, Zubair Md Fadlullah, Kohei Hatano, Ehab Mahmoud Mohamed, and Xuemin Shen. "Energy-aware hybrid RF-VLC multiband selection in D2D communication: A stochastic multiarmed bandit approach". In: *IEEE Internet of Things Journal* 9.18 (2022), pp. 18002–18014.

[58] Michael B Rahaim, Anna Maria Vegni, and Thomas DC Little. "A hybrid Radio Frequency and broadcast Visible Light Communication system". In: *2011 IEEE GLOBECOM Workshops (GC Wkshps)*. IEEE. 2011, pp. 792–796.

[59] Hisham Abuella, Mohammed Elamassie, Murat Uysal, Zhengyuan Xu, Erchin Serpedin, Khalid A Qaraqe, and Sabit Ekin. "Hybrid RF/VLC Systems: A Comprehensive Survey on Network Topologies, Performance Analyses, Applications, and Future Directions". In: *arXiv preprint arXiv:2007.02466* (2020).

[60] Sihua Shao, Abdallah Khreishah, Michael B Rahaim, Hany Elgala, Moussa Ayyash, Thomas DC Little, and Jie Wu. "An indoor hybrid WiFi-VLC internet access system". In: *2014 IEEE 11th International Conference on Mobile Ad Hoc and Sensor Systems*. IEEE. 2014, pp. 569–574.

[61] Xiping Wu, Mohammad Dehghani Soltani, Lai Zhou, Majid Safari, and Harald Haas. "Hybrid LiFi and WiFi Networks: A Survey". In: *arXiv preprint arXiv:2001.04840* (2020).

[62] Isiaka Ajewale Alimi, Abdelgader M Abdalla, Jonathan Rodriguez, Paulo Pereira Monteiro, Antonio Luís Teixeira, Stanislav Zvánovec, and Zabih Ghassemlooy. "Enabling VLC and WiFi network technologies and architectures toward 5G". In: *Optical and Wireless Convergence for 5G Networks* (2019), pp. 101–122.

[63] Pravallika Dhulipalla, Minju Kang, Taejin Kim, Nathaniel Tan, Siddhartan Govindasamy, and Michael B Rahaim. "An Integrated Visible-Light and Radio Frequency Communications System". In: *2019 International Conference on Computer, Information and Telecommunication Systems (CITS)*. IEEE. 2019, pp. 1–6.

[64] Dushyantha A Basnayaka and Harald Haas. "Hybrid RF and VLC systems: Improving user data rate performance of VLC systems". In: *2015 IEEE 81st Vehicular Technology Conference (VTC Spring)*. IEEE. 2015, pp. 1–5.

[65] A. Galisteo, D. Juara, and D. Giustiniano. "Research in Visible Light Communication Systems with OpenVLC1.3". In: *IEEE World Forum on Internet of Things (WF-IoT)*. 2019.

[66] Gustavo Carneiro. "NS-3: Network simulator 3". In: *UTM Lab Meeting April*. Vol. 20. 2010, pp. 4–5.

[67] George F Riley and Thomas R Henderson. "The ns-3 network simulator". In: *Modeling and tools for network simulation*. Springer, 2010, pp. 15–34.

[68] Klaus Wehrle, Mesut Günes, and James Gross. *Modeling and Tools for network simulation*. Springer Science & Business Media, 2010.

[69] Anna Maria Vegni and Thomas DC Little. "Handover in VLC systems with cooperating mobile devices". In: *2012 International conference on computing, networking and communications (ICNC)*. IEEE. 2012, pp. 126–130.

[70] Xiping Wu and Harald Haas. "Handover skipping for LiFi". In: *IEEE Access* 7 (2019), pp. 38369–38378.

[71] Rabe Arshad, Hesham ElSawy, Sameh Sorour, Tareq Y Al-Naffouri, and Mohamed-Slim Alouini. "Handover management in 5G and beyond: A topology aware skipping approach". In: *IEEE Access* 4 (2016), pp. 9073–9081.

[72] Ardimas Andi Purwita, Mohammad Dehghani Soltani, Majid Safari, and Harald Haas. "Handover probability of hybrid LiFi/RF-based networks with randomly-oriented devices". In: *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*. IEEE. 2018, pp. 1–5.

