Bio-Inspired Visible Light Communication

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Abstract—**Bioluminescent organisms offer transformative solutions for Visible Light Communication (VLC) adoption barriers. Learning from bio-mechanisms like counter-illumination, quorum sensing networks, and decoy-based resilience can shift the future VLC paradigm. These nature-inspired strategies overcome technical, implementation and market limitations, providing a high-capacity communication foundation for 6G-era applications in smart cities, healthcare, and Industry 4.0 while aligning with radio frequency ecosystems.**

I. INTRODUCTION

The evolution of wireless communication has been marked by relentless innovation to meet escalating connectivity demands [1]. Yet, as we enter an era dominated by artificial intelligence, the Internet of Things (IoT), and immersive multimedia applications, the limitations of traditional Radio Frequency (RF) spectrum technologies are becoming starkly evident [2]. By 2030, global mobile data traffic is expected to reach 415 Million Terabytes per Month, a 196% increase from 2024's 140 Million Terabytes per Month, yet the RF spectrum remains constrained, fragmented, and increasingly congested [3]. This spectrum scarcity crisis threatens next-generation networks, necessitating solutions beyond conventional RF paradigms. Visible Light Communication (VLC) has emerged as a versatile technology, capable of complementing RF systems or functioning independently. VLC leverages the visible light spectrum (430 – 770 THz), a resource previously untapped for wireless communication, to deliver high-speed data transmission that is inherently secure and immune to RF interference [4]. However, despite its promise, VLC faces significant adoption barriers that have limited its market penetration and commercial viability [5]. To overcome these barriers, we propose leveraging evolutionary strategies from bioluminescent organisms, which have optimized light-based communication for efficiency, security, and adaptability under challenging conditions. This paper introduces bio-inspired VLC, where principles from bioluminescent organisms are harnessed to overcome adoption barriers and launch a new era of optical wireless communication. The remainder of this paper delves into VLC's technical promise and existing limitations, then details biological principles from light-emitting organisms, and finally defines bio-inspired strategies for transforming VLC.

II. VISIBLE LIGHT COMMUNICATION TECHNOLOGY AT A CROSSROADS

VLC systems employ Light Emitting Diodes (LED)-based transmitters alongside photodiodes or image sensors as receivers, creating dual-purpose infrastructure for communication and illumination. Core component evolution includes micro-LED offering enhanced bandwidth and smartphone camera-based systems enabling optical camera communication where dedicated receivers are impractical [6]–[9]. Visible Light Communication demonstrates significant potential across diverse sectors. In smart buildings, it could enable environmental monitoring and security systems. For urban infrastructure, VLC may support traffic control and public safety networks. Vehicles might leverage VLC for critical safety communications via integrated LED lighting. Meanwhile, industrial settings stand to benefit from its ability to deliver simultaneous illumination, data transmission, energy harvesting, and localization.

VLC development follows key standards: IEEE 802.15.7 (2011), for short-range up to 96 Mbps; ITU G.9991 (2019), offering up to 10 Gbps for indoor environments; and IEEE 802.11bb (2023), which integrates with Wi-Fi and achieves 9.6 Gbps using near-infrared light. While these standards provide a robust foundation for the physical and MAC layers, they do not yet address higher-level challenges such as environmental adaptation and autonomous network management. Light Fidelity (Li-Fi), the VLC-based networking analog to Wi-Fi, leverages these standards to achieve high speeds (exceeding 100 Gbps in labs) with inherent security advantages [5], [10]. Commercial VLC products, including 802.11bb-compliant devices by PureLiFi [11] and Fraunhofer HHI [12], are now available. While pilot deployments progress in targeted sectors (e.g., defense, healthcare) [13], widespread adoption faces interconnected barriers:

Technical Limitations fundamentally constrain VLC's utility. Inherent line-of-sight (LoS) dependencies cause disruptions from physical obstructions, problematic in dynamic environments [5]. Simultaneously, ambient light interference (especially intense sunlight) degrades signal reliability despite filtering [14]. Li-Fi's restricted range of 2-3 meters per access point, markedly inferior to Wi-Fi, compounds these issues by necessitating substantially denser, costlier infrastructure deployments [15].

Implementation Challenges present significant hurdles for practical scenarios. Current systems often require specialized hardware (dedicated photodetectors/modified cameras) not integrated into mainstream consumer electronics, creating adoption barriers [16], [17]. The asymmetric nature of Li-Fi further complicates deployment: while downlink leverages lighting infrastructure, efficient uplink from mobile devices

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demands complex engineering (often separate transmitters) [18]. Incorporating Li-Fi also requires sophisticated handover mechanisms between light-based and RF systems for mobile users [17], [19].

