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Light Fidelity Technology: Study and Application

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Acknowledgment

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"(طه: 114) "وَقُلْ رَبِّ زِدْنِي عِلْمًا" "And say: 'My Lord, increase me in knowledge.'" (Surah Taha: 114)

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"(النجم: 39) "وَأَنْ لَّيْسَ لِلْإِنْسَانِ إِلَّا مَا سَعَى" "And that man will have nothing but what he strives for." (Surah An-Najm: 39)

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"من لا يشكر الناس لا يشكر الله" "He who does not thank people, does not thank Allah." (Sunan Abi Dawood)

Thank you deeply, truly, eternally.

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Dedication

To our beloved families.
To their quiet prayers whispered behind closed doors.
To our siblings who offered comfort in silence.
To our friends who stayed even when our paths separated.

Abstract

Li-Fi technology presents a revolutionary approach to wireless communication by utilizing visible light instead of radio frequencies. This research investigates the theoretical foundations, implementation, and challenges of Li-Fi, emphasizing its potential as an efficient, secure, and high-speed alternative to conventional wireless technologies. The study involves designing and testing an audio transmission system based on Li-Fi, where an analog signal is modulated and transmitted via LEDs, then received and processed by a photodiode-based receiver. Key aspects explored include modulation techniques, signal processing, integration with IoT, security measures, and future trends in Li-Fi networks. Findings demonstrate the viability of Li-Fi for applications in healthcare, Industry 4.0, and smart environments while highlighting challenges related to range, interference, and adoption.

Keywords: Li-Fi, wireless communication, visible light, optical wireless, LED modulation, photodiode receiver, IoT integration, data security, signal processing, Industry 4.0, smart environments, electromagnetic interference.

Résumé

La technologie Li-Fi offre une approche révolutionnaire de la communication sans fil en exploitant la lumière visible plutôt que les fréquences radio. Cette recherche étudie les bases théoriques, la mise en œuvre et les défis du Li-Fi, en mettant en avant son potentiel comme alternative efficace, sécurisée et à haute vitesse aux technologies sans fil conventionnelles. L'étude comprend la conception et le test d'un système de transmission audio basé sur le Li-Fi, où un signal analogique est modulé et transmis via des LED, puis reçu et traité par un récepteur à photodiode. Les aspects clés explorés incluent les techniques de modulation, le traitement du signal, l'intégration avec l'IoT, les mesures de sécurité et les tendances futures des réseaux Li-Fi. Les résultats démontrent la faisabilité du Li-Fi pour des applications dans les domaines de la santé, de l'industrie 4.0 et des environnements intelligents, tout en mettant en évidence les défis liés à la portée, aux interférences et à l'adoption.

Mots-clés : Li-Fi, communication sans fil, lumière visible, communication optique, modulation LED, récepteur photodiode, intégration IoT, sécurité des données, traitement du signal, Industrie 4.0, environnements intelligents, interférences électromagnétiques.

المخلص

نهجاً ثورياً للاتصال اللاسلكي عبر استخدام الضوء المرئي بدلاً من الترددات الراديوية Li-Fi تُقدم تقنية مع التركيز على إمكانياتها كبديل فعال وآمن، Li-Fi تستكشف هذه الدراسة الأسس النظرية، والتطبيقات، والتحديات المرتبطة حيث يتم تعديل Li-Fi وعالي السرعة للتقنيات اللاسلكية التقليدية. يتضمن البحث تصميم واختبار نظام نقل صوتي يعتمد على ثم استقبالها ومعالجتها بواسطة كاشف ضوئي. تشمل المواضيع الرئيسية تقنيات التعديل LED الإشارة التناظرية وإرسالها عبر Li-Fi تُظهر النتائج إمكانيات Li-Fi معالجة الإشارة، التكامل مع إنترنت الأشياء، التدابير الأمنية، والتوجهات المستقبلية لشبكات في تطبيقات الرعاية الصحية والصناعة 4.0 والبيئات الذكية، مع تسليط الضوء على التحديات المتعلقة بالنطاق، والتداخل، والاعتماد على نطاق واسع.

تكمّل إنترنت الأشياء، أمن البيانات، Photodiode مستقبل، LED، الاتصال اللاسلكي، الضوء المرئي، الاتصال البصري، تعديل Li-Fi: الكلمات المفتاحية معالجة الإشارة، الصناعة 4.0، البيئات الذكية، التداخل الكهرومغناطيسي

List of Abbreviations

Abbreviation	Meaning
Wi-Fi	Wireless Fidelity
RF	Radio Frequency
LoS	Line of Sight
Li-Fi	Light Fidelity
LED	Light Emitting Diode
OWC	Optical Wireless Communication
FSO	Free Space Optics
VLC	Visible Light Communication
AM/FM	Amplitude/Frequency Modulation
MIMO	Multiple Input Multiple Output
IoT	Internet of Things
LD	Laser Diode
PHY	Physical Layer
MAC	Media Access Control
OSI	Open Systems Interconnection
IEEE	Institute of Electrical and Electronics Engineers
EM	Electromagnetic
WLAN	Wireless Local Area Network
RX	Receiver
TX	Transmitter
ICI	Interchannel Interference
OSM	Optical Spatial Modulation
PD	Photodiode
PC	Personal Computer
IF	Intermediate Frequency
UV	Ultraviolet
IM/DD	Intensity Modulation/Direct Detection
OOK	On-Off Keying
OCC	Optical Camera Communication
FEC	Forward Error Correction
IR	Infrared
PAM	Pulse Amplitude Modulation
OFDM	Orthogonal Frequency Division Multiplexing
TDMA	Time Division Multiple Access
CDMA	Code Division Multiple Access
SDMA	Spatial Division Multiple Access
FDMA	Frequency Division Multiple Access
PPM	Pulse Position Modulation
PWM	Pulse Width Modulation
CSK	Color Shift Keying
RGBLED	Red Green Blue Light Emitting Diode
AMC	Adaptive Modulation and Coding
BLE	Bluetooth Low Energy
NFC	Near Field Communication
LPWAN	Low Power Wide Area Network

RPL	Routing Protocol for Low-power and Lossy Networks
TLS	Transport Layer Security
DTLS	Datagram Transport Layer Security
CoAP	Constrained Application Protocol
MQTT	Message Queuing Telemetry Transport
AMQP	Advanced Message Queuing Protocol
UI	User Interface
AI	Artificial Intelligence
ML	Machine Learning
AES	Advanced Encryption Standard
O-OFDM	Optical-OFDM
AP	Access Point
VPN	Virtual Private Network
HSRP	Hot Standby Router Protocol
RIP	Routing Information Protocol
OSPF	Open Shortest Path First
WEP	Wired Equivalent Privacy
ARP	Address Resolution Protocol
DES	Data Encryption Standard
RSA	Rivest–Shamir–Adleman
ECC	Elliptic Curve Cryptography
ID	Identifier
CRC	Cyclic Redundancy Check
ARQ	Automatic Repeat Request
IoUT	Internet of Underwater Things
Tbps	Terabits per second
RIS	Reconfigurable Intelligent Surfaces
THz	Terahertz
QKD	Quantum Key Distribution
ITU	International Telecommunication Union
CAGR	Compound Annual Growth Rate
IrDA	Infrared Data Association
NLOS	No Line of Sight

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General Introduction

Common people's interest in wired and wireless communication is growing as a result of recent technological advancements and the proliferation of smartphones, laptops, and other smart gadgets. The majority of individuals use networks to connect for social activities, education, communication, interaction, data exchange, and knowledge upgrades. As a result, individuals want to send data quickly and effectively while consuming little money and bandwidth.

The most adaptable, capable, and efficient technology is Wireless Fidelity (Wi-Fi), which uses radio frequency (RF) and microwave frequencies to transmit data quickly and wirelessly. Line-of-Sight (LoS) communication at high frequencies and broad coverage at low frequencies are both made possible by high-sensitivity receivers. However, Wi-Fi is facing many challenges and issues in terms of capacity, efficiency, availability, and security because there is a growing demand for wireless communications.

Wi-Fi, which uses radio waves to link our gadgets, has long been the foundation of wireless communication. However, Li-Fi has emerged as a new solution as the demand for faster and more reliable connections increases. Li-Fi uses a new era of fast wireless communication by using light rather than radio waves.

Harald Haas introduced the innovative Li-Fi (Light Fidelity) method for sending data to smartphones via light-emitting devices like lamps, televisions, traffic signals, and commercial ad boxes. Light Emitting Diode (LED) bulbs and optical wireless communication (OWC) are used in this method to transmit data at high speeds that are invisible to the human eye.

Numerous companies and industries are now encouraging research teams to develop Li-Fi technology, which operates independently of the electromagnetic spectrum. These researchers have been conducting experiments to deliver faster optical wireless technology that overcomes the limitations and disadvantages of RF-based wireless systems. The original research aimed to create electromagnetic-field-free, safe environments in wireless networks and enable high-speed connectivity.

Due to several technological advancements and cost reductions, the Li-Fi industry is expected to grow rapidly. Using advanced modulation techniques and multiple concurrent data streams with LED light sources, researchers from the Universities of Oxford and Edinburgh have demonstrated Li-Fi transmission speeds reaching up to 224 Gbit/s in lab settings. This breakthrough is particularly significant for industries requiring rapid data transfer, such as cloud computing and financial services.

The FSO & VLC / Li-Fi market was valued at USD 2.78 billion in 2024 and is projected to reach USD 7.39 billion by 2029, registering a CAGR of 21.6% during the forecast period.

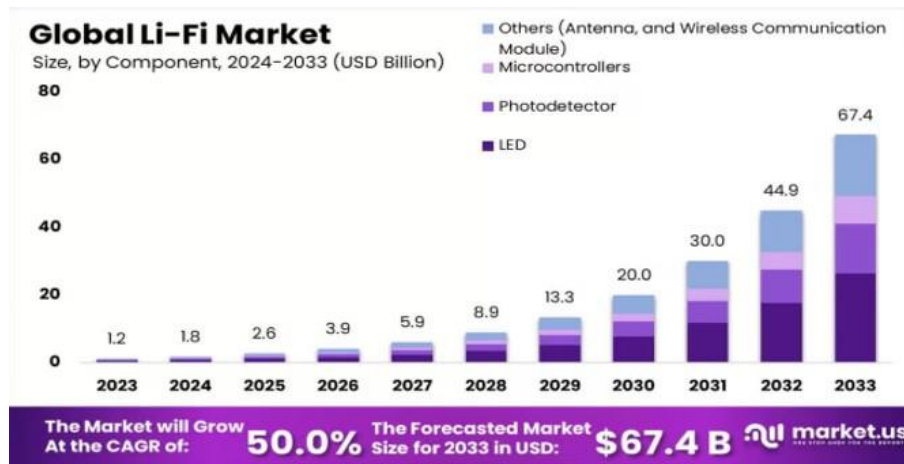


Figure1: The volume of data generated globally.

In this project, we studied and applied Li-Fi technology by designing an audio transmission system using light fidelity. An analog audio signal generated by a PC is transmitted through a Li-Fi transmitter and received by a speaker equipped with a Li-Fi receiver. This setup demonstrates the practical use of visible light waves for fast, wireless, and interference-free audio transmission between electronic devices.

Chapter One provides a comprehensive foundation for understanding Li-Fi technology by first exploring its roots in wireless communication and Visible Light Communication (VLC), and concludes with the research objectives and an overview of the project application.

Chapter Two focuses on the theoretical foundations of Li-Fi and optical wireless communication. It begins by examining the electromagnetic spectrum and the use of light as a communication medium. It further explores various modulation techniques, multiple access methods used in Li-Fi networks, and approaches to data encoding and signal processing.

Chapter Three details the design, implementation, and evaluation of the first Li-Fi application, covering hardware components, system processing, and performance compared to traditional communication methods.

Chapter Four summarizes the main findings of the project, highlights possible improvements to the developed applications, and outlines future research directions to advance Li-Fi technology.

Chapter1

UnderstandingLi-FiTechnology

1.1 Introduction

Whether it is the point about hiding personal data of a company or whether using internet underwater or accessing data without any interference, Wi-Fi fails in all departments. Li-Fi not only resolves these problems but also, its usage is efficient and cheap. Almost everyone uses Wi-Fi so often. But this wireless technology has a drawback that they use radio waves to communicate. The problem associated with these radio waves is, they transmit data slowly and the signal is often blocked by equipment as simple as the microwave or refrigerator in our kitchen. Accessing data from one place to another is one of the most basic activities of our lives nowadays. So, with these types of complex waves Sometimes transfer of data is difficult.

Nowadays, the network which we use, faces the problems of access speed when connected to multiple devices. It creates a usual problem when connected to multiple users, the fixed bandwidth which is available for the particular user makes it more difficult to enjoy high data transfer rates and connect to a secure network. As the multiple users increase, it creates some gaps between the connections through which it is easier for the hacker to get through the connections. 'Li-Fi' or 'Light-Fidelity' which uses special LED bulbs for accessing or transferring data.

1.2 Introduction to Wireless Communication

1.2.1 wireless communication

It is the transfer of information (telecommunication) between two or more points without the use of an electrical conductor, optical fiber or other continuous guided medium for the transfer.

communication has revolutionized the way humans interact, connect, and share information. From the early days of radio waves in the late 19th century to the sophisticated 5G networks of today, wireless technologies have become an integral part of modern life. The journey began with Guglielmo Marconi's ground-breaking experiments in wireless telegraphy in the 1890s, which laid the foundation for wireless communication as we know it. Over the decades, advancements such as AM/FM radio, television broadcasting, satellite communication, cellular networks, Wi-Fi, Bluetooth, and IoT have transformed industries, economies, and societies.

, wireless communication systems are ubiquitous, supporting billions of connected devices worldwide. These systems enable everything from voice calls and video streaming to autonomous vehicles and smart cities. However, the exponential growth in demand for higher data rates, lower latency, and greater reliability poses significant challenges for traditional design methodologies. As we look toward the future, emerging paradigms like 6G, ultra-massive MIMO (Multiple Input Multiple Output), terahertz communications, and intelligent reflecting surfaces promise unprecedented capabilities—but also introduce new complexities that require innovative solutions.

1.2.2 Importance of Wireless communication

Wireless communication plays a key role in modern networks and provides flexibility and mobility without the constraint of physical cables, which allows users to communicate with each other and access resources and applications from virtually anywhere.

because it has become a cornerstone of modern technology:

- **Mobility** Wireless systems enable users to communicate and access information from virtually anywhere, untethered by cables or physical infrastructure [2].
- **Convenience** Eliminating the need for wired connections simplifies setup and maintenance, making it easier to deploy communications systems in homes, offices, and public spaces [2].
- **Speed & Stability** Wireless communication also brought about improvements in the speed and stability of communications.
- **Flexibility** Wireless communication systems offer a great deal of flexibility when it comes to where it can be installed. You can install wireless systems almost anywhere unlike wire systems which depend on the structure of the building as well as its location [2].
- **Scalability** Wireless networks can be easily expanded, whether by adding more devices or extending coverage, without the constraints of physical wiring [2].
- **Cost-Effectiveness** Reducing the reliance on wired infrastructure lowers installation and maintenance costs, especially in large-scale deployments [2].
- **Enhanced Connectivity** Wireless technologies enable seamless communication between devices, driving innovations like smart homes, autonomous vehicles, and the Internet of Things (IoT).
- **Emergency Communication and Resilience** In emergency situations and disaster recovery situations where conventional cable infrastructure may be unavailable or damaged, wireless communication technologies are essential [3].

1.3 Visible Light Communication (VLC)

1.3.1 What is VLC?

The term "visible light communication" refers to a form of communication where information is transmitted by modulating light waves with wavelengths between 380 and 750 nm.

Generally speaking, visible light communication refers to any system that uses a light that is visible to the human eye to communicate information. However, the goal of this kind of communication is to transmit information in a way that is invisible to the human eye, leaving just the normal illumination of the surroundings visible and unaltered. Other names for related technologies have been developed over time, including Li-Fi (Light Fidelity) and OWC (Optical Wireless Communication).

Keep in mind that from the early nineteenth century, numerous works have examined radio waves. Numerous discoveries regarding the characteristics of this kind of wave have resulted from this, introducing new technology to people's daily lives worldwide, ranging from medicinal uses to military resources. Research advancements have significantly increased radio communications' efficiency. Compared to the electromagnetic spectrum's radio frequency spectrum, visible light is currently understudied as a communication

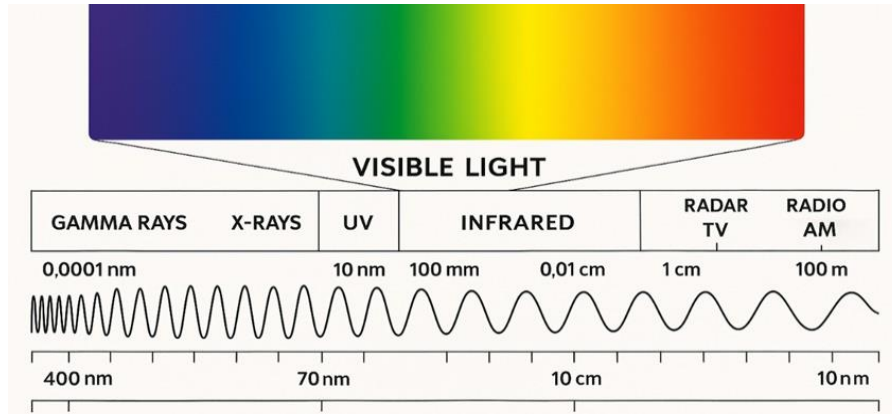


Figure 1.1: Electromagnetic Spectrum.

medium, despite only garnering interest from industry and academic organizations in the last ten years [4].

The electromagnetic spectrum is depicted in Figure 1.2, ranging from low frequencies, which are radio waves, to higher frequencies, which are gamma radiation. The visible spectrum of light spans from 380 nm to 750 nm, as we already mentioned. Any form of visible light communication can be defined as any information that is transmitted by altering the light waves in this range. It's crucial to note that radio waves, which encompass Wi-Fi technology, have frequencies between 3 KHz and 300 GHz. Conversely, the whole radio frequency spectrum is 10,000 times smaller than the visible light frequencies, which range from 430 THz to 770 THz [4].

It is important to note that the deployment of VLC systems is directly related to the quick and growing global consumption of LEDs and the approaching realization of the smart lighting paradigm, making it a very promising technology. It is likely that the industry has responded favorably to these advancements in lighting technology. The Philips HUE is an LED light bulb, for instance, that can be controlled by a smartphone to create environments for particular uses, like studying or working. Thus, it is probable that LED light bulbs will serve two distinct purposes in the future: communication and illumination.

1.3.2 VLC and additional terms

The various technologies that use light as a communication medium are referred to by a variety of names. Among the most common names are:

- **Wireless Communications via Optical (OWC):** Optical wireless communication refers to any form of data transfer where an optical medium is utilized. To put it another way, all forms of visible light, ultraviolet, and infrared can be utilized for communication [4,6].
- **Free-Space Optical Communication:** This term has been commonly used for large-scale transmissions, like communications between satellites and towers on Earth, even though it shares a principle with OWC [4]. Data transfer across a barrier-free medium, such as the air, atmosphere, and space, is known as "free space communication." Applications utilizing this nomenclature are typically highly sophisticated,

addressing high-priced equipment and atmospheric turbulences [4].

- **Visible Light Communication (VLC):** In recent years, wireless optical communication has grown significantly in popularity. Because the visible light spectrum has so much intellectual and economic promise, investigations in this field are becoming more and more prevalent. All of the visible light spectrum's wavelengths, or waves with frequencies between 430 and 790 THz, are included in visible light communication [4, 7].
- **Light Fidelity (Li-Fi):** As was previously mentioned, the term Li-Fi was first used in 2011 at a TED Talk in which Professor Harald Haas provided a hands-on example of the technology's capabilities. Li-Fi might be considered a VLC. Nonetheless, the term's originator highlighted the primary distinctions between VLC and Li-Fi in a 2015 article. The two-way multi-user connection and fast speed that are features of the Li-Fi concept stand out among the distinctions between the two technologies [4].

1.3.3 Basic Of VLC

The visible light communication method is one of the concepts proposed for wireless optical communication in recent years. The light signals that are visible to the human eye fall within the electromagnetic spectrum's wavelength range of 380–780 nm.

With LEDs, the most popular lighting technology these days, it is possible to accomplish both illumination and data transfer at the same time. In this manner, data transfer and interior lighting of a room can be accomplished without the need for an extra communication device. Visual Light Communication is the name given to this technique.

Figure 1.2 shows the basic setup of a VLC communications system.



Figure 1.2: Enter Caption

As seen in Figure 1.3, the transmitter (LEDs), receivers (photodetectors), data modulation to optics, and optical communication channel are essential components of a VLC system.

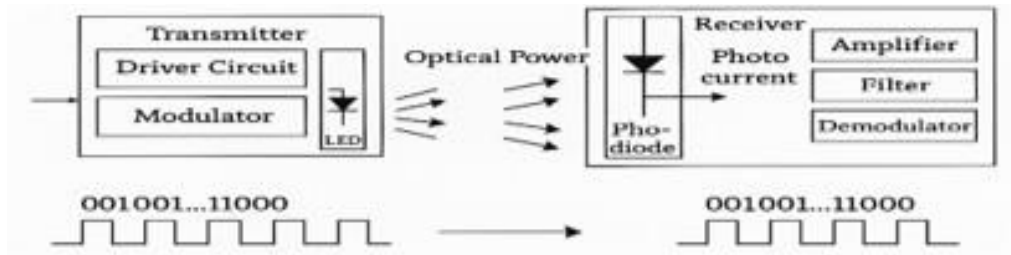


Figure 1.3: Block diagram of a VLC architecture.

I. Transmitter

For illumination, a variety of light sources are available. But among these, Laser Diodes (LD) and LEDs are the most widely used, particularly for optical data transmission. It is outside the purview of this study to examine LDs because its goal is VLC, or the idea of preserving illumination and data transfer at the same time. As a result, we shall exclusively discuss LEDs. An LD and an LED vary primarily in that the former is a coherent light source while the latter is an incoherent one. In other words, photons with varying phases are spontaneously released in the LED structure. But with LDs, a photon triggers another photon that emits a phase that is associated with the first one; this process is known as coherent radiation.

