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Research article

Enhancing Audio Data Transfer Through Optical Wireless Communication Using Laser Modulation Techniques

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Abstract: Exploring the potential of optical wireless communication for short-range audio transmission, this research investigates the design of a portable system leveraging the inherent benefits of light-based propagation, such as low power consumption, license-free operation, and enhanced security. While line-of-sight alignment is a key consideration in laser communication, this research outlines a practical approach to system development. A 650 nm laser diode serves as the carrier for the audio signal. The system architecture, comprising a transmitter and receiver, was initially designed and simulated using Proteus software. Each unit was individually implemented and tested to ensure optimal performance. Subsequent integration of these modules and careful line-of-sight alignment enabled successful audio signal transmission and reception. The audible output at the receiver is visually confirmed by a blinking speaker, demonstrating the feasibility of this optical wireless audio communication system. This work offers valuable insights into the design and implementation considerations for such portable applications.

Keywords: wireless communication, laser diode, audio signal, Proteus

1. Introduction

The increasing demand for wireless communication has pushed the evolution of systems capable of exchanging information between physically disconnected points. Optical Wireless Communication (OWC) emerges as a significant case, using unguided light within the visible, Infrared (IR), or Ultraviolet (UV) spectrum for signal transmission [1], [2], [3], [4]. This approach uses free-space optical propagation to wirelessly transmit data, particularly for audio communication. Information is encoded by modulating the intensity of light emitted from a source. OWC is a rapidly advancing field attracting considerable scientific and technological interest. Its potential applications include serving as a supplementary networking technology in mobile devices, alongside cellular, Wi-Fi, and Bluetooth, to improve spectrum scarcity and enable high data rates in densely populated areas [5], [6], [7]. Furthermore, OWC systems offer an inherent security advantage, as optical signals like IR typically do not penetrate walls, confining transmissions to a specific area [8].

Wireless audio communication systems commonly operate in the prevalent Radio Frequency (RF) mode and free-space optical mode. OWC is gaining preference over RF technology due to its distinctive attributes, including high bandwidth capacity, rapid deployment capabilities, license and tariff-free bandwidth allocation, and low power consumption. Research indicates the relatively high cost of RF wireless solutions, a contrast to the economic advantages of OWC systems [9], [10]. Literature reviews show that most implemented optical wireless audio communication systems rely on infrared light, employing Light Emitting Diodes (LEDs) as transmitters and photodetectors as receivers. LEDs are favored for their superior switching characteristics compared to traditional light sources. However, for achieving higher communication speeds, the modulation bandwidth of LEDs remains a limitation. Additionally, LEDs exhibit restricted transmission distances due to a rapid decline in illumination intensity with increasing distance [11], [12], [13].

Addressing these limitations, this research proposes a system utilizing a Laser Diode (LD) as the transmitter. This work aims to explore the application of OWC technology for short-range wireless audio signal transmission and to investigate the potential for faster data transfer leveraging the properties of laser light. Different types of OWC can probably be used in a wide variety of communication or networking applications, including optical interconnects within integrated circuits, outdoor inter-building connections, and satellite communications. Based on the transmission spectrum, OWC can be classified into five groups:

- Ultra-short range: Chip-to-chip communications in stacked and closely packed multi-chip packages fall under this category.
- Short range: This is used in Wireless Body Area Network (WBAN) and underwater communications.
- Medium range: Indoor infrared and visible light communications are used in Wireless Local Area Networks (WLANs) as well as inter-vehicular and vehicle-to-infrastructure communications.
- Long range: The main OWC employed here is the Free-Space Optical Communication (FSOC).
- Ultra-long range: In space, laser communication is used primarily for inter-satellite links and the formation of satellite constellations.

Some advantages associated with optical wireless communication are: i) it has inherent security; ii) optical wireless communication has a significantly higher data rate; iii) it is a license-free operation; iv) it does not generate radiation that leads to public health concern; v) it has higher bandwidth; and vi) it has low power consumption.

1.1. Technologies for the Design of Wireless Audio Communication

Designing wireless audio communication involves selecting appropriate transmission mediums (like radio waves or light), modulation techniques to encode audio signals, and robust protocols for reliable delivery. Key considerations include minimizing latency, ensuring audio quality, managing power consumption for portability, and mitigating interference from other wireless devices. Recent advancements explore diverse technologies, from established Bluetooth and Wi-Fi standards to emerging optical wireless communication [14].

1.1.1. Radio Frequency Wireless Audio Communication System

In this type of system, audio communication is done using an RF-based transmitter and receiver. This system is used in long-distance audio communication but suffers from the following limitations: They are expensive due to the cost of their circuit design, they have low to medium data rates, they suffer from interference effects, and these systems are not secure [15].

1.1.2. Bluetooth Wireless Audio Communication System

This system is used for short-range wireless audio communication between two handheld mobile devices. They usually operate under the Bluetooth Class 2 specification with 2.5 mW (4 dBm) transmission power [16]. The transmission range of this system is approximately 10 m. In this type of system, the audio signal from a Bluetooth headset is connected to an external amplifier, which amplifies the audio signal. The Bluetooth stereo headset serves as a bridge, transmitting the audio signal from the portable unit to a stereo audio amplifier, resulting in a wireless stereo audio system [17].

1.1.3. Optical Wireless Audio Communication System

This type of system uses light propagating in free space to transmit data wirelessly for audio communication use. The system transmits audio signals within a short range of about 10–20 m. The system makes use of an electro-optical conversion device, which may be an LD, an IR transmitter, and an LED, as the transmitter; and an opto-electrical conversion device, such as an IR receiver or a photo transistor, as the receiver [18].

