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Comparative Evaluation of 5G, WI-FI 6, AND LI-FI: A Performance-Centric Study in Modern Wireless Networks

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Abstract

The record-breaking growth in wireless data traffic, boosted by mobile devices, Internet of Things (IoT), and real-time applications, has motivated the development of even more high-performance, low-latency, and scalable wireless communication technologies. 5G, Wi-Fi 6 (IEEE 802.11ax), and Li-Fi (Light Fidelity) are a few of the strongest newcomers to this field, with each possessing the potential to address some performance issues in certain application environments. This paper offers a comprehensive, performance-comparison of these three technologies across eight significant metrics: data rate, latency, coverage, mobility, energy efficiency, device density, interference tolerance, and security. Following an exhaustive literature review, standardized performance modelling, and context-specific application mapping, the paper elaborates on each technology's highs and lows and deployment suitability. Results indicate that 5G works optimally in wide-area, high-mobility; Wi-Fi 6 in dense, indoor; and Li-Fi in secure, EMI (Electro Magnetic Interference)-sensitive, and short-range environments. The manuscript foresees a hybrid, context-aware fusion of the mentioned technologies to meet next-generation wireless ecosystems' requirements. Results justify strategic network planning, technology rollout, and research in future converged wireless infrastructures.

Keywords: Wireless Networks, Performance Evaluation, Comparative Study, Network Architecture, Wireless Communication Technologies

INTRODUCTION

There is increasingly a global requirement for broad, high-bandwidth, and reliable wireless communication that is growing very fast, driven in large part by pervasive use of mobile devices, advances in cloud computing, deployment of the Internet of Things (IoT), teleworking practices, and growing demand for real-time data services. The Cisco Annual Internet Report of 2020 predicted that IP traffic globally would reach more than 400 exabytes per month, and more than 29 billion devices were predicted to be connected by 2023. With growing data traffic and the increasing number of demands on networks, the need to address spectrum has emerged as a landmark challenge in wireless technology development. There have been different innovations undertaken to maximize data transmission efficiency in the constraints of the existing spectrum (Olanrewaju & Osunade, 2012). Notably, the wireless communications industry has witnessed the emergence of three revolutionary technologies: 5G (Fifth-Generation Mobile Network), Wi-Fi 6 (IEEE 802.11ax), and Li-Fi (Light Fidelity).

All of these technologies are aimed at addressing existing networking issues but with

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various approaches, data transmission methods, and performance objectives. 5G, developed based on the 3GPP (3rd Generation Partnership Project) standard, provides broad coverage with enhanced mobile internet, highly reliable low-delay communication (URLLC), and has the ability to serve a large number of devices simultaneously (mMTC) (ITU-R, 2020; Andrews et al., 2014). Wi-Fi 6, based on the IEEE 802.11ax standard, is designed to perform well in dense environments and enhance indoor performance through the aid of technologies such as OFDMA (Orthogonal Frequency-Division Multiple Access), MU-MIMO (Multi-User Multiple Input Multiple Output), and Target Wake Time (Bellalta, 2016; Khorov et al., 2019). Li-Fi utilizes visible light to deliver high-speed, interference-free, and secure data communication and is an excellent option for short-range applications where electro-magnetic interference is a problem (Haas et al., 2015; Tsonev et al., 2014).

The convergence of multiple networks, edge computing, and user demand in real time necessitates a comparison of these technologies, on theoretical basis, as well as application-specific applicability, implementation feasibility, and concomitant performance trade-offs. While many studies have focused on single technologies (Saad et al., 2019; According to Rappaport et al. (2013), a critical research gap exists in the absence of a unified, side-by-side comparison of these technologies, grounded in consistent performance criteria and deployment scenarios across diverse application domains such as smart cities, healthcare, Industry 4.0, and smart homes.

This research aims to bridge the gap by contrasting 5G, Wi-Fi 6, and Li-Fi in a simple manner. It contrasts all technologies based on key considerations: data rate, delay, coverage range, quantity of devices, usage of energy, mobility, capacity for interference handling, and security. The aim is to make it easy for researchers, practitioners, and policymakers to understand the strengths and weaknesses of each technology and how to utilize them.

The objective of the study is to contrast three new wireless technologies: 5G, Wi-Fi 6, and Li-Fi. The study will examine the main characteristics of the technologies such as data speed, delay, coverage area, energy consumption, and security. Apart from comparing the characteristics, the study also aims to determine the best applications of each technology. For instance, 5G is fitting in large-area mobility, Wi-Fi 6 is excellent in high-density environments, and Li-Fi is excellent in safety applications. Practical issues of using these technologies will also be explored by the research. The factors considered include, most importantly, the ease of deployment, along with their consumption requirements and capacity for mutual communication. These are the issues that dictate the usability and maintainability of these technologies. Ultimately, the study aims to provide a plan that integrates the merits of these technologies. This will allow them to coexist in future wireless systems and enable them to provide efficient, smart, and smooth communications.