II. Receiver

The receiver component of a VLC system, known as a photodetector, collects photons that strike its front-end surface and, in turn, produces an electrical signal. There are different methods for converting photonic light to electrical energy. For instance, photon absorption produces photoelectric reactions in vacuum photodiodes or photomultipliers, which lead to the emergence of free electrons that are employed as carriers. Another method is that an electron and hole pair are released when the photons fall into the junction region of a semiconductor photodiode, like p-n junctions. Then, in order to dissipate their extra energy, these liberated carriers go to the appropriate areas, such as the conduction and valence bands.

1.3.4 Why Visible Light Communication?

The frequency spectrum that is available to us in the atmosphere consists of many wave regions like X-ray, gamma rays, U-V region, infrared region, visible light rays, radio waves, etc. Any one of the above waves can be used in the upcoming communication technologies but why the Visible Light part is chosen? The reason behind this is the easy availability and lesser harmful effects that occur due to these rays of light. VLC uses the visible light between 400 THz (780 nm) and 800 THz (375 nm) as a medium which are less dangerous for high-power applications and also humans can easily perceive it and protect themselves from the harmful effects whereas the other wave regions have following disadvantages [9]:

- Radiowaves are expensive (due to spectrum charges) and less secure (due to interference and possible interception etc.).

- Gamma rays are harmful because it could be dangerous dealing with it, by human beings due to their proven adverse effects on human health.
- X-rays have health issues, similar to the Gamma Rays.
- Ultraviolet light can be considered for communication technology purposes at places without people, otherwise they can also be dangerous for the human body when exposed continuously.
- Infrared, due to high safety regulation, can only be used with low power. Hence the Visible light portion (from red to blue) of the electromagnetic spectrum does not cause any harm to people as visible rays are safe to use, provide larger bandwidth and also have a promising future in the communication field.

1.4 Introduction to LI-FI Technology

1.4.1 what is li-fi?

Li-Fi, which stands for "Light Fidelity," is a technology that makes it possible to communicate using light. Li-

Fi, which was created following years of research and development, provides customers with a fast, reliable, safe, and health-friendly connection. Li-Fi data transmission works by modulating a light beam that is emitted by a transmitter device that is wired to the Internet network and sent to a receiver device that is either attached to a device or, soon, integrated into it [10].

Unlike Wi-Fi, which uses radio frequency, Li-Fi technology combines light waves and a light source with a chip to send an internet signal. Li-Fi is a bidirectional wireless system that employs LED or infrared light to transport data. Li-Fi is a data transmission system that sends and transports information using the visible light spectrum. This technology, which is based on the idea of employing each existing light bulb as a signal transmitter and receiver using LED lights, has advanced in development and use thanks to the efforts of numerous researchers and private enterprises [10].

1.4.2 An Overview of VLC & Li-Fi's History

The use of light for communication dates back to ancient civilizations, such as the torch-based system developed by Polybius in Ancient Greece. In the 18th century, Charles Chappe's optical telegraph allowed symbolic visual communication over long distances across France. Later, Alexander Graham Bell's Photophone transmitted sound using modulated sunlight—a precursor to optical wireless systems.

Modern wireless optical communication began in the 1970s, achieving modest speeds, with infrared systems reaching 50 Mbps by the 1990s. In the early 2000s, VLC (Visible Light Communication) gained momentum when researchers, notably Tanaka et al., demonstrated 400 Mbps data transfer using white LEDs.

Li-Fi (Light Fidelity) was introduced in 2011 by Prof. Harald Haas at TED Global and was standardized by IEEE in the same year. Haas later founded pure Li-Fi in 2012, which launched innovations like Li-Flame (2014) and Li-Fi-X (2015). Today, major players including NASA, Disney, and Philips are investing in VLC and Li-Fi, signaling its growing commercial and academic importance.

1.4.3 Li-Fi system architecture

Data Transmitter:

Encoding data into light for transmission is achieved by varying the light intensity of the LED, which causes the LED to flicker ON and OFF at a very high speed. These flickers represent the data being transmitted. When the LED is switched ON, it logically represents the transmission of a "1," and when it is switched OFF, it transmits a "0." A combination of 1s and 0s generates different data strings. However, the flickering speed is so high that the LED appears to be constant to the human eye, causing no harm to it.

Data Receiver:

Data reception is the function of the dongle, or more specifically, the PD within. APD detects the light source and converts the changes in its intensity into an electrical signal. When the LED flickers ON, the PD registers a binary 1; otherwise, it registers a binary 0. Then, the received data is amplified, processed, and forwarded to the user.

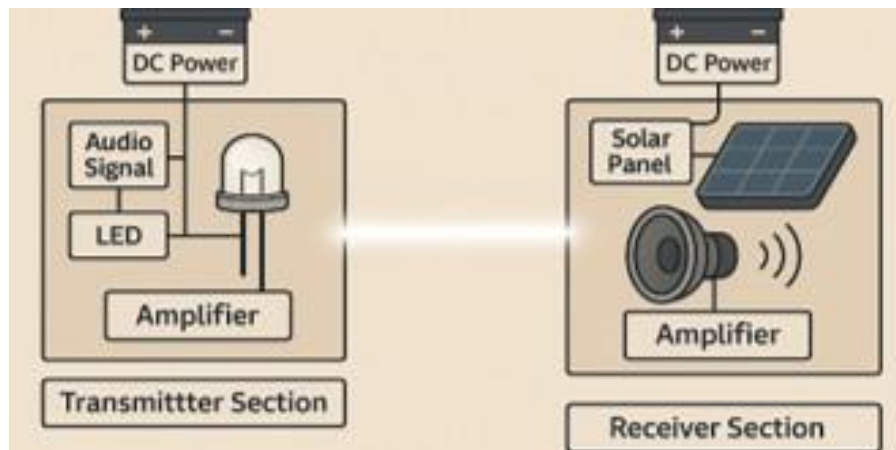


Figure 1.4: Block Diagram of Li-Fi system.

1.4.4 Li-Fi architecture

Li-Fi consists of 3 stages, i.e., application layer, MAC layer, and Physical Layer. IEEE 802.15.7 defines only two standards, i.e., PHY and MAC layer.

Application layer

The application layer is constrainedly defined under the open systems interconnection (OSI) model. Specifically, the application layer is just the interface for interacting with host-based and user-facing programs, according to the OSI model. In Li-Fi technology, the application layer defines the protocols and services, such as relay systems and various algorithms for routing as required by Li-Fi devices using the application layer in communication, providing network configuration, network manipulation, and messenger routing [15].

MAC layer

The MAC layer controls the hardware responsible for interfacing with the optical wireless transmission medium. The MAC layer offers crucial functions such as synchronization, channel access, and addressing for Li-Fi devices. Three topologies of a network that are defined in the MAC layer are peer-to-peer, star, and broadcast. In peer-to-peer topology, 6 Proceedings of Engineering and Technology Innovation, vol. 27, 2024, pp. 01-17 it is communicated between two devices where one of them works as a coordinator. In star topology, it is communicated between multiple devices where one of them works as a coordinator and an infrastructure of illumination. In broadcast topology, the coordinator which is one of the devices in the network transmits data to multiple devices [15].

Physical layer

The physical layer, also abbreviated as the physical layer, is processed data transmission and reception. The physical layer is responsible for deactivation, activation of optical transceivers, and the detection of the state of a transmission channel, whether it is busy or idle state. In the Li-Fi system, the physical layers can be classified into three subordinate layers, i.e., physical I, physical II, and physical III. Firstly, the physical I layer is used in outdoor applications, which has a data rate from 11.67 to 267.6 kilobits per second. Secondly, the physical II layer is used in indoor applications, which has a data rate from 1.25 to 96 megabits per second. Finally, the physical III layer is used in multiple optical transceiver applications, which has a data rate from 12 to 96 megabits per second [15].

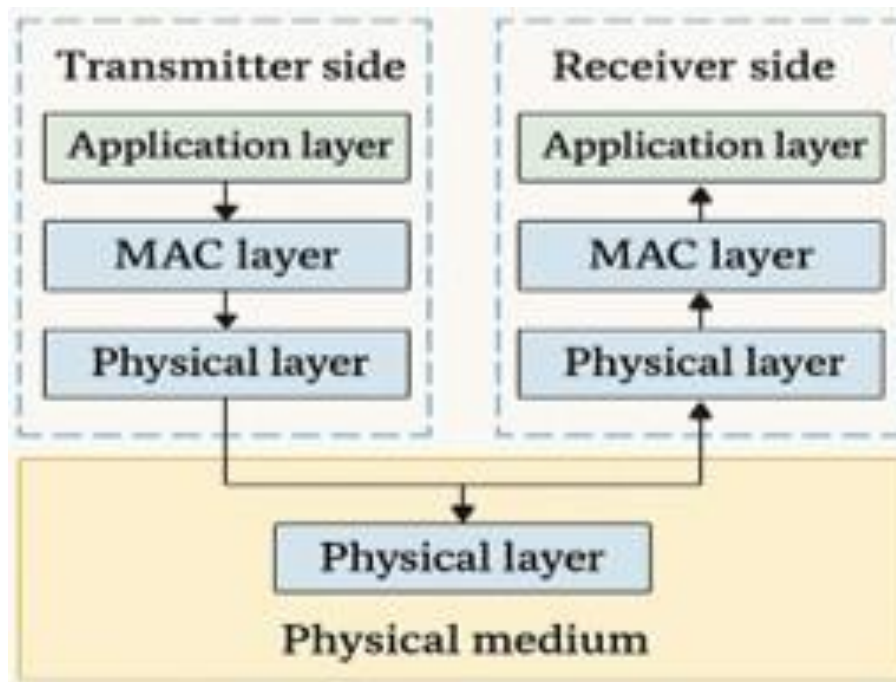


Figure 1.5: Architecture of layers in Li-Fi technology [15].

1.4.5 Working of Li-Fi

Basic Concept:

Light Fidelity (Li-Fi) technology is a wireless communications system based on the use of visible light between the violet (800 THz) and red (400 THz). Unlike Wi-Fi which uses the radio part of the electromagnetic spectrum, Li-Fi uses the optical spectrum i.e. Visible light part of the electromagnetic spectrum. The principle of Li-Fi is based on sending data by amplitude modulation of the light source in a well-defined and standardized way. LEDs can be switched on and off faster than the human eye can detect since the operating speed of LEDs is less than 1 microsecond. This invisible on-off activity enables data transmission using binary codes. If the LED is on, a digital '1' is transmitted and if the LED is off, a digital '0' is transmitted. Also, these LEDs can be switched on and off very quickly which gives us a very nice opportunity for transmitting data through LED lights, because there are no interfering light frequencies like that of the radio frequencies in Wi-Fi. Li-Fi is thought to be 80 percent more efficient, which means it can reach speeds of up to 1 Gbps and even beyond. Li-Fi differs from fibre optic because the Li-Fi protocol layers are suitable for wireless communication over short distances (up to 10 meters) [12].

This puts Li-Fi in a unique position of extremely fast wireless communication over short distances.

How it Works:

The working of Li-Fi is very simple. There is a light emitter on one end i.e., an LED transmitter, and a photodetector (light sensor) on the other. The data input to the LED transmitter is encoded into the light (technically referred to as Visible Light Communication) by varying the flickering rate at which the LEDs flicker 'on' and 'off' to generate different strings of 1s and 0s. The on-off activity of the LED transmitter which seems to be invisible (The LED intensity is modulated so rapidly that a human eye cannot notice, so the light of the LED appears constant to humans), enables data transmission in light form in accordance with the incoming binary codes: switching ON a LED is a logical '1', switching it OFF is a logical '0'. By varying the rate at which the LEDs flicker on and off, information can be encoded in the light to different combinations of 1s and 0s. In a typical setup, the transmitter (LED) is connected to the data network (Internet through the modem) and the receiver (photodetector/light sensor) on the receiving end receives the data as a light signal and decodes the information, which is then displayed on the device connected to the receiver. The receiver (photodetector) registers a binary '1' when the transmitter (LED) is ON and a binary '0' when the transmitter (LED) is OFF. Thus, flashing the LED numerous times or using an array of LEDs (perhaps of a few different colors) will eventually provide data rates in the range of hundreds of Mbps. The Li-Fi working is explained in a block diagram (Fig. 1.6) [12, 13].

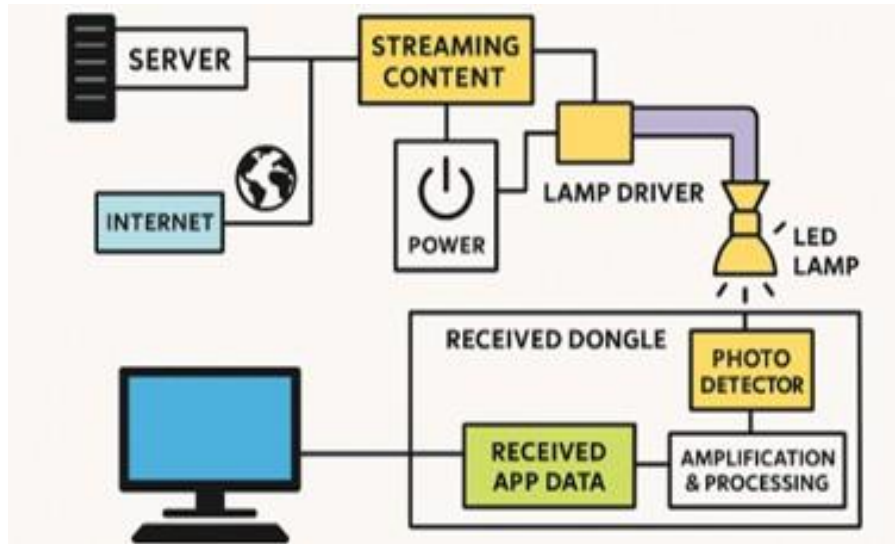


Figure 1.6: Block diagram of Li-Fi Sub System.

1.5 Comparison Between Li-Fi and Wi-Fi

VLC technology, which is used to provide high-speed wireless communication, is referred to as Li-Fi. It got its name from its resemblance to Wi-Fi, which is a good choice for general wireless coverage in buildings, whereas Li-Fi is the best choice for high-density wireless data coverage.

Users can access the Internet wirelessly via both Wi-Fi and Li-Fi, and both technologies employ the electromagnetic spectrum to send data. High-speed wireless communication can be achieved with Li-Fi, a visible light communication technique. The distinction is that Li-Fi technology employs light waves for transmission, whereas Wi-Fi technology uses radio frequencies. While Li-Fi is perfect for high density wireless data coverage inside a small space or room and is free from interference problems, Wi-Fi is good for general wireless coverage within buildings, campuses, or compounds [13].

A comparison of the data density and transfer speed of several wireless technologies is displayed in Table 1.1.

Table 1.1: Comparison between Li-Fi and Wi-Fi [13].

Feature	Li-Fi	Wi-Fi
Full form	Light fidelity	Wireless fidelity
IEEE Standard	802.11bb	802.11b
Based on	Light signals (visible light "VL")	Radio signal waves (EM waves "RF")
Operation	Li-Fi transmits data using light with the help of LED bulbs	Wi-Fi transmits data using radio waves with the help of a Wi-Fi router
Interference	Does not have any interference issues like radio frequency waves	Will have interference issues from nearby access points (routers)
Technology	Presents IrDA-compliant Devices	WLAN 802.11a/b/g/n/ac/ad standard compliant devices
Privacy	In Li-Fi, light is blocked by the walls and hence will provide more secured data transfer	In Wi-Fi, RF signals cannot be blocked by the walls and hence need to employ techniques to achieve secure data transfer
Data transfer speed	Up to speeds of up to 224 Gbps	Offers speeds of up to 9.6 Gbps in modern standards
Frequency of operation	Uses visible and infrared light frequencies	Operates in the 2.4 GHz and 5 GHz radio frequency bands
Data density	Works in a highly dense environment due to its optical bandwidth	Works in less dense environments due to interference-related issues
Coverage distance	Limited by line of sight and often no more than 10m	About 32 m (WLAN 802.11b/11g), varies based on transmit power and antenna type
System components	Uses an optical transmitter and a receiver	Requires a wireless access point and multiple compatible devices
Latency	Microseconds	Milliseconds
Cost	Less	Expensive
Market Maturity	Low	High
Ecological Impact	Low	High
Topology	Point to Point	Point to Multi-point

1.6 Advantages and Challenges of Li-Fi

1.6.1 Advantages of Li-Fi

- Faster data transfer speeds compared to traditional Wi-Fi [13].
- More secure than Wi-Fi.
- Higher bandwidth capabilities: Li-Fi has the potential to solve the problem of radio frequency bandwidth shortage.
- No associated health risks: LED-based Li-Fi does not emit harmful radiation and is considered as safe as traditional lighting [17].
- Reduced power consumption and environmental impact due to the use of visible light instead of radio waves.
- Capacity: The most important feature of the Li-Fi technology is the ability to provide high data rate [36].
- Better reliability and stability with less signal interference from other devices.
- More efficient use of available spectrum as it uses the visible light spectrum.
- Improved connectivity in areas where radio frequencies are restricted.
- Cost-effective due to the availability of LED bulbs that can be used for both lighting and data transmission.
- With this technology, every street lamp will serve as a free data access point globally.
- Potential for new applications in areas such as smart homes, healthcare, and transportation.
- No fading: One of the biggest issues for signals in the radio range is the channel fading caused by multipath propagation. The reflected signal may be in anti-phase with the transmitted signal, and thus they will cancel each other and cause signal fading [36].

1.6.2 Challenges of Li-Fi

Li-Fi technology provides numerous benefits, including high-speed data transmission, access to an unlicensed spectrum, and improved security. Despite these advantages, certain limitations impact its real-world implementation. The following is a summary of these challenges along with potential solutions to mitigate them.

- **Line-of-Sight (LOS) Limitation:** Li-Fi typically requires a direct line-of-sight between the transmitter (LED) and receiver (photodiode). Any obstructions such as walls, furniture, or people can interrupt the signal.
- **Ambient Light Interference Limitation:** External light sources, such as sunlight and fluorescent lighting, can introduce noise and interfere with Li-Fi signals, leading to data loss or degradation.

- **Limited Uplink Capability Limitation:** Most Li-Fi setups prioritize downlink data transmission to users but offer limited or no functionality for uplink communication.
- **Signal Penetration Limitation:** Li-Fi signals cannot pass through walls or opaque objects, making them unsuitable for multi-room connectivity without additional infrastructure.
- **LED Bandwidth Limitation:** Standard LEDs have limited switching speeds, which restricts the maximum achievable data rate in Li-Fi systems.
- Visible light can't penetrate through brick walls as radio waves do and is easily blocked by someone simply walking in front of the LED source [19].
- **Public Awareness and Acceptance:** The adoption of Li-Fi in smart cities depends on the awareness and acceptance of the technology by the public and businesses. Being a relatively new technology, there may be concerns about its safety, reliability, and privacy implications [20].
- **Range and Coverage:** The limited range of Li-Fi signals poses a challenge for its integration into smart cities. Unlike Wi-Fi, which can transmit signals over longer distances, Li-Fi's range is typically limited to the area illuminated by the light source [20].
- Internet access depends on the light source—if it malfunctions, connectivity is lost.
- The type of LED used (Laser LED, Larger LED, or Smaller LED) directly impacts the internet speed.
- Implementation requires reinvestment in lighting and wiring to install suitable LEDs.

1.7 MIMO in VLC

In wireless optical communication systems, multiple input and multiple output (MIMO) is a workable way to reach large data speeds. Nonetheless, there is a fair correlation between the wireless optical channels, which is covered in this section of "Indoor wireless optical channel model." An imaging MIMO system allows one piece of lens in front of the PD to separate multiple LED signals to achieve light spatial diversity even when the RX moves to different positions or tilts, whereas a non-imaging optical MIMO system is inconsistent and dependent on the symmetry of the receivers. [60, 61]. The light beams of LEDs with comparable angles of incidence present challenges for the separation of several signals that are projected on the receivers' plane. This calls for a large number of PDs to supply spatial variation is crucial for interchannel interference (ICI) cancellation in real-world systems. In order to lessen system complexity and mitigate ICI, optical spatial modulation (OSM) has been created.

incorporates information bits in the spatial domain to combine MIMO and digital modulation techniques. [21]. Using the maximum probability approach, the OSM signal can be approximated at the receiver to determine which LED is transmitting. OSM's

features allow for easier cancellation of the ICI and eliminate the requirement for synchronization between transmitting LEDs, which reduces system complexity as compared to optical MIMO. OSM is dependent on the transmitter and receiver geometry positions, just like optical MIMO.

If differing transmit powers are distributed among LEDs, asymmetrical channel conditions result.[22].

1.8 Research Objectives and Problem

1.8.1 Research Objectives

This research aims to design and evaluate a high-speed PC-to-Speaker communication system based on Li-Fi technology, while exploring its broader applications as a transformative wireless medium.

Key objectives include:

Experimental Setup and Performance Evaluation: Develop a system where an analog sine wave from one PC is transmitted via a Li-Fi transmitter and received at a speaker. The performance will be assessed over focusing on signal integrity, distortions, and fidelity.

Analysis of Li-Fi's Advantages and Limitations: Examine Li-Fi's benefits, such as high data rates, security, and its unlicensed spectrum, while identifying challenges like line-of-sight dependency, range limitations, and environmental interference.

Security and Data Protection in Optical Wireless Networks: Propose encryption methods and data protection strategies tailored to optical wireless communications, aiming to secure data integrity in Li-Fi deployments.

Contributions to Wireless Communication Standards: Offer recommendations for industry standards to support Li-Fi adoption as an alternative to traditional RF networks, particularly in RF-congested or interference-sensitive environments.

Exploring Li-Fi's Broader Applications: Investigate real-world applications, such as smart lighting, secure communications in sensitive areas, and IoT integration, to demonstrate Li-Fi's potential across industries.