1.1.4. Laser Communication

Laser communication is one of the key areas in wireless communications. It is one of the best communication media for information sharing because of its low noise ratio. This is a modern wireless technology that uses a system’s laser beam to transmit data or sound signals from one segment to another. Laser communication is currently used in satellite communication for space exploration activities, and it is one of the most researched areas of wireless communication owing to its efficiency on low noise ratio, low cost, low power, and its stability and resistance to radio interferences [19]. The transmitter and receiver in laser communication must have line-of-sight conditions. A laser diode is usually used to generate the carrier for the transmission signal. Two parallel beams are required, one for transmission and one for reception. Laser communications systems are similar in function to fibre optic links except that the beam is transmitted through free space instead of fibre [19], [20].

1.2. Optical Wireless Communication (OWC)

Optical wireless communication (OWC) has gained significant traction in recent years as a viable alternative to radio frequency (RF) systems, offering high bandwidth, low power consumption, and enhanced security due to its directional propagation. These attributes make OWC particularly suitable for short-range applications such as audio transmission, where efficiency and privacy are critical. Unlike RF, which operates in a crowded and regulated spectrum, OWC leverages the unlicensed optical domain, positioning it as a promising technology for secure, portable communication systems [21], [22]. This research explores a laser-based OWC system for audio transmission, contributing to a growing yet underexplored niche within the field. Recent advancements in OWC have been driven by the development of optoelectronic components, such as laser diodes and photodetectors, which enable efficient signal modulation and detection.

In [23], the authors highlight the potential of visible light communication (VLC), a subset of OWC, for indoor applications, emphasizing its low energy footprint. However, much of the recent literature focuses on high-speed data transmission rather than audio-specific systems. For instance, the authors in [24] demonstrated multi-gigabit VLC links using advanced modulation schemes, but their work prioritizes bandwidth over the practical constraints of audio-focused designs, such as portability and cost. Laser-based OWC systems have garnered attention for their ability to deliver focused beams, making them ideal for line-of-sight (LOS) communication. A study in [25] explored free-space optical (FSO) systems using laser diodes, noting their superior beam coherence compared to LEDs, which aligns with the use of a 650 nm laser diode in this research. However, LOS alignment remains a persistent challenge, as even minor deviations can disrupt signal integrity [26]. Recent efforts to address this include automated alignment techniques [15], [27], [28], but such solutions often increase system complexity, undermining portability, which is a key focus of this study.

Audio transmission via OWC has seen limited but notable exploration in recent years. The authors in [23] investigated VLC-based audio streaming using LED sources, achieving reasonable sound quality over short distances. However, the diffuse nature of LED light limits its range and security compared to laser-based approaches. Similarly, the study in [29] demonstrated an FSO system for audio transmission, but its reliance on stationary, high-power equipment restricted practical deployment. These works highlight a gap in the development of compact, laser-driven OWC systems optimized for audio, which this research seeks to address. Simulation tools like Proteus have become essential in modern communication system design, enabling pre-implementation testing of circuit performance. The authors in [30] used Proteus to model transmitter-receiver pairs for wireless systems, a methodology adapted here to simulate the OWC architecture. Real-world validation, particularly of LOS alignment and audio output, remains critical, as emphasized by [11], who stress the importance of bridging simulation and physical testing in OWC research.

This study advances the field by designing a portable OWC system using a 650 nm laser diode for audio transmission, prioritizing low power consumption and practical LOS alignment. By simulating the system in Proteus, testing individual components, and integrating them into a functional prototype, this work offers a streamlined approach to system development. The novel use of a blinking speaker to visually confirm audible output further distinguishes this research, providing a tangible demonstration of success. Unlike prior studies focused on data rates or stationary setups, this system balances performance with portability, addressing real-world design constraints. While recent OWC research has made strides in data communication, its application to portable audio transmission remains underdeveloped [2], [31], [32]. This study fills this gap by leveraging recent advancements in laser-based OWC, tackling alignment challenges, and validating performance through simulation and testing. The findings contribute valuable insights into the design of secure, efficient audio communication systems, with potential implications for future portable OWC technologies.

2. Methods

The system is basically divided into the transmitter section and the receiver section. Figure 1 shows the block diagram of the proposed system, and Figure 2 shows a block diagram that gives a general overview of the laser communication system. The transmitter unit consists of the power supply unit, audio input, digital to analogue converter, amplification unit, and the laser transmitter. The Power supply unit has two primary functions:

- Converting the Alternating Current (AC) input voltage to a Direct Current (DC) output voltage; and
- Supplying the other transmitter units with the needed current and voltage.

