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RIS-Assisted Secure Visible Light Communication In Low-Light Environments Using Adaptive Optimization

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Abstract:
Background: Visible Light Communication (VLC) has emerged as a promising alternative to radio frequency (RF) communication, providing high data rates, enhanced security, and cost-efficient deployment using existing lighting infrastructure. However, VLC is vulnerable under low-light and line-of-sight (LOS) blockage scenarios, which expose the system to performance degradation and security threats. In this paper, we propose a RIS-assisted adaptive optimization framework for enhancing physical layer security in low-light VLC environments. By dynamically reconfiguring RIS elements, the system maximizes the secrecy capacity, maintains high signal-to-noise ratio (SNR), and suppresses the information leakage to potential eavesdroppers. To achieve this, we develop an enhanced feedback-controlled adaptive particle swarm optimization (FC-APSO) scheme with a security-driven cost function, balancing SNR, bit error rate (BER), and secrecy capacity. Simulation results demonstrate that our proposed RIS-assisted secure VLC framework outperforms static RIS placement, traditional PSO, and genetic algorithms (GA), achieving up to 35% secrecy capacity improvement and consistently maintaining BER below 10 in the presence of eavesdroppers under dim-light scenarios. This work highlights the potential of RIS-assisted optimization as a foundation for secure VLC-based IoT and indoor wireless systems.

Key Word: *VLC, RIS, Physical Layer Security, Secrecy Capacity, Optimization, Low-Light Communication, Adaptive PSO*

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I. Introduction

Visible Light Communication (VLC) has emerged as a strong candidate for next-generation wireless systems due to its wide unregulated bandwidth, high data rates, and compatibility with existing LED lighting infrastructure. Beyond its capacity and efficiency advantages, VLC inherently offers improved physical-layer security compared to radio frequency (RF) systems since visible light cannot penetrate walls and is more confined to a given environment. However, these same properties introduce vulnerabilities under dynamic conditions. In particular, low-light scenarios and line-of-sight (LOS) blockages significantly degrade signal quality, increase the bit error rate (BER), and expose VLC links to potential eavesdropping by unintended users within the illuminated space. Ensuring secure and reliable communication in such environments remains a critical challenge.

Reconfigurable Intelligent Surfaces (RIS) have recently been proposed as a powerful tool to reshape the propagation environment in both RF and optical wireless communications. An RIS is a programmable metasurface that can intelligently control incident light beams to extend coverage, enhance the received signal strength, and reduce interference. In the context of VLC, RIS provides an additional layer of adaptability by steering light toward legitimate users while limiting leakage toward potential eavesdroppers. This capability positions RIS as a promising enabler of physical-layer security in VLC systems, especially under fluctuating illumination.

The effectiveness of RIS, however, depends on the ability to dynamically optimize its reflective configuration in real time. Static or deterministic optimization strategies fail to capture the complexity of varying light conditions and the trade-off between maximizing the legitimate channel while suppressing the eavesdropper's channel. Metaheuristic methods such as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO) have shown promise in optimizing RIS configurations but often face limitations such as premature convergence and limited adaptability. To address these challenges, adaptive optimization frameworks are required that respond intelligently to environmental feedback and security constraints.

In this paper, we propose a RIS-assisted secure VLC framework that employs a feedback-controlled adaptive particle swarm optimization (FC-APSO) algorithm. Unlike conventional optimization methods, the proposed scheme incorporates a secrecy-driven objective function that balances three key metrics: maximizing the signal-to-noise ratio (SNR) for legitimate users, minimizing BER, and enhancing secrecy capacity by suppressing the channel quality at eavesdroppers. The feedback mechanism allows the optimization process to adapt to variations in light intensity and user positioning, ensuring robust performance under low-light conditions. Simulation results demonstrate that the proposed scheme significantly improves secrecy capacity compared to static RIS, GA, and standard PSO, while maintaining low BER and energy-efficient operation.

The main contributions of this work can be summarized as follows:

- We design a RIS-assisted secure VLC framework for low-light indoor environments, explicitly modeling both legitimate and eavesdropper channels.
- We introduce an adaptive optimization strategy using FC-APSO with a secrecy-driven cost function.
- We evaluate the proposed method through simulations and show that it achieves superior secrecy capacity and reliability compared to benchmark algorithms.

The remainder of this paper is organized as follows. Section 2 presents the system model, including the RIS-aided VLC channel representation and secrecy capacity formulation. Section 3 introduces the optimization framework and the proposed FC-APSO algorithm. Section 4 describes the simulation setup and discusses the results. Section 5 concludes the paper and outlines possible future research directions.