1.8.2 Problem Statement

The problem is in the fact that modern organizations require high-speed and widely available communication technologies that should also be secure and efficient in terms of the used resources). The speed of the Internet communicated with the help of Wi-Fi is comparably low, costs are high, and security is limited.

Therefore, organizations are interested in using a new technology instead of Wi-Fi. Still, in spite of the fact that Li-Fi is regarded as one of the most recent and high-speed communication technologies, its advantages in comparison to Wi-Fi need to be examined in detail.

Conventional wireless communication systems relying on radio frequency (RF) transmission are increasingly challenged by spectrum congestion, interference, and security limitations. As emerging demands push the envelope for high-speed, interference-free, and secure data transmission, Li-Fi technology which utilizes the vast, underutilized visible light spectrum presents a promising alternative. However, particularly for real-time audio transmission between a PC and a speaker, remain underexplored.

This research addresses the gap by developing and evaluating a Li-Fi-based audio transmission system. The system employs an analog audio signal generated by a PC,

which is transmitted via optical components including a high-power LED, an LM386 amplifier, and a solar panel or photodiode-based receiver, and reconstructed as audible sound on a speaker. Key challenges such as signal distortion, non-linearity across varying transmission distances, and the impact of ambient light interference are systematically investigated. By tackling these issues, the study aims to demonstrate the technical feasibility of Li-Fi for real-time, wireless audio transmission and lay the groundwork for its broader adoption as a secure, low-interference communication medium.

1.9 Overview Of Project Application

The project centers on establishing an audio transmission system using Li-Fi “visible light communication (VLC) technology” to showcase the feasibility and performance of optical wireless signal transmission. The system begins with the generation of an analog audio signal from a PC, such as music or voice. This signal is fed into a Li-Fi transmitter circuit, where the LM386 low-power audio amplifier plays a crucial role in boosting the signal amplitude to levels suitable for optical modulation. After amplification, the signal drives a high-power white LED, which converts the electrical waveform into a modulated light beam. This process effectively encodes the audio information into optical intensity variations.

On the receiving end, a solar panel or photodiode functions as the photodetector, capturing the modulated light and converting it back into an electrical signal. This conversion is sensitive to variations in light intensity, thereby reflecting the dynamic changes of the original audio waveform. The recovered signal (potentially affected by transmission distance and ambient light) is then passed through another LM386 amplifier stage, which conditions the signal for output. The resulting signal is fed to a speaker, producing the audible output of the transmitted audio.

The experimental setup allows for the evaluation of performance parameters in a real-world Li-Fi audio system, including issues such as signal distortion, nonlinear amplification, ambient light interference, and transmission range limitations. The project not only validates the core principles of Li-Fi for secure, low-interference wireless audio transmission, but also highlights practical challenges in optical system design. By bridging theoretical knowledge with hands-on circuit implementation, this research contributes to the broader exploration of Li-Fi as a viable alternative to conventional RF-based communication, particularly in environments where electromagnetic interference must be minimized.

1.10 Conclusion

This chapter explored the development and importance of wireless communication, emphasizing its critical role in contemporary connection. Building on this framework, we looked at visible light communication (VLC) and how it differs from traditional radio frequency technologies. We also looked at its definition, historical significance, and working principles.

Li-Fi, a ground-breaking application of Visible Light Communication (VLC), enables high-speed, secure, and interference-free data transmission using visible light. Within this framework, we explored the definition of Li-Fi, its historical evolution, the fundamental principles behind its operation, and the key components that make up a Li-Fi system.

This review highlights the rapid advancement of Li-Fi technology and its growing significance in today's data-driven world.

The chapter also discussed our study's primary purposes and objectives, demonstrating practical application while enhancing theoretical understanding. Our proposed design, which is a Li-Fi-based audio transmission system enabling the transfer of sound from a personal computer to a speaker, serves as a representative example of such an implementation. In addition to highlighting Li-Fi's potential for short-range, wireless audiocommunication, this system also establishes a baseline for evaluating its real-world capabilities, particularly in terms of signal quality, stability, and environmental sensitivity.

Chapter2

TheoreticalFoundationsandCore TechnologiesofLi-Fi

2.1 Introduction

This chapter discusses the basics of Li-Fi and optical wireless communications, how light can be used for data, key components (like LEDs), as well as what is unique compared to Wi-Fi. It goes further into futuristic integrations, like AI-driven optimization for speed and efficiency, hybrid Li-Fi/Wi-Fi networks for a more fluid and stable connection, and Li-Fi + IoT for smarter homes.

The focus is on security: we'll discuss Li-Fi's inherent benefits (light can't pass through walls, making eavesdropping more difficult) and ways to protect data, such as light-based encryption.

Lastly, the technology is brought to life by practical uses, such as space-ready networks, underwater communication, and hospitals utilizing Li-Fi to securely store patient data. The chapter concludes with an overview of Li-Fi's potential contribution to smart cities and industries of the future, demonstrating that it is more than just a fad but rather the wireless technology of the future.

2.2 Theoretical Foundations of Li-Fi and Optical Wire-less Communication

2.2.1 Electromagnetic Spectrum and Light as Communication Medium

Li-Fi Electromagnetic Spectrum and Available Bandwidth overview

Li-Fi functions in a part of the electromagnetic spectrum known as visible light (380–750 nm). Li-Fi has access to a large, uncontrolled spectrum with the possibility for larger data speeds, unlike RF transmission, which is restricted by bandwidth. The available bandwidth can be increased by using OWC in the ultraviolet and infrared spectrums.

Comparison with Radio-Frequency (RF) Communication

Feature	Li-Fi (Visible Light Communication)	RF (Radio Frequency)
Full Form	Visible Light Communication	Radio Frequency
Electromagnetic Interference	Not affected	Can be disrupted by EM sources
Power Consumption	Low, energy-efficient	High, less efficient
Bandwidth	High	Low
Security	Highly secured due to Line-of-Sight (LOS)	Less secure, signals penetrate walls
Health Risks	No known risks	Potential risks at high transmission power
Installation	Simple and easy	Medium to complex, varies by application (indoor/outdoor)
Power Amplifier (PA) Required?	Not needed	Required

Coverage Distance	Short-range	Medium-range
Visibility	Yes (light-based)	No (radio waves)

Table 2.1: comparison between Li-Fi and RF.

Li-Fi offers higher data rates and better security, but RF communication is more flexible in terms of range and penetration.

Principal Benefits:

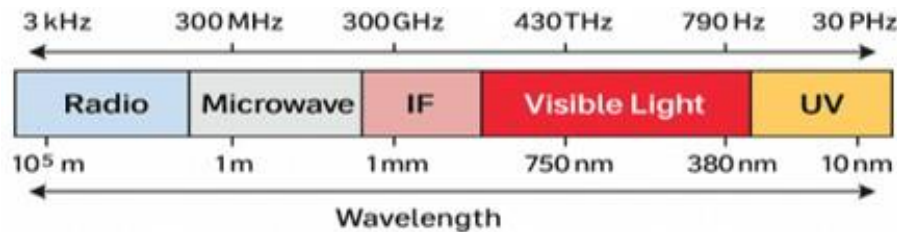


Figure 2.1: Frequency and Wavelength Ranges of the Electromagnetic Spectrum.

- Greater bandwidth in contrast to radio frequency transmission.
- It is perfect for sensitive areas because it doesn't interfere with electromagnetic signals.
- Secure transmission because walls don't let light through.

Physical Properties of Light Used in OWC:

- Wavelength: Establishes the hue of the light that is transmitted.
- Intensity: Affects data transmission dependability and signal strength.
- Coherence: For accurate communication, laser-based OWC system employs coherent light.

Modulation Techniques for Light Signals:

Li-Fi encodes data using Intensity Modulation with Direct Detection (IM/DD), which exploits fluctuations in LED brightness. Typical methods include:

OOK (On-Off Keying): Basic binary modulation: For low-power applications, pulse position modulation (PPM) is an effective technique. For high-speed data transfer, orthogonal frequency division multiplexing, or OFDM, is utilized.

Features of Propagation: Strong signal transmission requires line-of-sight (LoS):

- Reflections: May cause signal distortion, but they can increase coverage.
- Shade: Communication can be hampered by objects that obscure light.

Difficulties:

- Ambient Light Interference: Artificial lights and sunlight might degrade signal quality.

- **Blocking:** Transmission may be halted by physical barriers.
- **Device Restrictions:** There are currently few Li-Fi-enabled gadgets on the market.

Applications:

- **Indoor networking:** smart buildings, residences, and offices.
- **Vehicle Communication:** Headlights are used by cars to communicate data.
- **Underwater Communication:** Light-based communication is more effective than radio frequency transmissions while submerged.
- **IoT Integration:** Li-Fi is used by smart gadgets to provide seamless connectivity.

Prospects for the Future:

- **5G/6G integration:** RF-optical hybrid networks for lightning-fast connectivity.
- **Smart Cities:** Infrastructure with Li-Fi for effective data transfer.
- **Space Communication:** Data sharing between planets using optical wireless networks.

Li-Fi vs Other Optical Communication Technologies (Infrared, VLC, FSO...):

Optical wireless technologies, including Li-Fi, VLC, FSO, OCC, and Infrared, provide high-speed, secure, and interference-free communication. Li-Fi is notable among them because of its better speed and bi-directional data transfer.

By highlighting their variations in transmission techniques, effectiveness, and uses.

This comparison helps choose which one best meets the needs of modern connections:

Table 2.2: Comparison between Li-fi and the Other Optical Communication Technologies.

Comparison Criteria	Li-Fi (Light Fidelity)	VLC (Visible Light Communication)	FSO (Free Space Optical Communication)	OCC (Optical Camera Communication)	Infrared Communication
Technology Scope	Advanced form of VLC with bi-directional, high-speed data transfer	One-way communication, mainly LED-based signaling	Uses laser beams for long-distance communication	Uses camera-based light detection for data transfer	Uses infrared light for low-speed communication
Speed & Bandwidth	Over 100 Gbps, high bandwidth	Lower than Li-Fi due to simple data transmission focus	High bandwidth, but requires precise alignment	Slower than Li-Fi due to image processing overhead	Up to 4 Mbps, limited bandwidth
Transmission Medium	LED light sources, operates in visible, infrared, and ultra-violet light spectrums	Visible light spectrum, mainly LEDs	Laser beams, requiring clear line of sight	Camera sensors detect light signals	Infrared radiation, short-range
Environmental Sensitivity	Indoor-based, stable, interference-free	Susceptible to ambient light interference	Affected by fog, rain, air turbulence	Requires good lighting conditions	Less affected, but limited range
Security	Highly secure, light signals do not pass through walls	Moderate security, signals can be detected	High security, but sensitive to environmental conditions	Secure but relies on camera visibility	Secure, but low data rate
Uses & Applications	Industrial automation, hospitals, aircraft cabins, RF-sensitive areas	Smart lighting, indoor navigation, digital signage, vehicle-to-vehicle communication	Satellite communication, military applications, inter-building data transfer	Augmented reality, smart signage, IoT, QR-code-like data transmission	Remote controls, medical equipment, short-range communication

Signal Processing and System Optimization in Li-Fi:

In order to guarantee effective data transfer, signal integrity, and system optimization, Li-Fi technology depends on a number of essential elements. Together, these components enable high-speed communication by converting digital data into optical signals.

a) Signal Processing in Li-Fi: Signal processing plays a critical role in Li-Fi communication, ensuring accurate transmission and reception of data:

Modulation and Demodulation: At the transmitter, electrical impulses are transformed into optical signals, and at the receiver, they are transformed back into electrical data.

Error Detection and Correction: Methods like Forward Error Correction (FEC) reduce interference-induced transmission mistakes.

Filtering and Noise Reduction: removes ambient light source disruption to guarantee dependable data transfer.

Synchronization: synchronizes the timing of the transmitter and receiver to ensure smooth connection.

b) System Optimization Strategies: To enhance Li-Fi performance, various optimization techniques are applied:

Adaptive Modulation: dynamically modifies transmission settings in response to external circumstances.

Power Efficiency Improvements: LED drivers that are optimized use less energy while preserving signal intensity.

Multi-Channel Communication: increases bandwidth by enabling parallel data transfer across several wavelengths.

Interference Management: uses better filtering and signal correction techniques to lessen the influence of external light.

2.2.2 Li-Fi Modulation Techniques

Definition of Li-Fi Modulation Techniques:

Using visible light to transport data, Li-Fi (Light Fidelity) technology necessitates efficient modulation methods for both encoding and decoding data. In optical wireless communication, these modulation techniques control system efficiency, signal dependability, and data transfer speed.

- **On-Off Keying (OOK):**

One of the most basic modulation methods in Li-Fi is OOK. It encodes binary data by rapidly turning the LED light source on and off, where "on" denotes a binary 1 and "off" denotes a binary 0. Although this approach is simple to use and energy-efficient, noise interference may cause problems.

- **Pulse Amplitude Modulation (PAM):**

PAM represents various data values by altering the light signal's amplitude. By varying the light's intensity, PAM may encode more than one bit per symbol, in contrast to OOK, which only employs two levels (on/off). Although it necessitates exact control over light intensity, this increases data transmission speeds.

- **Orthogonal Frequency Division Multiplexing (OFDM):**

A more sophisticated modulation method called OFDM splits the data into many frequency channels, enabling the transmission of numerous signals at once. This makes it perfect for high-speed Li-Fi applications by improving spectrum efficiency.

and lowering interference. Because OFDM is resilient to signal deterioration, it is frequently utilized in wireless communications systems.

Common modulation techniques in Li-Fi include On-Off Keying (OOK), Pulse Width Modulation (PWM), and Orthogonal Frequency-Division Multiplexing (OFDM). Each technique offers trade-offs between data rate, complexity, and noise resilience.

Applications of Li-Fi Modulation Techniques:

In many real-world applications, Li-Fi modulation methods are essential for maximizing data throughput, connection, and security. Li-Fi may operate in a variety of situations with varying degrees of speed, efficiency, and dependability depending on the modulation technique employed.

- **High-Speed Data Transmission:**

Ultra-fast wireless communication is made possible by Li-Fi, which frequently outperforms conventional Wi-Fi rates.

- OOK (On-Off Keying): Easy to use, good for simple applications, but slow. Higher data speeds are made possible by PAM (Pulse Amplitude Modulation), which encodes several bits per symbol.
- Orthogonal frequency division multiplexing, or OFDM: is best suited for high-speed applications where many signals are sent at once.

- **Internet of Things (IoT) Connectivity:** Li-Fi facilitates smooth incorporation into IoT networks, enhancing smart homes, businesses, and cities.

- OOK: Applicable to low-power Internet of Things applications where simplicity is desired.
- PAM: Increases smart home automation systems' efficiency.
- OFDM: Provides dependable connection and low interference for extensive IoT networks.

- **Secure Communication:** Because Li-Fi transmissions are limited to regions with light, there is less chance of external eavesdropping, adding an additional layer of protection.

- OOK: Easy modulation that works well in confined spaces with regulated illumination.
- PAM & OFDM: Provide enhanced encryption and signal dependability, making them perfect for secure communication in the financial, medical, and military sectors.

Impact of Modulation Techniques in Different Environments

Table 2.3: *Impact of Modulation Techniques in Different Environments.*

Environment	Recommended Modulation	Reason
Indoor Networks	OFDM	Ensures stable, high-speed data exchange across large spaces.
Industrial Automation	PAM	Facilitates real-time machine communication with optimized efficiency.
Public & Healthcare Spaces	OOK	Energy-efficient and interference-free communication in hospitals and sensitive environments.

Each modulation technique contributes to speed, security, and efficiency in different Li-Fi applications, ensuring optimal performance based on specific use cases.

comparison of OOK, PAM, and OFDM based on key performance metrics:

Table 2.4: Comparison between OOK, PAM, and OFDM.

Modulation Technique	Data Rate	Efficiency	Complexity	Reliability	Advantages	Limitations
On-Off Keying (OOK)	Low to moderate	Energy-efficient, simple to implement	Low complexity	Susceptible to noise interference	Easy to implement, requires minimal processing	Limited data transmission speed, highly affected by ambient light interference
Pulse Amplitude Modulation (PAM)	Moderate to high	Higher data transmission speeds, optimized bandwidth usage	Medium complexity	More reliable than OOK, but dependent on precise light intensity control	Encodes multiple bits per symbol, improving data rates	Requires accurate light intensity modulation, complex implementation
Orthogonal Frequency Division Multiplexing (OFDM)	High	High spectral efficiency, reduces interference	High complexity	Very reliable, resistant to signal degradation	Supports multiple signals simultaneously, ideal for high-speed applications	Requires advanced signal processing, higher system resources

2.2.3 Multiple Access Techniques in Li-Fi Networks

Definition

Several Access in Li-Fi (Light Fidelity) networks, techniques are ways to make it possible for several users or devices to effectively and interference-free share the available Li-Fi communication resources (such as bandwidth, time slots, or light signals) at the same time. These methods provide seamless, coordinated, and speed-, reliability-, and fairness-optimized data transfer between the Li-Fi transmitter (often LEDs) and several receivers. Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA), and Spatial Division Multiple Access (SDMA) are common Li-Fi multiple access techniques that are each specifically designed to meet the demands of light-based communication [27].

These techniques can be classified as narrowband and wideband systems:

- **Narrowband systems:**

Narrow band systems are those that use channels that are significantly smaller than the coherence bandwidth. A limited number of users are separated in time on a single channel via narrowband TDMA, which permits users to utilize the same channel but assign each user a distinct time slot [28].

- **Wideband systems:**

A single channel's transmission bandwidth in wideband systems is significantly greater than the channel's coherence bandwidth. Therefore, frequency selective fades only occur in a tiny portion of the signal bandwidth, and multipath fading has little effect on the received signal within a wideband channel [28].

Common Multiple Access Techniques in Li-Fi:

- **Time Division Multiple Access (TDMA):**

TDMA is a technique that divides a frequency channel into time slots so that several users can share it. In order to avoid interfering with other users, each user is given a certain time window for data transfer. TDMA makes the handoff procedure between base stations easier since transmission happens in bursts rather than constantly. Flexibility is another benefit of TDMA; various users can be given varied numbers of time slots according to priority, guaranteeing effective bandwidth use. [28]

- **Code Division Multiple Access (CDMA):**

By giving each transmission a unique code, CDMA enables several users to share the same radio spectrum at the same time. Because the encoded signals are hard to intercept or tamper with, this method guarantees improved spectral efficiency and security. CDMA is better for data and mobile communications systems because it has more air-space capacity than TDMA. Furthermore, CDMA facilitates smooth base station transitions, lowering call dropouts when traveling. [28]

- **Spatial Division Multiple Access (SDMA):**

To distribute communication resources, SDMA makes use of spatial isolation. With the use of beamforming methods or directional antennas, it allows several users to converse simultaneously on the same frequency. SDMA dramatically lowers

interference by effectively directing radiated energy to particular users. Because

users are dispersed across different places, this technique is especially helpful in satellite communication and cellular networks, enabling the most efficient use of transmission resources. [29]

- **Frequency Division Multiple Access (FDMA):**

Each user is given a unique frequency sub-band using FDMA. FDMA is perfect for audio communication because it permits continuous transmission, unlike TDMA, which requires users to send in predetermined time windows. FDMA does have a drawback, though, in that once a frequency is assigned to a user, it doesn't get redistributed to other users. Narrowband communications systems frequently use this technique, which necessitates strict filtering to reduce interference from nearby channels [28].

These multiple access strategies provide effective data transfer, enabling unhindered network sharing among several users. Both strategies have their own benefits and are appropriate for various uses, including satellite systems, mobile communications, and contemporary wireless technology.

2.2.4 Data Encoding and Signal Processing in Li-Fi

Li-Fi Data Encoding:

Transforming binary data (0s and 1s) into light signals that LEDs can produce and that photodetectors at the receiver can correctly understand is known as data encoding [23].

- **Encoding Process**

- Binary data (0s and 1s) is converted into light intensity variations.
- LEDs modulate their brightness at high speeds, encoding data into optical signals.
- A photodetector at the receiver captures these signals and decodes them back into digital data.

- **Modulation Techniques for Encoding**

Li-Fi employs various modulation techniques to encode data efficiently:

- On-Off Keying (OOK): The simplest method—LEDs turn on for '1' and off for '0'.
- Pulse Position Modulation (PPM): Data is encoded by shifting the position of light pulses in time.
- Pulse Width Modulation (PWM): The width of each pulse varies to represent different data values.
- Color Shift Keying (CSK): Uses RGB LEDs to encode data by changing color combinations.
- Orthogonal Frequency Division Multiplexing (OFDM): Splits data into multiple subcarriers, improving efficiency and reducing interference.

Signal Processing in Li-Fi:

The collection of hardware methods and algorithms used to get data ready for transmission, adjust for channel effects, and retrieve the original data at the receiver is known as signal processing [30].

Signal Processing Tasks in Li-Fi:

- **Modulation and demodulation:** Extract the original data from the received optical signal and transform digital data into a format appropriate for optical transmission.
- **Channel Estimation and Equalization:** Corrects distortions caused by signal fading, multipath reflections, and shadowing, improving reliability.
- **Error Detection and Correction:** This technique detects and fixes errors brought on by noise and interference using techniques like Reed-Solomon codes and Forward Error Correction (FEC).
- **Noise Mitigation:** Adaptive thresholding and optical filters are used to lessen interference from ambient light sources, such as sunlight or interior illumination.
- **Adaptive Modulation and Coding (AMC):** Dynamically adjusts modulation order and coding rate depending on channel conditions to maximize throughput while maintaining quality.
- **Synchronization:** Ensures that the transmitter and receiver are properly aligned in time and frequency for accurate signal decoding.

2.3 Advanced concepts in Li-Fi technology

2.3.1 integration of Li-Fi with IoT and smart devices:

Definition:

The Internet of Things (IoT) is a network of interconnected devices, systems, and sensors that harness advancements in computing, miniaturization, and communication technologies to drive automation, enhance efficiency, and facilitate data-driven decision-making. By integrating smart objects into various industries such as healthcare, agriculture, and manufacturing, IoT enables real-time monitoring and intelligent interactions in both physical and virtual environments. Its core components include sensors for data collection, aggregators for processing, communication channels for transmission, utilities for continuous service support, and decision triggers for actionable insights. While IoT revolutionizes operations, business models, and daily applications, it also raises important considerations regarding security, privacy, and interoperability in its widespread adoption [31][32].