This comparison is beneficial to plan and design wireless systems by identifying how 5G, Wi-Fi 6, and Li-Fi operate in various locations. This study assists companies in making a decision about what technology to utilize, how to mix them together, and how to allocate resources based on strengths and deficiencies in terms of standard performance criteria. The results also offer insightful information to researchers, particularly on the integration of various networks, layer optimization, and system architecture of 6G and beyond (Omilabu et al, 2017; Saad et al., 2019; Shafi et al., 2017). With wireless technology advancing towards more flexibility, reliability, and security, it is increasingly essential to understand how these technologies fit together. This research establishes a theoretical basis for forward-looking and intelligent network design, with contributions that bridge theoretical frameworks and field deployment within the field of wireless communication.

LITERATURE REVIEW

The wireless network technologies have seen a rapid expansion with the advent of 5G, Wi-Fi 6 (IEEE 802.11ax), and Li-Fi (Light Fidelity) as the key enablers of next-generation networking. An overview of the latest literature suggests that each technology is fulfilling some performance requirements and deployment conditions. In these regards, an in-depth study of the enabling technologies, progress, and research advancements in the area of these wireless systems is discussed.

Fifth-Generation Mobile Network (5G)

5G, as planned by the 3rd Generation Partnership Project (3GPP) and outlined by the International Telecommunication Union (ITU-R, 2020), is designed to support three basic service categories: enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communications (URLLC), and Massive Machine-Type Communication versions that emphasized maximum data transmission rates, Wi-Fi 6 emphasizes efficiency, scalability, and multi-user support. Following Bellalta (2016) and Khorov et al. (2019), the introduction of Orthogonal Frequency Division Multiple Access (OFDMA), uplink/downlink multi-user multiple input multiple output (MU-MIMO), and 1024-QAM modulation significantly improves spectral efficiency and reduces latency, particularly in environments with a high device density.

mMTC). These categories cater to bandwidth-hungry applications (e.g., 4K streaming), latency-critical applications (e.g., remote surgery), and high-density IoT environments (e.g., smart cities), respectively.

Andrews et al. (2014) argue that 5G represents not just a technology development but a revolutionary transformation, defined by the advent of large MIMO systems, millimeter-wave (mmWave) frequency bands, and heightened network density. The application of a service-oriented architecture in the 5G Core (5GC) allows for network slicing and Multi-access Edge Computing (MEC) integration, thus lowering latency and improving the ability to tailor networks to meet particular application requirements (Taleb et al., 2017).

Key-enabling technologies include beamforming, carrier aggregation, and operational models referred to as non-standalone (NSA). According to Rappaport et al. (2013), effective deployment of 5G, marked by very high data rates and low latency is largely contingent on proficient millimeter-wave (mmWave) spectrum exploitation; nevertheless, it is hampered by propagation effects and constraints in coverage.

Despite its great potential, the deployment of 5G technology is faced with major challenges such as huge infrastructural costs, spectrum fragmentation, and higher energy consumption in highly populated installations (Olanrewaju & Osunade, 2018; Saad et al., 2019). In addition, differences in spectrum regulation persist in hindering the achievement of a unified deployment strategy (ITU-R, 2020).

Wi-Fi 6 (IEEE 802.11ax)

Wi-Fi 6, officially known as IEEE 802.11ax, reflects a significant upgrade in wireless local area network (WLAN) performance. Unlike previous Target Wake Time and Basic Service Set Coloring (BSS Coloring) are additional features that are aimed at enhancing energy efficiency and limiting co-channel interference, respectively. According to Surendranathan (2019), these features allow Wi-Fi to support over 50 client devices per access point with unchanged quality of service.

Operating on the 2.4 GHz and 5 GHz bands, with an extension to the 6 GHz band via Wi-Fi 6E, the technology offers a theoretical upper transfer data rate of 9.6 Gbps. However, in real-world situations, performance often depends on the environment and coexistence between pre-existing devices (Cisco Systems, 2020).

Despite its improvements, Wi-Fi 6 has a lack of network-level quality of service (QoS) assurances and mobility support, typical of cellular networks. Also, it suffers from performance degradation in unlicensed and crowded frequency bands. Although security improvements via WPA3 (Wi-Fi Protected Access 3) are important, adoption is uneven, partly due to constraints imposed by legacy hardware and software (Khorov et al., 2019).

Li-Fi (Light Fidelity)

Li-Fi, a technology created by Harald Haas based on Visible Light Communication (VLC), is defined as an optical wireless communication system based on transmitting information using a visible light spectrum (Haas et al., 2015). Unlike traditional radio frequency-based systems, Li-Fi uses LED (Light-emitting diode) lighting to encode data signal, promising benefits like extremely high bandwidth, radio-frequency-free operation, and enhanced physical security.

Tsonev et al. (2014) demonstrate the feasibility of exceeding data rates of 100 Gbps under controlled lab conditions by using parallel optical transmission with sophisticated OFDM (Orthogonal Frequency Division Multiplexing) techniques. Li-Fi also has an intrinsic immunity to electromagnetic interference, which makes it especially suitable for use in environments that must be shielded from electromagnetic radiation, such as hospitals, airplane cabins, and factories (Chowdhury et al., 2019).

However, technology is in a process of continuous maturation. Research by Komine and Nakagawa (2004) recognizes some major constraints such as dependency on line-of-sight (LOS), limited range, ambient lighting interference, and a lack of a standardization framework. The IEEE 802.15.7 task group is actively involved in specification development; yet it is not yet incorporated in commonly used devices because of a lack of integrated hardware.

