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Visible Light Communication in Next-Generation Wireless Networks: Potentials, Architecture, and Challenges

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ABSTRACT

As sixth-generation (6G) wireless infrastructures approach standard deployment matrices, the critical saturation of traditional radio-frequency (RF) spectrum pools requires alternative physical-layer transport domains. Visible Light Communication (VLC), which exploits the unlicensed optical spectrum from 380–780 nm, presents a foundational solution by combining architectural illumination with high-capacity data transmission tracks. This paper investigates the mechanical and mathematical principles governing state-of-the-art VLC platforms. Further, this paper assess a novel semiconductor developments, including Gallium Nitride micro-LEDs (µLEDs) and multi-channel Laser Diodes, alongside advanced orthogonal multi-carrier modulation frameworks configured under Intensity Modulation with Direct Detection (IM/DD) constraints. Furthermore, this work evaluates the deployment of deep learning layers to combat severe electro-optical non-linearities at the transmitter interface. Finally, the paper analyze key industrial application sectors—including tactical radio-silent environments, underwater optical telemetry, and vehicle-to-everything (V2X) nodes—while mapping the open technical hurdles and standardization path required for global adoption by 2030.

Keywords: Visible Light Communication (VLC), Intensity Modulation with Direct Detection (IM/DD), micro-LEDs (µLEDs)

INTRODUCTION

The relentless exponential curve of global wireless data requirements—catalyzed by massive machine-type communications, immersive virtual ecosystems, and real-time autonomous systems has brought modern radiofrequency frameworks to a point of critical spectral exhaustion[1,2]. To meet the aggressive throughput thresholds, ultra-low latency, and spatial densification indicators stipulated by emerging sixth-generation (6G) wireless models, network engineering must utilize previously untapped frequency domains. Visible Light Communication (VLC) presents a compelling paradigm shifting communications into the multi-terahertz unlicensed optical band without generating parasitic electromagnetic interference (EMI)[3][4].

Unlike RF signals, which propagate freely through typical internal structures, optical beams are natively confined by opaque spatial barriers[5]. This geometric confinement provides an exceptional structural advantage, enabling massive spatial frequency reuse patterns across adjacent rooms and providing robust physical-layer security against out-of-boundary signal interception[6][7] . By modulating the radiation intensity of consumer and industrial light-emitting diode (LED) frameworks at speeds imperceptible to the human eye, VLC transforms ubiquitous illumination networks into a highly parallelized data distribution layer[8][9]. This research paper explores the fundamental hardware bottlenecks, structural modulation algorithms, and advanced signal-restoration technologies defining modern VLC networks.

SYSTEM TOPOLOGY & TRANSRECEIVER DYNAMICS

The practical deployment of a high-speed VLC transmission loop relies on a specialized electro-optical conversion sequence designed to satisfy the rigorous limits of optical physical links[10]. At its core, a standalone VLC network relies on direct modulation of light intensity, a paradigm known as Intensity Modulation with Direct Detection (IM/DD). The transmission pipeline contains three primary stages[11][12]:

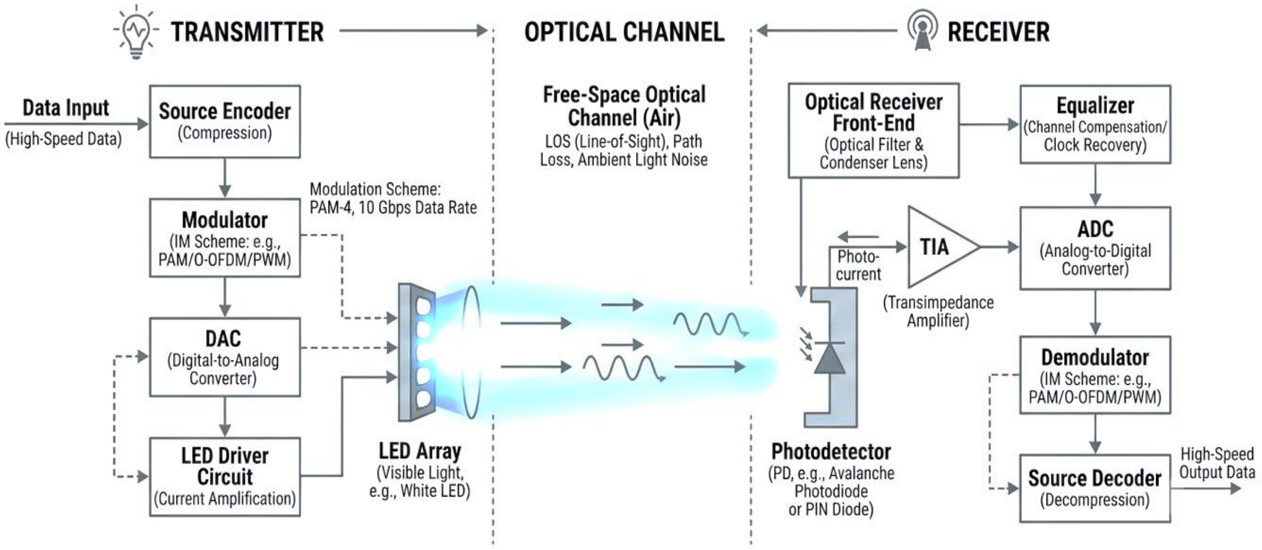


Figure: Block Diagram of High Speed Intensity Modulated Visible Light Communication Link

Transmitter Section: The transmitter converts digital data into variable optical power.