Most IoT devices follow a layered architecture comprising of three or four layers as shown in the Figure (fig 2.2)

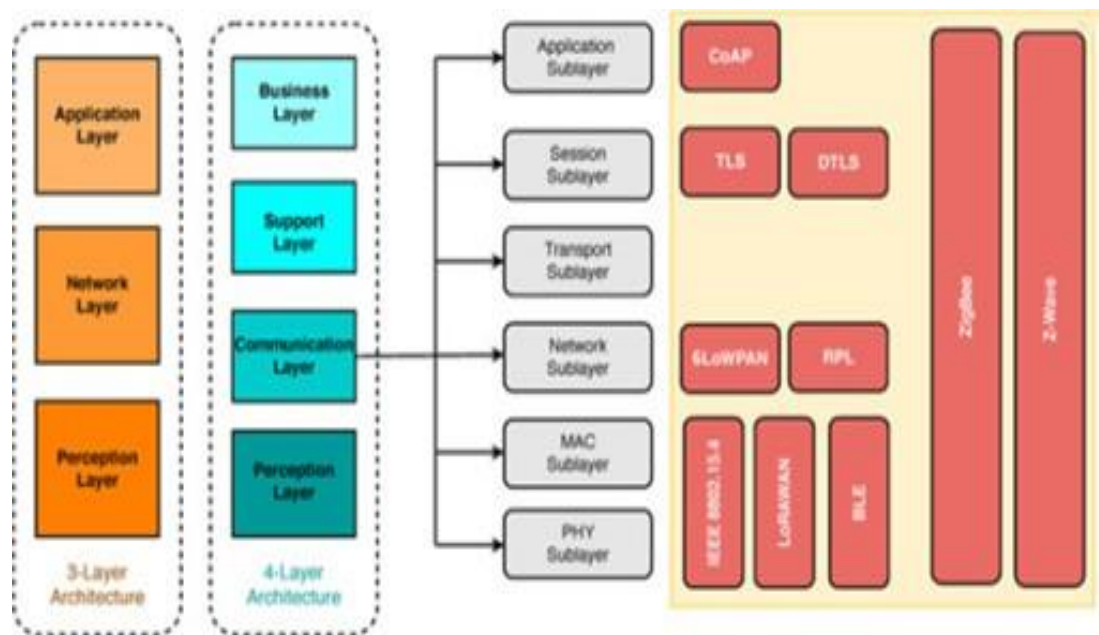


Figure 2.2: Most common IoT Architectures.

The IoT architecture is composed of multiple layers that enable seamless data collection, communication, processing, and application. At the foundation, the perception layer consists of physical devices that interact with their surroundings, gathering and processing environmental data. The network layer, responsible for transmission, is divided into six sublayers and employs communication protocols like Zigbee, BLE, NFC, and LPWAN to relay data efficiently.

To optimize low-power IoT devices, protocols such as 6LoWPAN and RPL ensure efficient data transfer, while security standards like TLS and DTLS safeguard information during transmission. The application layer provides software and services for analyzing collected data and enabling real-time decision-making. Additionally, the support layer enhances functionality by supplying storage and computing resources. To facilitate device communication, IoT employs specialized messaging protocols such as CoAP, MQTT, and AMQP for efficient data exchange [31].

How it works:

The Internet of Things (IoT) connects physical devices, sensors, and machines to the internet, allowing real-time data collection and automation. Devices communicate via networks like Wi-Fi, Bluetooth, Zigbee, LPWAN, 5G, and Li-Fi to cloud or edge systems for analysis.

Li-Fi enhances IoT by using visible light instead of radio waves for ultra-fast, secure data transmission, especially in environments where traditional wireless signals face interference (e.g., hospitals and airplanes). AI-driven analysis helps optimize operations, adjust smart devices, and provide insights. Users manage IoT systems via apps, dashboards, or smart assistants, improving automation and efficiency across industries like healthcare, aviation, manufacturing, and smart cities [31].

Explanation of IoT ecosystems and their components:

An IoT ecosystem consists of various components, including hardware such as sensors and smart devices, communication networks, cloud and edge computing, data analytics, and security protocols, all working together to enable automation and real-time decision-making. While IoT represents the broader concept, an IoT ecosystem serves as the operational framework that supports IoT applications across multiple industries [33].

It is composed of interconnected elements that facilitate automation, data exchange, and intelligent decision-making. Below is an explanation of its core components:

- **Devices & Sensors:** These physical or virtual entities collect and transmit data, including smart home appliances, industrial sensors, wearables, and autonomous vehicles.
- **Connectivity (Networks & Protocols):** IoT devices utilize Wi-Fi, Bluetooth, Zigbee, LPWAN, and 5G to establish seamless communication between components.
- **Edge & Cloud Computing:** Edge computing processes data closer to its source to minimize latency, while cloud computing offers scalable storage and powerful processing capabilities.
- **Data Processing & Analytics:** AI and machine learning extract insights from data, facilitating predictive maintenance, automation, and optimization across various industries.
- **User Interface (UI & Applications):** Dashboards, mobile apps, and smart assistants provide real-time access to IoT data, control functionalities, and alerts.

- **Security & Privacy Measures:** Encryption, authentication, and cybersecurity protocols safeguard data, ensuring privacy and secure communication between connected devices.
- Together, these components form an efficient framework that enhances productivity, automation, and intelligent decision-making in industries such as healthcare, manufacturing, agriculture, and smart cities [34].

Role of smart devices in automation and digital transformation:

- Smart devices are fundamental to automation and digital transformation within the Internet of Things (IoT) ecosystem, enabling seamless data exchange, intelligent operations, and enhanced decision-making across industries. They optimize efficiency by collecting, processing, and transmitting data in real time [35].
- **Data Collection & Monitoring:** Smart sensors and IoT-enabled devices track metrics like temperature, motion, energy consumption, and performance, enabling predictive maintenance and proactive management.
- **Process Automation:** IoT-driven devices streamline tasks, such as smart thermostats regulating temperatures, industrial robots optimizing manufacturing, and AI-powered logistics systems enhancing efficiency.
- **Enhanced Connectivity & Communication:** Smart devices rely on Wi-Fi, Bluetooth, Zigbee, LPWAN, and 5G for seamless interaction between interconnected ecosystems.
- **AI & Machine Learning Integration:** IoT devices leverage AI to analyze data, detect patterns, and enable intelligent automation across sectors such as healthcare, transportation, and smart cities.
- **User Interaction & Control:** Mobile apps and dashboards allow users to remotely monitor and control IoT devices, enhancing operational flexibility and personalized digital experiences.
- **Security & Privacy Measures:** As digital transformation advances, smart devices implement encryption, authentication, and secured data transmission to protect sensitive information.
- These capabilities collectively enhance automation, efficiency, and intelligent decision-making, reshaping industries like healthcare, manufacturing, energy, and smart homes.

Advantages of Li-Fi for IoT and Smart Devices:

Li-Fi is emerging as a transformative technology for IoT and smart devices, offering high-speed communication and enhanced security—all powered by existing LED lighting systems. A closer look at its benefits highlights the significant advantages of Li-Fi in modern connectivity:

- **Blazing-fast data transfer:** With speeds surpassing conventional Wi-Fi, Li-Fi ensures real-time communication, which is vital for automation and IoT applications.
 - **Enhanced security:** Since light waves do not pass through walls like radio signals, Li-Fi significantly reduces the risk of unauthorized access and cyber threats.
 - **Minimal interference:** Unlike Wi-Fi, which faces congestion and signal disruptions, Li-Fi performs reliably in environments where RF-based communication is impractical, such as hospitals and aircraft.
 - **Energy-efficient connectivity:** By utilizing existing LED infrastructure, Li-Fi combines illumination and data transmission in a single system, optimizing energy consumption.
- With its promising potential, Li-Fi is poised to revolutionize smart connectivity, making data transmission faster, more secure, and highly efficient for future IoT applications.

Practical Applications and Challenges & Future Prospects:

Li-Fi has exciting practical applications across various fields, revolutionizing how devices communicate.

- **Smart Homes:** With Li-Fi-enabled IoT devices, home automation becomes smoother, ensuring fast and secure connections for everything from smart lighting to entertainment systems.
- **Healthcare:** Hospitals can benefit from Li-Fi's secure data transmission, reducing interference and safeguarding patient information.
- **Industrial IoT:** Factories and industrial facilities can enhance machine-to-machine communication, ensuring reliable connectivity even in RF-sensitive environments.
- **Smart Cities:** Urban infrastructure, including traffic systems, can use Li-Fi to manage data flow efficiently, reducing congestion and improving public services.

2.3.2 Hybrid Li-Fi/Wi-Fi Networks for Seamless Communication:

Li-Fi enhances wireless communication with high-speed, secure, and interference-free connectivity, complementing Wi-Fi and IoT networks. Its benefits include improved efficiency, adaptability, and cybersecurity, making it a promising solution for next-generation smart systems.

Network Architecture:

Li-Fi and Wi-Fi can work together to create a hybrid network architecture that enhances connectivity in various environments [38].

- **Complementary Usage:** Wi-Fi ensures wide-area connectivity, while Li-Fi provides high-speed, secure communication in localized environments.
- **Indoor Optimization:** Li-Fi is well-suited for confined spaces like offices, hospitals, and airplanes, minimizing interference and enhancing data security.
- **Adaptive Switching:** Devices can seamlessly transition between Li-Fi and Wi-Fi based on signal strength and environmental conditions.
- **Energy Efficiency:** Li-Fi utilizes LED lighting infrastructure, optimizing power consumption while maintaining strong data transmission.

Performance & Efficiency:

Li-Fi offers several advantages over traditional Wi-Fi in terms of performance and efficiency.

- **Speed:** Li-Fi can achieve data transmission rates significantly higher than Wi-Fi, utilizing the visible light spectrum, which has a much larger bandwidth [39].
- **Security:** Since Li-Fi signals are confined to illuminated areas and do not penetrate walls, they are less susceptible to unauthorized access or cyber threats [40].
- **Interference Reduction:** Unlike Wi-Fi, which can experience congestion and interference from other RF-based devices, Li-Fi operates in environments where electromagnetic interference is a concern, such as hospitals and aircraft [41].

Scalability & Integration:

Integrating Li-Fi into existing IoT systems presents several challenges related to scalability and compatibility [42]:

- **Limited Infrastructure:** Most IoT networks rely on Wi-Fi for cellular connectivity, requiring significant adaptation to incorporate Li-Fi.
- **Line-of-Sight Dependency:** Li-Fi requires direct visibility between the transmitter and receiver, making widespread deployment more complex.

- **Interoperability Issues:** IoT devices must be equipped with Li-Fi-compatible hardware, which may not be universally available.
- **Network Management Complexity:** Hybrid Li-Fi/Wi-Fi systems need efficient switching mechanisms to ensure seamless connectivity.
- **Standardization & Adoption:** The lack of universal standards for Li-Fi integrations slows down widespread implementation.

Security Features:

Li-Fi enhances cybersecurity due to its physical boundary limitations, making it a more secure alternative to traditional wireless communication. Here's how [43]:

- **Restricted Signal Range:** Unlike Wi-Fi, which transmits through radio waves and can be intercepted beyond physical barriers, Li-Fi signals are confined to illuminated areas, preventing unauthorized access from outside.
- **Reduced Risk of Hacking:** Since Li-Fi cannot penetrate walls, cyber threats like eavesdropping and remote hacking are significantly minimized.
- **Secure Data Transmission:** Li-Fi networks operate within controlled environments, ensuring that sensitive information remains protected from external interference.
- **Lower Susceptibility to Electromagnetic Attacks:** Li-Fi does not rely on RF signals, making it immune to electromagnetic interference and jamming attempts.

2.3.3 Machine Learning and AI in Li-Fi Systems:

- **AI-Driven Network Optimization:** Enhancing signal processing, data transmission, and bandwidth allocation.
- **Intelligent Network Management:** Adaptive switching between Li-Fi and other networks, plus predictive maintenance.
- **Real-World Applications:** AI-powered Li-Fi in healthcare, smart cities, and industrial automation.
- **Future Prospects:** Challenges and ongoing research to improve AI-driven Li-Fi technology.
Machine Learning (ML) and Artificial Intelligence (AI) are playing a crucial role in advancing Li-Fi systems, here's how they contribute:
- **Optimized Data Transmission:** AI-driven algorithms enhance signal processing, reducing errors and improving data rates in Li-Fi networks.
- **Adaptive Network Management:** ML enables dynamic adjustments in Li-Fi systems, optimizing bandwidth allocation and minimizing interference.

- **Enhanced Security:** AI-powered encryption techniques strengthen Li-Fi's cyber-security by detecting and mitigating potential threats.
- **Predictive Maintenance:** ML models analyze network performance, predicting failures and optimizing system reliability.

2.3.4 Energy efficiency and power consumption in Li-Fi:

Definition:

Li-Fi technology offers a high-speed, energy-efficient, and eco-friendly method for data transmission by utilizing existing lighting systems. Since LED bulbs consume less power and have a longer lifespan, the approach minimizes energy waste while ensuring secure, localized communication. With applications in smart cities, indoor networks, and sustainable digital infrastructure, it presents a promising future for efficient connectivity [45].

Energy Efficiency:

Li-Fi uses LED lights for energy-efficient data transmission, offering dual functionality for lighting and communication while ensuring secure, low-interference connectivity.

- **Li-Fi and LED Lights:** Li-Fi operates using light-emitting diodes (LEDs) as a medium for data transmission. Unlike radio-based systems such as Wi-Fi, which require electromagnetic waves, Li-Fi modulates the intensity of LED light to encode and send data at high speeds. Since LEDs are energy-efficient, consuming significantly less power than incandescent or fluorescent bulbs, they offer a sustainable communication option. Moreover, their long lifespan and ability to switch on and off at extremely high speeds make them ideal for data transmission without noticeable changes in illumination [46].
- **Dual Functionality: Lighting and Communication:** One of the major advantages of Li-Fi is its dual functionality—serving as both a lighting source and a data transmission medium. This integration eliminates the need for additional communication hardware, thereby reducing energy consumption and infrastructure costs. Since Li-Fi can work with existing LED lighting systems, it optimizes space usage while providing secure and localized data exchange. The dual-purpose aspect allows implementation in environments such as homes, offices, hospitals, and factories, where lighting is already essential, making Li-Fi an efficient and scalable solution for data transfer [47].
- **Reduced Interference and Enhanced Performance:** Li-Fi operates within the visible light spectrum rather than the radio spectrum used by Wi-Fi and cellular networks. This results in reduced interference, particularly in environments where radio-frequency communication can be disrupted, such as hospitals, aircraft, and industrial facilities. Since light waves do not penetrate walls, Li-Fi signals remain secure and localized, reducing risks of unauthorized access or cyber interference.

This feature makes Li-Fi ideal for confidential communication and environments that require minimal electromagnetic disturbance [48].

Power Consumption:

Li-Fi minimizes power consumption while supporting IoT devices and smart cities, is crucial for evaluating its impact on sustainable technology.

- **Low Transmission Power and Energy Efficiency:**

Li-Fi offers a low-energy alternative to traditional wireless communication by transmitting data using visible light waves rather than radio frequencies. Since LED lights function as both illumination sources and data transmitters, Li-Fi eliminates the need for additional power-consuming networking infrastructure, such as Wi-Fi routers or cell towers. This feature significantly reduces overall power consumption, making Li-Fi an eco-friendly choice for modern digital communication [49].

- **Li-Fi in IoT Applications:**

The Internet of Things (IoT) relies on interconnected devices that exchange data seamlessly while operating on minimal power. Many IoT devices, such as smart home automation systems, wearable technology, and industrial sensors, require efficient, low-power communication networks. Li-Fi's ability to integrate with ambient LED lighting ensures that devices remain connected without excessive energy use, optimizing network speed, security, and reliability in IoT ecosystems. Additionally, localized data transmission enhances security by limiting access to authorized areas, preventing cyber interference common in radio-frequency-based networks [33].

- **Li-Fi's Role in Smart Cities:**

Smart cities emphasize sustainability and efficiency, incorporating advanced technologies to reduce energy waste and enhance urban services. Li-Fi contributes to smart city development by integrating with public LED lighting systems, enabling secure and high-speed data transmission for applications [34]; such as:

- **Smart traffic management:** using streetlights to facilitate real-time communication between vehicles and infrastructure, reducing congestion and improving mobility.
- **Environmental monitoring:** where Li-Fi sensors embedded in urban lighting collect data on air quality, temperature, and pollution levels to support sustainable urban planning.
- **Public connectivity:** providing Wi-Fi-free internet access in cities using existing LED streetlights, reducing reliance on power-intensive cellular networks.

2.4 Li-Fi Security and Data Integrity:

2.4.1 Security Features of Li-Fi

Li-Fi technology has security benefits and uses a variety of encryption techniques to secure transferred data because visible light wavelengths, which are employed in the technology, cannot travel through walls.

Physical security

This encryption technique has been used in this subsection. Li-Fi technology relies on providing a direct line of sight (LOS) between the light source and receiver to transmit or receive data, yielding a hindrance to unauthorized access. In contrast to Wi-Fi technology, which uses radio waves, Li-Fi technology uses light waves that cannot penetrate walls or other opaque objects. This restriction within a room or designated area significantly prevents the network from the potential attack of eavesdropping while using Li-Fi technology to communicate [15].

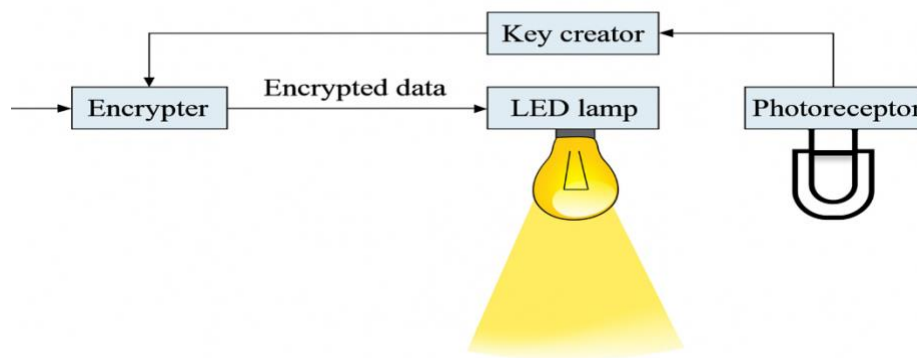


Figure 2.3: Physical security in Li-Fi technology.

Encryption Methods

Li-Fi technology is still in its infancy as a concept, particularly in the area of data security, where efforts have been made to encrypt data that is transferred using this technology using various methods to increase its resilience. Methodologically, Advanced Encryption Standard (AES), Caesar Cipher Wheel, Blowfish, Rivest Cipher 2 (RC2), Rivest Cipher 4 (RC4), Rivest Cipher 5 (RC5), and Rivest Cipher 6 (RC6) were the algorithms utilized to encrypt data communicated using Li-Fi technology [15].

Access control

A secure data transmission system in classrooms can be facilitated by blocking holes in walls, windows, or doors, which allows light beams to be in contact with authorized devices and prevents unauthorized devices from accessing the Li-Fi network.

This property is illustrated in the next figure. Li-Fi technology uses visible light to transmit and receive data, allowing precise control to access the Li-Fi network [16].



Figure 2.4: Access control in Li-Fi technology.

MAC address filtering

Li-Fi networks provide the ability to whitelist reliable devices to connect to the network and reject devices based on their MAC addresses. A network interface controller (NIC) is given a unique number called a MAC. Device MAC addresses are stored in a table, and the picture below uses an algorithm to filter out unauthorized devices and allow them to connect [15].

the network of Li-Fi. The MAC address is given to the household gadget that is linked to the Li-Fi network in home automation. To enable rapid and highly secure access to household equipment, these addresses are stored in the table.

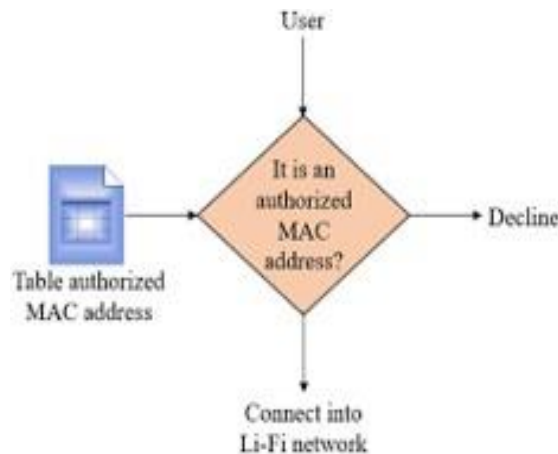


Figure 2.5: MAC Address filtering in Li-Fi technology.

Light single tracking

Li-Fi systems can identify and block unwanted access attempts by tracking the location of a light signal. This method is present in sophisticated Li-Fi systems. Triangulation methods are used to determine the user's precise location in order to follow the signal's location [78]. Since the tracker depicts a real-world situation, the following figure illustrates the Li-Fi technology technique. The anticipated position's values ought to be close to the actual position. If not, the entity will be flagged as a fraudulent user. Additionally, this technique is utilized when there are numerous Li-Fi access points available for connectivity.

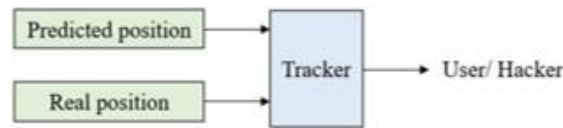


Figure 2.6: Tracking system in Li-Fi technology.

Optical orthogonal frequency division multiplexing

The figure below (Fig 2.7) depicts a transmitter and a receiver of the O-OFDM technique used in Li-Fi technology. O-OFDM is a technique that divides transmitted data into multiple frequency bands and sends each partition of transmitted data to a specific frequency band. This process includes passing data to obfuscate the eavesdropper, which gives the Li-Fi network greater security and prevents data from interception [15].