Market and Ecosystem Factors impede momentum despite technical promise [1], [2]. Major telecom providers show minimal deployment interest due to substantial RF investments, licensed spectrum business models, and commitments to RF evolution [20]. Continuous advancements in competing technologies (Wi-Fi 6/7, 5G) offer familiar performance improvements with lower adoption barriers [21]. Ecosystem challenges include standardization gaps raising interoperability concerns, unfavorable cost-benefit equations for general-purpose networking, and limited consumer awareness restricting demand and manufacturer incentives.

This paradox—technological promise without mainstream penetration—underscores VLC's critical stage. While integration with sustainable LED infrastructure aligns with energy-efficiency goals, conventional approaches fail to overcome these barriers. Transforming Li-Fi from niche technology to next-generation cornerstone requires innovative design beyond incremental improvements. To achieve this, we turn to nature's optical engineers, bioluminescent organisms, which possess inherently adaptive, secure, and energy-efficient light communication strategies [22].

III. LEARNING FROM NATURE'S OPTICAL PLAYBOOK

Bioluminescence represents one of the world's most sophisticated optical communication systems [23]. This biochemical light production demonstrates remarkable efficiency, specificity, and reliability under challenging environmental conditions. Emission mechanisms across diverse ecosystems form a natural "optical playbook," offering actionable insights for advanced optical communication design. Bioluminescence serves three primary ecological roles: defense (deterring/confusing predators), offense (attracting/ambushing prey), and reproduction (facilitating mate selection) [24]. Each role employs distinct strategies tailored to overcome ecological challenges. By analyzing these strategies and their underlying mechanisms, we uncover universal principles for engineering adaptive, energy-efficient, and context-aware VLC systems.

For defense, bioluminescent organisms employ sophisticated light-based defenses against predation. Key strategies include: startle displays to confuse attackers, smoke-screen emissions of glowing mucus, sacrificial decoys, counter-illumination camouflage, and burglar alarms attracting secondary predators [24]. Examples include [25]–[27]:

- Firefly squid: Counter-illumination matches downwelling blue light to conceal silhouettes from below.
- Vampire squid: Flashes startle predators and ejects bioluminescent mucus (instead of ink).
- Brittle stars: Detach glowing arms as decoys while escaping.
- Sea cucumbers: Transfer luminescent body parts onto fish, creating mobile decoys.
- Hatchetfish: Adjusts ventral light intensity to match overhead sunlight to erase shadows.

For offense, predators utilize bioluminescence as a precise hunting tool. Key strategies include: luring prey with deceptive light signals, illuminating surroundings with searchlight capabilities, disorienting prey with shocking displays, and attracting meals via beacon signals. Notable examples [26], [27]:

- Anglerfish: Uses a bioluminescent esca (head appendage) to lure curious fish within striking distance.
- Dragonfish (Loosejaws): Emits red bioluminescent light (invisible to most blue-light-sensitive prey) to illuminate surroundings while hunting.

For reproduction, species-specific light patterns facilitate mate attraction. Primary strategies include "come-on" broadcasts and "invitation" signals guiding mates to locations. Examples include:

- Fireflies: Species-specific flash patterns prevent cross-mating [26].
- Caribbean Ostracod (*Photeros annecohenae*): Males swim upward helixes emitting bright pulses followed by dim trills; females approach silently [28], [29].
- Bermuda Fireworm: Females secrete luminous mucus in surface circles; males respond with flashes [30].
- Fungi: Produce circadian-regulated "foxfire" (green-blue glow) on decaying wood as an invitation signal to attract spore-dispersing insects [31].

For adaptation, some organisms employ light for multiple distinct functions. Key strategies include wavelength division, life-stage adaptations, and dual-purpose signaling. Examples include [25]–[27]:

- Railroad Worm: Uses red headlights (invisible to prey insects) for hunting and yellow-green body lights for defense/species recognition [32].
- Comb Jellies: Switch between defensive light bursts and sustained communicative glows based on context.
- Glow-worms: Larvae lure prey with deceptive glows; adult females attract mates; both signal toxicity.
- Dinoflagellates: Defensive flashes startle predators, attract secondary predators, and signal toxicity.
- *Vibrio harveyi* Bacteria: Bioluminescence facilitates DNA repair, counters oxidative stress, enables quorum sensing, and creates vast "milky seas" visible from space.