Therefore, Li-Fi's role is seen as supplementary and not competitive, especially well-suited to safe, close-range, high-throughput applications in environments where radio frequencies are not available or are inappropriate.

Saad et al. (2019) argue that future communication networks should seek to integrate and interoperate various technologies so as to benefit from what each has to offer. The integration of these technologies, made possible by smart switching, hybrid access, and context-aware orchestration, will be foundational in creating resilient, scalable, and responsive wireless ecosystems, especially within the context of the 6G era and onwards.

Integration of Comparative Perspectives

The article demonstrates how each of the thr ee technologies is a major step forward in wireless
communication but shares vastly different design principles and ideal uses:

Table1. Comparative Analysis of Primary Strengths and Core Challenges of 5G, Wi-Fi 6, and Li-Fi Technologies.

Technology	Primary Strengths	Core Challenges
5G	High mobility, low latency, wide-area coverage, network slicing	High CAPEX, energy use, spectrum regulation
Wi-Fi 6	Indoor performance, dense-device support, cost-effectiveness	QoS limitations, shared spectrum interference
Li-Fi	High speed, physical security, EMI immunity	LOS requirement, immaturity, limited mobility and standardization

METHODOLOGY

This section describes the scientific method adopted for evaluating 5G, Wi-Fi 6, and Li-Fi technologies' performance on various parameters. The objective is to conduct a performance-based comparative study that is quantitatively strong and qualitatively high in terms of approaches being widely used in wireless network studies (Sauter, 2021; Yin, 2018).

Research Design

The study applies a comparative analytical approach that is based on theoretical benchmarking and literature-based empirical modeling. It is the most appropriate approach given the heterogeneity of the technologies involved and the lack of a common platform for deployment of the three under similar conditions. In the interest of reproducibility and consistency, the evaluation is guided by essential performance indicators (KPIs) from real and credible sources like the ITU-R IMT-2020 specifications (ITU-R, 2020), IEEE 802.11ax standard documentation (IEEE, 2021), and peer-reviewed technical papers and benchmarking reports such as Haas et al. (2015) and Andrews et al. (2014).

Selection of Technologies and Scope

The context is interested in three of the most widely recognized wireless communication technologies that are crucial in defining modern digital infrastructure: 5G, a cell-based wide-area network (WAN) technology; Wi-Fi 6 (IEEE 802.11ax), a local area network (LAN) technology; and Li-Fi, an optical wireless communication technology reliant on visible light. These have been taken up on the basis of their distinctive transmission media, different application domains, as well as disparate performance potentials, hence providing a sound foundation for meaningful comparative evaluation.

Evaluation Criteria and KPIs

The comparison assessment in the present study relies on eight key performance metrics which are widely recognized within research and industrial wireless communication assessment models (Rappaport et al., 2013; Khorov et al., 2019). The metrics form a strong base for evaluating the strengths and weaknesses of the selected technologies. The metrics of performance are: maximum data rate (in Gbps), latency (in ms), coverage area (in m or km), mobility support (in km/h), energy efficiency, and support for device density (devices per square kilometer), interference robustness, and security, tested by qualitative and architectural perspectives. Multi-dimensional testing is to carry out a fair and holistic comparison of the different wireless technologies.

Data Collection and Sources

Given the levels of commercialization and standardization of 5G, Wi-Fi 6, and Li-Fi, the data collection process includes a broad range of sources to enable a thorough and sensitive analysis. The major points of reference were the established standards and specifications: ITU-R for 5G, IEEE 802.11ax for Wi-Fi 6, and IEEE 802.15.7 for Li-Fi. This primary data was supplemented by empirical research and academic literature that included experimental research on Li-Fi (Tsonev et al., 2014), industry-sponsored studies of 5G (Rappaport et al., 2013), and IEEE-accredited case studies on Wi-Fi 6 (Bellalta, 2016).

In addition, systematic reviews were used to provide comparative results and to validate performance metrics obtained from simulations. The assessment also included simulation tools mentioned in current literature, such as NS-3 for Wi-Fi 6, MATLAB toolkits for 5G, and VLC simulators for Li-Fi. Where empirical or simulated data did not exist, specifically for Li-Fi, due to its relatively early developmental phase, normalized metrics and theoretical standards mentioned in the literature were adopted to provide consistency within the comparative framework.

Normalization and Comparative Analysis Framework

Since 5G, Wi-Fi 6, and Li-Fi are each designed for specific contexts and uses, a direct comparison of performance, if done without making any adjustments would probably lead to inaccurate conclusions. In order to rectify this problem, a standardized scoring system has been developed to ensure objectivity and relevance in the assessment process.

The suggested framework includes three essential elements: the normalization of metrics to a standardized index value between 0 and 10, where a 10 represents maximum possible performance under given conditions; context-dependent weighting, whereby metrics are weighted based on relative importance in specific application areas, e.g., higher priority is given to latency where timeliness is paramount, as in applications such as robotics and healthcare; and qualitative scoring, whereby subjective factors such as interference tolerance and security are scored on a Low/Medium/High basis prior to being converted to numerical values (e.g., Low = 3, Medium = 6, High = 9). This holistic approach allows for balanced assessment incorporating both quantitative performance measures and qualitative factors, required when dealing with a range of technologies as wide as radio frequency (RF)-based systems and optical communications platforms.

