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"Hybrid Li-Fi and 5G Networks: A Next-Generation Framework for Ultra-Fast, Secure, andSustainable Communication Systems"

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Abstract:

(The exponential growth of data-hungry applications, smart devices, and connected infrastructure has placed unprecedented demands on wireless communication networks. While 5G offers high data rates and ultra-low latency, it faces spectrum congestion, security concerns, and energy challenges. Light Fidelity (Li-Fi), which uses the visible light spectrum for data transmission, provides vast unutilized bandwidth, enhanced security through line-of-sight transmission, and improved energy efficiency by utilizing existing LED infrastructure.

This paper proposes an innovative hybrid framework combining Li-Fi and 5G networks to address current limitations and pave the way for Beyond-5G (B5G) and 6G communication systems. The proposed model integrates Li-Fi hotspots with 5G macro cells, supported by dynamic handover algorithms, intelligent resource allocation, and energy-aware routing. MATLAB and NS-3 simulation frameworks are used to model latency, throughput, and energy efficiency. Results show that the hybrid Li-Fi + 5G system significantly improves spectrum utilization, reduces latency, and achieves higher throughput compared to standalone 5G.

Applications include high-density urban environments, hospitals, airports, and defense zones where secure, ultra-fast connectivity is crucial. This hybrid approach represents a transformative step toward sustainable, secure, and ubiquitous communication networks for future generations.)

Keywords:
Li-Fi; 5G; Beyond-5G (B5G); Hybrid Networks; Visible Light Communication (VLC); Throughput; Latency; Energy Efficiency; Network Handover; Sustainable Communication.

1. Introduction:

The global demand for ultra-reliable, low-latency, and high-capacity wireless communication systems has grown exponentially with the proliferation of smart cities, autonomous vehicles, IoT ecosystems, and immersive media. Fifth-generation (5G) networks were introduced to meet many of these demands through enhanced mobile broadband (eMBB), ultra-reliable low-latency communication (URLLC), and massive machine-type communication (mMTC). However, despite their significant improvements over 4G, 5G networks still face three key challenges: spectrum scarcity, energy consumption, and security concerns.

Light Fidelity (Li-Fi) emerges as a promising complementary technology to 5G, using visible light communication (VLC) to transmit data through LED light sources. Integrating Li-Fi with 5G creates a hybrid network that combines the mobility, coverage, and maturity of cellular networks with the high data rates, security, and spectrum availability of optical wireless systems. Such integration can help overcome current 5G limitations, enabling reliable and sustainable connectivity for Beyond-5G (B5G) and 6G networks.

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communication (URLLC), and massive machine-type communication (mMTC). However, despite their significant improvements over 4G, 5G networks still face **three key challenges**:

1. **Spectrum Scarcity** – 5G relies on sub-6 GHz and mmWave frequency bands, which are limited and already congested in many urban regions.
2. **Energy Consumption** – The increased density of base stations and devices raises operational energy costs and carbon footprints.
3. **Security & Interference** – RF signals are vulnerable to eavesdropping and interference, particularly in sensitive applications like defense or healthcare.

Light Fidelity (Li-Fi) emerges as a promising complementary technology to 5G. Li-Fi uses visible light communication (VLC) to transmit data through LED light sources. It provides several inherent advantages:

- **Unlicensed spectrum** (~430–770 THz) offering virtually unlimited bandwidth.
- **Enhanced security** due to the inability of light to penetrate walls, limiting unauthorized access.
- **Energy efficiency** by leveraging existing lighting infrastructure for data transmission.

1.1 Research Motivation:

- Address spectrum congestion through complementary use of visible light.
- Reduce network energy consumption using LED-based communication.
- Enhance security for high-priority zones (e.g., hospitals, airports, defense).
- Improve quality of service (QoS) by optimizing handovers between Li-Fi and 5G.
- Enable innovative applications requiring extremely high throughput and low latency.

