A Novel Intelligent Management System Architecture for Hybrid VLC/RF Systems in Smart Retail Environment

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ABSTRACT

In this paper, we present a novel intelligent management system (IMS) for smart retail environments that integrates various components to optimize user experience, energy efficiency, and seamless connectivity. The proposed architecture incorporates an Intelligent Handover Controller, an Energy Harvesting Module, Adaptive Resource Management, Edge Tracking and Localization. Preliminary testbed results show promising performance in maintaining seamless handovers between VLC and WiFi links, as well as accurate tracking of user mobility based on CSI. This advanced architecture offers the potential for significant improvements in smart retail operations by providing uninterrupted connectivity, targeted marketing, optimized store layouts, and enhanced user experiences.

CCS CONCEPTS

• **Networks** → **Network management**; **Wireless local area networks**; **Cognitive radios**.

KEYWORDS

intelligent management system, hybrid architecture, visible light communication, handover

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1 INTRODUCTION

With the rapid proliferation of wireless communication technologies, there is an increasing need for solutions that capitalize on the complementary strengths of different systems. Visible Light Communication (VLC) and Radio Frequency (RF) are two such technologies that can be combined to enhance wireless communication capabilities. VLC offers high data rates and low latency, while RF provides wide coverage and robustness in non-line-of-sight conditions. Integrating these technologies requires an efficient management system to enable seamless handovers and optimized resource utilization. This paper presents a novel IMS architecture for hybrid VLC/RF systems that addresses these challenges. Through our testbed implementation, we demonstrate promising results in terms of implementing a robust handover scheme and accurately detecting user mobility within various scenarios. This innovative approach highlights the potential of the proposed architecture in enhancing the performance of hybrid VLC/RF systems and optimizing user experience.

2 NOVELTY OF THE PROPOSED SOLUTION

In this section, we introduce our novel architecture that overcomes the limitations of existing systems and ensures seamless connectivity. The proposed solution incorporates several key innovations: an intelligent handover controller for adaptive handovers; energy harvesting capabilities to utilize ambient energy sources; adaptive resource management that optimizes and reallocates resources within the hybrid VLC/RF network; edge computing that adapts to user movement patterns and network conditions while preserving privacy and enabling accurate tracking and localization. The proposed system architecture comprises six main components, as illustrated in Figure 1:

1. Hybrid VLC/RF Communication Infrastructure: This infrastructure combines dual-mode VLC-enabled LED lights for illumination and data transmission, with wideband RF access points ensuring seamless handovers between links through advanced beamforming and MIMO technology. The

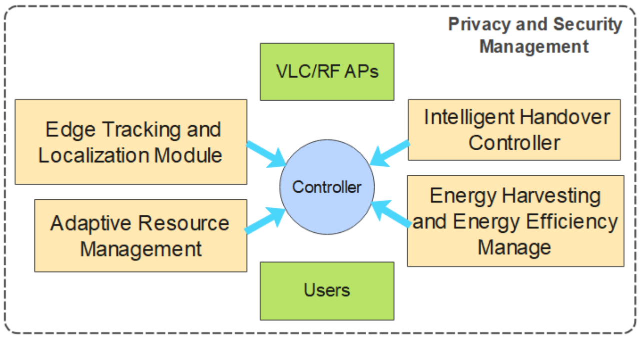

Figure 1: System design framework

hybrid architecture supports efficient resource allocation, interference mitigation, and adaptive modulation. It provides scalability and flexibility for various network topologies, devices, applications, and user densities. Current data collected by this infrastructure includes RSSI measurements from both VLC and RF networks and CSI information.

2. Intelligent Handover Controller (IHC): Utilizing context-aware decision-making and machine learning algorithm, the IHC adapts to user situations and conducts dynamic load-aware control for congestion prevention and resource balancing. The IHC processes user speed and location information derived from the RSSI and CSI data provided by the edge tracking module. Proactive handover prediction uses historical mobility data and real-time tracking. Multi-criteria optimization evaluates performance metrics, enabling seamless handovers across access technologies and same-technology cells. A fault-tolerant mechanism monitors the hybrid VLC/RF system and initiates fail-safe procedures when required.

3. Energy Harvesting and Energy Efficiency Manager (EHM) System: The EHM system captures ambient energy from various sources, converting it into electrical power[3]. An intelligent energy storage and management subsystem continuously monitors levels to maximize utilization. The energy efficiency adjusts VLC-enabled LED brightness, deactivates idle links, and reallocates resources for optimal usage. During handover decisions, the IHC takes energy efficiency into account, prioritizing efficient channels while sustaining a high-quality user experience and connectivity. The resource optimization scheme employed by this module is managing energy resources and balancing energy consumption across the network.

4. Adaptive Resource Management System (ARS): This system intelligently prioritizes traffic flows for optimal QoS, employing adaptive resource management to consolidate available resources from VLC and RF modules. Smart resource allocation uses machine learning algorithms to optimally distribute resources based on network conditions and user requirements, taking into account the RSSI and CSI data. Dynamic load balancing prevents congestion, and virtual network function orchestration manages the hybrid network's virtualized functions and resources, reducing complexity and enhancing efficiency.

