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Securing Optical Wireless Communication: A Cryptographic Approach for Li-Fi Networks

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Abstract

Li-Fi (Light Fidelity) has emerged as a revolutionary optical wireless communication (OWC) technology that uses visible light to transmit data at high speed, offering a compelling alternative to conventional RF-based systems, especially in environments sensitive to electromagnetic interference and those demanding high-density connectivity. Despite the inherent physical security advantage that visible light beams cannot penetrate walls, Li-Fi remains vulnerable to practical threats such as eavesdropping, interception, and sophisticated signal manipulation through channel leakage, reflection, and ambient light noise, which necessitates robust, network-layer security mechanisms. Addressing this critical gap, this research proposes a novel hybrid cryptographic framework specifically designed to be lightweight and scalable for the resource-constrained nature of OWC devices. The framework systematically combines the robust, high-throughput capabilities of the Advanced Encryption Standard (AES) for efficient bulk data encryption with the low-power, compact key size security of Elliptic Curve Cryptography (ECC) for efficient session key exchange, authentication, and non-repudiation. The proposed system ensures data confidentiality, integrity, and authentication between the transmitter (LED-based) and receiver (photodiode-based) nodes within a Li-Fi network, providing end-to-end security that is essential for mission-critical applications. Novel contributions include a lightweight key management protocol tailored to the dynamic and typically line-of-sight visible light links, and a detailed power consumption analysis of the cryptographic operations confirming its suitability for energy-efficient IoT Li-Fi applications. Experimental simulations, conducted on a realistic Li-Fi channel model incorporating signal-to-noise ratio degradation, demonstrate that the encryption overhead is minimal ($<8\%$), which is highly competitive, while simultaneously maintaining a high network throughput efficiency of 94.5%. Furthermore, the proposed hybrid cryptosystem is rigorously proven to achieve robust resistance against modern

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cryptanalytic attacks, including differential analysis, man-in-the-middle attacks, and brute-force key search, thereby establishing a new, feasible security benchmark for secure data transmission across practical Li-Fi deployments and laying the foundation for integrating advanced cryptographic features into future OWC standards.

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1. Introduction

The exponential growth in global data traffic has relentlessly driven the demand for higher bandwidth and greater spectral resources, leading to severe spectrum congestion and interference within the conventional radio frequency (RF) band. This challenge has prompted intensive research into new communication paradigms, most notably Li-Fi (Light Fidelity). Li-Fi is an innovative Optical Wireless Communication (OWC) technology that leverages the vast, unlicensed visible light spectrum (430–770 THz) to transmit high-speed data using Light Emitting Diodes (LEDs). By exploiting the dual function of illumination and communication, Li-Fi offers several distinct advantages over traditional Wi-Fi, including ultra-high bandwidth potential, superior energy efficiency, and complete immunity to electromagnetic interference. Initially conceptualized by Harald Haas in 2011, Li-Fi is now considered a core enabler for next-generation communication in dense urban environments, critical infrastructure, and highly interconnected systems like the Internet of Things (IoT) and future 5G/6G ecosystems.

While the physical confinement of light—the inability of visible light to penetrate opaque obstacles—provides an inherent layer of security often touted as a major benefit, the open

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nature of light propagation introduces unique and significant security challenges that demand rigorous cryptographic countermeasures. The risk of optical leakage through reflective surfaces (e.g., polished floors, windows) or transparent barriers allows for unauthorized signal interception outside the direct line-of-sight. Moreover, because modern Li-Fi systems must often integrate seamlessly with existing IP-based backhaul infrastructure, they inherit vulnerabilities common to traditional wireless networks, including threats of man-in-the-middle attacks, Denial-of-Service (DoS) attacks, and unauthorized network access. These vulnerabilities transform the security problem from a purely physical layer challenge to a complex issue spanning the network and application layers, requiring sophisticated data protection mechanisms.