Validation and Reliability

For determining the accuracy and reliability of the data utilized in this research, extensive cross-verification was carried out based on a wide variety of scholarly and technical sources. These sources included peer-reviewed papers published by renowned publishers like IEEE, Springer, and Elsevier; standards and specifications published by international bodies like ITU-R, IEEE, and 3GPP; as well as results published at major conferences and in peer-reviewed journals.

Where variability in data or uncertainty was noted, i.e., regarding latency or throughput measurements, performance results were presented in range form instead of a single value. Additionally, all underlying assumptions used within the analysis or reporting of such data were clearly defined to maintain transparency and ensure the integrity of comparative analysis.

Methodological Limitations

There are a few drawbacks that ought to be mentioned here. First, owing to a widely available testbed's scarcity between amongst three technologies, 5G, Wi-Fi 6, and Li-Fi, performing simultaneous real-time performance tests under the same circumstances is limited. Secondly, owing to a virtue of how relatively under-developed a technology a Li-Fi is, a majority of its performance indicators constitute either theoretical frameworks or lab experimental control setups and not typical real applications. Thirdly, research is heavily reliant on secondary data and research outcomes documented and not necessarily containing actual direct simulation or hardware validation. While these do have their constraints, research attains methodological uniformity by using cross checked, peer-checked data as well as following internationally agreed performance measures standards. This ensures proper and unique comparative results to reflect the currently available technology infrastructure.

RESULTS AND COMPARATIVE PERFORMANCE ANALYSIS

This section summarizes the findings of the comparative study performed according to the methodology above. 5G, Wi-Fi 6, and Li-Fi performance is compared based on a predefined set of key performance indicators (KPIs): data rate, latency, coverage, mobility support, energy efficiency, interference tolerance, device density support, and security. The data are synthesized from authoritative literature, standardized technical specifications, and peer-reviewed empirical research, normalized to a common performance comparison framework.

Table 2. Performance Metric Summary.

Performance Metric	5G	Wi-Fi 6 (802.11ax)	Li-Fi
Peak Data Rate	Up to 20 Gbps (DL), 10 Gbps (UL)	Up to 9.6 Gbps (theoretical)	>100 Gbps (experimental)
Latency	<1 ms (URLLC mode)	1–10 ms	<1 ms
Coverage Area	Wide-area (up to several kilometers)	Building-level (approx. 50–100 m)	Room-scale (up to 10 m)
Mobility Support	Up to 500 km/h	Low (nomadic use, limited roaming)	Very low (LOS-dependent, static use)
Energy Efficiency	High (edge computing, slicing)	High (TWT, scheduled access)	Very high (shared with LED lighting)

Interference Tolerance	High (beamforming, dedicated bands)	Medium (shared spectrum)	Very high (immune to RF interference)
Device Density Support	1 million devices/km²	50+ devices/AP (in dense environments)	Limited (per light zone)
Security	High (encryption, isolation)	Medium–High (WPA3, MAC filtering)	Very high (spatial confinement)

Key Performance Indicators (KPIs) Analysis

1. **Data Rate:** Li-Fi achieves the highest theoretical data rate of over 100 Gbps under controlled laboratory conditions (Tsonev et al., 2014). 5G, through the use of mmWave and carrier aggregation, provides practical data rates of up to 20 Gbps (Andrews et al., 2014), particularly in eMBB scenarios. Wi-Fi 6, though an enhancement over its predecessor, is limited by the availability of spectrum and interference and is capable of up to 9.6 Gbps theoretically, but typically less in practice (Khorov et al., 2019).
2. **Latency:** 5G and Li-Fi both have sub-millisecond latency. 5G provides it using URLLC, MEC, and dedicated slices (ITU-R, 2020). Li-Fi latency is aided by line-of-sight optical paths and low protocol overhead. Wi-Fi 6 latency is 1–10 ms, subject to network congestion and QoS setup (Bellalta, 2016).
3. **Coverage:** 5G is superior in wide-area coverage, particularly in suburban and urban macro-cell deployments. Wi-Fi 6 is best suited to indoor, medium-range coverage, usually within a building. Li-Fi is limited to room-scale *deployment* because of the inherent constraints of visible light, which cannot pass through walls (Komine & Nakagawa, 2004).
4. **Mobility Support:** 5G is designed for high mobility at high speeds of up to 500 km/h, making it most suitable for transportation and vehicular use (Rappaport et al., 2013). Wi-Fi 6 has limited mobility and is generally bound to localized access points. Li-Fi's requirement for line-of-sight (LOS) and short range precludes its use in mobile users (Haas et al., 2016).
5. **Energy Efficiency:** Li-Fi outshines energy efficiency with the convergence of data communications and lighting infrastructure. Target Wake Time (TWT) saves power in IoT and mobile devices by Wi-Fi 6. Network slicing and edge offloading bring efficiency in 5G, but its overall energy footprint is heavy in dense urban deployments (**Buzzi** et al., 2016).
6. **Interference Tolerance:** Li-Fi is also resistant to electromagnetic interference and hence ideal for applications like aircraft and hospitals. 5G uses beamforming and spectrum isolation to minimize interference. Wi-Fi 6, being in the unlicensed bands, is also prone to interference despite mitigation strategies like BSS coloring (Khorov et al., 2019).
7. **Device Density:** 5G supports the highest device density, 1 million devices/km², and therefore is best suited for smart cities and mass IoT deployments. Wi-Fi 6 improves access point (AP) capacity significantly with MU-MIMO and OFDMA, while Li-Fi supports only limited concurrency of users due to confinement of the light cone.
8. **Security:** Li-Fi offers built-in physical layer security through its inability to transmit through walls, reducing the possibility of eavesdropping. 5G includes higher-level encryption, mutual authentication, and slice-based isolation (3GPP TS 33.501, 2020). Wi-Fi 6 improves security with WPA3, though