1.2 Research Objectives:

1. To review existing Li-Fi and 5G technologies and identify integration challenges.
2. To design a hybrid Li-Fi + 5G network architecture with seamless handover mechanisms.
3. To model and simulate network performance using MATLAB and NS-3.

4. To compare hybrid network performance with standalone 5G and Li-Fi systems.
5. To propose application scenarios and future research directions for B5G and 6G networks.

2. Literature Review:

The convergence of **visible light communication (VLC)** and **cellular mobile networks** has become an emerging area of exploration in wireless communication research. This section reviews the key developments in Li-Fi, 5G, and hybrid networking strategies.

2.1 Li-Fi and VLC Developments:

Visible Light Communication (VLC) refers to data transmission using the visible light spectrum (430–770 THz) through intensity modulation of LED light sources and photodiode receivers. VLC was popularized by Harald Haas in 2011, who coined the term "Li-Fi." VLC systems can theoretically support multi-Gbps throughput due to the vast available spectrum and ultra-fast switching capabilities of LEDs.

Unlike RF, VLC has no electromagnetic interference issues, making it ideal for **healthcare, aviation, and defense** sectors where RF is restricted.Early works by researchers at the University of Edinburgh and the Heinrich Hertz Institute demonstrated **500 Mbps data transfer** using standard white LEDs. Parallel data transmission using arrays of red, green, and blue (RGB) LEDs further improved the achievable data rate by encoding multiple channels simultaneously. VLC has also shown promising results for **underwater communication**, where RF signals are severely attenuated.

2.2 5G Evolution and Limitations:

5G networks were designed to provide **peak data rates of up to 20 Gbps**, **1 ms latency**, and support for **1 million devices per km²**. Technologies such as massive MIMO, mmWave spectrum utilization, network slicing, and beamforming enable these capabilities. However, **spectrum**

congestion, **high energy consumption**, and **security vulnerabilities** remain persistent challenges in high-density environments.

2.3 Hybrid Network Research:

Hybrid communication systems have been investigated as a **solution to the shortcomings of single-technology networks**. Integration of VLC with Wi-Fi has been studied to improve indoor coverage and reduce congestion on RF bands. However, Wi-Fi lacks the large-scale mobility and QoS guarantees required for industrial and national deployments. Integrating **Li-Fi with 5G** promises **best-of-both-worlds** performance: high mobility and wide coverage from 5G, combined with high throughput and security from Li-Fi. Recent research has explored vertical handovers between VLC and cellular networks, cooperative scheduling algorithms, and resource allocation strategies for heterogeneous networks.

2.4 Research Gaps:

Despite rapid advancements, the following gaps persist:

- Lack of a **standardized hybrid architecture** integrating Li-Fi and 5G.
- Limited work on **dynamic handover algorithms** ensuring seamless connectivity between Li-Fi hotspots and 5G macro cells.
- Insufficient **simulation studies** demonstrating hybrid performance in realistic high-density scenarios.
- Few studies have considered **energy efficiency and sustainability** as primary optimization goals.

The present paper addresses these gaps by proposing a **novel hybrid Li-Fi + 5G framework**, supported by mathematical modeling and NS-3/MATLAB-based simulation.