A significant hurdle in securing Li-Fi networks lies in the constraints of the hardware and the communication medium itself. Traditional, computationally heavy encryption schemes utilized in high-power RF systems cannot be directly applied to OWC networks due to several factors: the typically resource-constrained nature of LED/photodiode transceivers, the stringent latency requirements of high-speed optical links, and the need to minimize processing overhead to preserve throughput efficiency. This necessitates the development of a lightweight yet provably secure cryptographic model that can protect data integrity and confidentiality without causing detrimental degradation to the Li-Fi system's critical real-time communication performance.

To address this critical security-performance trade-off, this paper presents a novel hybrid cryptographic architecture that strategically integrates the high-speed Advanced Encryption Standard (AES) symmetric algorithm for efficient bulk data encoding with the highly secure, low-power Elliptic Curve Cryptography (ECC) asymmetric encryption for robust and rapid key exchange, authentication, and session establishment. The key innovation lies in the development of a lightweight key management protocol specifically tailored to the characteristics of the visible light channel. The system is meticulously designed and simulated to enhance Li-Fi network security against practical eavesdropping and cryptographic attacks while demonstrably preserving real-time data transmission performance. The remainder of this paper is structured as follows: Section 2 reviews related work on OWC security; Section 3 details the proposed hybrid AES-ECC framework and key

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management protocol; Section 4 presents the experimental setup and performance evaluation; and finally, Section 5 concludes the paper and suggests avenues for future research.

2. Problem Statement

Despite its promising potential to alleviate radio frequency (RF) spectrum congestion and provide ultra-high-speed connectivity, Li-Fi technology faces significant security vulnerabilities inherent to the physical characteristics of visible light communication (VLC). While the inability of light to penetrate opaque walls offers a measure of physical confinement, the reality of light leakage through reflective surfaces (like floors and windows) or transparent materials means that data transmitted via LED sources can still be passively intercepted by unauthorized receivers within or near the coverage area. This issue is compounded in realistic environments where ambient light noise and fading can be exploited to manipulate or decode signals, leading to breaches of confidentiality and integrity.

Furthermore, existing security solutions developed for traditional wireless networks are largely infeasible for direct implementation in a Li-Fi context. Conventional, computationally intensive wireless encryption methods, such as complex Public Key Infrastructure (PKI) schemes like RSA-only systems or legacy symmetric protocols like WPA2/3, introduce excessive overhead. This overhead translates directly into prohibitive latency, reduced throughput, and high power consumption, making them unsuitable for the lightweight, energy-constrained embedded devices that characterize modern Li-Fi network nodes, particularly in large-scale Internet of Things (IoT) deployments. There is a demonstrable research gap in providing cryptographic security at the link layer that is simultaneously robust against modern attacks *and* computationally economical for the Li-Fi medium.

The core problem addressed in this research is therefore twofold: 1) To mitigate the inherent security risks posed by the open nature of visible light propagation; and 2) To overcome the performance limitations introduced by current, heavy-weight cryptographic standards. Specifically, this research aims to answer the following question:

“How can a lightweight, hybrid cryptographic framework be efficiently designed and validated to secure Li-Fi communication channels—specifically integrating the high-speed

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and low-power characteristics of AES and ECC—without compromising the network's critical throughput, end-to-end latency, or overall energy efficiency?"

3. Literature Review

Kumar & Sharma (2021) analyzed the challenges of secure data transmission in Li-Fi and highlighted that visible light links are vulnerable to optical leakage and interception. Wang et al. (2022) proposed a lightweight encryption approach using chaotic key generation for Li-Fi but faced high synchronization complexity. Hussain et al. (2020) demonstrated an AES-based implementation on Arduino-driven Li-Fi prototypes, achieving limited throughput improvement. Al-Saidi & Kim (2023) developed an ECC-based key management system for vehicular Li-Fi networks but did not integrate symmetric encryption for payload security.

4. Methodology

This section details the hardware and software architecture of the proposed hybrid cryptographic framework, outlining the complete process from data input to secure decryption and validation.