IV. BIOLUMINESCENT ORGANISMS AS ENGINEERING BLUEPRINTS

Bioluminescent organisms offer evolutionary blueprints for overcoming VLC challenges. By deconstructing these systems, we extract engineering principles that translate ecological adaptations into technological innovations. These biological strategies, synthesized from diverse species (Fig. 1), are articulated as core engineering principles below, including but not limited to:

Ambient-Adaptive Counter-Illumination - Inspired by the firefly squid's adaptive spectral camouflage, we propose ambient-adaptive optical transmission: signals dynamically adjust to environmental conditions while preserving information

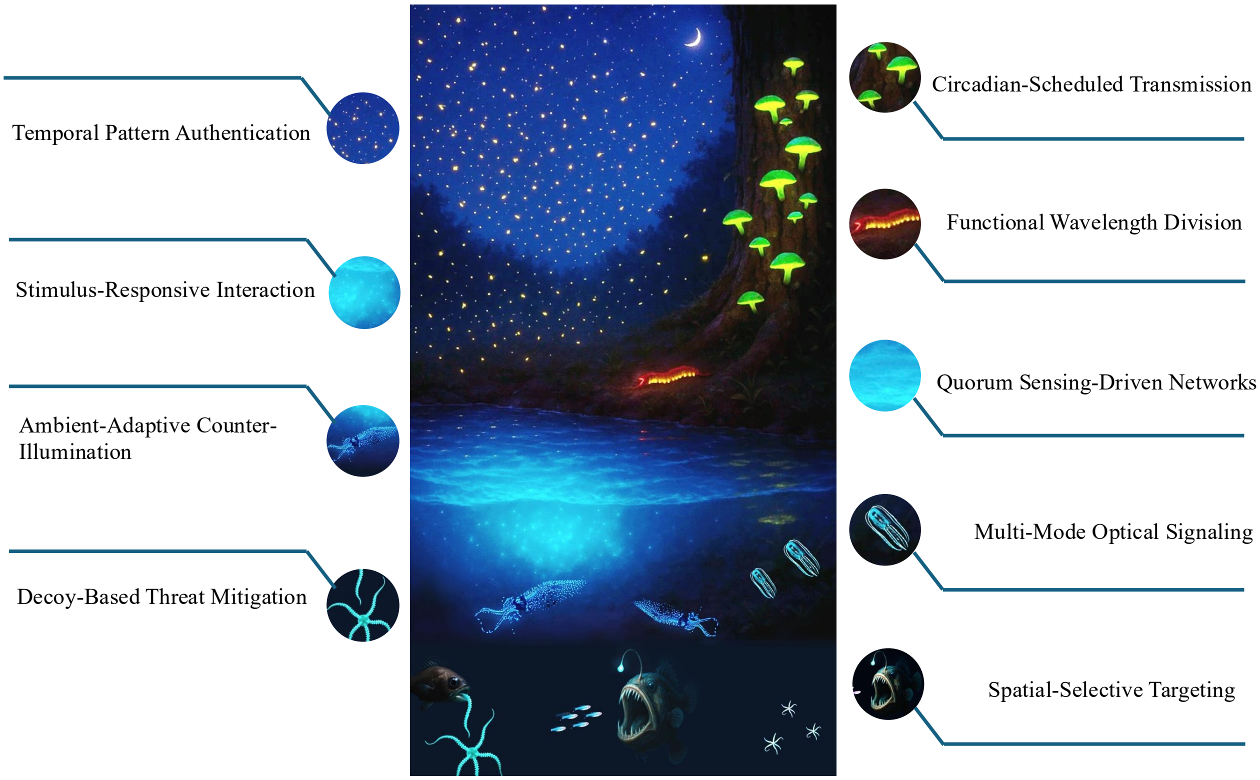

Fig. 1. Bioluminescent organisms and their corresponding bio-inspired VLC design principles.

integrity. This translates to VLC systems through: (1) multi-spectral ambient sensors characterizing background illumination; (2) dynamic wavelength-shifting transmitters modulating data across spectral bands; and (3) self-tuning detection algorithms extracting signals from natural light patterns. This enables signal camouflage, making the transmission imperceptible for applications ranging from covert communication (optical steganography) to non-intrusive user experiences, while mitigating ambient interference through adaptive signal-to-noise-ratio (SNR) optimization.

Multi-Mode Optical Signaling - Comb jellies switch contextually between defensive light bursts and sustained communicative glows, inspiring context-aware dual-mode transceivers that dynamically reconfigure emission parameters. VLC implementation features: (1) tandem micro-LED arrays switching between transmission modes (e.g., pulse, continuous); (2) embedded photodetectors enabling closed-loop feedback; and (3) edge controllers translating triggers (e.g., network congestion, security alerts) into data rate adjustments. This enables autonomous prioritization of security during intrusions or throughput during peak loads.