older devices and improper setup can still leave openings (Cisco Systems, 2020).

Aggregate Normalized Performance Score

To facilitate visual comparison, each of the KPIs was converted to a 0–10 scale with 10 being optimal performance. Weighting was use-case based.

Table 3. …

Metric	5G	Wi-Fi 6	Li-Fi
Peak Data Rate	8.5	7.0	9.5
Latency	9.5	7.0	9.0
Coverage	9.0	6.0	3.5
Mobility Support	10.0	5.5	2.0
Energy Efficiency	7.0	8.5	9.0
Interference Tolerance	8.5	6.5	10.0
Device Density Support	10.0	8.0	5.0
Security	9.0	7.5	9.5
Average Score	8.81	7.13	7.31

Interpretative Summary

The most performance-dense and flexible option is 5G, particularly for mobility-hungry, mission-critical, and large-scale applications.

Wi-Fi 6 offers robust support for high-density, indoor, cost-conscious applications such as homes, schools, and offices.

Li-Fi is the most secure, low-latency, and interference-free technology and, therefore, appropriate for sensitive and limited spaces like hospitals, underwater activities, and airplanes.

These results affirm the hypothesis that no technology is supreme over all others, and that the optimum option depends on application, cost, and environment.

Applications and Deployment Scenarios

Real-world usefulness of wireless technologies is best assessed by their real-world deployments and domain-specific suitability. While 5G, Wi-Fi 6, and Li-Fi are technically superb, their usefulness depends on the setting in which they are being implemented. This section covers the application domains where each technology has the optimal performance and adoption viability, according to existing case studies, technical reports, and research publications.

5G: Applications and Deployment Scenarios

5G is intended for ubiquitous connectivity and is optimized for high mobility, large scale, and real-time services. It is so multifaceted that it extends to several domains:

1. **Infrastructure and Smart Cities**

5G is also a baseline enabler for the development of smart city infrastructure, enabling high-speed, low-latency connectivity that will be required for many of the important applications. They include autonomous vehicle to everything (V2X) communications and vehicle traffic management systems, real-time data feed-based smart surveillance, and Internet of Things (IoT)-based solutions to monitor and manage utility monitoring and smart grid operations. The typical deployment model of these applications involves the use of macro-cells and very dense small-cell networks, complemented by edge computing and AI-based traffic control systems (Saad et al., 2019). This integration allows optimal response times and efficient urban management.

2. **Industrial Automation (Industry 4.0)**

In the context of Industry 4.0, 5G technology revolutionizes industrial automation by enabling real-time control of robots, continuous machine telemetry, and predictive maintenance solutions. 5G also enables the use of Augmented Reality (AR) for workforce training and diagnostics in complex industrial environments. These are usually facilitated by the deployment of private 5G networks on dedicated spectrums within industrial campuses that provide enhanced security, low latency, and high reliability demanded by mission-critical applications (Buzzi et al., 2016).

3. Remote Healthcare and Telemedicine

5G significantly improves health delivery with its promotion of ultra-reliable low-latency communications (URLLC), which enable sophisticated remote surgery and real-time data transmission. It also supports continuous monitoring of patients via wearable sensor networks and high-definition diagnosis delivery in rural or underdeveloped areas. Deployment in this industry is usually through the use of hospital-based networks with the help of Multi-access Edge Computing (MEC) and network slicing that is secure to ensure data privacy and service reliability (Dahlman et al., 2020).

4. Transportation and Logistics

For the transport and logistics sector, 5G enhances operational efficiency through real-time fleet tracking, autonomous drone flight control, and intelligent monitoring of metro and rail systems. It also enables port management and cargo operations to be optimized through efficient, low-latency communications. All of these uses operate on edge-based 5G infrastructures that have been developed through public-private partnerships, which are able to process information efficiently and respond to behavioral shifts in different modes of transport in a timely manner.

Wi-Fi 6: Deployment Scenarios and Applications

Wi-Fi 6 is designed for indoor high-density and moderate-mobility settings with performance enhancements at cost-effectiveness.

1. Educational Institutions and Campuses

Wi-Fi 6 is a game-changing feature in the modern learning environment in terms of the delivery of a smooth e-learning experience alongside remote class attendance. With immense user density, it offers campus connectivity even to high-density areas such as lecture halls, libraries, and labs. Moreover, the technology enables the integration of immersive technologies such as Augmented Reality (AR) and Virtual Reality (VR) with learning to augment science and engineering pedagogy and practical learning. The typical model of deployment utilized in the case of schools is mesh Wi-Fi networks that come with centralized controllers, that maximizes performance as well as management ease over expansive campus areas (Bellalta, 2016).