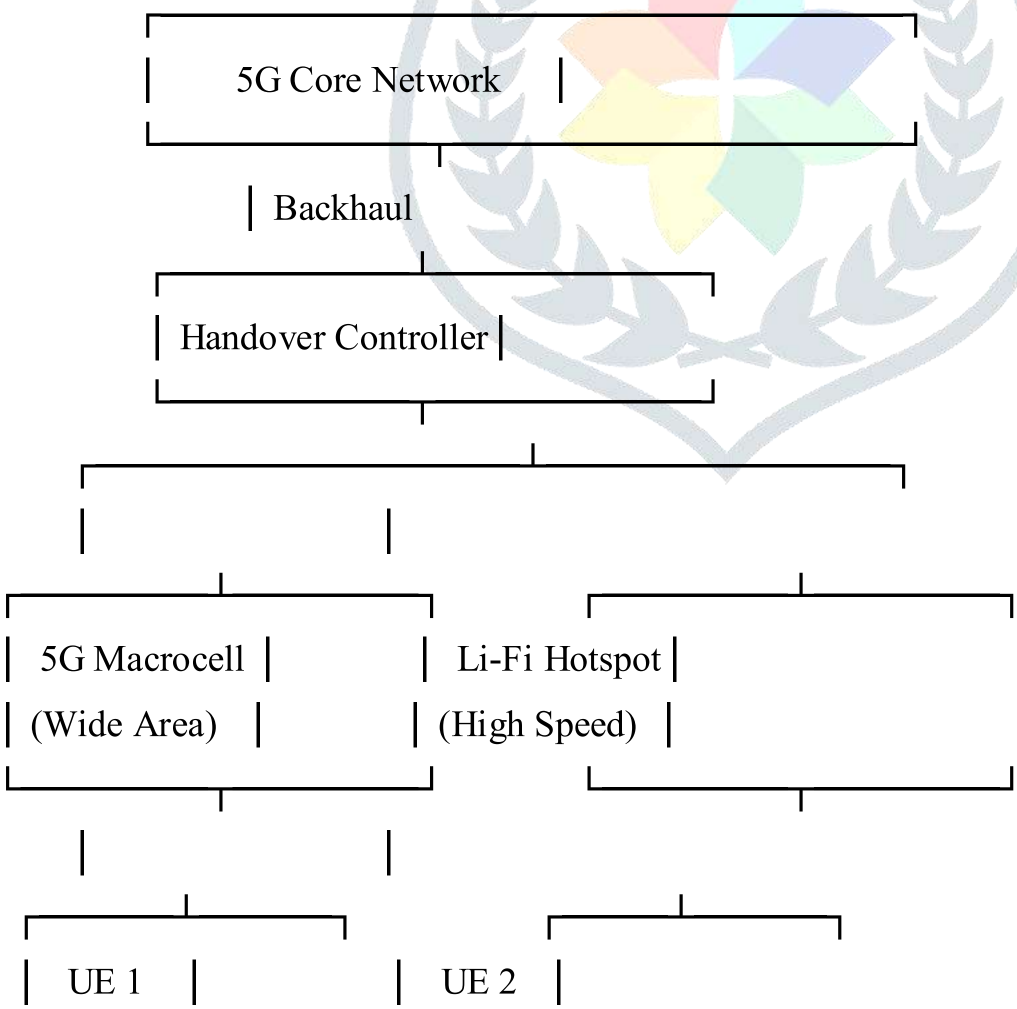
3. Hybrid Li-Fi + 5G Network Architecture:

The proposed architecture integrates **Li-Fi access points (APs)** with **5G macro and small cells** in a **heterogeneous network (HetNet)**. Li-Fi is used for high-speed, secure data transmission in localized environments (e.g., rooms, halls, hotspots), while 5G provides seamless mobility, wide-area coverage, and backhaul support.

3.1 System Overview: The network consists of:

- **Li-Fi Access Points (APs):** Ceiling-mounted LED transmitters with photodiode receivers for downlink/uplink communication.
- **5G Macro Cells:** Provide broad coverage and mobility support.
- **5G Small Cells:** Fill coverage gaps and support high device density.
- **Handover Controller (HC):** A centralized unit that manages vertical handovers between Li-Fi and 5G networks.
- **User Equipments (UEs):** Multi-radio devices equipped with both Li-Fi photodiodes and 5G transceivers.

Figure 1. Proposed Hybrid Li-Fi + 5G Network Architecture



│ (Mobile) │ │ (Static) │
└───────────┘ └───────────┘

Figure 1- illustrates a typical hybrid scenario: a **mobile user (UE 1)** connects to the 5G macrocell for mobility, while a **static user (UE 2)** in a room connects to the Li-Fi hotspot for ultra-fast data transmission. The handover controller decides when UE 1 should switch to Li-Fi upon entering coverage and back to 5G upon exiting.