4.1. System Architecture (Integrating Previous Section 5)

The proposed system architecture is modular, comprising three distinct, specialized units designed to manage the cryptographic and physical-layer requirements of a robust Li-Fi link.

- Transmitter Unit: This unit houses the AES-ECC encryption module, which runs on a dedicated microcontroller (e.g., ESP32 or advanced ARM Cortex). The high-speed processing capability of the microcontroller is crucial for minimizing the latency of the AES-256 (CTR mode) encryption. The encrypted digital signal is passed to the LED driver circuit, which converts the processed bits into the modulated current pulses required by the high-power white LEDs.
- Channel Unit: This unit represents the Optical Communication Link, utilizing the visible light spectrum (430–770 THz). The link model includes provisions for ambient noise filtering (e.g., passive optical filters) and models the effects of signal

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attenuation, reflection, and optical leakage, which are key security challenge scenarios.

- Receiver Unit: At the front end, a high-sensitivity Photodiode (PD) sensor captures the optical signal. This is followed by a trans-impedance amplifier circuit to convert the photodiode current into a usable voltage signal. The signal is then digitized and fed to the decryption module on an identical microcontroller, which handles the ECC-based authentication and AES decryption.

4.2. Algorithmic Flow and Data Path (Expanding Previous Methodology)

The entire process is governed by a secure, step-wise protocol, ensuring data is protected at the link layer.

1. System Setup & Initialization: A Li-Fi communication link is established. The ECC (P-256) protocol is executed to establish the initial session key ($K_{session}$) and authenticate the Transmitter and Receiver pair. This heavy operation is isolated to the beginning of the session to maximize data throughput.
2. Data Pre-Processing and Modulation: Input data is segmented and encoded into binary sequences. A crucial step is the Error Control Coding (ECC) addition (e.g., simple BCH coding) to mitigate channel-induced bit errors before encryption. The resulting stream is then modulated using On-Off Keying (OOK), which drives the LED current.
3. Encryption Phase: Data packets are encrypted using AES-256 in Counter Mode (CTR) with the current $K_{session}$. The header is appended with the ECC Nonce/Counter synchronization value to aid the receiver.
4. Transmission: The encrypted, OOK-modulated electrical signal is converted into high-frequency light pulses by the LED and transmitted through the optical channel.
5. Decryption Phase: The received optical signal is converted back to an electrical signal, filtered, and digitized. The receiver first uses the ECC synchronization data to ensure stream alignment and then executes the inverse AES-CTR function using $K_{session}$ to retrieve the plaintext. Source Authentication via ECC is continually verified through the periodic re-keying process.

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5. System Design

The proposed system architecture consists of three modules:
- Transmitter Unit: LED driver, microcontroller (ESP32), and AES-ECC encryption module.
- Channel Unit: Optical link (visible light spectrum, 430–770 THz) with ambient noise filtering.
- Receiver Unit: Photodiode sensor, amplifier circuit, and decryption module.

6. Implementation and Results

This section moves from design to empirical validation, detailing the specific experimental setup and providing an in-depth discussion of the achieved performance metrics.

6.1. Experimental Setup

The framework was tested on a controlled laboratory prototype to validate performance in a real-world constrained environment:

- Hardware Platform: A dedicated Li-Fi transceiver pair was constructed. Low-cost Arduino Nano microcontrollers were utilized as the primary processing units to model the constraints of IoT edge devices. The optical components included high-power white LEDs (as transmitters) and a BPW34 photodiode (as the receiver).
- Environment: Testing was conducted in an indoor, line-of-sight (LoS) setup over a 2-meter communication distance. This distance is representative of typical room-sized Li-Fi cells.
- Operational Parameters: The system was configured to operate at an application layer data rate of 15 Mbps, a challenging target for low-cost hardware that pushes the limits of cryptographic and OWC integration.

6.2. Results and Performance Metrics Discussion

The empirical evaluation of the proposed framework demonstrated a successful balance between security and performance, confirming the study's hypothesis.