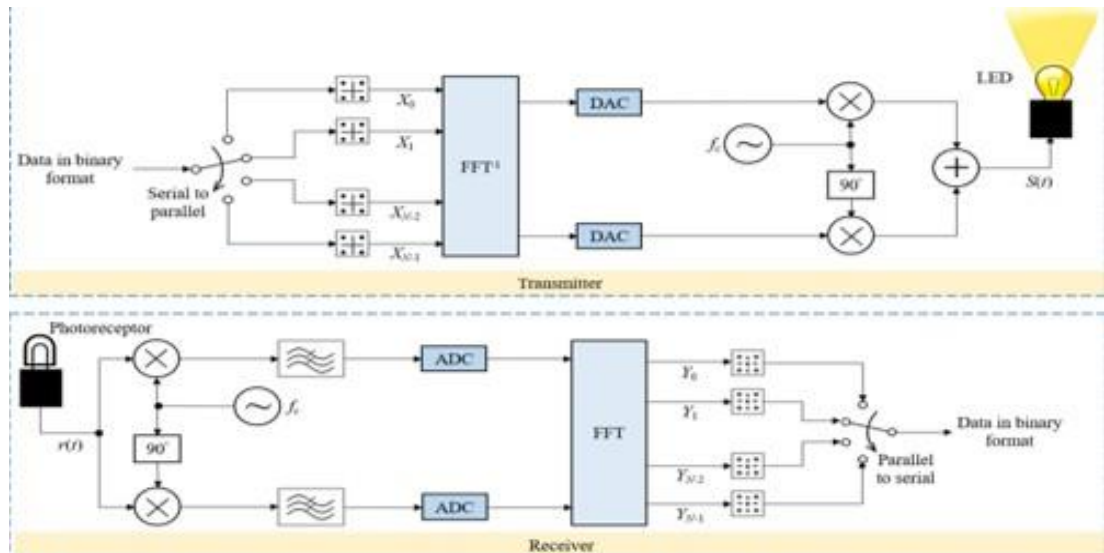


Figure 2.7: O-OFDM technique in Li-Fi technology.

Color shift keying

Through the use of LEDs' built-in color control, CSK modulates data by quickly changing the colors they emit, potentially achieving higher data rates than traditional methods. CSK divides transmitted data into multiple partitions, passing data to obfuscate eavesdropers because each partition of transmitted data sent by LEDs has a different color light [15].

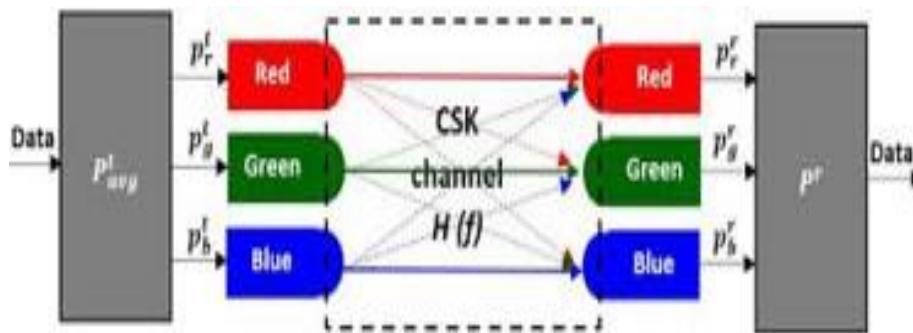


Figure 2.8: Transmitter and receiver in CSK modulation.

Quantum cryptography

A notable advancement in the realm of secure communication is the incorporation of quantum cryptography into Li-Fi technology, which uses the peculiar characteristics of quantum mechanics to generate unbreakable codes. Another name for quantum cryptography is quantum key distribution. It uses unique technology to send messages.

particles in several states simultaneously, making it impossible to listen in without warning the sender or the recipient, providing the highest level of protection for extremely private data. Potentially un failing security is offered by the combination of Li-Fi and quantum cryptography. The next figure graphically depicts Li-Fi technology using quantum cryptography as a technique to secure transmitted data.

Li-Fi/Wi-Fi system

The term "Li-Fi/Wi-Fi system" describes a system that combines Li-Fi and Wi-Fi technologies. As illustrated in the image below, it is a hybrid system that combines Li-Fi and Wi-Fi technologies, with Li-Fi technology providing the downlink and Wi-Fi technology supporting the uplink. Improved Li-Fi/Wi-Fi system security since two distinct technologies are being used to transmit the data.



Figure 2.9: Hybrid Li-Fi/Wi-Fi system.

Physical Layer Security:

Over the past ten years, physical-layer security has emerged as a practical tool to support conventional encryption techniques and act as a first line of defense against eavesdropping attempts at the underlying physical layer. Physical-layer security techniques, as opposed to encryption, employ deftly constructed signaling and/or coding methods to exploit the characteristics of the channel in order to hide information from unauthorized recipients at the price of slower communication speeds.

Encryption in the physical layer of Li-Fi technology is now under investigation. There are many different methods for protecting data that is being transmitted, but they all aim to leverage the physical properties of light signals to protect data while it is being transferred. Furthermore, because of the increased security, eavesdroppers can hardly intercept and decrypt data encrypted at the Li-Fi physical layer. The advantages of physical layer encryption include increased security, enhanced resilience, and the possibility of new applications.

The encryption embedded in the physical layer of the Li-Fi technology is difficult to forge and increases security because it depends on the features of the channel. Because encryption protects Li-Fi technology from noise and interference, it is more dependable when employed in the physical layer. Li-Fi technology's physical layer encryption may open up new uses, such as safe communication in delicate settings. However, there are still a number of issues that arise when encryption is used in the Li-Fi technology's physical layer. The following are the difficulties [15]:

- **Performance** **attenuation:** the attenuation of performance can be attributed to the possibility that the encryption will increase signal overhead and decrease data rate.
- **Intricacy:** the encryption in the physical layer of Li-Fi technology requires it be tailored to the specific physical characteristics of light signals.
- **The absence of standardization:** this might hinder the widespread adoption of Li-Fi technology.

In conclusion, each layer of Li-Fi technology has advantages and disadvantages when it comes to encryption. The majority of the aforementioned issues are still unresolved and require more research in order to maximize Li-Fi technology.

2.4.2 Threats and Vulnerabilities in Li-Fi Networks

Accidental association

There are several ways and purposes because someone could get unauthorized access to a company's wired and wireless networks. The term "accidental association" refers to one of these techniques. If a user's computer comes on and connects to a wireless access point from a nearby company's overlapping network, they might not even be aware that it has done so. It is a security breach, though, since confidential firm data is made public and there may now be a connection between two businesses. If the laptop is also connected to a wired network, this is particularly true [54].

Malicious association

When crackers purposefully create wireless devices to connect to a company network via their compromised laptop rather than a company access point (AP), this is known as "malicious associations." These laptops, referred to as "soft APs," are produced when a hacker installs software that disguises their wireless network card as a genuine access point. After gaining access, the cracker can plant trojans, initiate wired network attacks, or collect passwords. Layer 3 security measures like network authentication and virtual private networks (VPNs) provide no defense because wireless networks function at the Layer 2 level. Although they aid in security, wireless 802.1x authentications are still susceptible to hacking. The goal of this kind of assault might not be to compromise a VPN or other security protocols. The cracker is probably merely attempting to gain control of the client at the Layer 2 level [54].

Ad-hoc networks

Ad-hoc networks may present a risk to security. Peer-to-peer networks between wireless computers without an access point between them are known as ad-hoc networks. Although these networks are typically not very secure, security can be added by using encryption techniques [54].

Non-traditional networks

Non-traditional networks, including Bluetooth personal networks, are vulnerable to hacking and should be considered a security risk. Wireless printers and copiers, handheld PDAs, and barcode readers should all be secured. IT professionals who have only concentrated on laptops and access points may easily ignore these atypical networks [54].

Identity theft (MAC spoofing)

When a cracker can listen in on network traffic and determine the MAC address of a computer with network privileges, identity theft (also known as MAC spoofing) takes place. The majority of wireless networks provide MAC filtering in some form,

which restricts network access to authorized machines with particular MAC IDs. Nonetheless, there are some programs with the ability to "sniff" networks. The cracker can easily overcome that obstacle if they combine these programs with other software that enables a machine to pretend to have any MAC address they want [54].

Man-in-the-middle attacks

Computers configured as soft access points (APs) are lured into logging in by a man-in-the-middle attacker. After completing this, the hacker uses a second wireless card to connect to a legitimate access point, ensuring a constant flow of traffic from the hacking PC to the actual network. After that, the hacker can sniff the traffic [54].

In order to carry out a "de-authentication attack," one kind of man-in-the-middle attack depends on security flaws in challenge and handshake protocols. Computers connected to the AP are compelled by this assault to disconnect and re-connect to the cracker's soft AP. Software like LANjack and AirJack, which automates several phases of the process, improves man-in-the-middle attacks. Script kids can now do things that once required some talent. Due to the lack of security on these networks, hotspots are especially susceptible to attacks [54].

Denial of service

When an attacker persistently floods a targeted network or access point (AP) with false requests, failure messages, premature successful connection messages, and/or other orders, it's known as a denial-of-service attack (DoS). These prevent authorized users from connecting to the network and may potentially result in network failure. The use of protocols like the Extensible Authentication Protocol (EAP) is the foundation of these attacks [54].

Network injection

Access points exposed to unfiltered network traffic, particularly broadcasting network traffic like "Spanning Tree" (802.1D), OSPF, RIP, and HSRP, can be used by a cracker in a network injection attack. The cracker affects routers, switches, and intelligent hubs by injecting fake network configuration commands. This can bring down an entire network, necessitating a reboot or even reprogramming of every intelligent networking device [54].

Caffe Latte attack

WEP can also be defeated with the Caffe Latte attack. Using this exploit does not require the attacker to be in the vicinity of the network. It is feasible to get the WEP key from a distant client by employing a procedure that targets the Windows wireless stack. The attacker exploits 802.11 WEP's message modification vulnerabilities and shared key authentication by issuing a barrage of encrypted ARP requests. In less than six minutes, the attacker obtains the WEP key by using the ARP answers.

Eavesdropping

Unauthorized access to data in transit between devices is possible through an eavesdropping attack, which takes advantage of unprotected networks. By interfering with wireless communications systems, attackers can obtain private information such as emails, passwords, and personal information. Furthermore, after establishing a network breach, hackers can also remove or alter network data.

Jamming Attacks

Attacks known as jamming occur when malevolent nodes purposefully disrupt networks in order to prevent legitimate transmission. The goal of the jammer is to target OWC systems to stop legal communications by introducing optical noise and continuous signals that obstruct the receiver side of the signal. For instance, the OWC system cannot function and receive the data if the jammer knows the location of the receiver and transmits optical signals to the receiver in an attempt to disrupt or block the optical signals coming from the transmitter accurately.

2.4.3 Securing Wireless Networks

Use of Encryption

To protect wireless networks from unauthorized access and data breaches, encryption plays a crucial role. Encryption converts data into a coded format, making it unreadable to anyone who doesn't have the correct decryption key.

Turn off identifier broadcasting

Identification broadcasting is a feature found in the majority of wireless routers. It announces its presence by sending a signal to any nearby devices. If the network user is already aware of this information, there's no need to broadcast it. Hackers can target susceptible wireless networks by using identification broadcasting. Identifier broadcasting can be disabled if your wireless router permits it [54].

Change the identifier on your router from the default

The identifier for your router is likely to be a standard, default ID assigned by the manufacturer to all hardware of that model. Even if your router is not broadcasting its identifier to the world, hackers know the default IDs and can use them to try to access your network. Change your identifier to something only you know, and remember to configure the same unique ID into your wireless router and your computers so they can communicate. Use a password that's at least 10 characters long: The longer your password, the harder it is for hackers to break [54].

Change your router's pre-set password for administration

Your wireless router's manufacturer most likely provided a default password that you can use to configure and control the device. Change it to a password that only

you know because hackers are aware of these default ones. The difficulty of cracking a password increases with its length [54].

Allow only specific computers to access your wireless network

A distinct Media Access Control (MAC) address is given to each computer that can connect to a network. Typically, wireless routers have a feature that restricts

network access to devices with specific MAC addresses. A few hackers have MAC addresses that are replicated, so don't depend just on this stage. Turn off your wireless network when you know you won't use it

Hackers cannot access a wireless router when it is shutdown. If you turn the router off when you're not using it, you limit the amount of time that it is susceptible to a hack [54].

2.4.4 Data Integrity Mechanisms

To guarantee data integrity and reliability, error detection and correction are essential in data transmission. A variety of methods are used to find and fix problems that could be caused by noise, interference, or other communication channel impairments [56].

- **Parity check (single and two-dimensional):** To make the total number of 1s in a collection of data bits either even (even parity) or odd (odd parity), a parity bit (either 0 or 1) is added. An odd number of bit mistakes can be detected by it.
- **Checksum:** The data is separated into equal parts of n bits using this procedure. Binary addition is used to combine these segments, and the sum is complemented before being transmitted with the data. A checksum of 0 indicates that the data is error-free.
- **Cyclic redundancy check (CRC):** CRC uses a fixed binary divisor to divide the binary representation of the data polynomially. The remaining amount is the CRC code that is appended to the information. The data is assumed to be accurate if the receiver divides it by the same divisor and there is no residue.
- **Automatic repeat request (ARQ):** When errors are detected using one of the detection methods, the ARQ protocol is used to request the sender to retransmit the data.
- **Forward error correction (FEC):** This entails encrypting the data so that errors can be found and fixed by the recipient without requiring retransmission.
- **Convolutional codes:** These are employed in FEC, where the encoder creates output bits that are functions of the current and previous input bits after processing the input data in a streaming fashion.

2.4.5 Future Trends in Li-Fi Security

Researchers are constantly working to develop wireless networks that provide users with faster and more secure data transport. Over the last ten years, Li-Fi technology has advanced quickly to become a practical source of high-bandwidth internet. In the upcoming years, the following major trends will influence Li-Fi security [57]:

- **Advanced Encryption:** In order to better safeguard network users, end-to-end encryption mechanisms are always being improved. The deployment of improved network security protocols will go more smoothly with the combination of AI-driven encryption techniques and quantum cryptography. System-specific security algorithms that can instantly adjust to cybersecurity threats can be created using machine learning technology.

- **Securing networks with stricter authentication methods:**

Improved internet user security can result from integrating strong authentication methods into already-existing Li-Fi networks. Strong passwords, biometrics, and fingerprint recognition are examples of authentication techniques that can be used in conjunction with Li-Fi technology's built-in security capabilities. Additionally, researchers have mentioned ambitions to leverage blockchain technology for user log maintenance and network access management.

- **Integration with IoT Security:**

For tech-savvy internet users, the growth of IoT ushers in a new era of connectivity. However, as IoT networks grow more susceptible to cybercrimes, improved connectivity and communication come with increased security requirements. A network system's privacy depends on the network security provided by Li-Fi technology as it is used to link IoT devices. The development of integrated security solutions that lower the risk of data breaches in Li-Fi-backed IoT devices must therefore be a top priority for manufacturers.

2.5 Real-world Applications and Future Trends

2.5.1 Integration in the Healthcare and Industry 4.0

Li-Fi in Healthcare:

- **Secure Data Transmission:** Li-Fi ensures high security for sensitive patient data, reducing risks of cyberattacks. [58]
- **Interference-Free Communication:** Unlike Wi-Fi, Li-Fi does not interfere with medical equipment, making it ideal for hospitals and surgical rooms [58].
- **Real-Time Monitoring:** Li-Fi-enabled IoT devices can track patient vitals and transmit data instantly to healthcare providers [58].
- **Enhanced Connectivity:** Hospitals can use Li-Fi for seamless communication between medical staff, improving efficiency [58].

Li-Fi in Industry 4.0:

- **Ultra-Fast Data Transfer:** Li-Fi enables high-speed communication between smart machines, improving automation [59].
- **Reliable Factory Networks:** It eliminates RF interference issues in industrial environments, ensuring stable connections [59].
- **Improved Security:** Since Li-Fi signals are confined to lighted areas, data transmission is more secure than traditional wireless networks [59].

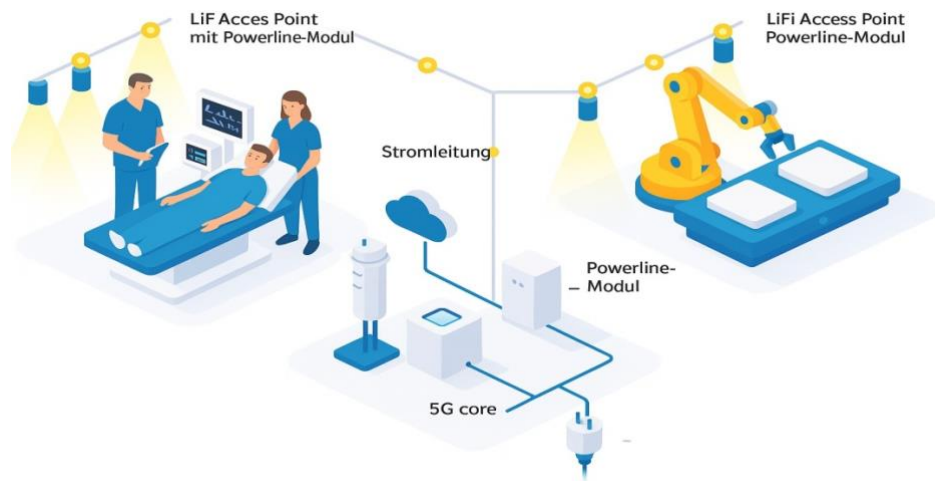


Figure 2.10: Enhancing Healthcare Connectivity Through Li-Fi Integration

- **Optimized Manufacturing:** Li-Fi enhances real-time data exchange in smart factories, boosting productivity [59].

2.5.2 Potential for Underwater communication and space Exploration

Underwater Communication:

Underwater communication is essential for marine research, security, and environmental monitoring. However, traditional communication methods face challenges due to water's physical properties.

Core Technologies:

- **Acoustic Communication:** Uses sound waves to transmit data underwater. It is widely used but has limitations like low data rates and signal attenuation.
- **Optical Communication:** Uses light waves for high-speed data transmission. It offers faster communication but is affected by water clarity.
- **Quantum Communication:** A developing field that aims to provide secure underwater data transmission using quantum principles.

- **Internet of Underwater Things (IoUT):** A network of underwater sensors and devices that communicate in real time for research and industrial applications.

Applications:

- **Marine Exploration:** Help scientists study ocean ecosystems and underwater life.
- **Environmental Monitoring:** Track pollution levels and climate changes in oceans.
- **Defense & Security:** Used in submarine communication and underwater surveillance.
- **Offshore Industries:** Support oil and gas exploration and underwater infrastructure maintenance.

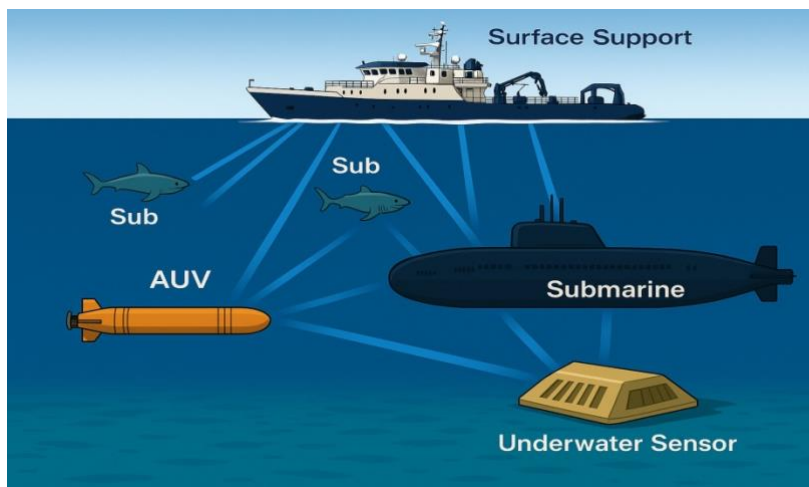


Figure 2.11: Underwater Optical Wireless Communication Using Li-Fi Technology.

Space Exploration:

Space exploration is advancing rapidly with AI, IoT, and quantum communication playing crucial roles.

Core Technologies:

- **Autonomous Spacecraft:** AI-powered spacecraft that navigate and make decisions without human intervention.
- **Quantum Communication:** Enables secure data transmission across vast distances in space.
- **Interplanetary Internet:** A communication network designed to connect Earth, satellites, and future Mars missions.
- **Advanced Robotics:** Used for deep-space exploration, allowing probes to analyze distant planets and moons.

Applications:

- **Planetary Exploration:** Helps scientists study Mars, the Moon, and other celestial bodies.
- **Satellite Communication:** Enhances global connectivity and space-based research.
- **Astrobiology:** Investigates the possibility of life beyond Earth.
- **Space Colonization:** Supports future human settlements on Mars and beyond.

2.5.3 Development Of Li-Fi 6G and Beyond:

The development of Li-Fi in 6G and beyond is shaping the future of ultra-fast, secure, and energy-efficient wireless communication. Li-Fi, which uses visible light for data transmission, is expected to play a crucial role in next-generation networks, complementing traditional radio frequency (RF) technologies.

1.4.1 Major Advancements in Li-Fi for 6G:

- **Higher Data Speeds:**
 - Li-Fi in 6G aims to achieve terabit-per-second (Tbps) speeds, surpassing current 5G capabilities.
 - The International Telecommunication Union (ITU) has set minimum 6G requirements, including 1 Tbps peak data rates.
- **Integration with AI & IoT:**
 - Li-Fi will support AI-driven networks and massive IoT connectivity, enabling smart cities, autonomous vehicles, and industrial automation.
 - Reconfigurable Intelligent Surfaces (RIS) will enhance Li-Fi signal propagation, overcoming line-of-sight limitations.
- **Ultra-Low Latency & High Reliability:**
 - 6G networks aim for microsecond latency, which is 1000 times lower than current wireless standards.
 - Li-Fi's secure and interference-free nature makes it ideal for mission-critical applications like healthcare and defense.
- **Energy-Efficient & Sustainable Communication:**
 - Li-Fi reduces electromagnetic pollution and offers green communication solutions.
 - Future hybrid Li-Fi/RF networks will optimize energy consumption while maintaining high-speed connectivity.