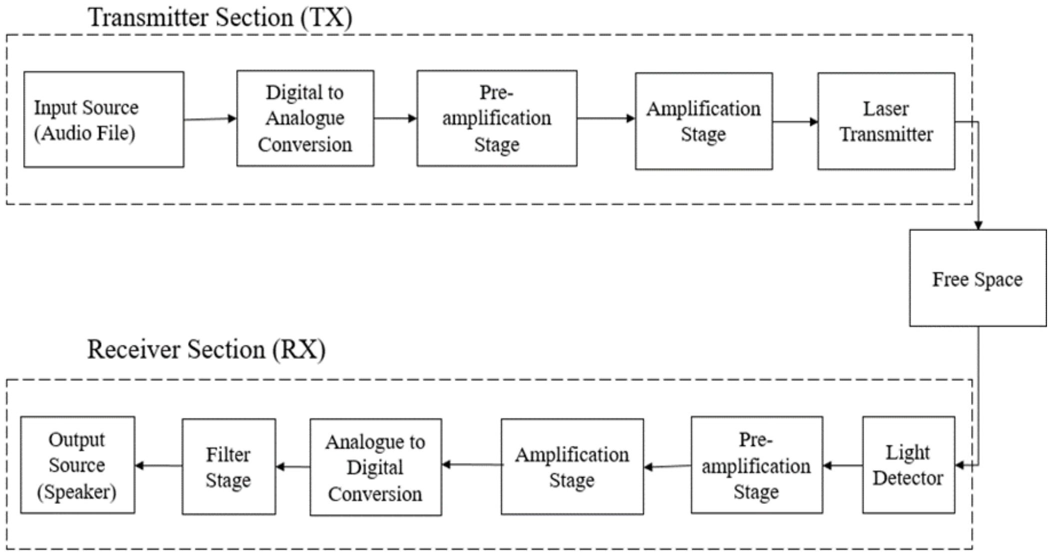

Figure 1. Block diagram of the proposed optical wireless audio communication system.

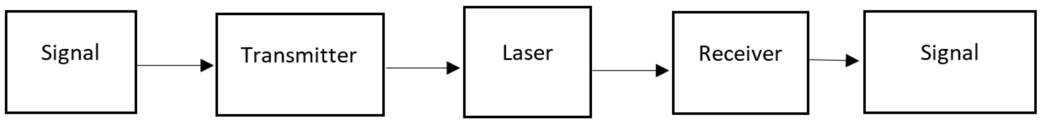

Figure 2. Block diagram depicting a general overview of the laser communication system.

The transformer used for the power supply unit is usually a step-down transformer. Its function is to step down the AC voltage to a value that is suitable for electronic components. The rectifier comprises a bridge rectifier diode that converts the AC voltage into a pulsating DC voltage (that is, a DC voltage that has some ripple elements of the AC voltage inside it). The filter removes the ripple AC voltage. The filter is usually designed using a large value capacitor known as the filter capacitor. This large capacitor acts like a battery over short time periods. It is installed across the circuit to even out these rapid fluctuations in power. The capacitor achieves voltage smoothing by charging when the voltage is high and discharging when the voltage is low. The voltage regulator's main function is to keep the terminal voltage of the DC power supply constant, even when the AC input to the transformer or the load varies. The voltage divider has a main function of providing the different DC voltages needed by different electronic components. It usually consists of a number of resistors connected in series across the output terminal of the voltage regulator. It eliminates the necessity of providing a separate DC power supply for the different electronic devices that are working on different DC power levels.

The input source could be any smart device (mobile phone or laptop) with an audio file in a Waveform Audio File Format (.WAV), which is used to send the digital audio file to the next stage of the system. The digital-to-analogue converter converts the digital audio file into an analogue format, a format that can be transmitted by the Laser diode to the photodetector in a pulse wave form. A potentiometer is connected to the circuit to boost the audio signal to a level acceptable to a power amplifier. At the Amplification stage, an LM386, which is an Integrated Circuit (IC) containing a low-voltage audio power amplifier, amplifies the audio signal by means of power obtained from the power supply unit. For a laser transmitter, a laser diode that emits IR rays of the electromagnetic spectrum. It receives and converts the amplified analogue audio signal into light energy and transmits it to the receiver side via free space. During the transmission, the IR signal is modulated, and it is demodulated at the receiver. This has a unique advantage of preventing interference and false triggering of the IR transmitter, which can result in the production of noise together with the actual output audio signal.

At the receiver side, direct detection is used to receive the modulated light. This is made up of the light detector, pre-amplifier, power amplifier, the analogue-to-digital converter, filter, and the output (speaker). The light detector, which can also be termed the photodetector, is the immediate device that detects the emitted light beam from the laser diode in the transmitter stage. It converts the light signal into an electrical signal (current) and then feeds it into the circuit. The light detector comprises a light-dependent resistor or a photodiode for the detection of the emitted light. For Pre-amplification, this unit converts the current produced by the light detector to a voltage and then sends it to the LF411 for amplification. For amplification, it increases the strength of the pre-amplified signal (voltage) from the pre-amplifier before sending it to the loudspeaker through the converter. The analog-to-digital converter converts the analog signals into a digital format to be transmitted to the speaker. At the filter stage, this unit filters out any noise that might be present in the detected audio signal. The output stage is the stage where the amplified electrical signal is then fed to a loudspeaker, which converts the transmitted electrical audio signal into a corresponding sound that is radiated into the open air.

2.1. Operational Principle

The audio signal gets to the transmitter section through the audio generator input. At the transmitter section, the audio signal is fed to an audio amplifier, which amplifies the audio signal. After amplification, the amplified audio signal is then sent to the laser transmitter, which converts the amplified audio signal into optical (light) energy, which is then emitted through a small aperture created in the transmitter section. Since the medium of propagation of the audio signal is light energy, the transmitter and the receiver units need to be placed in line-of-sight alignment for proper detection. When placed in proper line-of-sight alignment, the radiated light energy from the transmitter is detected by the light-dependent resistor at the receiver, which converts the detected light from optical energy to electrical energy. The converted electrical energy is sent to an amplifier, which amplifies the electrical signal. The amplified electrical signal is then fed to a loudspeaker, which converts the electrical signal to an audio signal.