2. Enterprises and Co-Working Spaces

In workplaces and collaboration areas, Wi-Fi 6 is built to offer integrated communications comprising voice, video, and real-time collaboration solutions. Its capacity to serve numerous IoT devices such as smart lighting systems, HVAC control units, and access management tools makes it perfect for digital-first workplaces. It also supports the growing trend of Bring Your Own Device (BYOD) with safe and efficient connectivity for various user devices. Installation in such setups is typically enterprise-level APs with multi-user load balancing and Orthogonal Frequency Division Multiple Access (OFDMA) scheduling to manage concurrent connections effectively (Khorov et al., 2019).

3. Consumer IOT and Smarts Homes

In residential settings, Wi-Fi 6 significantly speeds up the performance and operation of smart homes by making easy multi-device streaming, 4K and 8K content, possible, as well as voice assistant, smart hub, and other automation system operations. The protocol is especially tailored to optimize energy-saving IoT devices with longer battery life and stable connectivity. Rollout in this space typically involves consumer-grade routers and access points, often accompanied by Target Wake Time (TWT)-supporting devices to cut power consumption yet keep communication ready all the time. This makes Wi-Fi 6 a corner-stone in the growth of connected living and home automation infrastructure.

Li-Fi: Deployment Case Scenarios and Applications

Li-Fi's niche capabilities make it well-suited to EMI-sensitive, security-critical, and short-range environments.

1. Hospitals and Healthcare

Li-Fi technology has unique advantages in the medical environment, primarily due to the fact that it is RF-free, and this is extremely important near sensitive medical equipment. It offers interference-free and safe communication within sensitive areas such as operating rooms and Intensive Care Units (ICUs). Li-Fi also allows for low-latency data transfer needed for real-time patient monitoring and diagnostic procedures. The hospital deployment model is typically made up of ceiling-mounted LED lights that are Li-Fi enabled and are hung directly over surgical zones and patient beds, offering localized, high-speed data transfer and safety and electromagnetic compatibility (Haas et al., 2016).

2. Aviation and In-Flight Communication

In aviation, Li-Fi presents a credible alternative to traditional wireless systems through RF interference elimination in the aircraft environment. Li-Fi provides high-class onboard entertainment systems and facilitates internal communication within cabin crews, contributing to a more efficient and networked in-flight operation. Li-Fi is also capable of supporting aircraft system diagnosis through ensuring reliable data transfer via light links. The deployment plan is to integrate Li-Fi LED panels into the aircraft's overhead lighting systems to utilize existing infrastructure for effortless deployment (Chowdhury et al., 2018).

3. Security and Confidentiality Configuration

The spatial and line-of-sight operation characteristic of Li-Fi makes it especially suited for secure communication in defense and government scenarios. It is particularly useful for its application in transferring encrypted data in military premises, secure government areas, and other high-security applications where managed wireless access is of high significance. Compared to standard radio frequency systems, Li-Fi offers a more limited and secure wireless network, thus minimizing interference or illicit access by a high margin. Deployment of such technology in these situations typically involves integrating encrypted optical communication systems in secure chambers to maintain high-level confidentiality (Tsonev et al., 2014).

4. Underwater and Subsea Operations

Li-Fi offers immense benefits in applications pertaining to underwater and subsea communications while ordinary radio frequency signals are quickly damped and made unusable. In such applications, Li-Fi enables high-speed data transmission via optical media between submerged nodes and hence allows effective point-by-point communication. This technology finds particular use in short-range applications pertaining to water-based environments, such as marine researches, submarine robots, and subsea explorations. The deployment process usually involves blue-green Li-Fi beams, which have been customized for marine applications owing to their optimum water propagating traits.

Figure 4. Technology Fit Matrix.

Application Domain	Best-Fit Technology	Justification
Smart Cities	5G	Wide coverage, high mobility, multi-service network slicing
Smart Campuses	Wi-Fi 6	Indoor coverage, high density, cost-efficient deployment
Hospitals and Healthcare	Li-Fi	EMI immunity, low latency, physical-layer security
Industrial Automation	5G	Real-time control, private 5G, massive

		machine-type communication
Smart Homes	Wi-Fi 6	IoT support, TWT power saving, multi-device streaming
Aircraft and Aviation	Li-Fi	Non-RF environment, cabin-safe data communication
Underwater Communication	Li-Fi	Optical medium penetration in water
Defense/Secure Environments	Li-Fi	Spatially confined, eavesdrop-resistant communication

Hybrid Deployment Strategies

Increasing amounts of academic research foster integrated deployment scenarios allowing the coexistence and collaboration of more than one wireless technology, namely 5G, Wi-Fi 6, and Li-Fi, for the sake of increased aggregate network performance. Scholars such as How old is addition He knew there was a pleasure and Khorov et al. (2019) advocate unified architectures leveraging 5G as a high-capacity backhaul technology while exploiting Wi-Fi 6 and Li-Fi as access technologies well-optimized and well-suited for various environments and users' requirements. Hybrid systems of this nature are envisioned to achieve context-aware handover mechanisms dynamically switching connections according to parameters such as latency requirements, users' mobility, and environmental interference.

