Experimental Analysis and Implementation of a Low-Cost Practical Laser-based Communication System

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ABSTRACT
This paper presents a cost-effective and practical laser-based communication system specifically designed for educational and prototyping purposes. Utilizing commonly available components such as a laser diode, photodiode sensor, and an ESP32 microcontroller with Python-based software, the system offers a simple yet effective platform for wireless data transmission. Comprehensive experimental analyses evaluated the impacts of baud rate variation, optical beam focusing, and simulated environmental interference on transmission performance. Results revealed that increased baud rates significantly reduce effective communication distance due to heightened signal degradation sensitivity. Optical beam focusing through notably mitigated beam diffusion, extending transmission ranges by up to 54%. Environmental interference demonstrated a pronounced negative impact on communication reliability. Additionally, the implementation of a half-duplex mode for file transmission confirmed consistent performance irrespective of file size or type. This practical testbed, distinguished by its accessibility, simplicity, and affordability, provides substantial educational value and offers a viable alternative to more complex systems such as the RONJA project by Twibright.

General Terms
Optical Communication, Wireless Communication, Data Transmission, Experimental Evaluation, System Design.

Keywords
Laser Communication, Free-space Optics, ESP32 Microcontroller, Baud Rate, Environmental Interference, Low-cost Communication, Educational Testbed.

1. INTRODUCTION
The exponential growth in data communication requirements has led researchers and industries to explore various communication technologies capable of meeting contemporary demands. Wired technologies, though robust, face limitations in flexibility and deployment costs. Wireless communication technologies, particularly radio frequency (RF)-based systems, have become widespread due to their convenience and relatively low implementation costs. Nevertheless, RF communication suffers from significant challenges including limited available spectrum, susceptibility to electromagnetic interference, and security vulnerabilities, driving the necessity to explore more efficient alternatives [1].

In this context, Optical Wireless Communication (OWC), especially Free-Space Optical (FSO) communication using lasers, has gained considerable attention due to its ability to deliver extremely high data rates, superior security through directed transmission beams, and immunity to RF interference [2]. Recent advancements in laser communications, as reported by Hemmati, highlight their suitability for terrestrial and space applications, significantly enhancing communication performance even under challenging operational scenarios [3]. Laser-based communication systems, however, traditionally rely on sophisticated, costly equipment and require complex setups and alignments, limiting their widespread accessibility and practical usage for educational and prototyping purposes. Systems such as the Reasonable Optical Near Joint Access (RONJA) developed by Twibright Labs exhibit high performance but involve substantial complexity and cost, posing barriers to broader educational adoption [4]. Therefore, there exists a distinct need for simple, affordable systems that retain fundamental capabilities of laser-based communication while ensuring practical ease of implementation.

Recent literature illustrates notable advances in laser communication systems and associated measurement techniques. Ahmad et al. (2024) presented a comprehensive review of recent developments, such as adaptive optics and innovative modulation schemes, to enhance laser communication performance under diverse environmental conditions [5]. Additionally, Gao et al. (2023) discussed recent improvements in both half-duplex and full-duplex laser communication protocols, underscoring their respective operational benefits and challenges in practical environments [6]. Wang and Zhang (2023) provided experimental insights into the impact of atmospheric turbulence, emphasizing the need for adaptable system configurations and performance evaluation methodologies to effectively counter environmental challenges [7]. Comparative studies further emphasize laser communication’s advantages over traditional RF methods, particularly concerning security, bandwidth efficiency, and minimized electromagnetic interference. Swami et al. (2022) notably demonstrated laser communication’s capacity to efficiently manage and transmit sensitive information securely in increasingly congested RF environments [1]. However, practical deployments of laser systems continue to face hurdles, predominantly due to atmospheric interference and signal attenuation caused by environmental factors such as fog and dust, necessitating continuous practical experimentation and innovation [7].