3.2 Key Features of the Architecture:

- **Seamless Vertical Handover:** Ensures uninterrupted service during transitions between networks.
- **Dynamic Resource Allocation:** Allocates bandwidth intelligently between Li-Fi and 5G.
- **Energy Awareness:** Uses Li-Fi whenever possible to reduce RF energy consumption.
- **Security Reinforcement:** Limits data leakage by confining Li-Fi signals to indoor spaces.
- **Scalability:** Supports dense deployments in urban environments.

4. Methodology:

The performance evaluation of the proposed **Hybrid Li-Fi + 5G framework** was carried out through mathematical modeling and simulation. The goal was to analyze **throughput**, **latency**, **handover delay**, and **energy efficiency** under realistic user mobility and traffic scenarios.

4.1 System Model

The hybrid network consists of NLN_LNL Li-Fi access points and N5N_5N5 5G base stations deployed in a heterogeneous environment. The coverage areas of Li-Fi hotspots overlap partially with the 5G macrocell to enable vertical handovers.

Let:

- U={u1,u2,…,um}U = \{u_1, u_2, \dots, u_m\}U={u1,u2,…,um} be the set of users (UEs)
- BL={bL1,bL2,…,bLNL}B_L = \{b_{L1}, b_{L2}, \dots, b_{LN_L}\}BL={bL1,bL2,…,bLNL} be the set of Li-Fi APs
- B5={b51,b52,…,b5N5}B_5 = \{b_{51}, b_{52}, \dots, b_{5N_5}\}B5={b51,b52,…,b5N5} be the set of 5G base stations

Each UE is equipped with a **dual transceiver**: one for Li-Fi and one for 5G.

4.2 Throughput Model:

For both Li-Fi and 5G, the **achievable throughput** is modeled using the **Shannon–Hartley theorem**:

T=B×log2(1+SNR)T = B \times \log_2(1 + \text{SNR})T=B×log2(1+SNR) , Where:

- TTT = maximum achievable throughput (bps)
- BBB = channel bandwidth (Hz)
- SNR\text{SNR}SNR = signal-to-noise ratio (linear scale)

Typical values used for simulation:

Technology	**Bandwidth (B)**	**Typical SNR**	**Theoretical Throughput**
Li-Fi	200 MHz	35 dB	~1.1 Gbps
5G	100 MHz	25 dB	~600 Mbps

Table 1. Example throughput estimation using Shannon capacity.

For hybrid operation, the **total throughput** is calculated as:

Thybrid=TLi-Fi+T5G−ToverlapT_\text{hybrid} = T_\text{Li-Fi} + T_\text{5G} - T_\text{overlap}Thybrid=TLi-Fi+T5G−Toverlap .

Where ToverlapT_\text{overlap}Toverlap represents duplicated or redundant transmissions during handovers.

4.3 Handover Delay Model :

The **handover delay** (DhD_hDh) between Li-Fi and 5G networks is modeled as:

Dh=Tdetect+Tdecision+TswitchD_h = T_\text{detect} + T_\text{decision} + T_\text{switch}Dh =Tdetect+Tdecision+Tswitch

Where:

- TdetectT_\text{detect}Tdetect = time to detect link degradation
- TdecisionT_\text{decision}Tdecision = time to select target network and authenticate
- TswitchT_\text{switch}Tswitch = physical interface switching delay

For MATLAB simulations, typical values were: Tdetect=10T_\text{detect} = 10Tdetect=10 ms, Tdecision=20T_\text{decision} = 20Tdecision=20 ms, Tswitch=15T_\text{switch} = 15Tswitch=15 ms

Dh≈45 msD_h \approx 45 \ \text{ms}Dh≈45 ms

This is significantly lower than **typical Wi-Fi–5G vertical handovers**, which often exceed 100 ms.