Quorum Sensing-Driven Networks - The milky sea phenomenon demonstrates density-responsive coordination: synchronized illumination activates only when bacterial density exceeds thresholds. VLC translation involves: (1) distributed nodes with proximity sensors; (2) threshold-triggered intensity activation; and (3) inter-node synchronization protocols. This provides spatial scalability, resilience against single-point failures, and power optimization by activating transmitters only when receivers are present.

Functional Wavelength Division - The railroad worm's dual-color system inspires multispectral functional division. VLC implementation includes: (1) wavelength-division transceivers for task prioritization; (2) adaptive beamforming lenses focusing emissions into secure links; and (3) interference cancellation preventing spectral crosstalk. This enables zero-latency emergency alerts and simultaneous multi-service operation (illumination, positioning, ultra-reliable low latency communication) within unified infrastructure.

Spatial-Selective Targeting - Anglerfish esca mechanics inspire spatially prioritized optical engagement. VLC architecture features: (1) steerable micro-LED arrays with adaptive lensing; (2) proximity-sensing modules activating localized hotspots; and (3) encoded modulation delivering location-specific data. This hierarchical connectivity provides general ambient coverage while targeting high-value zones with enhanced data rates or prioritized content.

Temporal Pattern Authentication - Fireflies' species-specific flashes yield dynamic temporal authentication using non-replicable pulse-encoded signatures. VLC implementation involves: (1) signature-encoded LED emitting optical handshakes; (2) neural-net processors authenticating temporal patterns; and (3) adaptive modulation maintaining signature integrity. This enables zero-trust networking while reducing power versus continuous transmission.

Decoy-Based Threat Mitigation - Brittle stars' arm detachment exemplifies decentralized resilience through strategic sacrifice. VLC translation includes: (1) distributed arrays with sacrificial nodes; (2) autonomous threat-detection activating decoy data streams; and (3) self-healing topologies rerouting communications. This maintains integrity during attacks via multi-layered security protocols.

Stimulus-Responsive Interaction - Dinoflagellates' mechanotransduction inspires environmentally triggered signaling. VLC systems incorporate: (1) motion-sensitive transceivers detecting movement/gestures; (2) threshold-triggered protocols minimizing standby power; and (3) context-adaptive modulation optimizing parameters based on stimuli. This enables zero-power standby with instant response for intuitive human-environment interfaces.

Circadian-Scheduled Transmission – Foxfire fungi's circadian-regulated bioluminescence for spore dispersal inspires predictive time-gated operation that minimizes energy waste and light interference. VLC implementation employs: (1) real-time clock modules synchronizing transmissions with low-ambient-light windows (e.g., night); (2) machine learning forecasting demand cycles for bandwidth pre-allocation; and (3) hybrid solar harvesting systems charging by day to power night-active LED. This achieves significant energy savings for IoT applications while avoiding daylight interference through temporal spectral isolation.

V. A TAXONOMY OF BIO-INSPIRED VLC SYSTEM COMPONENTS

The translation of biological light communication strategies into engineered systems requires a systematic categorization of component technologies. This taxonomy organizes bio-inspired VLC innovations into functional categories (Fig. 2) that parallel evolutionary adaptations, providing a framework for understanding the analogy and guiding future research.

Light Emission Mechanisms. Bio-inspired VLC transmitters implement sophisticated emission strategies beyond simple on-off keying. Adaptive emitters inspired by railroad worms dynamically adjust intensity, wavelength, and spectral characteristics based on communication needs. Distributed emitters modeled after bioluminescent bacterial colonies maintain functionality through redundant nodes despite partial failures. Stimulus-responsive emitters mimicking dinoflagellates' mechanotransduction activate only when triggered by external events, minimizing power consumption. The system development is feasible using off-the-shelf sensors (e.g., passive infrared (PIR) motion sensor or mmWave radar) to detect stimuli, coupled with commercially available micro-LED arrays and CMOS drivers [33], [34] for adaptive emission control. MEMS-based mirror arrays further enable robust real-time beam steering [35].