- **Modulation:** Traditional light sources cannot be switched fast enough to achieve gigabit-per-second rates. Digital signal processing units map data onto advanced modulation formats, such as Orthogonal Frequency Division Multiplexing (OFDM) or M-ary Quadrature Amplitude Modulation (QAM), to maximize spectral efficiency
- **Optical Emitters:** Solid-state light sources serve as the physical antennas. While standard White LEDs (WLEDs) are highly accessible, their modulation bandwidth is inherently limited to a few megahertz due to slow phosphor response times .To transcend this, modern high-speed systems leverage LEDs (μLEDs) and Laser Diodes (LDs), which unlock multi-gigahertz bandwidths and enable transmission speeds exceeding 100 Gb/s[13] .

The Optical Channel

The modulated light waves travel through the air, which serves as the physical communication channel. Unlike RF waves, visible light does not penetrate opaque obstacles like walls While this physical containment guarantees exceptional security and prevents eavesdropping, it also restricts VLC primarily to line-of-sight (LOS) conditions and makes the channel highly vulnerable to shadowing and ambient light noise[14][15].

Receiver Section: The receiver captures the optical power and translates it back into an electrical signal.

- **Photodetectors (PDs):** Positive-Intrinsic-Negative (PIN) photodiodes or Avalanche Photodiodes (APDs) are widely utilized for high-speed indoor setups due to their rapid response times.
- **Image Sensors:** Complementary Metal-Oxide-Semiconductor (CMOS) camera sensors found in smartphones can also decode VLC signals. However, standard camera frame rates drastically limit data reception speeds compared to dedicated photodetectors[16][17].

ADVANCED MATHEMATICAL MODULATION FRAMEWORKS

VLC systems operate almost exclusively via Intensity Modulation with Direct Detection (IM/DD). This operational model introduces a strict mathematical boundary: the driving electrical signal mapped to the emitter must be real-valued and strictly non-negative, such that:

$$s(t) \geq 0 \quad rall \quad t$$

This structural condition prevents the direct execution of standard complex-valued radio frequency modulation models, requiring specialized variations of multi-carrier transmission formats [18][19]

Optical Orthogonal Frequency Division Multiplexing (OFDM)

To maximize spectral efficiency across highly band-limited semiconductor junctions, researchers heavily rely on specialized optical modifications of OFDM:

DC-Biased Optical OFDM (DCO-OFDM): In this topology, Hermitian symmetry is enforced across the subcarriers to force the output time-domain signal to be purely real-valued. To resolve the negative voltage excursions, a positive DC bias current is added. While straightforward to execute, the persistent DC bias inserts significant power inefficiencies into the transmission grid[20].

Asymmetrically Clipped Optical OFDM (ACO-OFDM): This approach maps data symbols exclusively onto odd-indexed subcarriers. The resulting time-domain signal possesses a distinct asymmetric wave structure where all negative peaks can be hard-clipped to zero without causing distortion to the data symbols. This provides exceptional optical power efficiency, though it sacrifices half of the raw spectral capacity.