Applications of laser-based communication technologies have been steadily growing across terrestrial and space domains, underscoring their practicality and versatility. For instance, NASA's recent Laser Communications Relay Demonstration

(LCRD) showcases substantial advancements in space-to-ground data transmission, promising significant improvements in data rates and overall communication reliability for future space missions [8]. Terrestrial applications similarly benefit, particularly in urban infrastructure, emergency communication setups, and remote deployments where conventional RF or wired infrastructure is impractical or compromised [3]. Motivated by these existing gaps and needs, this research presents a low-cost, practical, laser-based communication testbed designed explicitly for educational and early prototyping purposes. The novelty of this study lies in its systematic evaluation of critical operational parameters such as baud rate impacts, simple optical beam-focusing solutions, and realistic interference emulations. Unlike complex systems previously described in literature, the proposed testbed integrates accessible components and user-friendly software to encourage widespread replication and experimentation.

The main objectives of this research include investigating the effects of baud rate variations on effective communication distances, exploring affordable methods to mitigate signal diffusion, evaluating performance robustness under various interference conditions, and developing a reliable half-duplex file transfer mechanism. Through addressing these objectives, this study aims to provide practical insights and accessible methodologies for broader educational engagement and effective prototype development in laser-based wireless communication.

2. SYSTEM DESCRIPTION AND METHODOLOGY

The laser transmission system begins with a computer connected via micro-USB to an ESP32 microcontroller [9]. This microcontroller prepares and transmits data through a KY-008 laser diode [10]. Due to the voltage mismatch between the ESP32 and the laser module, a transistor-based amplification circuit—comprising a 100Ω resistor and a 2N3904 NPN transistor—is used to power the laser adequately. On the receiving end, another ESP32 microcontroller is paired with a laser photodiode sensor that captures the transmitted data, processes it, and forwards it to a connected computer. This setup, illustrated in Figure 1, requires accurate alignment between transmitter and receiver for reliable communication. Figure 1 (A) is the Computer, (B) is the micro USB cable, (C) is the Microcontroller, (D) is the Laser transmitter and (E) is the Laser sensor.

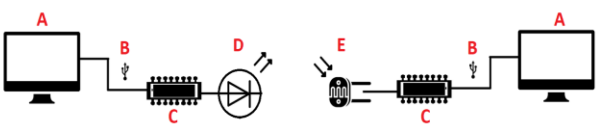

Fig 1: Laser transmission system design

To ensure reproducibility and practical accessibility, the system was constructed using the ESP32-WROOM-32 microcontroller board, which includes a dual-core Xtensa® 32-bit LX6 processor (80–240 MHz), 520 KB SRAM, and UART support for serial communication. The laser transmitter is a KY-008 module rated at 650 nm wavelength and 5 mW optical output power, operating at 5 V with >40 mA current draw. The receiver uses the ISO203 photodiode-based sensor module, which integrates an optical detection tube, a built-in amplifier, and an open-collector output transistor. These components were selected for their low cost, off-the-shelf availability, and straightforward integration with Python-controlled microcontroller environments.

2.1 Transmission system

The transmission system is driven by an ESP32-WROOM-32 microcontroller, which controls the KY-008 laser module via a transistor-based switching circuit. As shown in Figure 2, the ESP32's GPIO17 pin is connected to the base of a 2N3904 NPN transistor through a 100 Ω resistor. The transistor's emitter is grounded, and its collector is connected to the cathode of the laser module. The anode of the KY-008 module receives a 5 V supply from the ESP32 board. This setup allows the 3.3 V control signal from the microcontroller to switch the 5 V laser without exceeding the current limits of the GPIO pin.

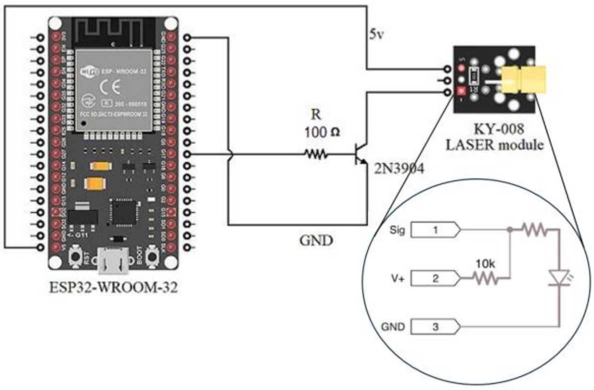

Fig 2: Composite schematic of the laser transmission setup

The diagram also illustrates the internal structure of the KY-008 module, which integrates a laser diode and a 10 kΩ current-limiting resistor. The module has three pins: Signal (Sig), Voltage supply (V+), and Ground (GND). The complete circuit is assembled on a breadboard, forming the core of the laser transmission unit used in the experiments.