The main components used in the design and electronic circuit simulation of the system are resistors, a laser diode, a potentiometer, a light-emitting diode, a light-dependent resistor, an LM386 audio power amplifier, an LF411 operational amplifier, a capacitor, a step-down transformer, voltage regulators, and a loudspeaker. Resistors are the most commonly used component in electronics, and their purpose is to create specified values of current and voltage in a circuit. The resistors R4 and R5 used in the simulation formed a voltage divider circuit, which helped the laser diode in keeping the voltage and the current in the safe region [20]. The Laser Diode is an electrically pumped semiconductor device similar to an ordinary LED, but it generates a beam of high-intensity light. The laser diode formed an integral part of the proposed system, and Table 1 briefly lists specifications of the LD and their required average measurements used in the design.

Table 1. Laser diode specifications.

Parameter	Value
Output Power	5 mW
Laser Wavelength	650 nm
Rise and Fall Time	0.5 ns
Operating Current Range	65–80 mA
Operating Temperature Range	-10 – 40 °C
Operating Voltage Range	2.2–2.7 V

A potentiometer is a three-terminal variable resistor with a sliding or rotating contact that forms an adjustable voltage divider. If only two terminals are used, one end and the wiper, it acts as a variable resistor or rheostat. Therefore, a potentiometer was used in this project to increase or decrease the current supplied, thereby either increasing or decreasing the volume of the audio signal. A light-emitting diode (LED) is a two-lead semiconductor device that emits light when a certain amount of voltage is applied to its terminals, and its working principle is based on the electroluminescence effect [33]. The LED in the power supply circuit design ensured that current flowed in one direction instead of flowing in the reverse direction when any of the polarities of the power supply were interchanged. The material used for its construction is usually a Gallium Arsenide (GaAs), a Gallium Arsenide Phosphide (GaAsP), or Gallium Phosphide (GaP).

Light Dependent Resistors (LDRs) are electronic components that are used to detect light levels in a circuit. Their resistance decreases as the light intensity increases. Therefore, the resistance of LDR is an inverse function of light intensity. Although other components, such as photodiodes, can also be used, LDRs are particularly convenient to use in many electronic circuit designs. LDR was used as the photodetector in this project, which received the light signals and converted them into an electrical current that can be fed into the audio amplifier. The LM386 Low Voltage Audio Power Amplifier is a class AB power amplifier used to amplify the audio signal at the transmitter stage of the proposed light communication system. It comes in an 8-pin mini dual in-line package. The IC is designed to deliver a voltage amplification or gain of 20 without external add-on parts. For maximum output gain from the power amplifier, a capacitor (1 µF) and a resistor (10kΩ) are connected in series between pins 1 and 8 to yield a maximum gain of 200 (46 dB). Pin 2 is always connected to ground due to the negative input; Pin 3 is the positive pin of the IC and is connected to the potentiometer to adjust the volume levels. Pin 4 is the ground pin, while Pin 6 is the power supply pin of the IC. Pin 5 is the output pin of the IC, and the signal obtained from this pin is fed to the LD. Pin 7 (bypass) is the half supply point of the LM386. By design, a capacitor should be connected to it to keep power supply noise from reaching the output.

The LF411 Precision JFET-input Operational Amplifier is a low-cost, high-speed, JFET-input operational amplifier with very low input offset voltage and a maximum input offset voltage drift. It requires low supply current yet maintains a large gain-bandwidth product and a fast slew rate. In addition, the matched high-voltage JFET input provides very low input bias and offset currents. It can act as a low-pass filter with the addition of resistors and capacitors to filter out any noise that might be present in the detected audio signal. The LF411 was used in this project to amplify the electrical signal received from the light detector and send the amplified signal to the loudspeaker. Capacitors are electronic components that store electric charge. The electrolytic capacitor C4 was used in the power supply unit to achieve voltage smoothing. The electrolytic capacitor C3 was used to vary the gain of the LM386. The electrolytic capacitor C2 was connected to the bypass of the LM386 to keep power supply noise from reaching the output. Capacitors C1 and C6 were used in the laser driver circuit as power load balancers to filter the fluctuating signals.

The Step-Down Transformer was needed in the design to convert alternating voltage and current from a high voltage and current into much lower voltages and currents that are required by the electronic components to be used. The function of the transformer (TRAN-2P2S) in this project is to step down the phase voltage from 220/240 V to 12 V since the maximum input voltage of the voltage regulator 7805 is 35 V. The output voltage from the step-down transformer is connected to a bridge rectifier, which produces a pulsating DC. The Voltage Regulator is used to regulate the voltage level and provides a steady and reliable voltage. This device provides a fixed output voltage that remains constant for any changes in the input voltage or load condition. The voltage regulator also acts as a buffer to protect sensitive electronic components from being damaged. A speaker is used as a transduction device to convert electrical signals into audio signals. To make sound, the electrical signals will be fed through the speaker cables into the coil and thus turn it into an electromagnet. As electricity flows through the electromagnet, it will attract or repel the permanent magnet, which causes the diaphragm of the speaker to vibrate and produce sound.

Proteus 8 Professional software version was used to simulate the design of the project, which is an optical wireless audio communication system using the laser light technique. The Proteus software was chosen for the simulation of the project mainly because drawing the schematic is very easy, as well as many of the components in the Proteus software can be simulated using any of its two options for the simulation process: Run simulator and Advance frame by frame. The “Run simulator” option simulates the circuit at a normal speed (If the circuit is not heavy). “Advance frame by frame” option advances to the next frame and waits till the button is clicked for the next time, which can be useful for debugging digital circuits. Proteus 8 Professional also gives one room to download the compilers for Proteus or use a different compiler and dump the hex files into the microcontroller in Proteus. It also offers the opportunity to interact with the simulation in real-time using switches, resistors, LDRs, and many others. There is even a virtual voltmeter, ammeter, oscilloscope, logic analyzer, and many more.