In addition, these hybrid systems use sophisticated load-balancing algorithms to allow network traffic to be directly rerouted and transfer data from 5G or saturated Wi-Fi networks to regions of free Li-Fi coverage. The intentional combination significantly improves user experience by providing seamless connectivity while fostering cost savings and resilience. Such hybrid systems are especially valuable in challenging, high-density settings, such as smart hospitals, international airports, and educational institutions, where a wide variety of connectivity demands must be accommodated simultaneously by a multitude of applications and users.

Restraints and Challenges

Despite their significant developments and promises, 5G, Wi-Fi 6, and Li-Fi face significant barriers involving technology, deployment, and adoption that hinder their efficient deployment and scalability of performance. It is crucial to identify these barriers in guiding future research activities, infrastructure funding, and policy making. The following section presents a discussion on the major barriers associated with each of these technologies based on knowledge amassed from research papers, standards materials, and empirical studies.

5G Technology's Advantages and Disadvantages

i. **Increased Infrastructure Investment:** Another major concern widely cited in 5G technology discourse is the high capital expenditure (CAPEX) involved in constructing high-density small cell networks, fibre-optic backhaul infrastructure, and edge computing systems (Andrews et al., 2014; Saad et al., 2019). Such costs represent a major barrier to universal access, particularly in remote and socio-economically challenged regions.

ii. **Spectrum Fragmentation and Limitation by Regulators:** Though 5G operates on a broad range of spectrum, sub-1 GHz as well as millimeter wave, spectrum allocation lacks harmonization worldwide. Long timeframes and divergence of authorization approvals can hinder harmonized deployment and device interoperability (ITU-R, 2020).

iii. **Energy Consumption:** The deployment of 5G networks requires closely spaced base stations and high-capacity radio units, especially when using millimeter wave technology, thus boosting aggregate energy requirements. Buzzi et al. (2016) note that 5G exhibits better energy efficiency per bit, though aggregate power consumption can exceed Long-Term Evolution (LTE), particularly in very densely networked configurations.

iv. **Societal Views and Health Issues:** While concerns about radiofrequency (RF) radiation and its potential health effects are largely unsubstantiated, these concerns have produced social opposition and hindered infrastructure development in some regions. This represents a sociotechnical problem that cannot be solved by technical fixes (Shafi et al., 2017).

Recognizing and Overcoming Limitations and Hurdles

i. **Spectrum Congestion:** Wi-Fi 6 operates mainly in the 2.4 GHz and 5 GHz unlicensed frequency bands, which are heavily congested by other competing technologies like Bluetooth, Zigbee, and previous Wi-Fi standards. Even though high-end technology like OFDMA and BSS Coloring have been used, interference still exists in high-user-density environments (Khorov et al., 2019).

ii. **Legacy Device Compatibility:** Wi-Fi 6 is designed to retain backward compatibility, a circumstance that can lead to performance constrains when legacy clients do not support enhanced functionalities like MU-MIMO and TWT. Settings with a mix of devices often compromise the promised advantages of a new standard (Bellalta, 2016).

iii. **Limited QoS and Network Slicing:** Compared to 5G, Wi-Fi 6 lacks native support for application-specific QoS provisioning and network slicing, limiting its effectiveness for real-time or mission-critical applications without external configuration.

iv. **Security Vulnerabilities in Non-Managed:** Though WPA3 was introduced as part of Wi-Fi 6 to boost and modernize security protocols, many implementations use outmoded encryption techniques because of legacy devices or inferior configurations. Public networks that are not secure remain backdoors to man-in-the-middle attacks and data breaches (Cisco Systems, 2020).

Limitations and Challenges of Li-Fi Technology

i. **Line-of-Sight (LOS) Requirement:** The system requires a constant visual link between the photodetector and the light-emitting diode (LED) source. Walls, furniture, people, or other things can interrupt these connections and thus limit mobility and operating functionality in real time (Haas et al., 2016).

ii. **Restricted Range and Measurement Scale:** The range of Li-Fi is inherently confined to the illumination zone of the light source. This necessitates dense deployment of Li-Fi-enabled LED arrays for full room or building coverage, increasing installation complexity and cost (Komine & Nakagawa, 2004).

iii. **Ambient Light Interference:** Sunlight and other ambient light sources introduce noise into the optical channel, affecting signal clarity. While filters and modulation techniques can mitigate interference, they add to system complexity (Chowdhury et al., 2018).

iv. **Creating a System and Culture:** Unlike Wi-Fi or 5G technology, Li-Fi hasn't found widespread commercial use or standardization. The IEEE

802.15.7 task group is still at a development stage, and consumer devices rarely have native support for Li-Fi, thus necessitating dongles or adapters (Tsonev et al., 2014).

Table 5. Summary of Limitations.

Technology	Key Limitations
5G	High CAPEX, spectrum licensing complexity, energy demands, public resistance
Wi-Fi 6	Congested spectrum, backward compatibility issues, limited native QoS
Li-Fi	LOS dependency, short range, ambient light interference, ecosystem immaturity

Overcoming Challenges: Views from Academic and Practical Fields

While tackling 5G-based technical and operative complexities related to next-generation radio systems, research-based organizations propose a range of focused solutions. In a 5G context, network virtualization, infrastructure sharing, and deployment of energy-efficient algorithms have been found to be viable alternatives for reducing capital and operating costs while minimizing energy wastage in a simultaneous manner (Buzzi et al., 2016; Saad et al., 2019). These measures not only enable increased scalability but are also in conformity with sustainability demands of modern telecommunication networks.