2.2 Receiving System

The receiving side has its ESP32 module connected to the ISO203 laser photodiode sensor [11]. The GND pins are linked, pin G16 receives the sensor output, and the VCC of the sensor is connected to the ESP32's 3.3V output. These elements form the laser detection and reception circuit (see Figure 3). The ISO203 module outputs a digital signal that reflects laser intensity, allowing direct sampling via ESP32 GPIO without additional analog signal conditioning. Although phototransistors offer higher sensitivity, the photodiode-based ISO203 was preferred for its lower cost, availability, and sufficient response speed for the baud rate range considered (up to 614400). Its digital output simplifies integration with the UART decoder logic implemented in Python, minimizing the need for ADC processing.

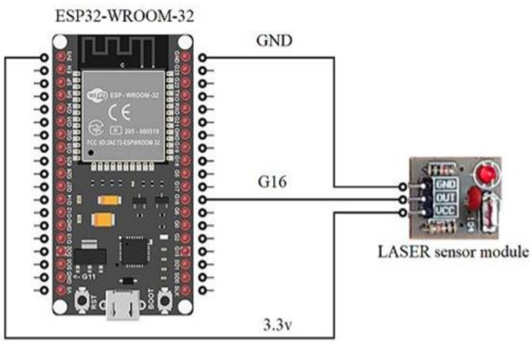

Fig 3: electrical connections for the receiving system

A more detailed view of the laser sensor module and its internal structure is presented in Figure 4. The ISO203 module integrates a photodiode and an internal amplification stage, producing a clean digital output when light is detected. This output is connected to the ESP32's GPIO16 input. The open-collector transistor design ensures compatibility with microcontroller input levels, while the internal circuitry also includes a power indicator LED and a decoupling capacitor for stable operation. The inclusion of this module simplifies signal detection without the need for external analog conditioning.

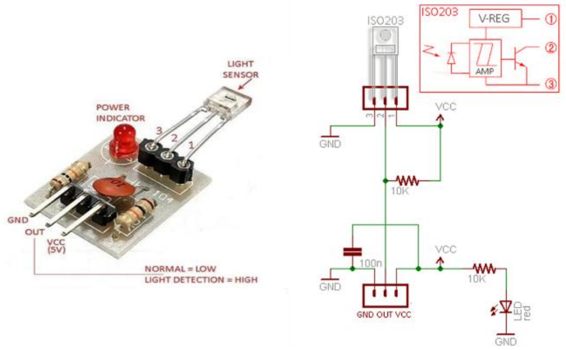

Fig 4: Detailed view of the ISO203 laser receiver module

2.3 Hardware Integration

To ensure reliable alignment during testing, both laser and sensor modules were mounted on height-adjustable bases (see Figure 5). This allows for stable positioning during range and interference testing, especially important when analyzing the effects of beam focusing and baud rate changes.

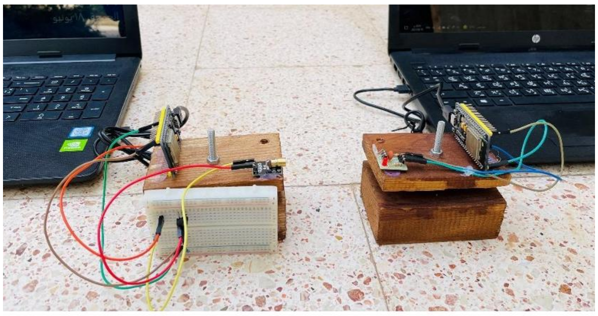

Fig 5: Full laser transmission system

2.4 Microcontroller Software and Algorithm

The ESP32 is programmed in Python using Visual Studio Code [12]. The software enables mode selection (transmit or receive), baud rate configuration, UART execution, pin assignment, and data processing. It supports both character and file-based transmissions and adheres to defined serial parameters: 8 data bits, no parity, and 1 stop bit. The software also includes input validation and UART-based data exchange.