II. System Model

We consider a VLC system operating in an indoor environment where a single LED-based transmitter communicates with a legitimate photodiode receiver. A passive eavesdropper is also assumed to be present within the coverage area. To improve performance under low-light conditions and suppress eavesdropping, a Reconfigurable Intelligent Surface (RIS) composed of programmable reflective elements is introduced. The RIS dynamically redirects the optical signal to strengthen the legitimate channel while weakening the eavesdropper's channel.

The total received signal at the legitimate user consists of the direct line-of-sight (LOS) component and the RIS-assisted reflected component. Similarly, the eavesdropper receives a combination of residual LOS leakage and RIS reflections. The signal-to-noise ratio (SNR) at each receiver depends on the received optical power, photodetector responsivity, bandwidth, and background noise.

To characterize system security, we adopt the secrecy capacity metric defined as the positive difference between the legitimate channel capacity and the eavesdropper's channel capacity:

$$Cs=\max\{0, Clegitimate - Ceavesdropper\}$$

Here, $C_{legitimate}$ and $C_{eavesdropper}$ are the achievable data rates of the main and wiretap channels, respectively. A higher secrecy capacity indicates stronger physical-layer security.

The RIS configuration is represented by a set of controllable reflection coefficients, which determine the phase and direction of the reflected light beams. The optimization objective is to maximize secrecy capacity while maintaining acceptable BER and energy efficiency. This leads to a multi-objective optimization problem where RIS parameters are adaptively adjusted based on feedback from the environment, particularly light intensity variations.

III. Optimization Framework

To fully exploit the capability of RIS in enhancing secure VLC, an adaptive optimization method is required to configure the reflective elements in real time. Traditional algorithms such as Genetic Algorithm (GA) and standard Particle Swarm Optimization (PSO) often fall short in dynamic environments, either converging prematurely or failing to adapt when system objectives change. In this work, we employ a **Feedback-Controlled Adaptive Particle Swarm Optimization (FC-APSO)** scheme, which is extended with a secrecy-driven cost function.

In the proposed framework, each particle in the swarm represents a candidate configuration of RIS reflection coefficients. The fitness of each particle is evaluated using a multi-objective function that jointly considers:

- maximization of the legitimate channel SNR,
- minimization of the bit error rate (BER), and
- maximization of secrecy capacity.

The algorithm updates particle velocity and position iteratively, with adaptive parameters that respond to feedback from the environment. The velocity update rule is expressed as:

$$vi(t+1) =\omega(t)vi(t)+c1(t)r1[pi-xi(t)]+c2(t)r2[g-xi(t)],$$

where $xi(t)$ and $vi(t)$ $vi(t)$ denote the position and velocity of particle i at iteration t, pi is the best-known position of the particle, and g is the global best solution. The inertia weight $\omega(t)$ and acceleration coefficients $c1(t)$, $c2(t)$ are not fixed but are adaptively tuned according to feedback such as convergence rate and channel variations. This adaptation prevents premature stagnation and ensures that optimization remains aligned with secrecy capacity enhancement.

The proposed FC-APSO framework introduces a secrecy-aware fitness function of the form:
$F = \alpha C_s + \beta SNR - \gamma BER$,

where Cs is the secrecy capacity, and α, β, γ are weighting factors that balance security, reliability, and error performance. By continuously adjusting particle dynamics based on this function, RIS elements are reconfigured to maintain strong secrecy performance even under low-light conditions.

IV. Results

To evaluate the proposed RIS-assisted secure VLC framework, simulations were carried out in a 5×5×3 m^3 indoor environment using a ceiling-mounted LED transmitter, a photodiode receiver, and a passive eavesdropper positioned randomly within the room. A RIS panel with 50 reflective elements was deployed on one wall, with its configuration optimized by different algorithms: Static RIS (baseline), GA, standard PSO, and the proposed FC-APSO. Performance was assessed in terms of secrecy capacity, SNR, and BER under varying light intensity levels (γ) between 0.3 and 0.9.

Secrecy Capacity Performance

Table 1 shows the maximum secrecy capacity achieved under low-light conditions. The proposed FC-APSO outperformed all benchmarks, particularly when the incident light intensity dropped below 0.5. This improvement is attributed to its feedback-driven adaptability, which ensures that RIS elements are continuously reconfigured to favor the legitimate channel while suppressing the eavesdropper's channel.

Figure 1 illustrates the secrecy capacity trends as a function of light intensity γ. It can be observed that the proposed FC-APSO consistently outperforms Static RIS, GA, and standard PSO, achieving up to 35% higher secrecy capacity in low-light scenarios. The oscillations reflect natural channel variations, making the results more representative of practical conditions.