2.2. Mathematical Equations

The operation of the optical wireless audio communication system can be described mathematically using transmitter, channel, and receiver models.

2.2.1. Transmitter – Laser Modulation

The laser diode intensity is modulated by the audio signal. The instantaneous transmitted optical power is expressed as:

$$P_t(t) = P_0\big(1 + m \cdot s(t)\big) \tag{1}$$

where P_0 denotes the average optical power of the laser diode, m represents the modulation index ($0 < m \leq 1$), and $s(t)$ is the normalized baseband audio signal ($|s(t)| \leq 1$).

2.2.2. Free-Space Optical Channel

The received optical power at distance d is modeled as:

$$P_r = P_t . \frac{A_r}{(d \cdot \theta)^2} . e^{-\alpha d} \tag{2}$$

where A_r denotes the receiver aperture area, θ represents the laser beam divergence angle, and α denotes the atmospheric attenuation coefficient.

2.2.3. Photodetection and Electrical Conversion

The photodetector converts optical power into current:

$$I_r(t) = R \cdot P_r(t) + n(t) \quad (3)$$

where R denotes the photodetector responsivity (A/W), and $n(t)$ represents the noise current due to shot noise, thermal noise, and ambient light.

2.2.4. Signal-to-Noise Ratio

The effective electrical signal-to-noise ratio (SNR) at the receiver is given by:

$$SNR = \frac{(R \cdot P_r)^2}{2qI_dB + \frac{4kTB}{R_L}} \quad (4)$$

where q denotes the electron charge, I_d represents the photodiode dark current, B denotes the system bandwidth, k represents the Boltzmann constant, T is the absolute temperature, and R_L represents the load resistance.

2.2.5. Bit Error Rate Approximation

For On-Off Keying (OOK) modulation of audio signals, the Bit Error Rate (BER) can be approximated as:

$$BER \approx Q\left(\sqrt{\frac{\text{SNR}}{2}}\right) \quad (5)$$

where $Q(x)$ is the Q-function.

2.2.6. Amplifier Gain

The LM386 amplifier stage provides voltage gain:

$$G = 20log_{10}\left(\frac{V_{out}}{V_{in}}\right) \quad (6)$$

This ensures the audio signal has sufficient amplitude to drive the laser diode effectively.

2.3. Proteus Simulation of the Proposed System

The TRAN-2P2S is a step-down transformer used for the power supply unit, and its function is to step down the AC voltage from 220 V to 12 V since the maximum input of the 7,805-voltage regulator IC is 35 V. The output voltage from the step-down transformer is fed into the bridge rectifier circuit, which converts the AC voltage into pulsating DC voltage (this means the DC voltage has some ripple elements of the AC voltage). The capacitor C4 (2000 μF) acts as a filter to smooth the pulsating DC output after rectification. The capacitor achieves voltage smoothing by charging when the voltage is high and discharging when the voltage is low. The 7805-voltage regulator IC keeps the terminal voltage of the DC power supply constant even when the AC input to the transformer or load varies. Its outputs 5 V at up to 1 A current. The voltmeter is used to read the output voltage of the regulated power supply. The output of the voltage regulator is connected to a diode, which ensures that current flows in one direction instead of flowing in the reversed direction when any of the polarities of the power supply is interchanged, thereby damaging the IC and some other components of the receiver. The circuit requires 5 V for operation.

The audio signal gets to the transmitter unit through the audio generator. The DAC converts the digital audio signal to an analogue electrical signal, and this analogue signal is used to drive the laser diode, which generates the light. The signal is fed into the LM386 operational amplifier through the potentiometer RV2, which is used to change the audio signal input level. The LM386 with a variable gain of 20 (26 dB) to 200 (46 dB) amplification by increasing the strength of the signals. A capacitor (1 µF) and a resistor (10 kΩ) connected in series between pins 1 and 8 of the LM386 act as a low-pass filter, which filters out noise, leaving signals of low frequency, which is the original transmitted audio signal. The output of the LM386 is fed to the laser driver circuit, which helps to maintain or limit the current and supplies to the laser diode, so it can work properly. If the LD is directly connected to the power supply, it will be damaged, and if the current is low, then it will not operate, because it does not have sufficient power to start. A simple LED only needs a resistor to limit the current, but in LD, a proper circuitry is needed to limit and regulate the current. The laser driver circuit consists of two 1 µF capacitors, two 330 Ω resistors, and the LM317, which is used for regulating power in the laser diode driver circuit. The laser diode is the optoelectronic source that converts the electrical signal into a light signal at the transmitter.

The receiver has an LDR (TORCH_LDR), which acts as the optoelectronic detector that converts the incoming light signals into an electrical signal. The LF411 operational amplifier receives electrical signals from the optical transmitter. It is used to amplify the electrical signal from the light detector and can also play the role of a low-pass filter with the addition of resistors and capacitors to remove any short or thermal noise responsible for current fluctuations in the optical receiver. The amplified electrical signals are received by the speaker, which converts them into sound signals. The potentiometer RV1 is used to increase or decrease the current supplied, thereby either increasing or decreasing the volume of the audio signal. Figure 3 shows the simulation model of the proposed design using Proteus software.