The detailed logic of the system is encapsulated in the flowchart shown in Figure 6. It outlines how the system initializes, prompts user input for mode and baud rate, performs UART configuration, and handles data I/O.

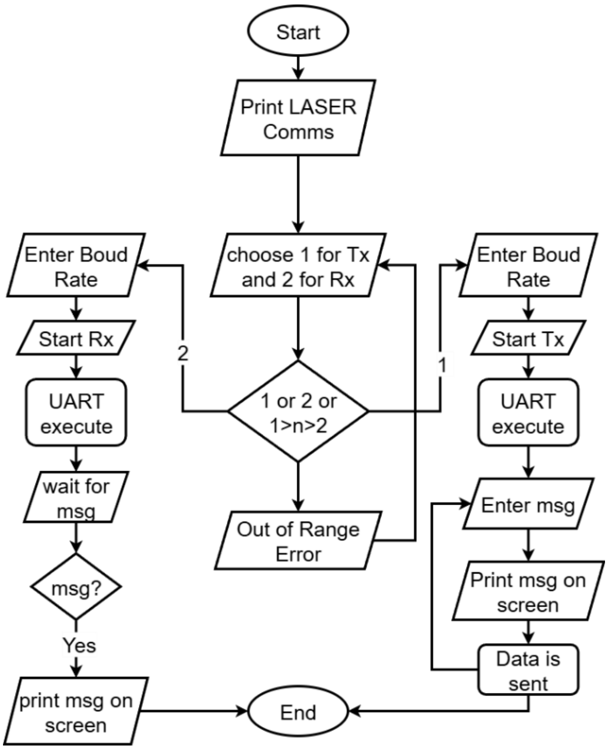

Fig 6: Microcontroller program flow chart

2.5 Experimental Setup

The experimental tests were conducted by aligning the laser and sensor on opposite ends of a linear path with variable distances. Tests covered:

- Varying baud rates from 75 to 614400
- Use of a magnifying glass (90 mm diameter, 2× magnification) positioned between the receiver and laser at optimal distances (30–50 cm depending on the range)
- Testing under environmental interference simulated using fading sheets of 50%, 20%, 15%, and 5% tint levels

Each condition was repeated for consistency. The tests were also extended to include a half-duplex communication system, featuring an additional laser-sensor pair for bidirectional transmission and improved software with GUI control. The schematic for this enhanced wiring is shown in Figure 7, and the completed implementation is depicted in Figure 8.

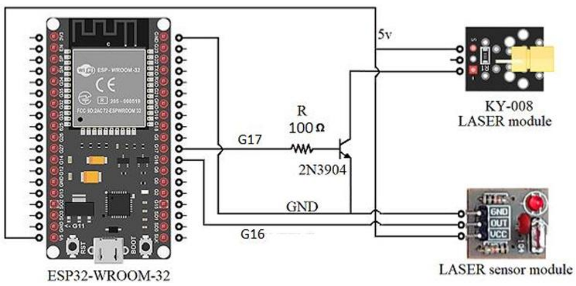

Fig 6: half-duplex Laser file transmission system wiring

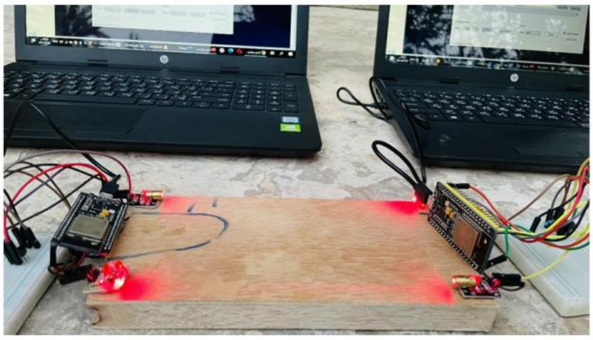

Fig 7: half-duplex file transmission system implementation

The corresponding software algorithm is detailed in the flowchart shown in Figure 9.