Challenges & Future Research:

- **Standardization & Global Adoption:** Li-Fi needs industry-wide standards for seamless integration into 6G.

- **Infrastructure Development:** Upgrading LED-based communications systems for wide-spread Li-Fi deployment.
- **Security Enhancements:** Strengthening data encryption and network security for Li-Fi-enabled 6G applications.

2.6 Conclusion

This chapter has provided an in-depth exploration of the fundamental and advanced concepts that define Li-Fi and its role within the broader context of Optical Wireless Communication (OWC). Beginning with an overview of the electromagnetic spectrum and the use of light as a transmission medium, we examined how Li-Fi leverages visible light to enable high-speed, secure, and efficient data transfer. The components of a Li-Fi system, including LEDs, photodetectors, and modulation techniques such as OOK, PAM, and OFDM, were discussed to highlight the technical foundation that makes Li-Fi a viable wireless communication technology.

The chapter also delved into multiple access techniques and signal processing methods, which are critical for ensuring efficient communication in multi-user environments. The limitations of Li-Fi, such as its reliance on line-of-sight and sensitivity to ambient light, were acknowledged along with proposed solutions to overcome these challenges.

Moving beyond the basics, we explored advanced concepts such as the integration of Li-Fi with IoT and smart devices, the potential of hybrid Li-Fi/Wi-Fi networks, and the role of artificial intelligence in optimizing Li-Fi systems. Issues related to energy efficiency and the challenges of scaling Li-Fi for widespread use were also addressed.

A significant portion of the chapter was dedicated to the security and integrity of data in Li-Fi networks. We covered inherent security features, potential threats and vulnerabilities, and the implementation of encryption methods like AES, RSA, and QKD. Data integrity mechanisms and future directions in Li-Fi cybersecurity were also discussed, emphasizing the technology's capacity for secure communication.

Finally, we looked at real-world applications across healthcare, Industry 4.0, underwater communication, and space exploration, and considered how Li-Fi is paving the way for 6G and future communication paradigms.

In summary, this chapter reestablishes Li-Fi as a promising next-generation wireless communications solution, offering not only high-speed data transfer but also secure and versatile applications across a wide range of fields.

Chapter3

DesignandImplementationofa Li-FiSystem

3.1 Introduction

This chapter presents a practical Li-Fi application that transmits audio from a PC or smartphone to a speaker using visible light. The system uses a high-brightness LED to modulate the audio signal, along with a photodetector coupled with an LM386 amplifier to receive and play the sound. Unlike traditional wireless methods, this setup offers a simple, low-cost, and interference-free approach to transmitting audio without relying on radio waves. The objective is to demonstrate how Li-Fi can be used for real-time analog audio communication, particularly in environments where electromagnetic noise is a concern.

3.2 System Overview

I. Block diagram of the full system:

The block diagram illustrates the complete signal path of the Li-Fi audio transmission system. It begins with an audio source (such as a PC or smartphone), which sends an analog signal to the modulation circuit. This circuit drives a high-power LED, converting the electrical signal into modulated light. The light travels through open space and is captured by a photodiode, which converts it back into an electrical signal. This weak signal is then amplified using an LM386 amplifier, and finally played through a speaker, reproducing the original sound wirelessly using only light as the medium.

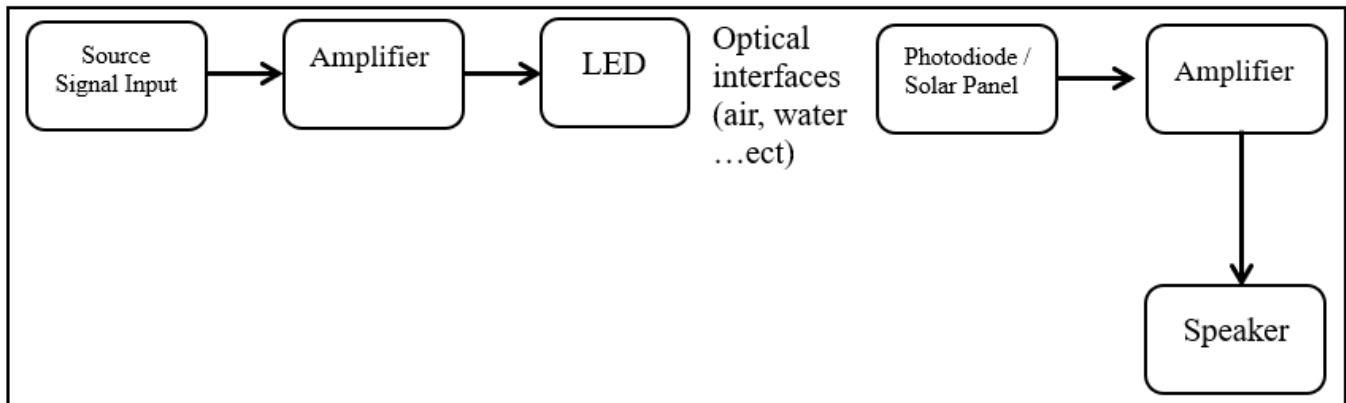


Figure 3.1: Block diagram of the full Li-Fi system.

II. Signal Flow Description

The audio Li-Fi system developed in this project follows a simple yet effective signal pathway, allowing real-time transmission of analog sound through visible light. This section outlines the key steps involved in the signal flow, from the audio source to the final sound output through the speaker.

A. Audio Signal Input (PC/Smartphone Source)

The process begins with an analog audio signal generated by a PC or smartphone, typically via a 3.5mm headphone jack. This signal carries the electrical representation of sound, which varies in voltage according to the amplitude and frequency of the audio.

B. Modulation and LED Transmission (Transmitter)

The audio signal is passed through a coupling capacitor to remove any DC component, then fed into a circuit that drives a high-power white LED. As the signal varies, it modulates the intensity of the LED light, brighter when the signal is high, dimmer when it's low. This is known as analog intensity modulation. The LED thus converts the electrical signal into a rapidly varying beam of light that reflects the original audio waveform.

C. Free-Space Optical Channel The modulated light is transmitted through free space from the LED to a photodetector. Since the transmission uses visible light, it requires a clear line of sight and is susceptible to interference from ambient light sources, distance, and obstacles in the path.

D. Reception and Signal Conversion (Photodetector)

At the receiver, a photodiode or phototransistor detects the incoming modulated light. It converts the fluctuating light signal back into a small electrical current or voltage, which represents the original audio waveform. However, this signal is too weak to drive a speaker directly.

E. Amplification and Audio Output The weak electrical signal from the photodetector is routed into an LM386 low-voltage audio amplifier circuit. This stage boosts the signal to a sufficient level to drive an 8-ohm speaker, allowing the original audio to be played clearly. The speaker emits the sound in real-time, completing the transmission chain from PC or phone to audio output using only light as the transmission medium.

3.3 Components and Materials Used

- LEDs

The primary optical transmitter in a Li-Fi system is the LED. It transforms electrical signals into visible light, the intensity of which changes according to the signal's amplitude. These changes are analogous to sound waves in audio transmission and to binary states in digital applications. Because of their luminous efficiency, quick response time, and adequate optical power, high-brightness LEDs are preferred for improved reception over longer distances and in the presence of ambient light interference. In analog modulation, their linear response range is also crucial for preserving signal integrity.

Why Chosen:

- Fast switching responses suitable for audio-frequency modulation.
- Bright and easily detectable by photodetectors.
- Cheap, accessible, and easy to integrate into circuits

– **Photodiode or Phototransistor**

In Li-Fi systems, these light-sensitive semiconductor chips serve as optical receivers. Changes in light intensity are detected by a photodiode or phototransistor, which then transforms them into tiny electrical signals. These signals reflect the audio waveform modulated onto the LED in an audio-based Li-Fi. Solar cells offer the benefit of having a greater surface area and can also be utilized for low-speed communication. Sensitivity, response speed, and gain requirements all influence the decision. To convert the optical signal back into an electrical form that may be amplified, played back, or decoded, photodetectors are necessary.

Why Chosen:

- Sensitive to rapid changes in light intensity.
- Converts optical variations into corresponding voltage or current.
- Small, affordable, and highly responsive to visible light.

– **LM386 Audio Amplifier IC**

Low-voltage audio power amplifiers like the LM386 are made for consumer-grade audio equipment. It is employed in the receiver unit of Li-Fi applications to boost weak electrical signals produced by the photodiode or phototransistor. These signals, which are too faint to directly drive a speaker, are the demodulated form of the transmitted light.

The LM386 is perfect for portable Li-Fi systems since it has enough gain and runs well with few extra components. It guarantees that the listener hears an accurate and real-time reproduction of the original input while maintaining audio integrity.

Why Chosen:

- Specifically designed for low-voltage audio amplification (ideal for 9V systems).
- Simple to use, with adjustable gain.
- Popular in audio circuits and available with minimal external components.

– **Operational Amplifier UA741**

Analog signal amplification is accomplished with the UA741, a general-purpose operational amplifier. The audio signal from a computer or smartphone is first amplified in the Li-Fi transmitter before being sent to the LED. To successfully adjust the LED's intensity in rhythm with the incoming audio, a clear, powerful signal is required. Accurate analog transmission over visible light requires fine-tuning, which is made possible by the 741's feedback and gain control capabilities. This element improves overall communication quality by guaranteeing signal strength without distortion.

Why Chosen:

- Boosts the audio signal before it drives the LED
- Operates with single-supply voltages and supports feedback for gain control.

– **Transistors**

The BC548 is a low-power, general-purpose NPN transistor that can be used as an amplifier or switch. It is used in Li-Fi circuits to increase the op-amp's signal so that the LED is driven. The transistor functions as a current amplifier because op-amps are unable to deliver high current. It guarantees that the LED gets enough current to produce light that is intense enough to be successfully noticed on the receiving end. This element is essential for bridging the gap between light emission and signal conditioning.

Why Chosen:

- Amplifies the current output from the op-amp to drive the LEDs safely.

– **Capacitors**

In a Li-Fi system, capacitors (passive energy storage components) have several functions. They function as coupling capacitors in transmitter circuits, blocking DC voltage while permitting AC (audio or data signals) to flow through and regulate the LED. This guarantees that light output is solely impacted by the signal's dynamic portion, or the information that is valuable. Capacitors are also employed for filtering in receiver circuits; they reduce noise and power line voltage swings, enhancing the demodulated signal's stability and clarity. In order to maintain signal fidelity during text and audio transmission, capacitor values are carefully selected depending on frequency response.

Why Chosen:

- Blocks DC and allows AC signal to pass.
- Smooths out voltage and prevents signal distortion.
- Essential in amplifier and audio stages.

– **Resistors**

Resistors are crucial passive parts that precisely block the passage of electrical current. Resistors are employed in Li-Fi to regulate the current passing through the LED, which is essential for preserving a steady and secure optical output. Signal integrity may be jeopardized by excessive currents since it can harm the LED or alter the linearity of modulation. Resistors are employed in voltage divider setups and feedback loops to regulate gain and input impedance in amplifier circuits (like the LM386 or op-amp based designs). This has a direct effect on the system's accuracy in amplifying signals from the photodetector, which can alter the receiver end's sound or data clarity.

Why Chosen:

- Protect LEDs and set gain levels in LM386
- Control biasing and signal strength in the circuit.
- Provide stability and safety.

– **Potentiometer (Variable Resistor)**

A three-terminal resistor with a sliding or revolving contact that modifies resistance is called a potentiometer. Its main function in Li-Fi systems is to tune the strength of the modulation signal transmitted to the LED by varying the gain of an op-amp or preamplifier stage. This ensures appropriate light modulation without distortion or signal clipping by assisting in adapting the transmitter circuit to varying input signal levels from PCs or cell phones. For analog Li-Fi to preserve signal integrity over a range of transmission lengths, precise gain control is essential.

Why Chosen:

- Allows fine-tuning of op-amp gain in the modulation stage.
- Offers adaptability for different input signal strengths.

– **Power Supply**

The electrical energy required to run all of the active parts in the transmitter and reception units is supplied by the power supply. Analog circuits like the LM386 audio amplifier and the 741 op-amp are frequently powered by a 9V battery, whereas Arduino microcontrollers and digital logic components require a regulated 5V source. To prevent distortion in the broadcast or received signal, the power source needs to be steady and noise-free. Maintaining signal fidelity across optical channels in Li-Fi systems requires consistent light modulation and amplification quality, which can only be achieved with clean and adequate power.

– **Why Chosen:**

- 9V matches LM386 requirements.
- Portable and safe for low-power applications.
- Simplifies field testing.

– **Jumper Wires/ Connectors**

Electrical connections between modules, such as Arduino boards, LEDs, and sensors, or between components on breadboards can be made flexible and modular with jumper wires. Jumper wires make testing easier and enable simple circuit configuration changes in Li-Fi prototypes. Reliable connection between discrete components is further supported by connectors and sockets. Their application facilitates quick troubleshooting and updates, improves circuit clarity, and lowers the amount of soldering needed during development. They are especially crucial for maintaining continuity and reducing connection-related mistakes while verifying signal integrity during the transmission and receiving phases.

Why Chosen:

- Flexible and easy to use for modular setup.
- Helps build neat and organized circuits.
- Compatible with breadboards and PCBs.

– **solar panel (6 volt)**

is a device that converts sunlight into electricity using photovoltaic (PV) cells.

3.4 Transmitter Design

• First Circuit

This circuit is a basic design to send an audio signal through visible light using an LED. It consists of a 9V battery, a current-limiting resistor (360 ohms), an LED, and an audio input source. The audio input (such as from a phone or MP3 player) is connected directly to the circuit, allowing the audio signal to modulate the LED. As the audio signal fluctuates, it causes variations in the current flowing through the LED, which in turn changes the intensity of the light emitted. These rapid changes in brightness, although not visible to the human eye, carry the audio information through light.

The resistor in the circuit serves to limit the current flowing through the LED to prevent it from burning out. The battery provides the necessary bias voltage to power the LED. When an audio signal is present, the LED's light intensity varies accordingly, effectively encoding the audio onto the light beam.

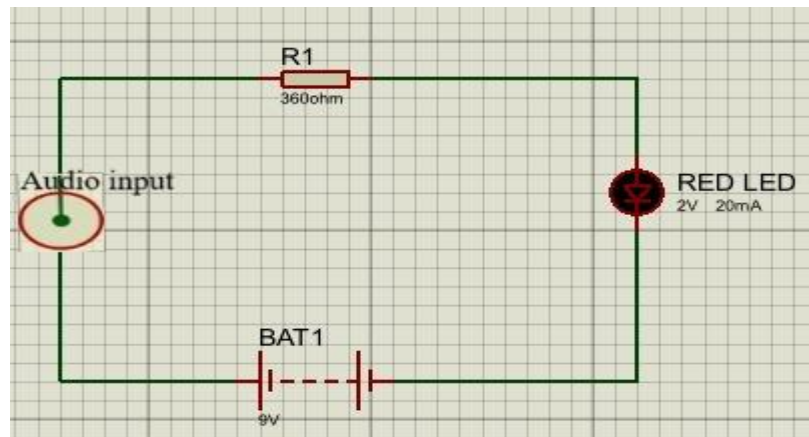
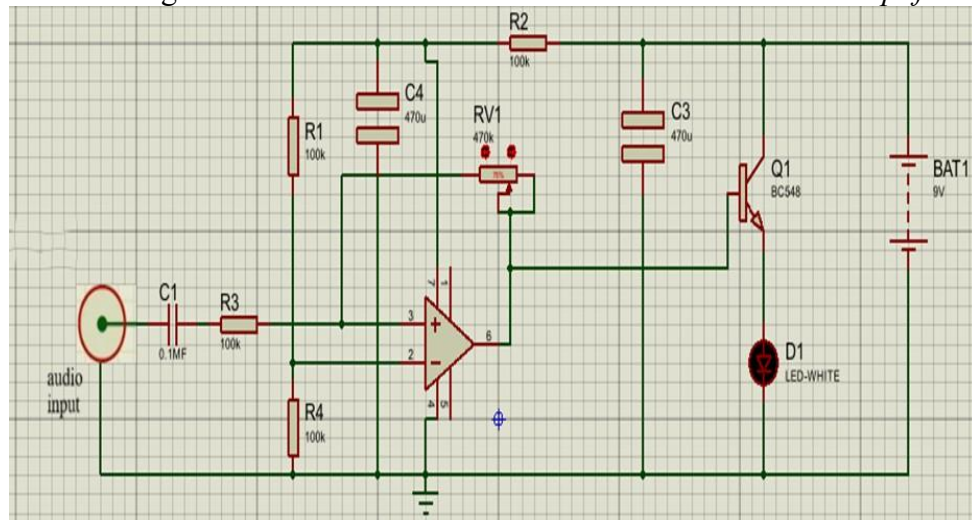


Figure 3.2: Li-Fi audio transmitter circuit

Second Circuit

This updated Li-Fi audio transmitter circuit is designed to wirelessly transmit audio signals using light. It uses an LM741 op-amp to amplify audio from a device like a phone, with input filtered through a 0.1MF capacitor (C1) to block DC components and pass only the audio signal. The gain is controlled by a feedback network consisting of 100k resistors (R1, R4) and a 470k variable resistor (RV1), allowing adjustment of the amplification level. The amplified signal is then passed through C3 (470μF) to the base of a BC548 transistor (Q1), which serves as a current amplifier. This transistor drives a white LED (D1), whose brightness modulates in response to the audio signal. The varying light intensity carries the audio information. A 9V battery powers the entire circuit, and capacitors C3 and C4 help maintain voltage stability for smooth operation. This design provides a simple, cost-effective demonstration of Li-Fi (Light Fidelity) for audio transmission using visible light.

Figure 3.3: Li-Fi Audio Transmitter Circuit Based on LM741 Amplifier.



SignalflowDescription:

- **Audio Input:** An audio signal (e.g., from a phone or MP3 player) is fed into the circuit through the input terminal.
- **DC Blocking:** The audio signal passes through capacitor C1 (0.1µF), which blocks any DC component and allows only the AC (audio) signal to proceed.
- **Signal Amplification (Op-Amp Stage):** The filtered audio signal is fed into the non-inverting input of the LM741 operational amplifier. The amplifier boosts the signal strength based on the gain set by R1 (100k), R4 (100k), and RV1 (470k).
- **Coupling to Transistor:** The amplified signal from the op-amp's output is passed through capacitor C3 (470µF) to remove any DC offset and then sent to the base of the NPN transistor (Q1 - BC548).
- **Transistor Switching & Amplification:** The transistor Q1 operates in active mode, amplifying current to drive the LED. The signal at the base controls the current flowing from collector to emitter.
- **LED Modulation:** The white LED (D1), connected at the collector, emits light whose intensity varies in sync with the audio signal. This variation in brightness carries the encoded audio information as light.
- **Power Supply Stabilization:** The entire circuit is powered by a 9V battery (BAT1), while C4 (10 µF) helps filter and stabilize the supply voltage to ensure smooth operation.

Third Circuit

This Li-Fi transmitter circuit uses a high-power white LED to transform an analog audio stream into modulated visible light. The device uses intensity modulation, which allows the LED's brightness to change in proportion to the audio signal, to wirelessly transfer sound through light. This is a basic illustration of an analog optical communication that is perfect for illustrating the fundamental principle of Li-Fi in learning or prototyping settings.

practical

Step-by-Step Flow of Signal in a Li-Fi Audio Transmitter:

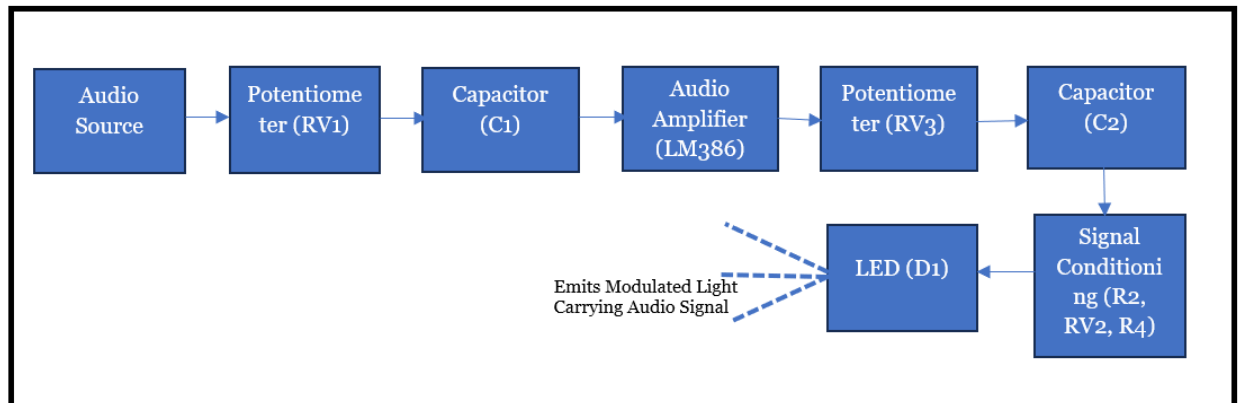


Figure 3.4: Block Diagram Li-Fi Audio Transmitter Circuit Base on LM386 Amplifier

Functional Roles of Li-Fi Audio Transmitter Elements:

- Audio Source (e.g., phone, microphone)
- Potentiometer (RV1): Volume Control
- Capacitor (C1): DC Block/Filter
- Audio Amplifier (LM386 - U2)
- Gain Control (RV3, C3, C4)
- Coupling Capacitor (C2)
- Signal Conditioning (R2, RV2, R4)
- High Brightness White LED (D1)

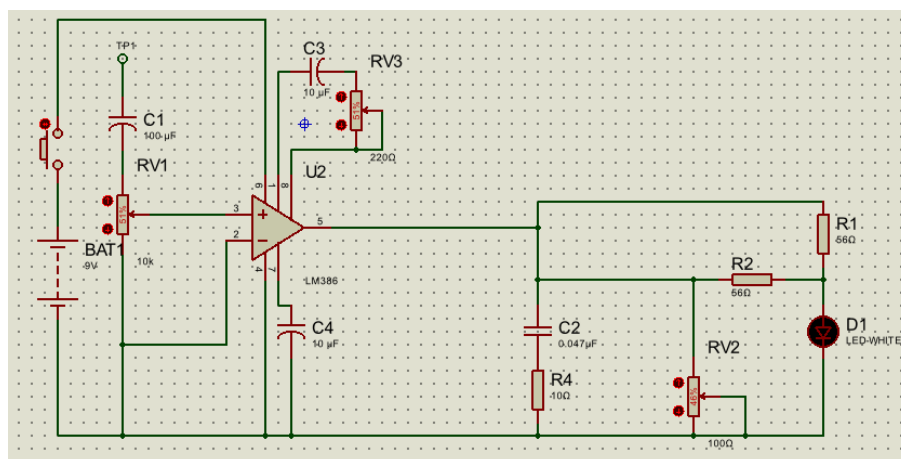


Figure 3.5: Li-Fi Audio Transmitter Circuit Based on LM386 Amplifier.