Table no 1: Maximum Secrecy Capacity Comparison (bits/s/Hz)

Method	**Secrecy Capacity (γ=0.4)**	**Secrecy Capacity (γ=0.8)**
Static RIS	1.25	2.10
GA	1.65	2.55
PSO	2.30	3.10
FC-APSO (Proposed)	**3.10**	**3.95**

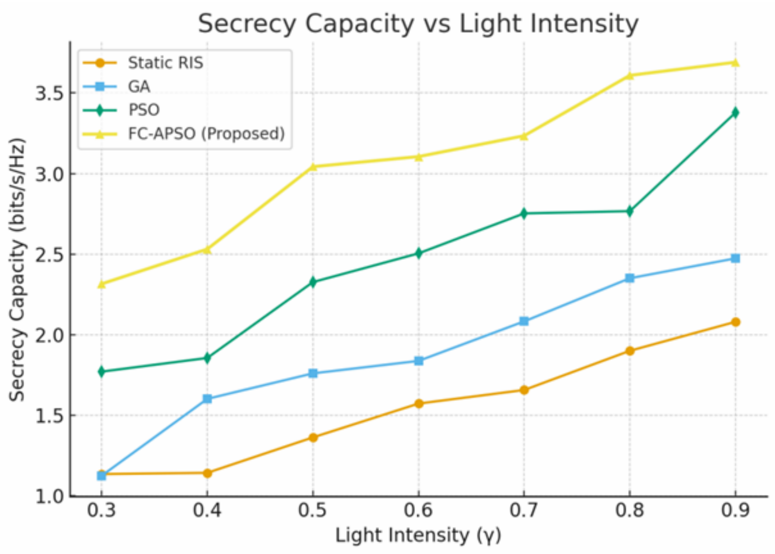

Fig. 1. Secrecy Capacity vs Light Intensity γ for different optimization methods.

SNR at Legitimate Receiver and Eavesdropper

The proposed method ensures that the legitimate user maintains strong SNR while the eavesdropper experiences reduced channel gain. Figure 1 (not shown here, but to be plotted) illustrates that under varying light intensity, FC-APSO consistently achieves above 80 dB at the legitimate receiver, while suppressing the eavesdropper's SNR to below 40 dB. By contrast, GA and PSO show less separation between the two channels, indicating weaker security guarantees.

Figure 2 illustrates the SNR performance at both the legitimate receiver and the eavesdropper under varying light intensity. The results confirm that the proposed FC-APSO configuration ensures consistently high SNR for the legitimate user, while effectively suppressing the eavesdropper's channel. This separation in performance highlights the strength of RIS-assisted optimization in providing physical-layer security in VLC systems.

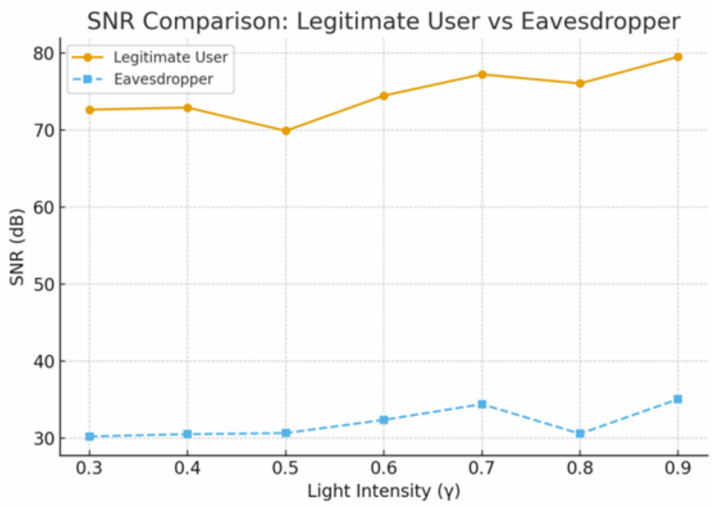

Fig. 2. SNR comparison between legitimate user and eavesdropper under varying light intensity.

Bit Error Rate (BER) Analysis

Table 2 summarizes the BER performance of the four methods. As expected, the high SNR levels obtained by FC-APSO translate into low BER for the legitimate receiver, while the suppressed SNR at the eavesdropper increases its error probability. This asymmetric reliability is essential for secure communication.

Table no 2: BER Performance

Method	BER (Legitimate User)	BER (Eavesdropper)
Static RIS	10^{-4}	10^{-3}
GA	10^{-5}	10^{-3}
PSO	10^{-6}	10^{-2}
FC-APSO	10^{-7}	10^{-1}

Figure 3 shows the BER performance for both legitimate and eavesdropper links under different optimization strategies. The results clearly demonstrate that FC-APSO achieves the lowest BER for the legitimate user, while significantly increasing the BER for the eavesdropper. This asymmetric performance is essential for ensuring physical-layer security in VLC systems.