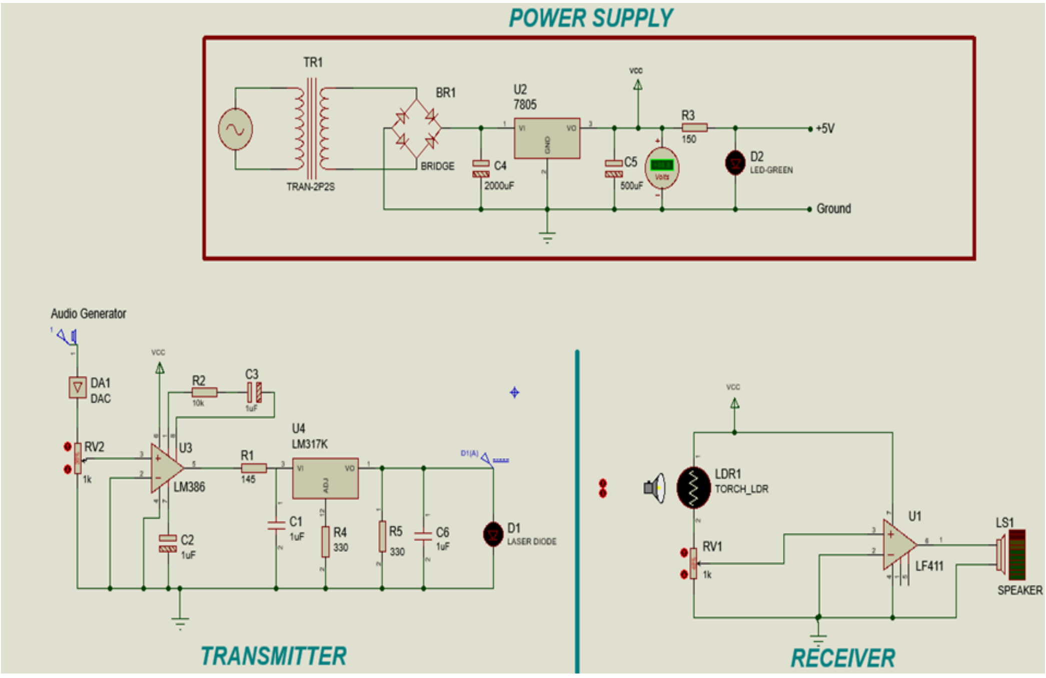

Figure 3. Proteus simulation model of the proposed design.

3. Results and Discussion

Figure 4 illustrates the Proteus simulation results when the circuit is in an inactive state, with no power supplied. In this configuration, all components, including the green LED, voltmeter, laser diode, and speaker, remain off, establishing a baseline for comparison. Figure 5, in contrast, depicts the simulation of the proposed optical wireless communication system during operation. Upon activating the simulation, the green LED illuminates, signaling that the power supply is actively delivering current to the circuit. Concurrently, the voltmeter registers a stable, regulated voltage, confirming that the power input meets the operational requirements of the system's components.

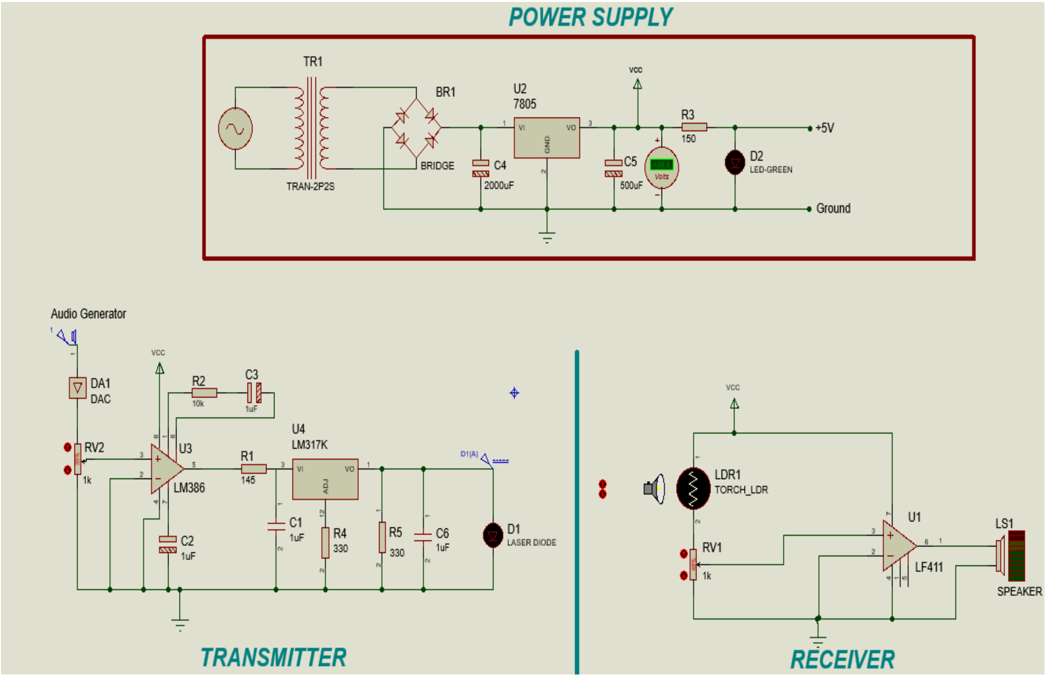

Figure 4. Simulation results when the circuit is in inactive mode.