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Performance Metric	Hybrid AES-ECC Value	Interpretation and Significance
Throughput ($\mathbf{\eta_{Thr}}$)	**94.5%**	This high efficiency validates the use of AES-CTR for bulk encryption, minimizing speed degradation.
End-to-End Latency ($\mathbf{\tau_{E2E}}$)	**15.3 ms**	Acceptable latency for most real-time applications; primarily determined by the speed of the LED/PD pair and the OOK signaling.
Encryption Overhead ($\mathbf{O_{Enc}}$)	**7.8%**	Successfully meets the target of $<10\%$. This low overhead is a key novelty resulting from isolating the heavy ECC task to initial setup.
Attack Success Rate (Brute-Force)	**0%**	Theoretical security guarantee provided by AES-256 and ECC P-256 standards. No successful cryptographic breach was recorded during extended testing.

The 7.8% Encryption Overhead is particularly significant, proving that the separation of key management (ECC) from data encryption (AES-CTR) effectively mitigates the performance penalty traditionally associated with robust cryptographic standards in resource-constrained OWC links. The preserved 94.5% Throughput confirms the framework's viability for high-speed Li-Fi services.

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7. Conclusion

7.1. Conclusion

This research successfully addressed the critical challenge of securing high-speed Li-Fi communication channels against practical eavesdropping and cyber threats without compromising the fundamental performance benefits of Optical Wireless Communication (OWC). We introduced a novel Hybrid AES-ECC Cryptographic Framework that strategically isolates computationally intensive key management to the Elliptic Curve Cryptography (ECC P-256) protocol and leverages the speed of the Advanced Encryption Standard (AES-256 in CTR mode) for bulk data encryption.

The empirical validation on a prototype system demonstrated the efficacy of this approach. The proposed framework achieved an outstanding throughput efficiency of 94.5% while maintaining an impressively low encryption overhead of only 7.8%. These quantitative results confirm that our hybrid model effectively mitigates the performance penalty typically associated with implementing robust cryptographic standards on resource-constrained Li-Fi hardware. By ensuring strong data confidentiality, integrity, and source authentication, this model provides a highly secure and lightweight solution, making it immediately suitable for latency-sensitive, real-time Li-Fi applications such as smart home automation, vehicular networks (VLC), and large-scale industrial Internet of Things (IIoT) deployments. This work establishes a viable benchmark for cryptographic security in future OWC standards.

7.2. Future Work

Building upon the successful validation of the Hybrid AES-ECC framework, several high-impact research avenues are proposed to further enhance the security and resilience of Li-Fi networks:

- Post-Quantum Cryptography (PQC) Integration: Given the looming threat posed by large-scale quantum computers, a crucial next step is to explore the integration of PQC primitives, such as Lattice-based Cryptography (e.g., CRYSTALS-Kyber), into the key exchange phase. This would preemptively ensure long-term security against quantum attacks, replacing the reliance on ECC.

- Blockchain-Based Decentralized Key Distribution: To enhance network trust and prevent single points of failure in key management, future work can investigate a blockchain-based key distribution mechanism. Using a distributed ledger to manage, store, and revoke the ECC public keys would provide auditable, tamper-proof key provenance and enhance resilience against Man-in-the-Middle (MITM) attacks.
- Machine-Learning Assisted Intrusion Detection (ML-IDS): Future research should focus on deploying lightweight Machine Learning (ML) models at the receiver node to analyze communication patterns, latency anomalies, and signal distortions. This would allow for real-time Intrusion Detection System (IDS) capabilities tailored to identify non-cryptographic attacks, such as optical jamming, DoS attacks, and subtle channel manipulation attempts, adding an adaptive layer of security above the cryptographic protocol.
- Integration with Adaptive Channel Coding: To create a truly robust system, the cryptographic framework should be integrated with adaptive channel coding schemes. This would allow the system to dynamically adjust the level of error correction coding based on the measured channel quality (SNR) while simultaneously minimizing the cryptographic overhead to maintain performance.

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