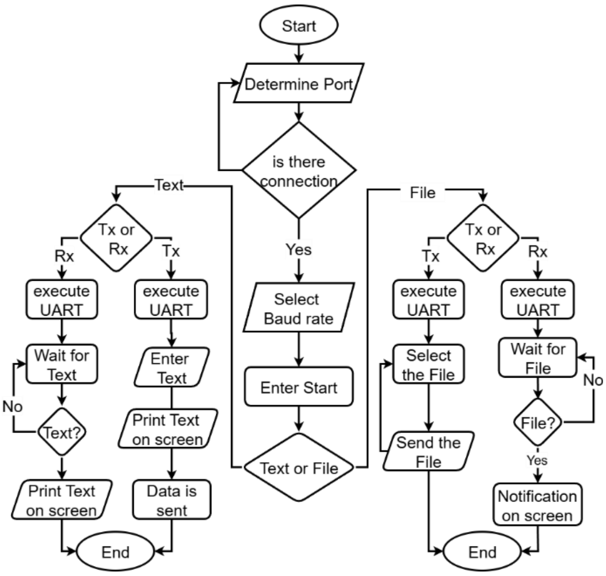

Fig 9: Half-duplex Laser file transmission system software flow chart

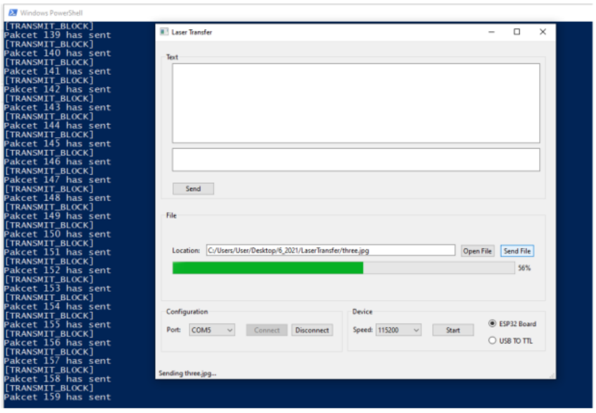

Fig 10: File transmission process in the user interface

Users interact with the half-duplex system through a Python GUI, selecting baud rates and ports, uploading files, and observing real-time transmission and reception processes as seen in Figure 10. All experimental tests were repeated a minimum of three times to ensure repeatability, with the results averaged across trials. The laser and sensor modules were mounted on custom-built, height-adjustable wooden bases to facilitate precise alignment. Environmental conditions such as ambient light levels were kept constant during indoor testing to minimize measurement error. The effective transmission distance was recorded as the point at which consistent byte-level reception was no longer possible. For each baud rate setting, successful reception was confirmed via both real-time console output and logged file validation.

3. RESULTS AND DISCUSSION

3.1 Effect of Baud Rate

The impact of baud rate on maximum achievable transmission distance was examined by varying baud rates between 75 and 614400. Results indicate a clear inverse relationship between baud rate and maximum transmission distance. As baud rates increase, the effective communication range significantly decreases due to increased sensitivity to signal degradation and timing mismatches in data reception (see Figure 11).

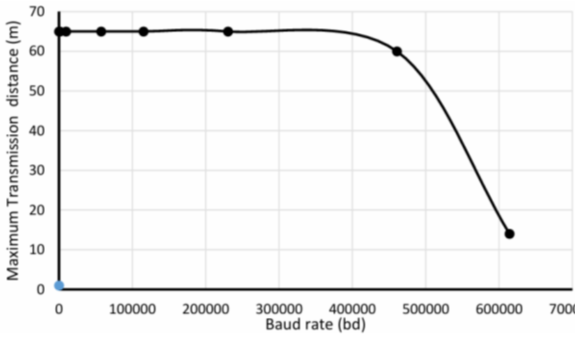

Fig 11: Effect of the baud rate on the maximum transmission distance

At lower baud rates (75–230400), the system maintained stable transmission up to 65 meters, with minimal errors. However, at higher baud rates (460800 and beyond), transmission distances dropped sharply, with data loss observed beyond 60 meters at 460800 baud and complete transmission failure occurring at 614400 baud, which only achieved 14 meters. This degradation is consistent with previous studies on optical wireless communication, which highlight the increased bit error rate (BER) at higher baud rates due to limited synchronization tolerance [6].