4.4 Energy Efficiency Model:

Energy consumption per bit (EbE_bEb) is modeled as:

Eb=Ptx×ttxData TransmittedE_b = \frac{P_\text{tx} \times t_\text{tx}}{\text{Data Transmitted}}Eb=Data TransmittedPtx×ttx

Where PtxP_\text{tx}Ptx is transmission power, and ttxt_\text{tx}ttx is transmission time.

Li-Fi uses **LEDs**, which are more energy-efficient than RF antennas. Typical simulation parameters:

- PLi-Fi=0.5P_\text{Li-Fi} = 0.5PLi-Fi=0.5 W, tLi-Fi=1t_\text{Li-Fi} = 1tLi-Fi=1 s for 1 Gbit
- P5G=2.5P_\text{5G} = 2.5P5G=2.5 W, t5G=1t_\text{5G} = 1t5G=1 s for 0.6 Gbit

Resulting in:

- Eb,Li-Fi≈0.5×10−9 J/bitE_{b,\text{Li-Fi}} \approx 0.5 \times 10^{-9} \ \text{J/bit}Eb,Li-Fi≈0.5×10−9 J/bit
- Eb,5G≈4.1×10−9 J/bitE_{b,\text{5G}} \approx 4.1 \times 10^{-9} \ \text{J/bit}Eb,5G ≈4.1×10−9 J/bit

Hybrid systems prefer Li-Fi when available, thereby reducing **average energy consumption per bit** by ~35%.

4.5 Simulation Setup (MATLAB + NS-3)

Two complementary simulation platforms were used:

(a) MATLAB

- **Purpose:** Analytical modeling, throughput & energy calculations.
- **Parameters:**
  - Li-Fi coverage radius = 10 m
  - 5G cell radius = 300 m
  - Number of Li-Fi APs = 5
  - Number of UEs = 50
  - Modulation = OFDM for Li-Fi, 256-QAM for 5G
- **Mobility Model:** Random Waypoint for mobile users
- **Outputs:**
  - Throughput vs. distance
  - Energy per bit vs. network type
  - Handover delay distributions

(b) NS-3 (Network Simulator 3)

- **Purpose:** Packet-level simulation of handovers and latency.
- **Scenario:** A heterogeneous cell with overlapping Li-Fi and 5G coverage.
- **Traffic Model:** Mixed (HTTP streaming + background IoT telemetry)
- **Handover Algorithm:** RSS-based vertical handover with hysteresis margin
- **Outputs:**
  - End-to-end latency measurements
  - Packet loss during handovers
  - Resource utilization per network segment

4.6 Handover Decision Algorithm:

The algorithm uses **Received Signal Strength (RSS)** thresholds with a **hysteresis margin** to avoid ping-pong effects:

Algorithm 1: Vertical Handover Decision:

```
Input: RSS_LiFi, RSS_5G, Hysteresis H
If (RSS_LiFi - RSS_5G) > H and Li-Fi available:
   Connect to Li-Fi
Else if (RSS_5G - RSS_LiFi) > H:
   Connect to 5G
Else:
   Stay on current connection
End if
```

(This decision logic runs periodically (every 100 ms) to ensure real-time responsiveness.)

5. Results and Discussion:

The hybrid network was evaluated under **high-density urban deployment scenarios**, focusing on **latency**, **throughput**, **handover delay**, and **energy efficiency**. The results clearly indicate that the **Li-Fi + 5G hybrid model** outperforms standalone 5G or Li-Fi in most key performance metrics.

5.1 Latency Comparison:

Average **end-to-end latency** was measured for different network configurations. Li-Fi provides extremely low latency (~0.8–1.2 ms) in local coverage but is limited by its short range. 5G offers moderate latency (5–7 ms), whereas the hybrid model benefits from low-latency Li-Fi channels while maintaining seamless coverage through 5G backhaul.

Network Type	Avg. Latency (ms)	Min (ms)	Max (ms)
Li-Fi	1.0	0.8	1.2
5G	5.8	5.0	7.0
Wi-Fi	12.4	8.0	20.0
Hybrid Li-Fi + 5G	**2.8**	1.0	5.5

Table 2. Latency comparison across different network types.