Signal Reception and Processing. Bio-inspired reception mechanisms mirror nature's ability to interpret light signals in complex environments. Adaptive receivers inspired by firefly visual systems dynamically adjust sensitivity thresholds and gain amplification to extract signals from ambient noise. Signature-authenticating receivers implement fireflies' species-specific pattern recognition through temporal analysis to authenticate transmission sources. Density-aware receivers incorporate quorum sensing principles, measuring local node concentration to improve reliability as device density increases. These advanced reception strategies are feasible by leveraging the embedded processing capabilities of standard CMOS image sensors for adaptive filtering and temporal pattern analysis [36], augmented by multi-spectral sensors for density-aware functionality [37].

System-Level Features. System-level bio-inspired features create holistic communication platforms with integrated adaptability. Context-aware adaptation from deep-sea organisms enables sensing of user location and environmental conditions to maintain optimal link quality. Network management incorporating bacterial quorum sensing implements distributed decision-making without centralized controllers. Energy harvesting parallels bioluminescent ecosystems' chemical recycling by integrating photovoltaic cells for self-sustaining nodes. Security mechanisms derived from brittle stars deploy countermeasures and self-healing topologies to maintain connectivity during disruptions. Implementing these system-level features is viable through a modular architecture built upon low-power microcontroller units (MCUs) and systems-on-chip that can run context-aware adaptation algorithms , manage decentralized security protocols, and interface with integrated solar harvesting circuits.

Environmental Interaction. Bio-inspired environmental interaction mechanisms optimize communication while minimizing energy use. Adaptive light control derived from counter-illumination techniques dynamically modulates emission to match ambient conditions, enhancing signal visibility across varying light environments. User interactive interfaces inspired by dinoflagellates implement presence detection and activity-responsive behaviors that initiate on-demand data sessions without manual pairing. This interactive capability is achievable by integrating off-the-shelf, low-power PIR motion sensors, millimeter-wave radar chips, and multi-spectral ambient light sensors with the transceiver unit [38], enabling real-time adaptive control and stimulus-responsive interaction.

Network Topology. Bio-inspired network topologies implement distributed yet coordinated architectures for resilient communication. Decentralized networks draw from firefly synchronization to enable autonomous coordination without centralized management. Regenerative routing inspired by brittle stars implements self-healing pathways and deliberate redundancy that preserve critical network functions during disruptions. Multi-mode operation derived from railroad worms enables transitions between broadcast illumination, multicast group-targeted messages, and directional links based on application needs.The required decentralized coordination and multi-mode operation are readily implementable with distributed algorithms running on interconnected, low-cost MCUs at each network node, leveraging standard IEEE 802.15.5 mesh networking protocols adapted for optical media [39].

VI. REWRITING THE RULES OF VISIBLE LIGHT COMMUNICATION

Our bio-inspired framework extends standards like IEEE 802.11bb with backward-compatible enhancements. These mechanisms provide the adaptability and resilience to overcome adoption barriers (Table I) while preserving standard device operation. This ensures baseline interoperability and

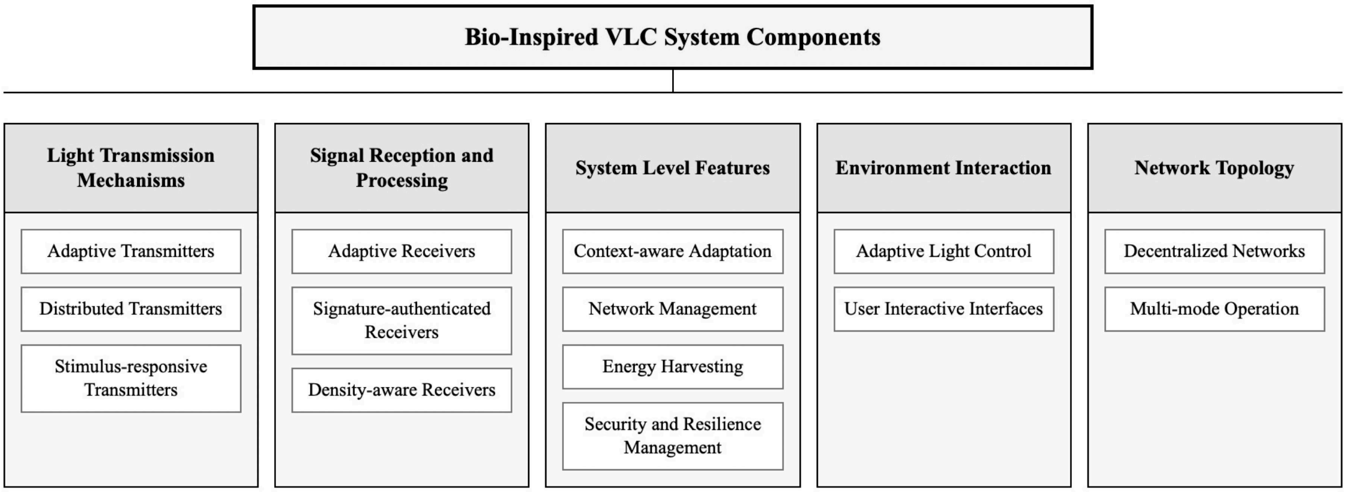

Fig. 2. Bio-inspired VLC taxonomy mapping bioluminescent strategies to five components enabling adaptive and resilient design.

unlocks advanced capabilities, paving the way for the next evolution of optical wireless communication.