The trend observed suggests that the transmission performance is highly tolerant to baud rate increases up to 230400 bd, after which the system enters a nonlinear degradation phase. Between 230400 bd and 460800 bd, the maximum transmission distance dropped by 7.69%, and further decreased by 76.67% when baud rate reached 614400 bd. This confirms the expected rise in bit error rate (BER) and increased UART synchronization difficulty at higher speeds, as outlined in prior optical wireless studies [6]. During experiments, successful transmission at 614400 bd was only reproducible within a very narrow alignment window (<2° angular tolerance), indicating a sharp decline in robustness at high baud rates.

3.2 Effect of Beam Collimation and Focusing

The use of a converging lens, specifically a magnifying glass, significantly improved transmission distance by reducing laser beam divergence, thereby enhancing beam collimation. At 1200 baud, transmission range increased from 65m to 100m, yielding an approximate 54% improvement (see Figure 12). This result is consistent with the principles of geometric optics, where a convex lens focuses or collimates a divergent beam, maintaining higher irradiance over longer distances.

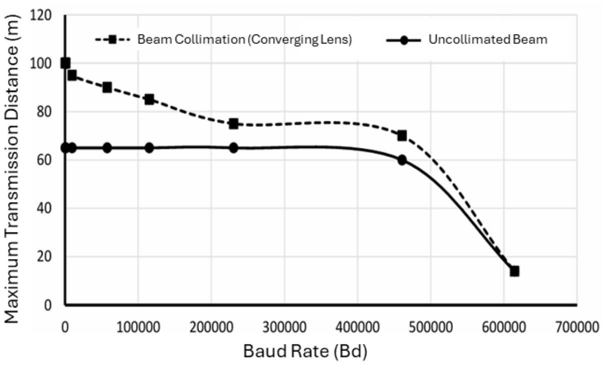

Fig 12: Effect of beam collimation

The effect of beam focusing at different baud rates is summarized in Table 1. While the lens-based beam collimation mitigated losses at moderate data rates, its effectiveness decreased at higher baud rates. One key limitation of this method is its alignment sensitivity as a slight misalignment in the optical path can result in substantial power loss or beam deviation, especially over longer distances. Despite this, lens-assisted beam collimation provides a simple and effective solution for medium-range optical communication—particularly in static environments where mechanical stability and precise optical alignment can be maintained as shown in the table below.

Table 1. Effect of beam focusing

Baud Rate	Using Lens (m)	Base Case (m)	Percentage of Increase (%)
75	100	65	53.85
1200	100	65	53.85
9600	95	65	46.16
57600	90	65	38.47
115200	85	65	30.77
230400	75	65	15.39
460800	70	60	16.67
614400	14	14	0

The lens-assisted collimation improved transmission range by 15–54% across most baud rates. This improvement was most significant at lower baud rates (e.g., 75–1200 bd), where beam divergence was the primary limiting factor rather than timing sensitivity. At 1200 bd, the range increased from 65 m to 100 m, a 53.85% gain. However, for 614400 bd, there was no observed benefit, which reinforces the idea that at high baud rates, temporal errors outweigh geometric alignment losses. These findings are consistent with geometric optics principles and suggest that passive optical focusing can be a practical enhancement for low-speed free-space communication systems in educational or IoT applications.