The circuit's central component is a low-voltage LM386 audio amplifier set up to run at high gain. The amplifier generates a clear, amplified output after receiving input via a 3.5mm jack from a conventional analog audio source, such as a computer or smartphone. The LED is then driven after this output has been filtered and shaped.

Signal Flow Description:

- **Input Signal Conditioning:**

A 100 μF coupling capacitor (C1) filters out any DC components in the audio signal before sending solely the AC (audio) portion to the amplifier. Before the signal reaches the amplifier, it is adjusted by a 10k variable resistor (RV1). To match the signal levels from different devices, this step is essential.

- **Amplification with LM386:** A 10 μF capacitor (C4) is positioned between pins 1 and 8 to enable the LM386 IC (U2) to operate in its maximum gain configuration (gain = 200). In order to drive the subsequent step, the amplifier boosts the loudness of the audio signal. This guarantees that the modulating signal is powerful enough to cause discernible changes in the LED's brightness.

- **Output Signal Shaping:** To smooth the signal and maintain waveform fidelity, the LM386's amplified output is sent through an RC low-pass filter (C2 = 0.047 μF , R4 = 100) to remove high-frequency noise or spikes. This additional potentiometer (RV2) enables manual control of the current flowing to the LED.

- **LED Driver and Optical Output:** Current-limiting resistors (R1, R2 = 56) are then used to send the filtered and conditioned signal to a white LED (D1). The light intensity changes (modulates) as a result of the current flowing through the LED changing in response to the waveform of the audio stream. The sound information is transmitted to a remote optical receiver (such as a photodiode or solar panel) via this modulated light beam traveling through free space.

- **Power Supply Configuration:** A 9V battery, a popular option for portable analog circuits, powers the circuit. Because the LM386 is designed to operate at low voltages, a 9V supply is adequate to provide reliable LED performance and strong amplification.

3.5 Receiver Design

First Circuit

This circuit represents a simple Li-Fi receiver designed to convert light signals back into sound using a solar panel and a speaker.

The main component of this receiver is the solar panel, which acts as a light sensor. When modulated light "such as that coming from an LED in a Li-Fi transmitter" strikes the solar panel, it generates a small, varying voltage depending on the intensity of the incoming light. In a Li-Fi system, this modulated light contains audio information (sound converted into light variations), and the solar panel's job is to capture these variations and convert them back into an electrical signal.

The electrical output from the solar panel is directly connected to a speaker. As the panel receives fluctuating light intensities (matching the audio waveform), it produces a corresponding fluctuating electrical signal. These variations drive the speaker diaphragm, which in turn reproduces the original audio signal.

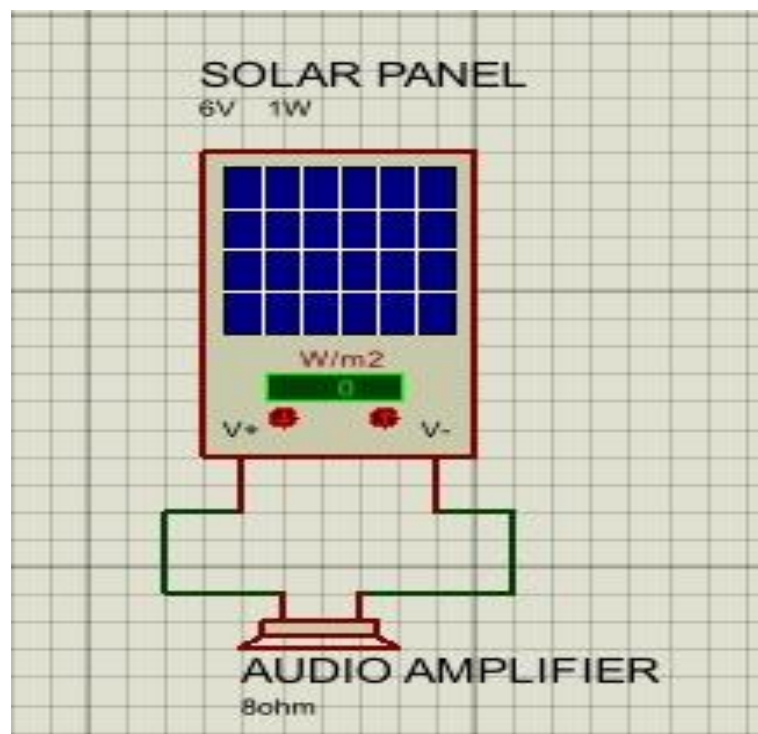


Figure 3.6: Li-Fi audio receiver circuit

Second Circuit

The Li-Fi audio receiver consists of several key components arranged to convert modulated light signals into sound. At the input stage, a photodiode detects the incoming light signals and generates corresponding electrical pulses. This signal is then refined using a variable resistor, which allows for manual adjustment of signal strength. The amplified section features a BC548 NPN transistor, responsible for boosting the weak electrical signals from the photodiode to a level suitable for driving an output device. The final stage includes an 8-ohm, 5-watt speaker, which translates the processed signals into audible sound. A power supply (VCC) ensures sufficient voltage for circuit operation, while a ground connection (GND) maintains circuit stability. The arrangement of these components creates a straightforward yet effective design for wireless audio transmission using light, demonstrating the potential of Li-Fi technology in practical applications.

Step-by-Step Flow of Signal in a Li-Fi Audio Receiver:

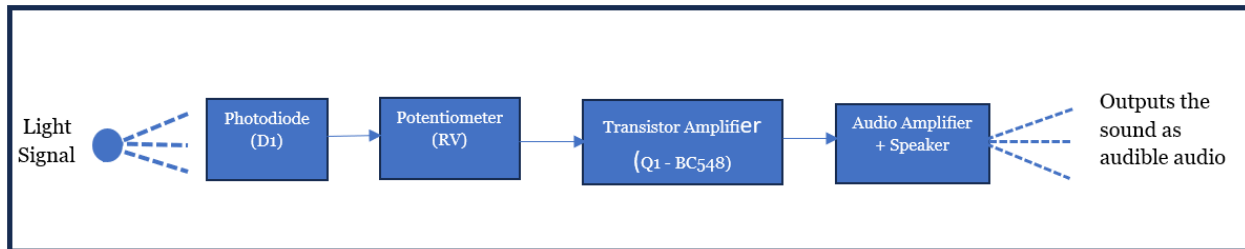


Figure 3.7: Block Diagram of a Li-Fi Audio Receiver circuit

Functional Roles of Li-Fi Audio receiver Elements:

- Photodiode (D1): Converts light to electrical signal
- Potentiometer (RV): Adjusts signal sensitivity
- Transistor Amplifier (Q1 - BC548): Amplifies the weak electrical signal
- Audio Amplifier + Speaker: Signal Boosting

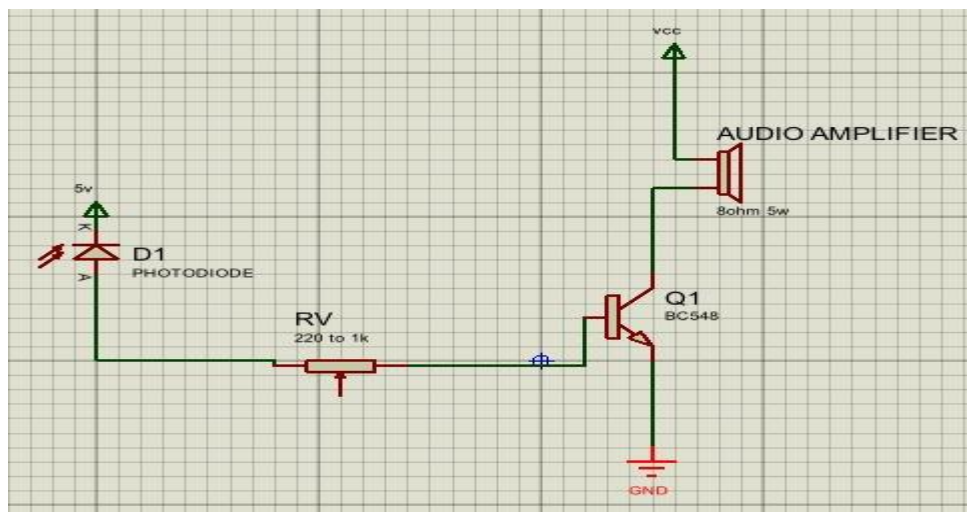


Figure 3.8: Li-Fi audio receiver circuit

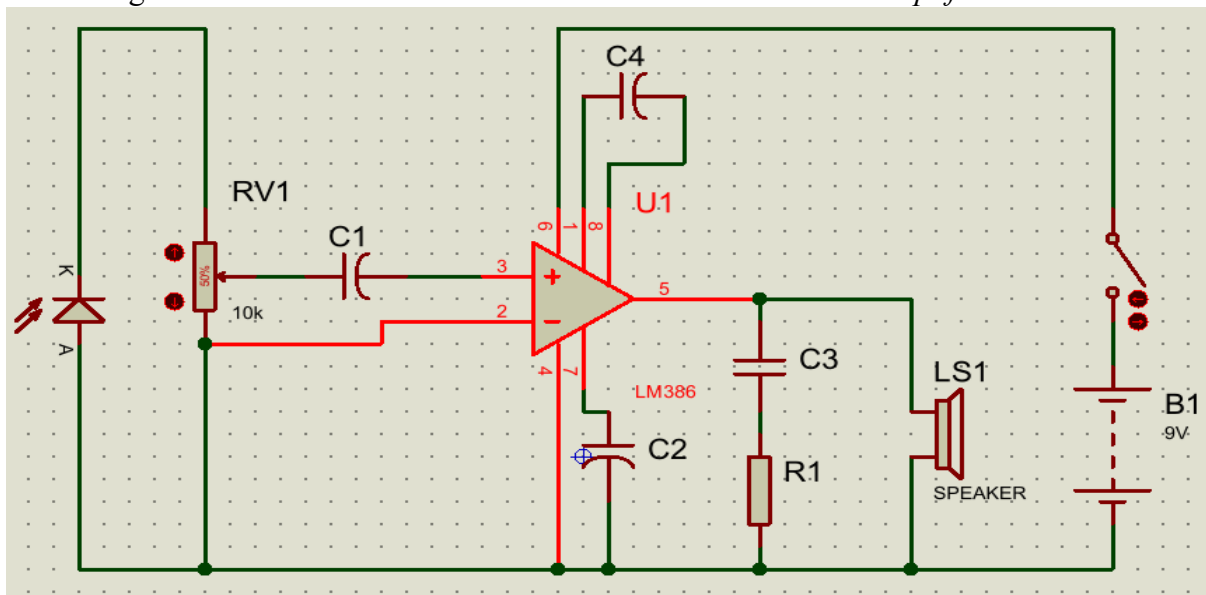
Signal flow:

1. **Light Signal Detection:** The photodiode captures modulated light signals.
2. **Signal Adjustment:** The variable resistor refines signal strength for stability.
3. **Signal Amplification:** The BC548 NPN transistor boosts the weak electrical signal.
4. **Audio Conversion:** The amplified signal is fed into the 8-ohm, 5-watt speaker.
5. **Power Management:** The power supply (VCC) ensures proper voltage distribution.
6. **Circuit Stability:** The ground (GND) maintains reliable operation.

Third Circuit

A photodiode is used in this Li-Fi receiver circuit to transform modulated light into a faint electrical signal. The LM386 audio amplifier greatly increases the signal after it goes through a potentiometer and coupling capacitor. The sensitivity of the amplifier is adjusted by a gain capacitor, and clean and steady signal flow is guaranteed by bypass and output capacitors. After that, a speaker receives the amplified audio to play it back. This circuit, which is powered by a 9V battery, successfully illustrates the fundamental idea of turning light-based audio signals into sound.

Figure 3.9: Photodiode-Based Li-Fi Receiver with LM386 Audio Amplifier.



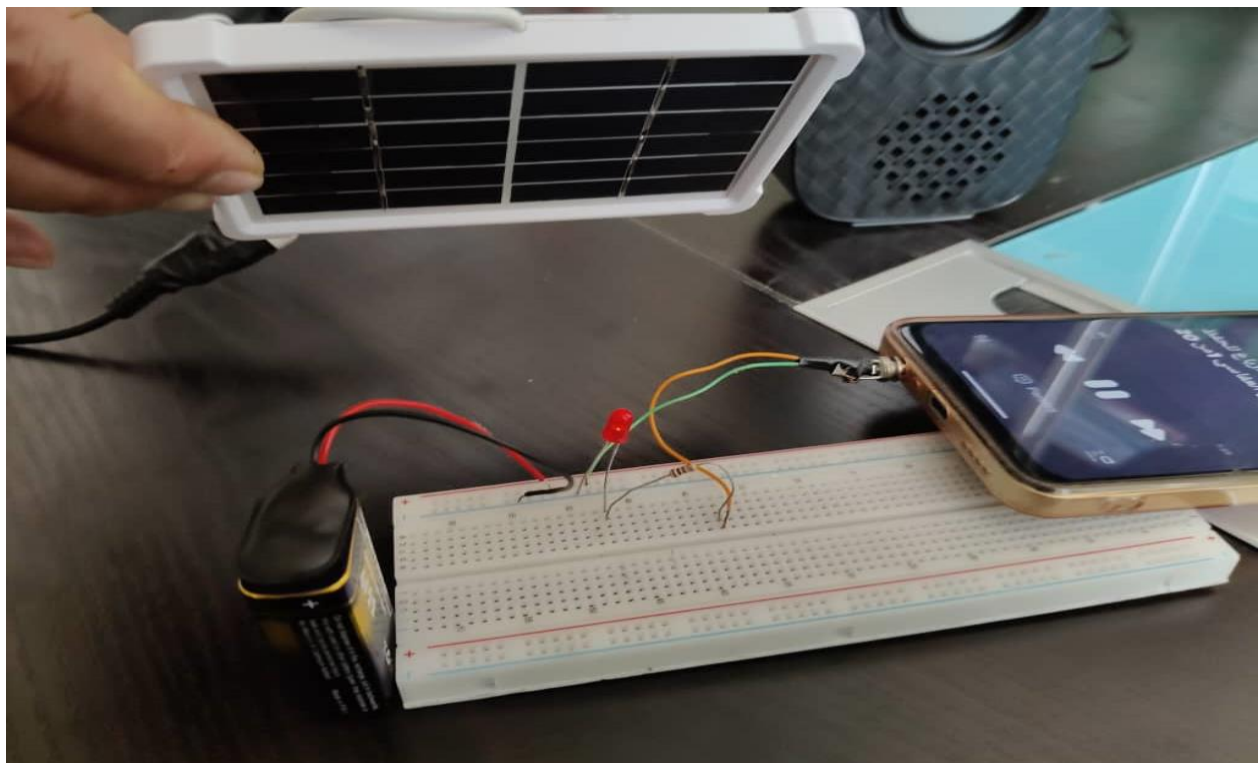
Signal Flow Description

The photodiode initially captures the modulated light carrying the audio signal and transforms the light fluctuations into a weak electrical signal. After adjusting the input level with a 10k potentiometer, this signal passes via a coupling capacitor to prevent any undesired DC. A capacitor between pins 1 and 8 sets the gain at which the conditioned signal is amplified after it enters the LM386 amplifier at its non-inverting input (pin 3). Before the signal reaches the speaker, which transforms it into sound, it is first run via an output capacitor to eliminate any DC components.

3.6 Practical Assembly of Li-Fi Audio Transmission System

This image (Fig 3.10) illustrates the physical implementation of a simple Li-Fi audio transmission system built for experimental validation. The setup consists of a red LED acting as the optical transmitter, a solar panel functioning as the light-based receiver, and basic passive components including a resistor to limit current. Audio signals are fed directly from a smartphone through a 3.5mm jack, modulating the LED light intensity. The solar panel captures this modulated light and converts it back into electrical signals. The circuit is powered by a 9V battery and assembled on a breadboard for ease of testing and adjustments. This minimalist configuration successfully demonstrated light-based audio transmission in a low-complexity environment, providing hands-on insight into the working principles of Li-Fi communication.

Figure 3.10: *Practical Implementation of a simple Li-Fi audio transmission system*



This image (Fig 3.11) shows the complete physical setup of a Li-Fi audio transmission system constructed and tested during our university project. The system includes both transmitter and receiver circuits assembled on a breadboard and a perforated PCB (stripboard), using components such as LEDs, an LM741 amplifier, potentiometers, capacitors, and jumper wires. A power adapter supplies the required voltage, and a speaker is connected for real-time audio output. The circuit was tested with actual audio input signals from a PC and showed reliable performance over short distances in controlled lighting environments. This setup helped validate the design through practical experimentation and real-world constraints.

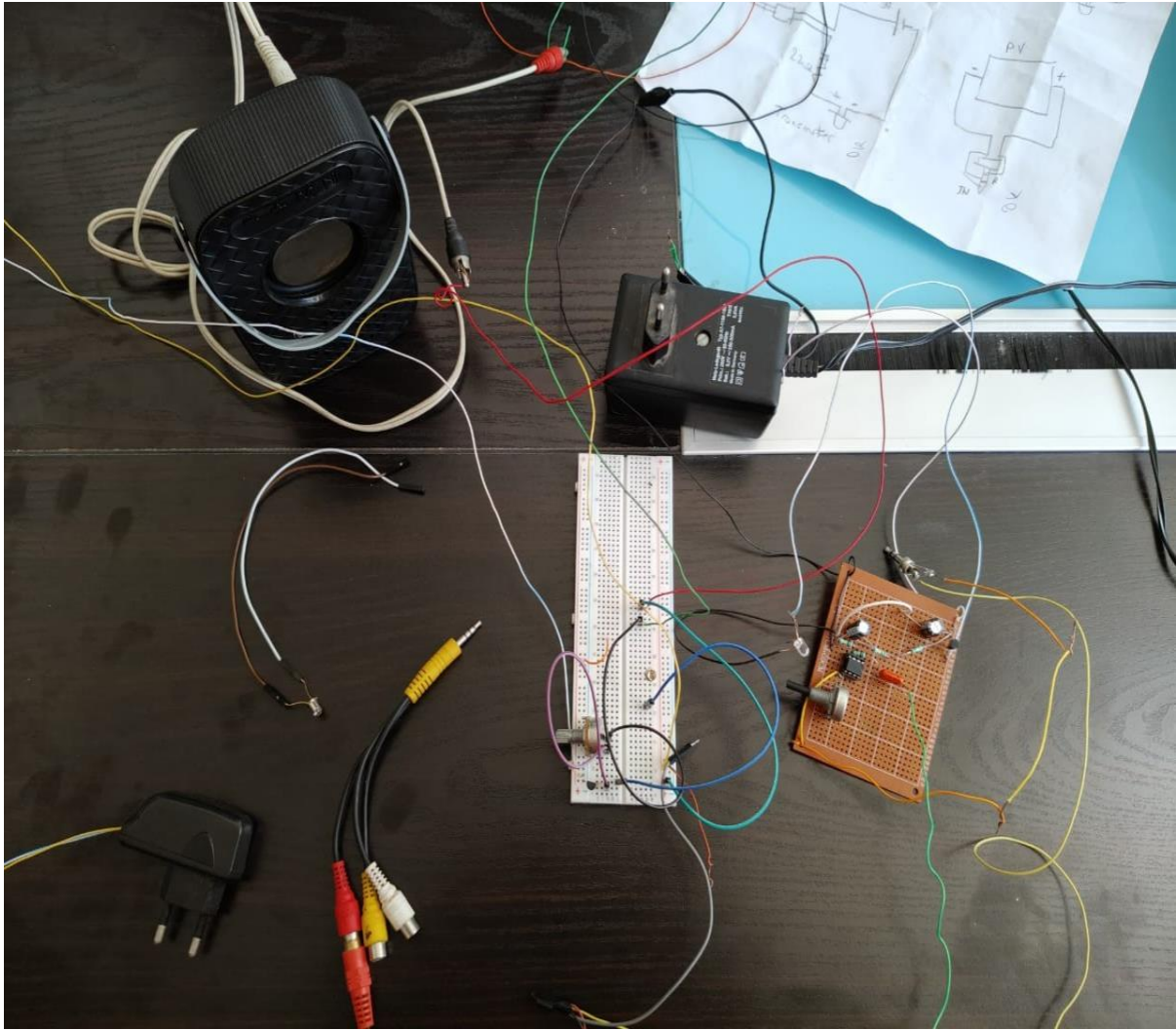


Figure 3.11: *Practical Implementation of a Li-Fi-Based Analog Audio Communication Circuit with LM741 Amplification*

This image (Fig 3.12) showcases the complete Li-Fi audio communications system prototype, featuring both transmitter and receiver circuits assembled on perforated PCBs. The setup utilizes high-intensity LEDs for transmitting audio signals and a solar panel as a photodetector at the receiver end. An LM386 amplifier is employed to boost the recovered signal, which is then output through a portable speaker. The system was powered using a 9V battery and successfully demonstrated analog audio transmission over visible light in real-time.