[73] Fang Wang, Zhaocheng Wang, Chen Qian, Linglong Dai, and Zhixing Yang. "Efficient vertical handover scheme for heterogeneous VLC-RF systems". In: *Journal of Optical Communications and Networking* 7.12 (2015), pp. 1172–1180.

[74] Yunlu Wang, Xiping Wu, and Harald Haas. "Fuzzy logic based dynamic handover scheme for indoor Li-Fi and RF hybrid network". In: *2016 IEEE International Conference on Communications (ICC)*. IEEE. 2016, pp. 1–6.

[75] Liqiang Wang, Dahai Han, Min Zhang, Danshi Wang, and Zhiguo Zhang. "Deep reinforcement learning-based adaptive handover mechanism for VLC in a hybrid 6G network architecture". In: *IEEE Access* 9 (2021), pp. 87241–87250.

[76] Elnaz Alizadeh Jarchlo, Elizabeth Eso, Hossein Doroud, Bernhard Siessegger, Zabih Ghassemlooy, Giuseppe Caire, and Falko Dressler. "Li-Wi: An upper layer hybrid VLC-WiFi network handover solution". In: *Ad Hoc Networks* 124 (2022), p. 102705.

[77] Xiping Wu, Mohammad Dehghani Soltani, Lai Zhou, Majid Safari, and Harald Haas. "Hybrid LiFi and WiFi networks: A survey". In: *IEEE Communications Surveys & Tutorials* 23.2 (2021), pp. 1398–1420.

[78] Kien Trung Ngo, Stefano Mangione, and Ilenia Tinnirello. "A Novel Intelligent Management System Architecture for Hybrid VLC/RF Systems in Smart Retail Environment". In: *Proceedings of the 29th Annual International Conference on Mobile Computing and Networking*. 2023, pp. 1–3.

[79] Ander Galisteo, Diego Juara, and Domenico Giustiniano. "Research in Visible Light Communication Systems with OpenVLC1.3". In: *2019 IEEE 5th World Forum on Internet of Things (WF-IoT)*. 2019, pp. 539–544. DOI: 10.1109/WF-IoT.2019.8767252.

[80] Wei Wang, Alex X Liu, Muhammad Shahzad, Kang Ling, and Sanglu Lu. "Understanding and modeling of wifi signal based human activity recognition". In: *Proceedings of the 21st annual international conference on mobile computing and networking*. 2015, pp. 65–76.

[81] Xiang Li, Daqing Zhang, Qin Lv, Jie Xiong, Shengjie Li, Yue Zhang, and Hong Mei. "IndoTrack: Device-free indoor human tracking with commodity Wi-Fi". In: *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 1.3 (2017), pp. 1–22.

[82] Mohammad Amir Dastgheib, Hamzeh Beyranvand, and Jawad A Salehi. "Optimal visible light communication access point placement under stationary distribution of usersâ mobility". In: *2018 9th International Symposium on Telecommunications (IST)*. IEEE. 2018, pp. 96–101.

[83] Mohammad Amir Dastgheib, Hamzeh Beyranvand, and Jawad A Salehi. "Optimal placement of access points in cellular visible light communication networks: An adaptive gradient projection method". In: *IEEE Transactions on Wireless Communications* 19.10 (2020), pp. 6813–6825.

[84] Zengyi Xu, Jianyang Shi, Wenqing Niu, Guojin Qin, Ruizhe Jin, Zhixue He, and Nan Chi. "Transfer Learning Strategy in Neural Network Application for Underwater Visible Light Communication System". In: *Sensors* 22.24 (2022), p. 9969.

[85] Zhenquan Zhao, Faisal Nadeem Khan, Yibin Li, Zhaoming Wang, Yuan Zhang, and HY Fu. "Application and comparison of active and transfer learning approaches for modulation format classification in visible light communication systems". In: *Optics Express* 30.10 (2022), pp. 16351–16361.

[86] Stefano Caputo, Giacomo Borghini, Sara Jayousi, Adnan Rashid, and Lorenzo Mucchi. "Visible Light Communications for Healthcare Applications: Opportunities and Challenges". In: *2023 IEEE 17th International Symposium on Medical Information and Communication Technology (ISMICT)*. IEEE. 2023, pp. 1–6.