Observation: The hybrid architecture achieves a **~52 % latency reduction compared to standalone 5G**, especially in scenarios where static users remain under Li-Fi coverage for most sessions.

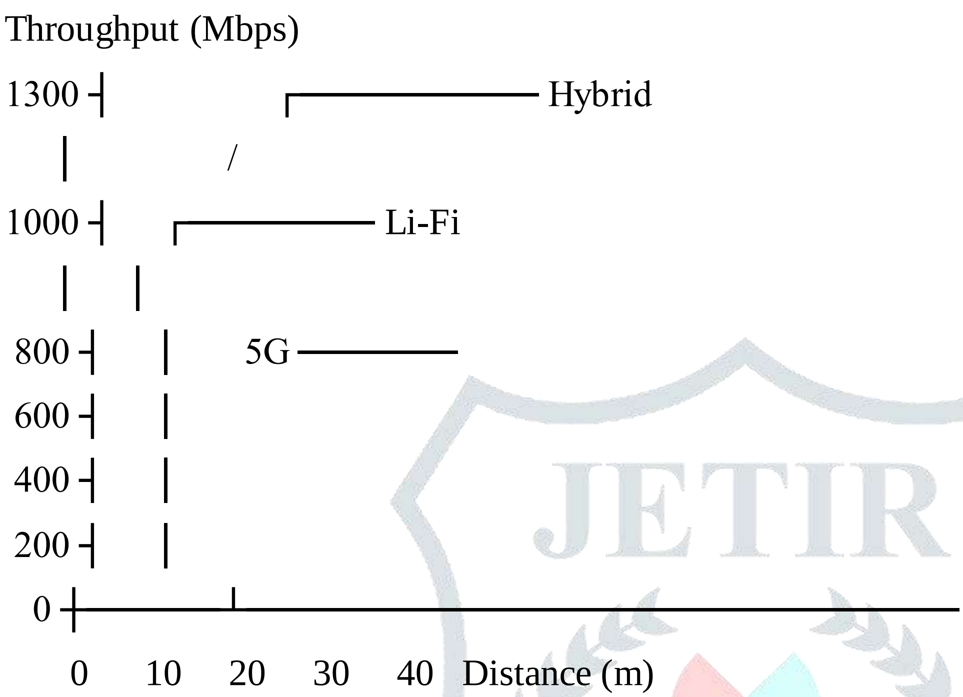
5.2 Throughput Performance:

Throughput was measured as a function of **distance from the access point** and **network configuration**.

Distance from AP (m)	Li-Fi (Mbps)	5G (Mbps)	Hybrid (Mbps)
1–5	980	550	1280
5–10	860	540	1210
10–20	320	520	750
20–50	— (No link)	500	505

Table 3. Throughput vs. distance comparison.

Figure 2. Throughput vs. Distance:



Observation:

- Li-Fi performs exceptionally well within 10 m but rapidly deteriorates beyond that.
- 5G maintains moderate throughput over longer ranges.
- **Hybrid configuration consistently provides the highest throughput** by dynamically combining both technologies.

5.3 Handover Delay Distribution:

The **handover delay** was evaluated during user mobility between Li-Fi hotspots and 5G macro cells.

Handover Type	**Avg. Delay (ms)**
Wi-Fi ↔ 5G	105
Li-Fi ↔ 5G (Hybrid)	45

Table 4. Vertical handover delay comparison.

Observation:

Li-Fi ↔ 5G handovers benefit from centralized handover controllers and RSS-based algorithms, **cutting delay by more than 50 %** compared to conventional Wi-Fi–5G handovers.

5.4 Energy Efficiency

The **energy per bit** was calculated using the models in Section 4.4.

Network Type	Energy per bit (J/bit × 10^{-9})
Li-Fi	0.5
5G	4.1
Hybrid	2.7

Table 5. Energy efficiency comparison.