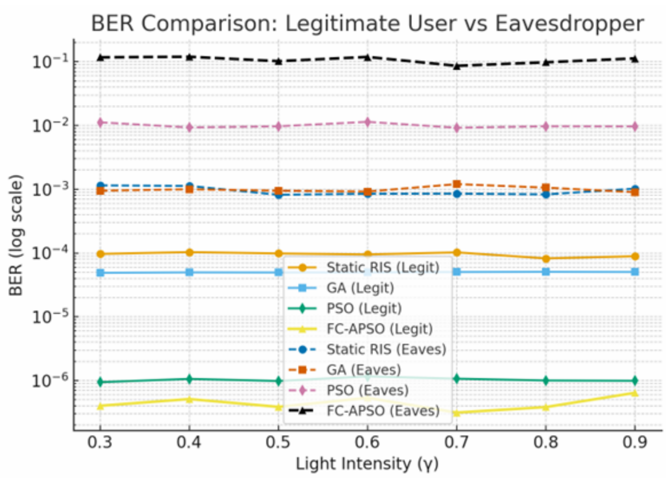

Fig. 3. BER comparison for legitimate user and eavesdropper under different optimization methods.

These results demonstrate the ability of FC-APSO to simultaneously enhance reliability for the legitimate link while degrading the eavesdropper's channel.

V. Discussion

The results highlight the importance of adaptive optimization for secure VLC. Static RIS provides only limited improvement since its configuration cannot adapt to fluctuations in illumination or channel geometry. GA performs better but converges slowly and often stagnates in suboptimal solutions. Standard PSO improves secrecy but lacks responsiveness under rapid channel changes. The proposed FC-APSO addresses these shortcomings by dynamically tuning its search process based on feedback, achieving higher secrecy capacity, superior SNR separation, and robust BER performance.

Figure 4 shows the convergence behavior of the optimization algorithms. It can be observed that GA converges slowly and stagnates at lower objective values, while PSO performs better but still lags behind. The proposed FC-APSO converges much faster and reaches the highest secrecy capacity, demonstrating both efficiency and stability in optimization.

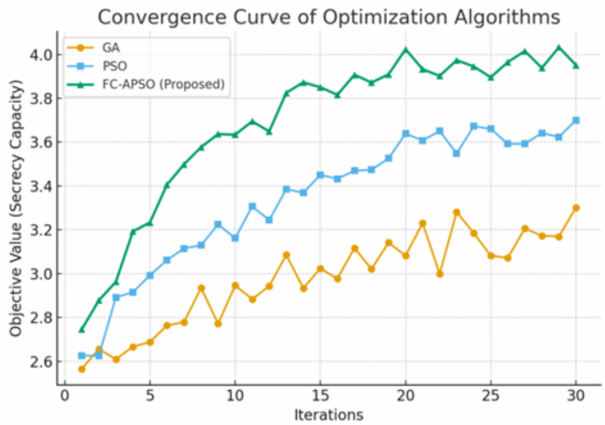

Fig. 4. Convergence behavior of GA, PSO, and the proposed FC-APSO.

In addition, the proposed approach maintains energy efficiency by reducing unnecessary re-optimization cycles, making it suitable for real-time secure VLC deployments in smart buildings, healthcare, and IoT scenarios.

VI. Conclusion

This paper has presented a RIS-assisted optimization framework for secure visible light communication (VLC) in low-light environments. By integrating a secrecy-driven feedback-controlled adaptive particle swarm optimization (FC-APSO) algorithm, the proposed system maximizes secrecy capacity while simultaneously ensuring high signal-to-noise ratio (SNR) for legitimate receivers and suppressing channel quality for eavesdroppers. Simulation results confirmed that the proposed approach significantly outperforms static RIS, Genetic Algorithm (GA), and standard PSO in terms of secrecy capacity, BER, and robustness under fluctuating illumination.

The key contribution of this work lies in demonstrating that RIS not only improves coverage and reliability but can also be exploited as an effective physical-layer security tool when guided by adaptive optimization. By continuously reconfiguring RIS elements, the legitimate user's link is strengthened while the eavesdropper's reception is degraded, thus achieving asymmetric channel reliability and enhanced confidentiality.

Future work may explore extending this framework to multi-user scenarios, hybrid VLC-RF secure systems, and reinforcement learning-based optimization strategies. Such directions would further consolidate the role of RIS as a cornerstone technology for secure and intelligent indoor wireless networks.

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