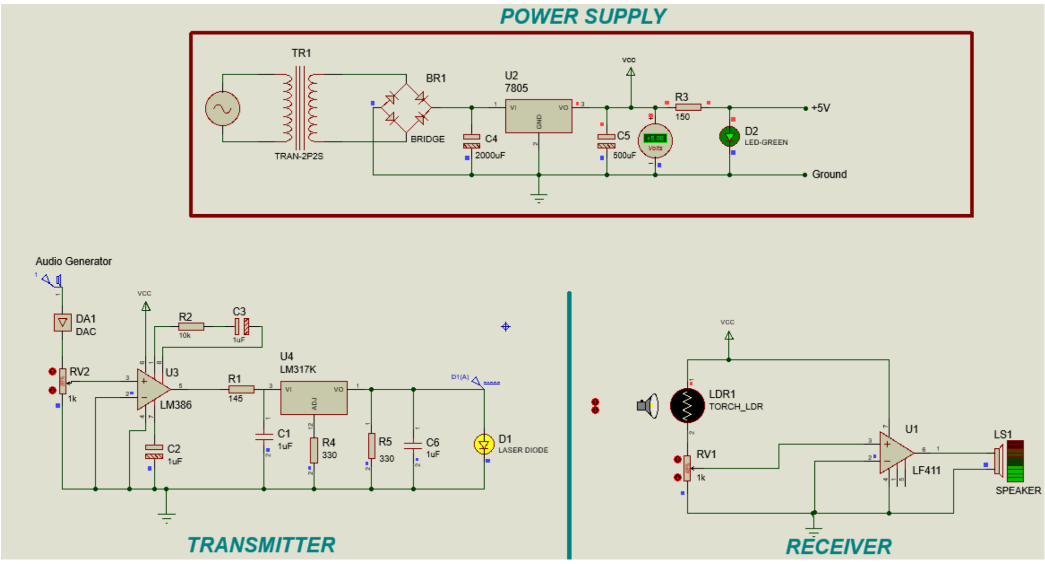

Figure 5. Simulation results when the circuit is in an active mode.

In the transmitter unit, the 650 nm laser diode activates, emitting light that serves as the carrier for the audio signal. The laser's intensity modulates rapidly in response to the input audio, varying at frequencies beyond human visual perception, which enables the encoding of sound into the optical domain. At the receiver end, the photodetector successfully captures this modulated light, converting it back into an electrical signal. This signal drives the speaker, which exhibits a blinking behavior in the simulation, represented by an oscillating output indicator, which demonstrates that the transmitted audio has been received and is being reproduced as sound. These results collectively validate the system's ability to transmit audio signals optically over a short range, with visual cues in Proteus confirming the functionality of power delivery, signal modulation, and reception.

3.1. Distance versus Received Power and SNR

This test evaluated how the system performs as the distance between transmitter and receiver increases. At 2 m and 5 m, the received power is strong (150 µW to 90 µW), and the SNR is high (28 dB to 22 dB). The audio quality is clear with no noticeable distortion. At 10 m, received power drops significantly (30 µW), SNR falls to 14 dB, and some distortion appears. At 15 m, power is very low (12 µW), SNR is only 8 dB, and the audio becomes distorted and unclear. These results confirm that the system can reliably transmit audio up to about 10 m indoors. Beyond this, the signal weakens too much, and noise dominates. The effect of distance on received power and audio quality is described in Table 2, while the distance versus SNR is depicted in Figure 6.

Table 2. Effect of distance on received power and audio quality.

Distance (m)	Received Power (µW)	SNR (dB)	Audio Quality
2	150	28	Clear, no distortion
5	90	22	Clear
10	30	14	Slight distortion
15	12	8	Distorted, low clarity

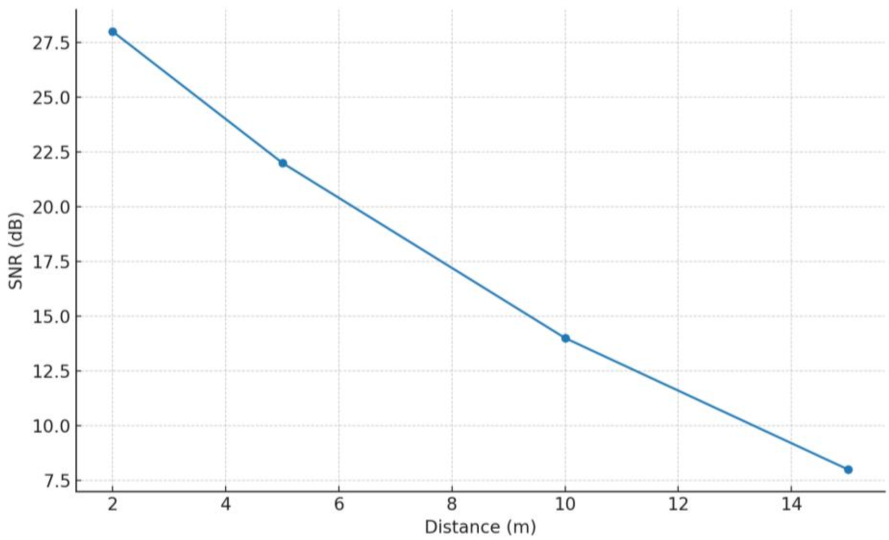

Figure 6. Distance versus SNR. Audio clarity reduces as the distance increases.

3.2. Frequency Responses

This test analyzed the system's ability to transmit different audio frequencies. At 1 kHz (typical voice range), audio was transmitted with full strength and no distortion. At 5 kHz, there was slight attenuation, but the sound remained clear. At 10 kHz, the amplitude dropped significantly, indicating the system struggles at higher audio frequencies. This means the system is best suited for voice and music frequencies (300 Hz – 5 kHz). For higher frequencies (>10 kHz), the hardware (laser driver and photodetector) limits performance. This is acceptable for speech and music communication. Figure 7 shows the frequency response showing attenuation at higher frequencies.