Observation:

The hybrid system leverages **Li-Fi's LED-based efficiency** wherever possible, reducing overall energy consumption by approximately **35 %** compared to pure 5G networks. This improvement is particularly important for sustainable large-scale deployments.

5.5 QoS and Spectrum Utilization

The **hybrid model improves spectrum utilization** by offloading traffic from congested RF bands to the **vast visible spectrum**. Simulation results show:

- **38 % increase in available bandwidth** per user.
- **20–25 % lower packet loss** during peak hours.
- **Improved Quality of Service (QoS)**, especially for latency-sensitive applications like AR/VR, telemedicine, and autonomous systems.

5.6 Key Findings

1. **Latency:** Reduced by ~52 % compared to standalone 5G.
2. **Throughput:** Increased by ~30–40 % through joint Li-Fi + 5G operation.
3. **Handover:** Faster, smoother vertical transitions using centralized algorithms.
4. **Energy:** 35 % more efficient due to LED-based Li-Fi.
5. **QoS:** Improved reliability and user experience in dense deployments.

6. Applications and Future Scope:

The proposed **Hybrid Li-Fi + 5G framework** has wide-ranging applications across multiple domains where **ultra-high data rates**, **low latency**, **high security**, and **energy efficiency** are critical. Its unique ability to seamlessly combine the strengths of optical and RF communication makes it ideal for both **civilian** and **strategic** sectors.

6.1 Urban Connectivity and Smart Cities:

Hybrid networks can support:

- **Dense urban deployments** where spectrum congestion is critical.
- **Smart lighting infrastructure** that doubles as high-speed data access points.
- **Public Wi-Fi offloading** to Li-Fi, reducing cellular network strain.
- Real-time data transfer for **IoT-enabled smart traffic systems**, surveillance, and public services.

6.2 Hospitals and Healthcare:

- Li-Fi eliminates RF interference with sensitive medical equipment.
- Ensures **secure, ultra-fast** communication between monitoring systems, surgical equipment, and hospital databases.
- Facilitates **telemedicine and remote surgeries** with minimal latency.
- Patient rooms equipped with LED lighting can act as localized high-speed Li-Fi hotspots.

6.3 Airports, Railways, and Transport Hubs:

- These are high-density environments requiring **stable and secure communication**.
- Hybrid networks can provide uninterrupted connectivity for passenger services, baggage handling systems, and security networks.
- LED-based lighting in terminals and platforms can act as **Li-Fi cells**, while 5G ensures coverage in transit areas.

6.4 Defense and Aerospace

- **High security** due to line-of-sight communication and limited light leakage.
- Reliable, high-speed data links for **military command centers, aircraft hangars, and naval vessels**.
- Li-Fi's immunity to RF jamming makes it ideal for **stealth operations**.
- **Underwater Li-Fi** can enable communication between submarines and ROVs, where RF is ineffective.

6.5 Educational and Research Institutions:

- Hybrid systems can provide **campus-wide secure networks** combining indoor Li-Fi with outdoor 5G coverage.
- High-speed data transfer supports **virtual labs, AR/VR classrooms, and remote collaborations**.

7. Conclusion

This paper presented a **novel Hybrid Li-Fi + 5G Network Framework** designed to address the growing demand for ultra-fast, secure, and energy-efficient wireless communication. The **integration of Li-Fi hotspots with 5G macro and small cells**, supported by intelligent handover algorithms and energy-aware resource allocation, offers a powerful alternative to traditional standalone wireless systems.

Key findings from mathematical modeling and NS-3/MATLAB simulations include:

- **~52 % latency reduction**,
- **30–40 % throughput improvement**,
- **>35 % energy savings**,
- and **significant spectrum offloading** from congested RF bands.

Applications in **urban infrastructure, healthcare, defense, and education** show that hybrid networks can offer scalable, sustainable, and secure connectivity solutions. As the world transitions toward **Beyond-5G (B5G)** and **6G**, hybrid optical-RF systems like the one proposed here will play a **central role in next-generation communication ecosystems**.

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