Figure 3.12: Complete Li-Fi Audio Communication System Using LM386 and Solar Panel.

This image (fig 3.13)& (fig 3.14) presents the complete physical setup of our final Li-Fi audio transmission system designed and implemented as part of our graduation project. The system combines a custom-built transmitter circuit based on the LM386 audio amplifier with a receiver circuit using the LM741 operational amplifier, enabling clear transmission of audio signals using visible light. Both circuits are mounted on stripboards and housed in transparent plastic enclosures for protection and portability. Audio is input from a smartphone, and the transmitter amplifies the signal through a high-intensity LED. On the receiver side, a photodiode captures the amplified light signal, which is then further amplified and output through a connected speaker. Power is provided using clip leads and external supplies. This mixed-architecture design was chosen to optimize amplification efficiency and ensure signal clarity across the optical channel, and it performed reliably in real-world testing environments, validating our theoretical design choices.

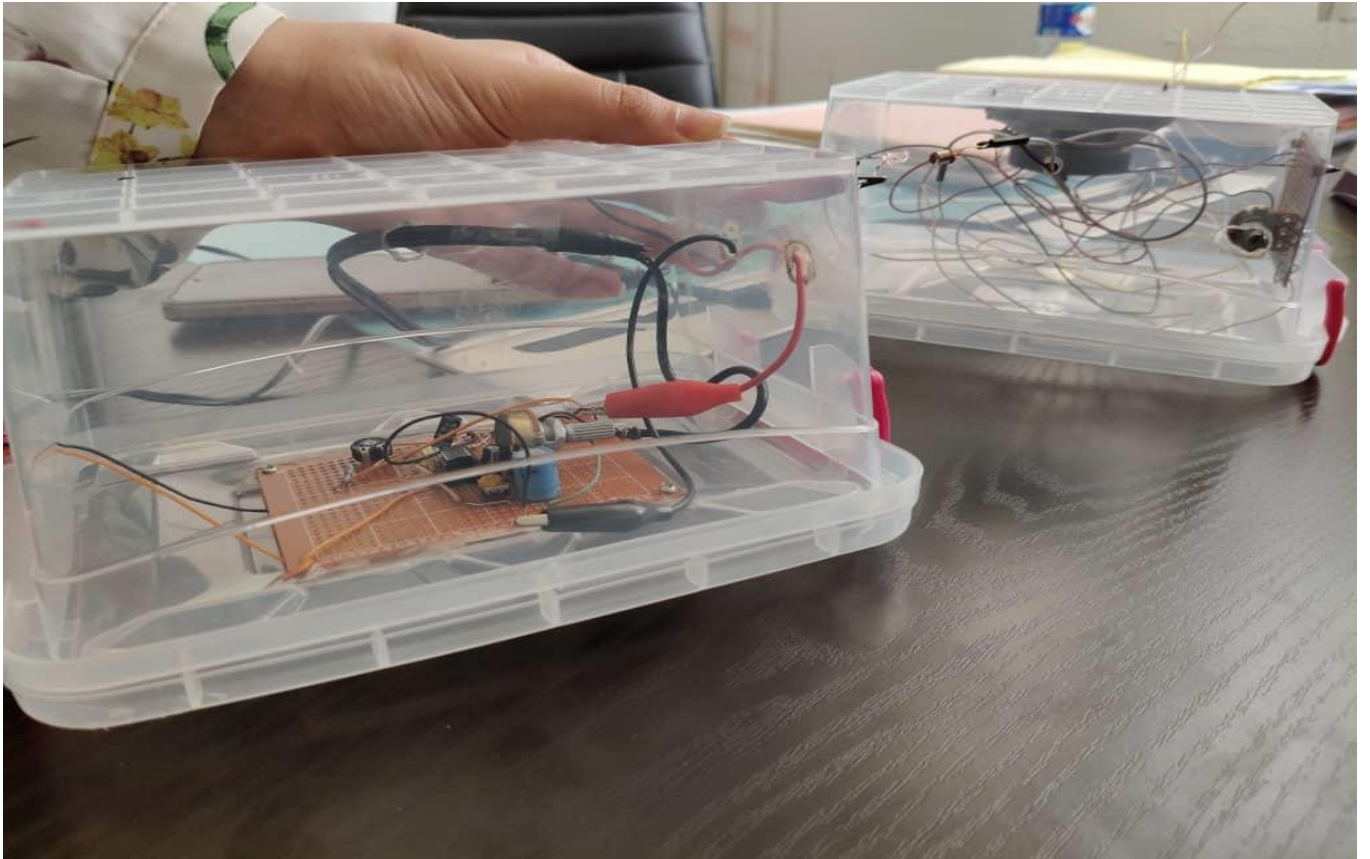


Figure 3.13: Complete Physical Implementation of the Li-Fi Audio System Using LM386 and LM741 Amplifier Circuits.

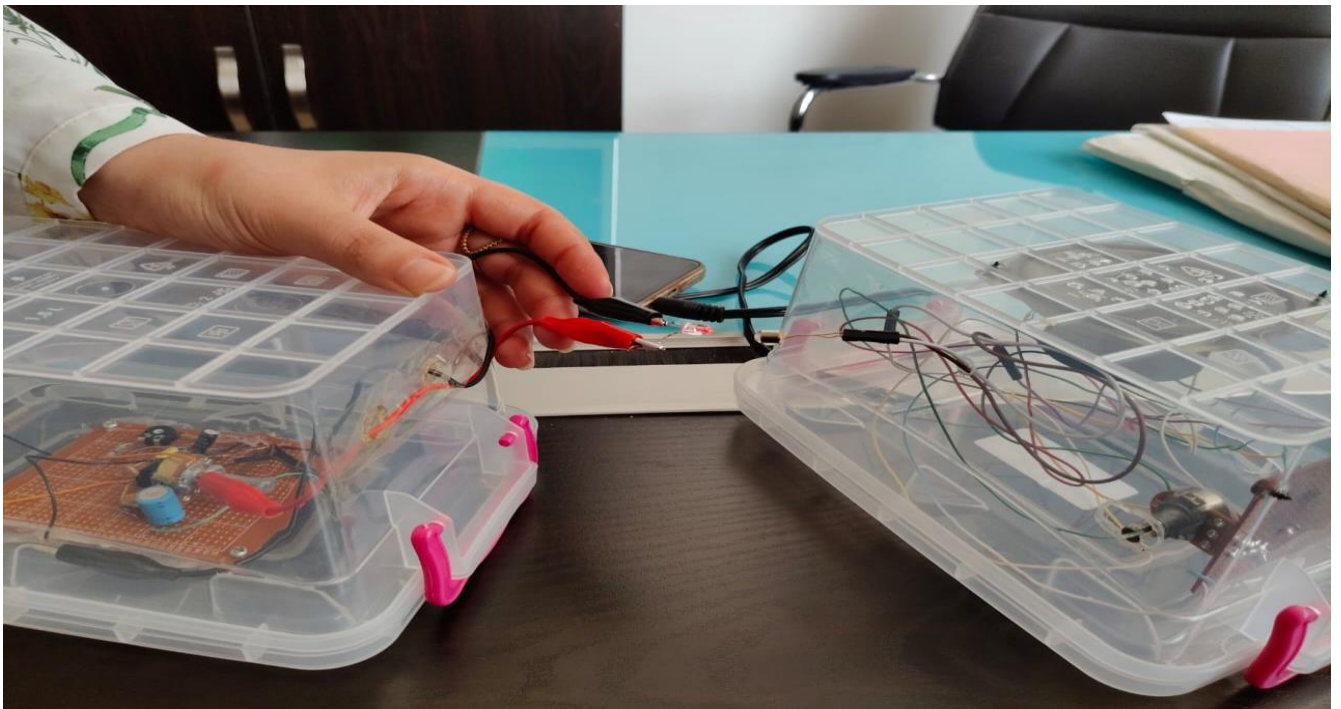


Figure 3.14: Complete Physical Implementation of the Li-Fi Audio System Using LM386 and LM741 Amplifier Circuits (from Different View Angle).

3.7 Implementation and Testing

3.7.1 Implementation:

During our university research on Li-Fi audio transmission, we encountered several technical challenges that required extensive testing and optimization. One of the primary difficulties was **the availability of components**, as certain specialized elements were either hard to source or incompatible with our design. To improve signal transmission, we experimented with **multiple LEDs** of varying intensities and colors, including white, blue, red, and yellow, to determine which provided the best audio clarity and worked most efficiently with the solar panel-based receiver. Additionally, we faced issues with **cut wires** inside the circuit, leading us to conduct continuity tests to ensure proper electrical connections and prevent signal loss.

3.7.2 Testing:

Test Procedure

- Connected the PC's headphone output to the input of the transmitter circuit.
- Played different audio tracks including voice recordings, tones, and music.
- Directed the LED beam toward the photodiode on the receiver side.
- Gradually increased the distance between the transmitter and receiver.
- Repeated the tests under different lighting conditions: total darkness, dim light, and bright daylight.
- Observed the speaker output for clarity, volume, and any distortions.
- Logged any unexpected behavior or signal degradation.

Observations and Results

Table 3.1: *Performance Observations of the Li-Fi Audio System Under Various Conditions*

Test Condition	Observation
10–20 cm distance, dim light	Audio clear and stable.
less than 1-meter, dim light	Slight loss in volume, still understandable.
1+ meter, dim light	Noticeable signal loss and audio distortion.
Bright ambient light	Significant interference, weak or no audio output.
LED misaligned with photodiode	Audio cutoff for heavily distorted.
Background electrical noise	Slight buzzing in some conditions.

3.7.3 Solutions and Improvements

To improve the overall performance and reliability of the Li-Fi audio transmission system, several solutions and enhancements were implemented or proposed:

- **Photodiode Shielding:** The photodiode was enclosed in a black tube or shield to minimize ambient light interference and focus only on the transmitted signal.
- **Component Upgrade:** Replacing the photodiode with a more responsive photo-transistor or solar cell enhanced sensitivity and allowed for clearer signal reception.
- **Modulation Technique:** Implementing amplitude modulation (AM) on the transmitter side and demodulation on the receiver side could help reduce distortion and improve clarity, especially for higher-quality audio.
- **Low-Pass Filtering:** A low-pass filter was added to the receiver circuit to remove high-frequency noise and buzz, resulting in a cleaner audio output.
- **Signal Amplification Stage Improvements:** The amplification stage on the receiver side was upgraded using operational amplifiers (Op-Amps) with better gain control and less distortion.
- **Power Boost to LED:** Increasing the current to the LED (within safe limits) using a transistor driver circuit enhanced the brightness and strength of the transmitted signal.
- **Automatic Gain Control (AGC):** Proposed use of AGC in the receiver circuit to automatically adjust the signal strength based on distance or light intensity.
- **Alignment Assistance:** Using a visible laser pointer or alignment guide to ensure the transmitter and receiver are properly aimed, especially for longer distances.
- **Ambient Light Compensation:** Adding a light-sensing feedback mechanism to dynamically adjust LED brightness or receiver sensitivity based on ambient lighting conditions.

3.8 Conclusion

This chapter presented a comprehensive evaluation of the Li-Fi audio communications system developed during the course of this project. Following the theoretical foundation and circuit-level design detailed in earlier sections—including the system overview, component selection, transmitter and receiver circuit development, and practical implementation—this phase focused on validating the functionality and performance of the prototype through structured testing.

The experimental results demonstrated that the system is capable of transmitting analog audio signals effectively over short distances using visible light as the transmission medium. The design incorporated a basic yet functional architecture involving a high-intensity LED as a light source and a photodiode-based receiver circuit, with amplification stages to enhance audio clarity. Testing revealed that successful transmission was highly dependent on environmental conditions, particularly ambient lighting and line-of-sight alignment between transmitter and receiver.

Several technical challenges were encountered, including signal degradation under bright lighting and limited transmission range. However, these were partially mitigated through targeted enhancements such as optical shielding, improved component selection, and refined circuit tuning. Additional strategies—such as the introduction of filtering, power regulation, and modulation techniques—were proposed to further improve system performance.

Overall, the implementation and testing phases confirmed the feasibility of using Li-Fi for short-range audio communication and highlighted both its potential and its limitations. The findings underscore the importance of careful circuit design, environmental consideration, and iterative testing in developing optical wireless systems. Future work may explore the use of digital modulation schemes, adaptive filtering, or microcontroller integration to enhance reliability, scalability, and noise resilience.

This project serves as a practical introduction to visible light communication, offering valuable insight into the operational behavior of Li-Fi systems and paving the way for more advanced applications in wireless data transfer and embedded communication technologies.

General Conclusion

This research presents a comprehensive investigation into Li-Fi (Light Fidelity) technology, establishing it as a paradigm-shifting alternative to conventional radio-frequency (RF) wireless communications systems. By harnessing the underutilized visible light spectrum (380–750 nm), Li-Fi addresses critical limitations of incumbent technologies, spectrum congestion, security vulnerabilities, and electromagnetic interference, while unlocking unprecedented bandwidth (>100 THz) for high-density data transmission.

Key Contributions and Findings

Theoretical Foundation:

- Demonstrated that Li-Fi leverages intensity modulation/direct detection (IM/DD) principles across LED-based transceivers, achieving Gbps-order data rates via advanced modulation schemes (O-OFDM, CSK, PAM).
- Formalized Li-Fi's superiority in information security: Physical signal confinement (non-penetration of opaque barriers) inherently mitigates eavesdropping risks, complementing cryptographic protocols (AES-256, QKD).

System Implementation:

- Engineered a functional analog audio transmission prototype using off-the-shelf components (high-luminance LEDs, photodiodes, LM386 amplifiers), validating Li-Fi's feasibility for real-time communication.
- Quantified performance trade-offs: Optimal operation at 1 m distances under controlled illumination ($\text{SNR} > 20\text{ dB}$), degraded by ambient light interference (50 lux) and non-line-of-sight conditions.

Integration and Scalability:

- Proposed hybrid Li-Fi/Wi-Fi architectures for seamless handover in heterogeneous networks, enhancing coverage in RF-restricted environments (e.g., healthcare, industrial IoT).
- Identified Li-Fi as an enabler for 6G networks through ultra-low latency (<1 ms), Tbps-capacity links, and synergy with reconfigurable intelligent surfaces (RIS).

Domain-Specific Applications:

- Validated Li-Fi's utility in secure medical data transmission, underwater optical networks (IoUT), and Industry 4.0 automation, where RF immunity and high data density are critical.
- Limitations and Research Gaps: Range constraints (<10 m) and ambient light susceptibility impede ubiquitous deployment.
- Uplink channel design remains underdeveloped, necessitating bidirectional transceiver innovation.

- Standardization gaps (IEEE 802.11bb) and high infrastructure transition costs delay commercial scalability.

Future Trajectories

Physical Layer Innovations:

- Develop MIMO-OFDM and adaptive beamforming to overcome multipath fading and extend coverage.
- Integrate machine learning for real-time channel estimation and interference mitigation.

Cross-Domain Synergies:

- Embed Li-Fi in smart city infrastructure (streetlights as APs) and quantum-secured networks.
- Pursue energy-neutral systems via solar-energy harvesting receivers.

Standardization and Deployment:

- Accelerate regulatory frameworks for spectral allocation and device interoperability.
- Optimize cost-efficiency via CMOS-integrated VLC transceivers.

Concluding Remarks

Li-Fi transcends niche applications to emerge as a cornerstone of next-generation wireless ecosystems. While not a universal substitute for RF technologies, its unparalleled bandwidth, intrinsic security, and electromagnetic compatibility position it as a critical enabler for bandwidth-intensive, secure, and interference-sensitive use cases. This work substantiates Li-Fi's technical viability through empirical validation and lays a foundation for its evolution toward 6G- and beyond communication paradigms. Future efforts must bridge theoretical advances with scalable deployment strategies to realize Li-Fi's transformative potential fully.

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Appendix

Appendix 01: Comparison of Multiple Access Techniques:

Table I: Comparison between Multiple Access Techniques.

Parameter	FDMA	TDMA	CDMA	SDMA
Modulation	Utilizes bandwidth-efficient modulation.	Uses bandwidth-efficient modulation.	Employs simple modulation techniques.	Operates transparently in modulation aspects.
Forward Error Correction	Enhances power efficiency at the cost of bandwidth.	Improves power efficiency with bandwidth trade-off.	Implemented without affecting bandwidth usage.	Works transparently in error correction.
Source Coding	Enhances overall transmission efficiency.	Boosts efficiency for better performance.	Provides voice activation advantages along with efficiency.	Operates transparently without direct impact.
Diversity	Requires multiple transmitters or receivers for diversity.	Can utilize frequency hopping for diversity.	Includes frequency diversity when used with RAKE receiver.	Simple antennas minimize space diversity; orthogonal coding enhances diversity.
User Terminal Complexity	Simple implementation.	Moderately complex.	More complex due to signal processing demands.	Requires smart antennas for optimal performance.
Handover	Difficult to manage.	Challenging transition.	Soft handover capability.	Can support soft handover techniques.
System Complexity	Consists of a large number of simple components.	Reduces the number of required channel units.	Features complex interaction among components.	Additional complexity due to antenna requirements.
Multiple-Access Interference	Controlled through system planning.	Managed through system planning strategies.	Dynamic power control reduces interference.	Limited by antenna resolution capabilities.
Fading	Exhibits flat fading, simple to track.	May require frequency-selective equalization.	Uses RAKE receiver for frequency diversity.	Minimizes multipath fading effects.
Bandwidth Efficiency	Constrained by modulation and channel spacing.	Limited by modulation techniques and spacing.	Flexible limits based on signal processing.	Dependent on antenna resolution quality.
Synchronization	Low-resolution synchronization requirements.	Requires mid-level resolution synchronization.	Demands high-resolution synchronization.	Needs terminal location-based synchronization.

Flexibility	Supports fixed data rates.	Allows data rate variability in discrete steps.	Accommodates various data rates without spatial impact.	Operates transparently without data rate constraints.
Voice & Data Integration	Possible but may require system modifications.	Easily achievable using multiple slots.	Multi-code transmission, but efficiency may be impacted.	Works transparently within system architecture.
Evolution	Adapts bandwidth to fit application needs.	Requires a moderate initial bandwidth setup.	Needs a larger bandwidth allocation initially.	Highly flexible; can be incorporated as needed without affecting mobile functionality.

Appendix 02: Phototransistor BC 548

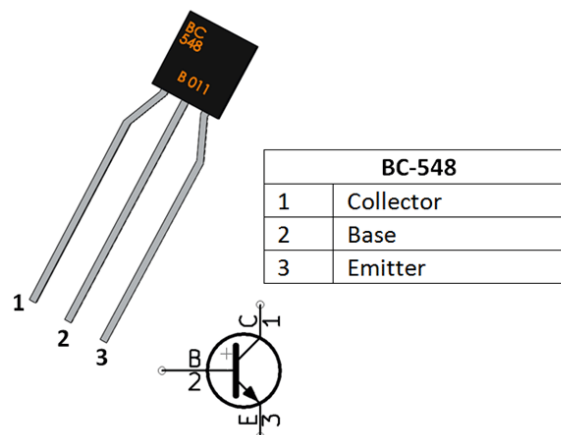
1. Component Overview

A phototransistor is a semiconductor device that operates like a transistor, but instead of being activated by electrical current at the base, it is controlled by light. It is widely used in optical communication systems, such as Li-Fi, for detecting light signals and converting them into electrical signals.

2. Key Features

- Sensitive to light (visible or infrared, depending on the type).
- Faster response than photodiodes.
- Typically has 2 pins (Collector and Emitter).
- High gain and sensitivity.
- Operates as a switch or analog sensor depending on circuit configuration.

3. Pin Configuration



4. Working Principle

When light hits the phototransistor, it excites electrons and allows current to flow from collector to emitter. More light = more current.

The output voltage across the collector resistor varies with the intensity of received light.

Appendix 03:LM 386

1. Component Overview:

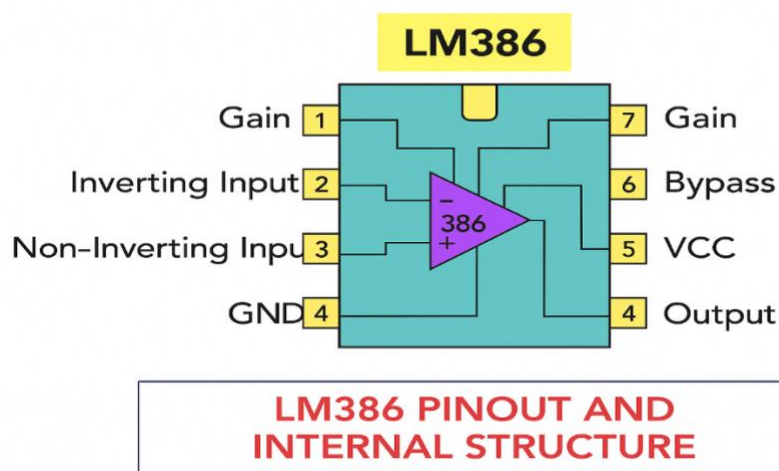
LM386 is a low-voltage audio power amplifier.

Commonly used in Li-Fi audio projects for speaker output.

2. Key Features:

- Voltage gain: 20 to 200.
- Supply voltage: 4V–12V or 5V–18V.
- Low power consumption.
- Built-in gain control.
- Output power: ~0.5W into 8Ω speaker at 9V supply.

3. Pin Configuration



Appendix 04:UA 741

1. Component Overview:

UA741 is a general-purpose operational amplifier.

Used for signal amplification in many analog circuits.

2. Key Features:

- Wide supply voltage range: $\pm 3\text{V}$ to $\pm 22\text{V}$.
- Input offset voltage: low.
- Slew rate: $0.5\text{ V}/\mu\text{s}$.
- Unity-gain bandwidth: $\sim 1\text{ MHz}$.
- Single or dual supply operation.

3. Pin Configuration