Environmental Intelligence. Advanced VLC systems should implement environmental awareness through integrated sensing and adaptive response. These systems incorporate multi-spectral sensors that continuously monitor ambient lighting conditions and dynamically adjust transmission parameters, such as wavelength, intensity, modulation depth, and spectral characteristics, to maintain optimal signal integrity. Additionally, they integrate motion and proximity detection to enable context-responsive communication, activating transmission based on user presence, gestures, operational requirements or specific application demands. This approach simultaneously addresses multiple barriers: ambient-adaptive modulation overcomes light interference for reliable operation across lighting conditions, while stimulus-responsive operation reduces power consumption. Service providers gain consistent connectivity with energy efficiency advantages, expanding market potential to dynamic settings.

Spatial Selectivity. Next-generation VLC implements dynamic directional control through steerable micro-LED arrays and adaptive optics that focus light precisely, tracking users and navigating obstacles. Rather than flooding spaces, they concentrate energy on active receivers. This transforms LoS dependency into a flexible parameter, extending communication distance while reducing leakage to improve range, efficiency, and security. Implementation stakeholders enable customized service delivery where traditional VLC fails, accelerating adoption by maintaining connectivity despite movement.

Resilient Network Architecture. Advanced VLC networks implement distributed architectures with autonomous coordination. Nodes make local routing decisions based on real-time sensing, automatically rerouting through alternative channels when blocked. They measure local device density and adjust coverage without centralized control. This transforms topology to interconnected meshes with redundant pathways, enabling self-healing during failures and self-optimization for changing user distributions. Implementation stakeholders simplify deployment through seamless scalability where fixtures self-join and self-calibrate. Service providers gain reliable operation in high-variability environments like stadiums and transportation hubs, offloading congested RF networks.

Multi-Function Communication. Advanced VLC implements adaptive transmission through reconfigurable hardware and signal processing, transitioning between specialized modes based on content priorities. Functional wavelength division isolates services (emergency alerts, positioning, authentication, high-speed data) on dedicated spectral bands with minimal crosstalk. This addresses implementation/ecosystem barriers by dynamically allocating resources based on actual needs, optimizing bandwidth and energy efficiency. The wavelength division enables each single LED infrastructure simultaneously provides illumination, data, positioning, and sensing. The economic incentives accelerate adoption by offering enhanced returns on investment and enabling infrastructure deployment before device critical mass.

Dynamic Security Mechanisms. Bio-inspired VLC implements physical-layer multi-layered security with three complementary defensive mechanisms: (1) Temporal authentication with unforgeable optical handshakes; (2) Strategic decoy nodes emitting misleading data while routing critical communications separately; (3) Active monitoring detecting unauthorized observation and disrupting interception. This transforms security into an intrinsic transmission property. Authentication eliminates encryption overhead while preventing spoofing; decoys increase interception resources; monitoring enables adaptive defense. Service providers could offer unprecedented protection for healthcare/finance/defense, creating differentiated value over RF technologies.

Ecosystem Integration. Inspired by foxfire fungi's symbiosis, VLC integrates with RF in hybrid frameworks: VLC handles localized high-security/multifunctional services; RF manages broader coverage with management capabilities. Spatially selective targeting aligns with emerging technologies LiDAR/AR/VR for precision localization. Energy-efficient

TABLE I

Bio-inspired VLC design rules mapping biological mechanisms to technical implementations, with each rule addressing specific adoption barriers through nature-derived solutions.