3.3 Effect of Environmental Interference

To assess the impact of environmental interference on the laser communication link, optical filters with known transmittance levels were used to simulate various atmospheric visibility conditions. Rather than using arbitrary tint percentages, these filters approximate real-world scenarios such as haze and fog by controlling the fraction of light allowed to pass through. The experiment draws parallels to meteorological visibility by relating transmittance to the atmospheric extinction coefficient using the Koschmieder equation [13]:

$$V = \frac{3.912}{\beta} \quad (1)$$

Where V is the meteorological visibility (in km), and β is the atmospheric extinction coefficient (in km^{-1}).

As shown in Figure 12, a filter with 50% transmittance corresponds to an extinction coefficient of approximately 1.386 km^{-1}, indicating a visibility of around 2.82 km—comparable to moderate haze. Under these conditions, the maximum transmission distance was reduced by 91.67%. At 75 baud, complete signal attenuation occurred with filters allowing only 20% transmittance, equivalent to visibility of roughly 0.86 km, mimicking dense fog. These results highlight the high sensitivity of laser-based communication systems to light scattering and absorption under reduced visibility, emphasizing the need for adaptive modulation or hybrid fallback mechanisms in such environments.

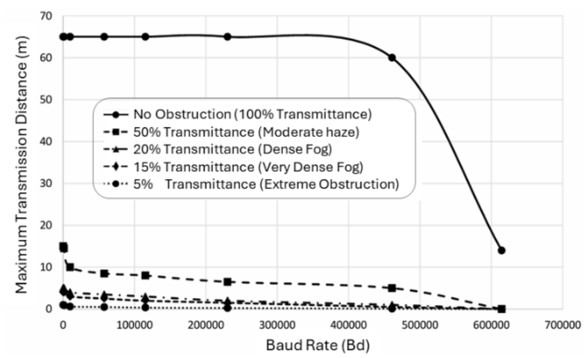

Fig 13: Maximum transmission distance at varying visibility condition vs base case

Further results in Figure 14 demonstrate the transmission losses for different opacity levels.

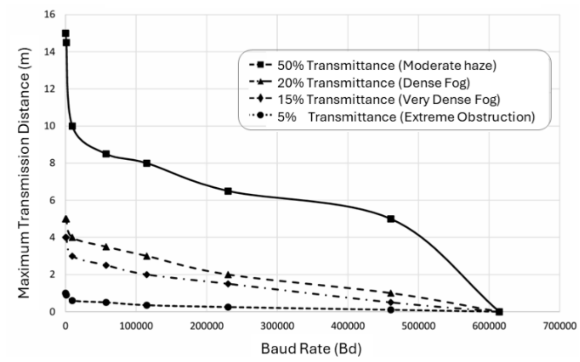

Fig 14: Maximum transmission distance at varying visibility condition

These results are consistent with previous studies on free-space optical communication, which emphasize atmospheric turbulence and particulate matter as significant sources of signal degradation [7]. Practical applications of laser communication must, therefore, consider dynamic environmental conditions, necessitating adaptive modulation techniques or hybrid RF-optical approaches in challenging deployment scenarios.

The correlation between transmittance level and transmission distance degradation was found to be nonlinear. For instance, reducing transmittance from 100% (base case) to 50% caused a distance drop of over 90%, even though only half of the light intensity was attenuated. This suggests a threshold-based sensitivity in laser reception, where small reductions in beam intensity lead to large reception failures beyond certain SNR cutoffs. The laser system, being purely line-of-sight and unmodulated, lacks adaptive thresholding or AGC (automatic gain control), which explains this steep decline. Moreover, at 614400 bd, no signal was received even under the least tinted filter (50%), confirming that high baud rates are not only sensitive to timing but also to SNR loss under minor atmospheric attenuation.

3.4 Half-Duplex System Performance

The half-duplex implementation of the system was tested for text and file transmission to assess performance reliability under varying conditions. Text transmission at lower baud rates showed minimal latency and consistent success across all distances up to 100m. File transmission tests demonstrated reliable operation with text files up to 50KB, but larger files (>500KB) experienced increased transfer time and occasional failures at baud rates above 115200 (see Figure 15).