Within the context of Wi-Fi 6, there is a suggestion of a move toward future standards like Wi-Fi 6E and Wi-Fi 7, backed by artificial intelligence-controlled network administration; this is considered a possible solution to difficulties involving interference, density of users, and quality of experience. It is anticipated that these developments would enhance spectral efficiency and enable better high-demand scenario performance (Khorov et al., 2019**).** In relation to Li-Fi, ongoing research and development activity involves developments related to non-line-of-sight visible light communication (VLC), hybrid integration of Wi-Fi and Li-Fi technology, and their integration into intelligent lighting systems. These advances aim to make use simpler, enhance signal robustness, and promote widespread commercial use of Li-Fi technology by public and private organizations (Haas et al., 2016; Chowdhury et al., 2018). Together, these advances represent a key development toward satisfying changing needs for wireless communications in complex and diverse environments.

CONCLUSION

The rapid evolution of wireless communication technologies has led to the emergence of 5G, Wi-Fi 6, and Li-Fi as pivotal enablers of ubiquitous connectivity, high-speed data transmission, and application-specific networking. This study presented a comprehensive, performance-centric comparative analysis of these three technologies, evaluating them across a range of technical KPIs, deployment scenarios, and operational challenges.

5G is identified as a versatile and comprehensive solution that can ensure extremely low latency, high mobility, and the capacity to connect a massive number of devices. Smart city projects, industrial automation, remote healthcare services, and transport networks are its best applications. Still, its massive deployment is hindered by hefty infrastructure costs, complex regulatory standards, and high energy demands.

Wi-Fi 6 offers a cost-effective and high-capacity solution suited for indoor use, especially for high-density use cases like corporate buildings, schools, and smarter homes. Technology advances related to OFDMA, MU-MIMO, and TWT make it fit for new applications; however, concerns related to spectrum congestion, quality of service restrictions, and legacy device suitability remain.

Li-Fi, though still maturing, provides unmatched benefits in electromagnetically sensitive, high-security, and confined environments, such as hospitals, aircraft, and underwater systems. Its strengths lie in physical-layer security, RF immunity, and ultra-high bandwidth, but its LOS requirement, short range, and ecosystem immaturity remain barriers to large-scale deployment.

The studies demonstrate that no single wireless technology can be considered best for use in a given case. Instead, wireless communication progress relies on the keen combination of different technologies through hybrid systems that benefit from their own complementing strengths. Co-existence and mutual collaboration between 5G, Wi-Fi 6, and Li-Fi through hierarchical deployments can realize different performance requirements, different application needs, and requirements for spectrum efficiency.

Principal Findings

The comparative analysis of 5G, Wi-Fi 6, and Li-Fi technology reveals their separate merits corresponding to their defined goals and use scenarios.

The 5G technology stands out in scenarios involving outdoor use, high mobility, and mission-centric uses, offering high data rates, low latency, and high capability for wide-area coverage. It is particularly suited best for applications like smart cities infrastructure, industrial automation, and remote healthcare applications, where both performance and reliability are a priority.

Whereas Wi-Fi 6 is uniquely suited for densely occupied indoor environments, where cost-efficiency and high capacity for users become a priority, its suitability for schools, office spaces, and residential networks lies in its ability to manage hundreds of connections at once while still supporting applications necessitating high-bandwidth use.

The technology offers a viable option for applications that require secure, interference-immune, and short-range radio communication. By employing optical transmission, it offers a viable solution for deployment within healthcare units, military bases, and other applications wherein minimizing radio frequency interference is of key significance. These observations as a whole highlight the mutually supplementary nature of the three technologies, wherein each offers different advantages suited for particular application scenarios.

Projected developments and research into the field of wireless communication are expected to focus on integrating a wide range of different technologies by infusing artificial intelligence (AI) and edge computing. This enables wise and intelligent management, a requirement for facile switching between 5G, Wi-Fi 6, Li-Fi, and upcoming technologies, thus optimizing network efficiency in a way that is responsive to real-time circumstances, application needs, and end-user interaction. Sophisticated technology handling is required to tackle rising complexity and variability inherent in future wireless ecosystems.

At the same time, ongoing efforts will focus on standardization and interoperability development to ensure smooth device and system integration and use of various devices and systems. Furthermore, research activities will focus on designing energy-efficient, secure, and green sustainable wireless communication systems to cater to expanding demand for cleaner and more robust infrastructure. In addition, exploration into sixth-generation (6G) communication systems is proceeding rapidly, aiming to integrate optical, radio frequency (RF), and quantum layers into a unified and dynamic system. This futuristic plan envisions a previously unseen boost in speed, security, and intelligence for future worldwide connectivity.

Final Thought

While continued advances in wireless communication enable a worldwide digital revolution, future prosperity will increasingly depend on mutual efforts and technology co-design instead of competition between them, in a scenario marked by interconnectivity, intelligence, and flexibility of wireless systems.

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