Rule	Technical Implementation	Biological Inspiration	Key Benefits	Primary Barriers Addressed
Environmental Intelligence	Multi-spectral sensing arrays with adaptive modulation and stimulus-responsive operation	Firefly squid counter-illumination; Dinoflagellate mechanotransduction	Reliable secure operation across varying light conditions with minimal power consumption	Technical: Ambient light interference Market: Energy efficiency and security
Spatial Selectivity	Steerable micro-LED arrays with adaptive optics and real-time user tracking	Anglerfish luring mechanism; Deep-sea predator targeting	Extended range, improved security, maintained connectivity despite obstructions	Technical: LoS dependency Implementation: Hardware density requirements
Resilient Network Architecture	Distributed routing algorithms with autonomous node coordination and density-based resource allocation	milky seas bacterial coordination; brittle star modular physiology	Automatic rerouting around obstructions, adaptive response to varying user densities	Technical: Connectivity reliability Implementation: Complex deployment planning
Multi-Function Communication	Dynamic mode switching and wavelength division multiplexing with specialized optical filtering	Comb jelly multi-purpose signaling; Railroad worm dual-color system	Optimized performance for different applications, simultaneous services through unified infrastructure	Implementation: Complex application requirements Ecosystem: Infrastructure utilization
Dynamic Security Mechanisms	Temporal pattern authentication and strategic transmission diversification with anomaly detection	Firefly species-specific flash patterns; Brittle star sacrificial defense	Inherent security with reduced computational overhead, multi-layered protection	Market: Security-sensitive applications Technical: Data protection
Ecosystem Integration	Dual-purpose LED infrastructure with progressive capability enhancement and cross-technology interfacing	Mutually beneficial symbiotic relationships in marine bioluminescent ecosystems	Progressive adoption with incremental benefits at each stage	Ecosystem: Technology fragmentation Market: Investment justification

dynamic activation targets specific users/applications. This strategy ensures seamless connectivity through hybrid handovers and adaptive modulation. The hybrid model aligns with telecom RF investments, incentivizing collaboration. Building operators gain energy efficiency and occupancy insights, while incremental upgrades enable future scalability. Cross-industry collaboration resolves standardization gaps, positioning VLC as a complementary next-generation layer.

VII. Conclusion

VLC faces persistent adoption barriers hindering its transition from niche applications to mainstream deployment. This work demonstrates how bio-inspired strategies, derived from bioluminescent organisms, fundamentally redefine VLC's capabilities, as quantified in the comparative analysis of Table VI and Fig. 3, while ensuring full backward compatibility with foundational standards. Mechanisms such as ambient-adaptive signaling (firefly squid), decentralized coordination (bacterial quorum sensing), and temporal authentication (fireflies) address interference, scalability, and security challenges while resolving market barriers through hybrid RF-VLC integration and cost-efficient infrastructure. By embedding environmental intelligence and multi-functional operation, this paradigm positions VLC as a sustainable, high-capacity pillar for next-generation networks, supporting smart cities, Industry 4.0, and immersive technologies. Future research should focus on real-world validation, standardization, and expanding biological analogies to optimize adaptability. Bridging biological ingenuity with optical engineering, this approach overcomes current bottlenecks and pioneers a future where light-based communication underpins global connectivity.

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Comparative analysis of IEEE 802.11bb and bio-inspired VLC Systems across different performance metrics categorized by autonomy level: static, reactive, adaptive with real-time feedback, and proactive.

Metric	IEEE 802.11bb	Bio-inspired VLC
Environmental Adaptability (Adjusting to environmental changes such as ambient light and obstacles)	**Static:** Fixed wavelength range (800-1000 nm), minimum receive sensitivity (-15 dBm), and no dynamic environmental sensing.	**Adaptive:** Ambient-adaptive counter-illumination, multi-spectral sensors, and dynamically shifts wavelength and intensity. Can camouflage the signal to optimize SNR. **Proactive:** Uses circadian-scheduled transmission, real-time clocks, and ML forecasting to treat predictable environmental changes.
Interference Resilience (Mitigating noise, crosstalk)	**Reactive:** Employs standard Carrier Sense Multiple Access (CSMA) with Clear Channel Assessment (CCA) to detect a busy channel and avoid collisions. Uses fixed PHY-layer specifications, OFDM and WDM.	**Adaptive:** Features Functional Wavelength Division and ambient-adaptive signaling with continuous environmental monitoring, dynamic spectrum allocation, and optimized modulation and SNR to avoid unintentional noise and crosstalk.
PHY-Layer Security (Authentication, confidentiality, anti-eavesdropping, anti-jamming)	**Static:** Relies on inherent physical-layer security of optical signals. No PHY-specific security mechanisms; security is entirely deferred to higher-layer encryption (e.g., WPA3).	**Adaptive:** Uses temporal pattern authentication where the optical handshake evolves over time to prevent replay attacks. **Proactive:** Features decoy-based threat mitigation that adapts to neutralize perceived threats.
Link Reliability & Mobility (Maintaining connection despite movement, blockages)	**Static:** Inherently dependent on LoS. **Reactive:** Defines an optional light communication (LC) repetition mechanism to overcome hidden node problems. No dynamic user tracking or handover mechanisms.	**Adaptive:** Uses spatial-selective targeting with steerable micro-LED arrays and adaptive optics to track users. It dynamically extends the reliable link range and navigates around obstacles.
Energy Efficiency (Minimizing power consumption, especially for IoT)	**Static:** Follows standard Wi-Fi power management modes (e.g., sleep/awake). The transmission is not optimized for energy efficiency as CCA and optional LC require constant receiver operation.	**Proactive:** Employs stimulus-responsive interaction and quorum sensing with predictive demand forecasting, which enables zero-power standby until activated. **Proactive:** Uses circadian-scheduled transmission to align communication with optimal environmental conditions (e.g., at night).
Network Scalability (Performance in dense device deployments)	**Reactive:** Relies on traditional CSMA/CA and CCA. Uses MIMO/WDM without intelligence or scalable coordination mechanisms.	**Proactive:** Uses quorum sensing-driven networks where nodes activate and synchronize only when a density threshold is met. **Adaptive:** Features "firefly synchronization" where nodes autonomously coordinate their timing and connection in real-time without a central controller.