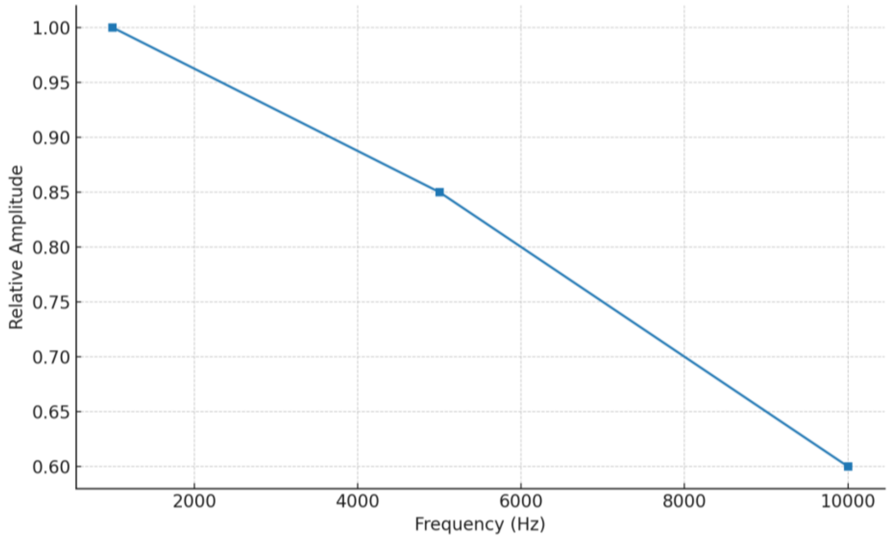

Figure 7. Frequency response showing attenuation at higher frequencies.

3.3. Effect of Misalignment

This test examined what happens when the transmitter and receiver are not perfectly aligned. With 0° misalignment, the received power was maximum, and the SNR was at 25dB. At 2° misalignment, power dropped by 40% and SNR fell by 7dB. At 5° misalignment, the system nearly failed (SNR was at 10dB, audio was very distorted). These results show the system is highly sensitive to alignment. Even small deviations degrade signal quality significantly. This shows a limitation of laser-based OWC, where line-of-sight precision is critical. Table 3 summarizes the effect of misalignment, and the misalignment versus SNR is depicted in Figure 8.

Table 3. Effect of misalignment on received power and SNR.

Misalignment (degrees)	Received Power (µW)	SNR (dB)
0	100	25
1	80	20
2	60	18
5	20	10

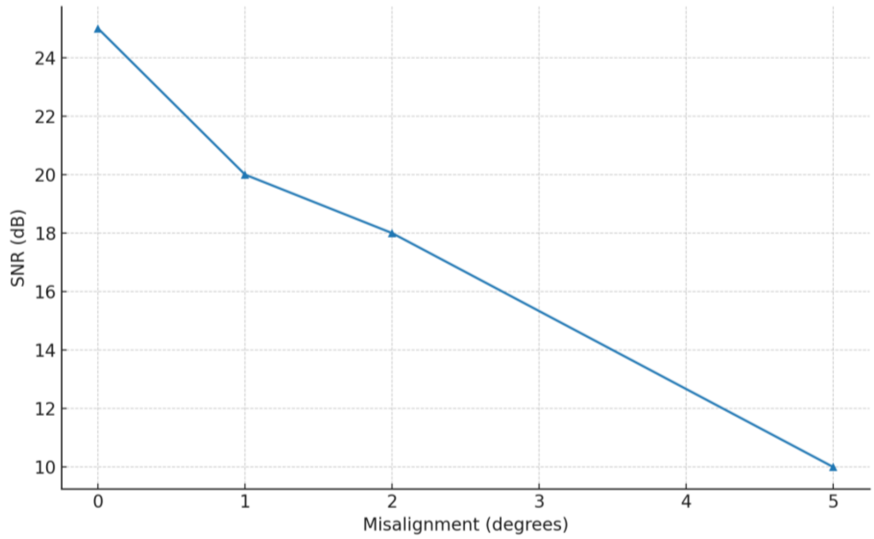

Figure 8. Misalignment versus SNR. Performance degrades rapidly with angular error.

3.4. Noise Robustness

Tests were conducted under different lighting conditions. Indoors with fluorescent lighting, clear transmission was possible up to about 8 m. Under direct sunlight, the photodetector saturated due to strong background light, reducing SNR by 10dB. This shows the system performs best indoors, while outdoor applications require shielding or optical filters to block background light and pass only the 650 nm laser signal.

4. Conclusions

The escalating demand for wireless connectivity has led to significant congestion within the radio frequency (RF) spectrum, prompting the exploration of alternative communication technologies. Optical Wireless Communication (OWC) has emerged as a promising research domain in response to this challenge. While early OWC systems predominantly utilized Light Emitting Diodes (LEDs) as transmitters, Laser Diodes (LDs) are increasingly attracting attention for high-speed communication applications. This shift is driven by the superior modulation bandwidth and high energy efficiency offered by LDs, enabling gigabit-class data transmission. This project report details the development of an audio communication system employing an LD as the optical source to transmit audio signals from a dedicated transmitter to a receiver unit. Furthermore, the inherent properties of laser light, such as coherence and directionality, facilitate potentially faster signal transmission compared to other wireless methodologies. This exploration highlights the potential of LD-based OWC for efficient and rapid audio communication.

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