Deep Learning-Based Mitigation of System Non-Linearities

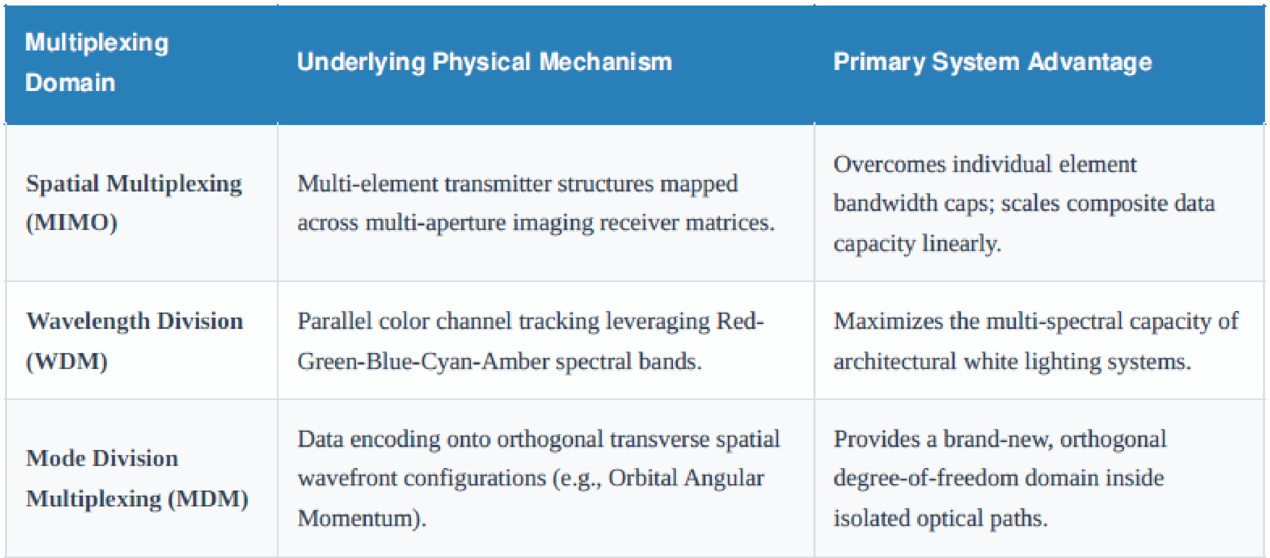
Semiconductor LEDs exhibit highly non-linear electro-optical transfer curves, characterized by sharp turn-on voltage thresholds and severe high-current saturation regions. When driven by multi-carrier formats like DCOOFDM, which naturally possess high Peak-to-Average Power Ratios (PAPR), the signal experiences intense nonlinear distortion. This distortion generates significant in-band intermodulation noise and out-of-band spectral regrowth.

To counteract these non-linearities, modern research is replacing traditional analytical models (such as the Volterra series) with Physics-Informed Neural Networks (PINNs). These specialized deep learning models are trained to characterize the specific dynamic non-linear properties of the electro-optical front end. Operating as realtime pre-distortion or post-equalization blocks, PINNs dynamically invert signal distortions, preserving low Bit Error Rates (BER) even when operating the transmitter at maximum structural throughput.

MULTI-DIMENSIONAL DIMENSIONALITY SCALING

To scale system capabilities toward the next-generation target of 1Tbs research has shifted focus from single-channel links to multi-dimensional multiplexing architectures:

Multiplexing Domain



Multiplexing Domain	Underlying Physical Mechanism	Primary System Advantage
Spatial Multiplexing (MIMO)	Multi-element transmitter structures mapped across multi-aperture imaging receiver matrices.	Overcomes individual element bandwidth caps; scales composite data capacity linearly.
Wavelength Division (WDM)	Parallel color channel tracking leveraging Red-Green-Blue-Cyan-Amber spectral bands.	Maximizes the multi-spectral capacity of architectural white lighting systems.
Mode Division Multiplexing (MDM)	Data encoding onto orthogonal transverse spatial wavefront configurations (e.g., Orbital Angular Momentum).	Provides a brand-new, orthogonal degree-of-freedom domain inside isolated optical paths.

MODERN DEPLOYMENT VERTICALS

VLC networks are transitioning out of specialized laboratory environments into target application sectors where radio-frequency propagation is fundamentally restricted, hazardous, or physically unviable:

Radio-Silent Tactical Environments: In naval command centers, defense installations, and aerospace structures, maintaining absolute radio silence is paramount. Bidirectional VLC systems establish high-capacity communication links completely immune to RF eavesdropping, side-channel sniffing, or remote signal tracking. Because light waves are fully blocked by physical walls, sensitive data remains securely contained within the intended space.

Subsurface Maritime Operations: Traditional RF waves experience near-instantaneous attenuation when propagating through conductive aquatic environments, while acoustic links are bottlenecked by low bandwidth and slow propagation velocities. High-frequency blue-green spectrum VLC systems bypass these limitations, delivering short-to-medium-range, multi-gigabit data exchanges that enable real-time telemetry between autonomous underwater vehicles (AUVs) and submerged sensor networks.

OPEN TECHNICAL ROADBLOCKS

Achieving ubiquitous deployment requires resolving several prominent technical hurdles. The first is intense ambient light interference; solar radiation and high-frequency artificial lighting ballasts introduce severe shot noise into photodetectors, risking sensor saturation. This requires the development of adaptive optical tracking filters. Second, the absolute Line-of-Sight (LoS) dependency of light waves creates vulnerabilities to physical blockages. To maintain continuous service, networks must implement unified hybrid coordination layers that can execute sub millisecond handovers to backup RF millimeter-wave systems whenever the primary optical path is broken.

CONCLUSION

Visible Light Communication has matured into a robust, high-capacity technology capable of providing vital spectrum relief to next-generation 6G networks. By integrating high-bandwidth semiconductor materials, deep learning signal processing, and multi-dimensional multiplexing, VLC cleanly overcomes the physical limitations of legacy wireless networks. The trajectory of global commercial adoption now depends on standardizing hybrid coordination protocols and establishing international hardware interoperability criteria.

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