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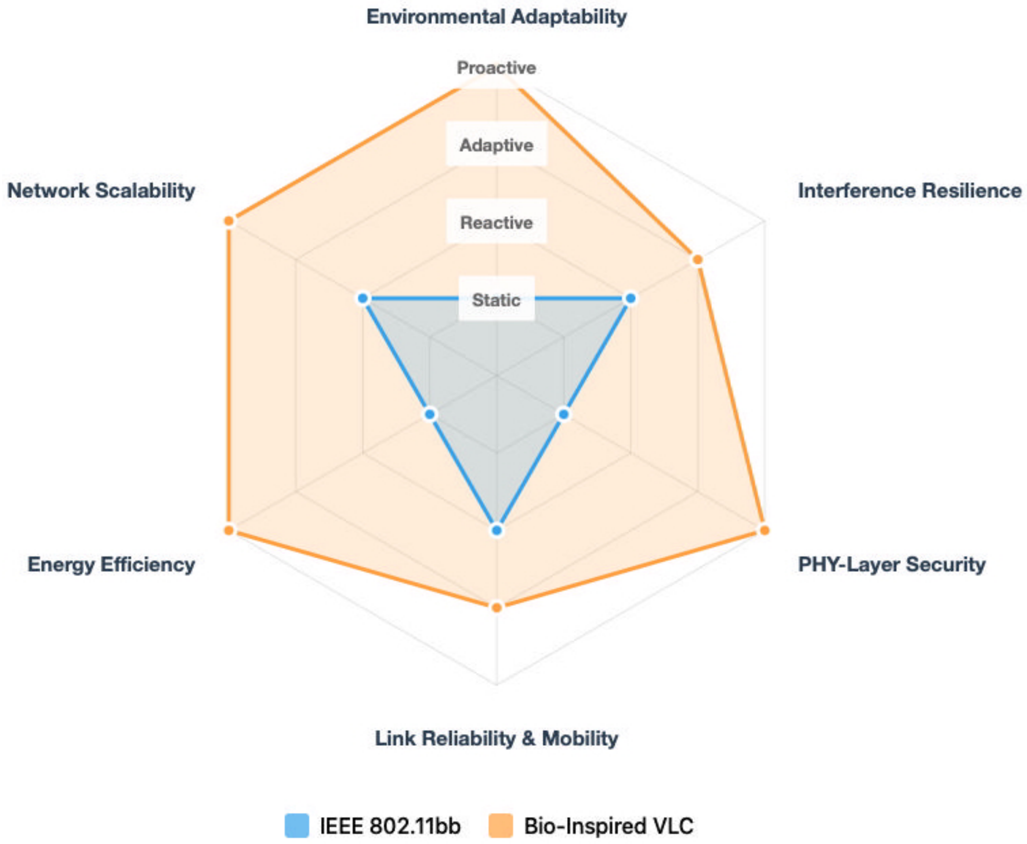

Fig. 3. Radar chart visualization of autonomy level comparison of IEEE standard 802.11bb and the bio-inspired VLC. IEEE 802.11bb operates at lower autonomy levels while Bio-inspired VLC achieves higher autonomy across all performance dimensions, illustrating the paradigm shift to intelligent, self-adapting VLC systems.

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