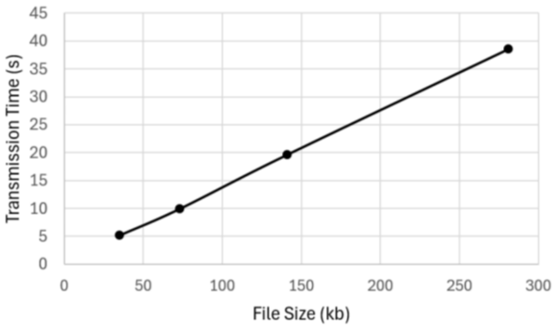

Fig 15: Transmission time for each file size

Transmission speed was observed to remain consistent regardless of file size, as shown in Table 2, with an average transmission speed of 7.16 kb/s. File type was also tested, confirming that transmission performance was not affected by whether the file was an image or text document.

Table 2. Transmission time and transmission speed for each file size

File Size (kb)	Transmission Time (s)	Transmission Speed (kb/s)
35	5.15	6.80
73	9.9	7.37
141	19.6	7.19
281	38.53	7.29
Average		7.16

Although transmission speeds averaged around 7.16 kb/s, there was slight variation due to initial connection latency and UART handshaking delays. The transmission times were linearly correlated with file sizes ($R^2 > 0.99$), confirming stable throughput under ideal alignment conditions. Notably, file type had no measurable impact on performance, as the system processes data as binary blocks. However, for files exceeding 500 KB, occasional retransmission was required due to synchronization losses during long continuous streams, especially at baud rates above 115200. This limitation could be addressed in future iterations by implementing buffering or block-based retransmission with checksum validation. A key advantage of half-duplex communication is its ability to facilitate bidirectional communication while minimizing synchronization issues. However, the primary trade-off is latency due to the alternating nature of data flow. Future improvements could involve full-duplex implementation or buffering techniques to optimize performance for larger file transfers. These results affirm the practical applicability of the system for short to medium-range secure communication, particularly in controlled environments where interference can be minimized.

3.5 Evaluation Scope and Future Extensions

The evaluation conducted in this study covered multiple practical transmission scenarios, including baud rate scaling, beam collimation with a low-cost lens, environmental interference emulation using calibrated tint filters, and varying file types and sizes in a half-duplex transfer setup. These scenarios were selected to reflect real-world constraints relevant to low-cost, educational, and prototyping applications of free-space optical communication.

To further extend the evaluation, future work may include stress testing under variable ambient light conditions (e.g., daylight interference), angular misalignment tolerance studies, and incorporation of modulated laser signaling for noise resilience. Additionally, introducing lightweight error correction protocols or assessing the system under controlled outdoor field conditions would provide deeper insight into deployment feasibility. These scenarios could expand the dataset of operational conditions, further validating the robustness and usability of the system beyond lab constraints.

3.6 Conclusion

This study presented the design, implementation, and experimental evaluation of a low-cost, practical laser-based communication system intended for educational and prototyping applications. The system demonstrated effective one-way and half-duplex transmission capabilities using readily available hardware components and Python-based microcontroller software. Experimental results confirmed that higher baud rates reduce transmission distance due to increased sensitivity to signal degradation, while optical focusing using a simple lens setup can significantly extend the communication range—up to 54% improvement at low baud rates. Environmental interference tests further highlighted the vulnerability of laser-based communication to atmospheric attenuation, underscoring the importance of alignment and visibility. The half-duplex file transfer system proved to be reliable for small to medium-sized files, maintaining a consistent transmission speed and operating independently of file type.

This system provides a scalable foundation for further development in low-cost optical communication. Future work could explore the adoption of modulation techniques (e.g., pulse-width or amplitude modulation) to improve data robustness, the implementation of full-duplex communication to reduce latency, and the integration of error detection or correction protocols to mitigate transmission loss in noisy environments. Outdoor deployment trials, support for longer-range transmission, and adaptive optical alignment mechanisms may further extend the system's practical utility. Additionally, the platform holds considerable value for academic settings, offering a hands-on, cost-effective tool for demonstrating optical communication principles in laboratory courses or student research projects.

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