5. Edge Tracking and Localization (ETL): ETL leverages edge computing for localized processing, decreasing latency and enhancing user experience[2]. Federated learning algorithms maintain privacy while enabling collaborative model training. The ETL node processes RSSI measurements from both VLC and RF networks and CSI information from RF to infer user speed and location. Dynamic handover prediction minimizes service interruptions, and real-time adaptation ensures consistent performance. Privacy-preserving techniques, such as federated learning, differential privacy, and secure multi-party computation, safeguard user information during collaboration and decision-making.

6. Privacy and Security Management: ETL employs federated learning for secure tracking and localization. The IHC utilizes advanced encryption techniques for handover protection. Real-time threat monitoring allows for detection and mitigation of cyber threats, while security-aware resource allocation gives priority to secure channels for critical applications. Privacy-preserving data processing and storage technologies ensure the protection of user data both at rest and in transit.

3 SMART RETAIL ENVIRONMENT

In smart retail environments, the IMS in a hybrid system to improve customer experiences and streamline store operations. Hybrid access points offer high-speed data transmission for personalized promotions based on customers' locations. The ETL component tracks customer movements, allowing retailers to optimize layouts, product placements, and shopping experiences by analyzing behavioral patterns. It also employs predictive analytics for anticipating future customer locations. The IHC ensures uninterrupted connectivity as users navigate the store, enabling smooth transitions between VLC and RF networks. Energy efficiency is prioritized through dynamic adjustments of LED brightness levels considering ambient light, customer presence, and store requirements while managing idle links intelligently to conserve energy and reduce operational costs. The ARS works in conjunction with the IHC and ETL components to allocate resources efficiently, intelligently prioritizing traffic flows and delivering enhanced user experiences while minimizing expenses. Robust privacy and security measures, including encryption algorithms, authentication mechanisms, and access control policies, protect customer data and ensure secure communications within VLC and RF networks, fostering trust in retail services and safeguarding user privacy.

4 PERFORMANCE EVALUATION

4.1 Experimental Setup

In the evaluation, we focus on two main aspects: seamless connectivity managed by the IHC and tracking user mobility using the ETL. Our testbed is based on OpenVLC 1.3 [1]. The testbed comprises two VLC/WiFi transmitters, one VLC/WiFi receiver, and an IHC developed using the Fabric framework to gather information and control all devices within the network. Regarding seamless connectivity, we implemented a simple and effective fuzzy logic controller to handle all handover operations. There are three parts to the handover process: sensing, decision-making, and execution periods. We set the sensing time at 3 seconds, striking a balance between system performance and user experience. The decision-making is based on the RSSI values from both networks with a certain threshold, where we observed a significant drop in QoE for the end-user. The algorithm is designed to manage both VHO and HHO and we prioritized HHO over VHO in most cases. Finally, we recorded the execution time to observe the transition duration between networks for users. This time can also be seen as an interruption time since we employed hard handover in this case. Regarding the ETL, we collected CSI from the WiFi channel and extracted the Doppler velocity element as a characteristic to estimate user mobility in our testbed. The receiver moved linearly between two transmitters following this pattern: accelerated movement for 10 seconds, standstill for 10 seconds, and then decelerated movement for 10 seconds.

4.2 Overall Performance

Preliminary results from our testbed implementation reveal promising outcomes for the IHC, indicating effective handovers between different links with minimal disruption (approximately 250 ms) for both HHO and VHO, as shown in Table 1. Regarding ETL, accurate user movement tracking is crucial for system adaptability based on user condition. The Doppler velocity element allows for precise estimation of users' mobility, as depicted in Figure 2, within our testbed scenario. This information can be used to optimize network operations and predict potential bottlenecks. In summary, the initial performance evaluation of the IMS highlights its potential in providing seamless connectivity and accurately tracking user mobility within a smart retail environment.

5 CONCLUSIONS

Integrating hybrid VLC/RF Access Points with IHC, ETL, and EHM systems, the IMS architecture provides seamless connectivity, intelligent handovers, precise tracking, localization, energy efficiency, privacy, scalability, flexibility, and enhanced network coordination. Preliminary results show promising performance in managing the hybrid system. The IHC demonstrates promising performance in managing handovers between VLC and RF links for seamless transitions and QoS. ETL crucially tracks user mobility using CSI, allowing the system to adapt LED brightness, resource allocation, and store operations for improved customer experiences and energy efficiency.

Table 1: Handover process

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

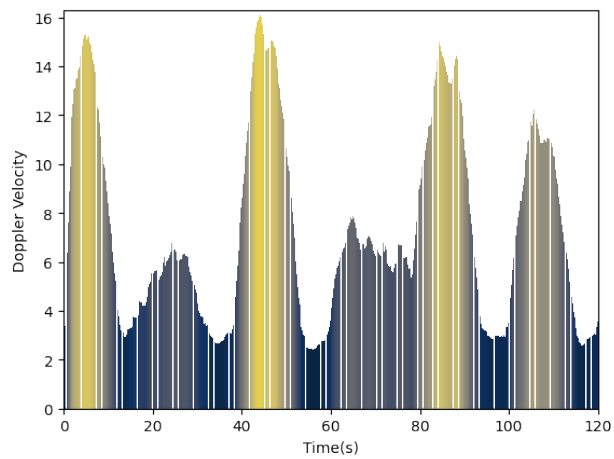

Figure 2: Doppler velocity envelope extracted from CSI

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