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Reliable V2V networks via LED-based Li-Fi technology for road safety applications

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ABSTRACT

Road traffic accidents remain a significant global challenge, causing substantial loss of life and severe injuries annually. This research proposes a vehicle-to-vehicle (V2V) communication system based on light fidelity (Li-Fi) technology to enhance road safety through low-latency and reliable optical wireless communication. The proposed approach utilizes visible light communication, where light-emitting diodes (LEDs) integrated into vehicle headlights and tail lights act as optical transmitters, while photodiodes installed on receiving vehicles detect transmitted signals. Manchester coding is employed to improve signal integrity by reducing noise effects and enhancing reliable data transmission. The developed system was evaluated through simulation analysis and experimental validation using a hardware prototype and digital storage oscilloscope (DSO) measurements. The results demonstrate successful transmission and reception of digital data with low error rates and consistent agreement between simulation and practical outcomes. The prototype achieved reliable communication over a distance of 15 cm, with performance influenced primarily by transmitter–receiver separation, light intensity, and photodiode sensitivity. The findings confirm that Li-Fi-based V2V communication is a promising, cost-effective, energy-efficient, and low-latency solution for future intelligent transportation systems. Further improvements using LED arrays, advanced modulation techniques, and signal processing methods can extend communication range and enhance system robustness for real-world applications.

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1. INTRODUCTION

The rise of wireless communication has profoundly transformed the nature of human interaction, the flow of information, and the development of intelligent systems [1]. In recent decades, there has been a significant increase in the need for communication systems that are fast, dependable, and devoid of interference. This trend has light-emitting diode (LED) to the exploration of innovative alternatives to

conventional radio frequency (RF-based) systems, such as Wi-Fi. Among the innovative technologies, light fidelity (Li-Fi) has garnered considerable interest [2]. Professor Harald Haas of the University of Edinburgh first presented the idea of Li-Fi in a TED Talk, where he showed how visible light may be used for fast wireless communication. This technology largely relies on LEDs, which are capable of conducting rapid intensity modulation to communicate digital information at speeds that are imperceptible to the human eye [3], [4]. Reliable and affordable vehicle safety solutions are desperately needed, as seen by the rising number of traffic incidents across the globe. Road safety is a major concern for both policymakers and researchers, as the World Health Organization reports that over 1.2 million people die in traffic accidents annually [5], [6]. In this regard, vehicle-to-vehicle (V2V) communication has become a potential technique for lowering accidents by exchanging vital data in real time, including vehicle position, speed, and direction. V2V communication systems have historically relied on RF technologies. These systems do, however, confront a number of difficulties, such as restricted spectrum availability, signal interference, and security flaws. Li-Fi, which functions within the framework of visible light communication (VLC), has been suggested as an effective, safe, and interference-resistant substitute for traditional RF-based vehicular communication systems in order to overcome these drawbacks [7]–[9]. Li-Fi is a cutting-edge optical wireless communication technology that uses photodiodes as receivers, LEDs as transmitters, and the atmosphere as the transmission medium. LEDs are ideal for both illumination and data transfer applications due to their inherent qualities, which include excellent energy efficiency, a long operating lifespan, and compact size [10]. The inability of visible light to pass through solid obstacles like walls, in contrast to RF transmissions, improves communication system security. High-speed data transmission is also made possible by the visible light spectrum's substantially larger bandwidth compared to the RF spectrum [11], [12]. Because of these benefits, Li-Fi is especially well suited for automotive communication contexts, where low-latency data interchange, safety, and dependability are crucial criteria [13].

The implementation of Li-Fi technology in V2V communication systems offers numerous advantages. Contemporary vehicles are equipped with LED headlights, tail lights, and interior illumination, which can be readily adapted to function as optical transmitters [14]. Vehicles are capable of utilizing photodiodes to identify optical signals, thereby ensuring efficient data reception. This approach leverages automotive infrastructure to reduce implementation expenses. Li-Fi systems exhibit immunity to electromagnetic interference, rendering them suitable for safety-critical environments where RF-based communication could face disruption or congestion [15], [16]. Visible light diminishes health risks and bolsters worldwide efforts to advance environmentally sustainable and energy-efficient communication technologies [17].

Recent advancements in Li-Fi and VLC technologies have notably improved modulation techniques, prototypes, and applications. Research has investigated multiple modulation techniques, including on-off, amplitude-shift, frequency-shift, and Manchester coding, aimed at enhancing the speed, reliability, and noise resilience of these systems [18]. Among these, Manchester coding has surfaced as a noteworthy technique for automotive applications, owing to its capacity to maintain optical power, minimize flickering, and facilitate receiver synchronization [19]. Experimental findings indicate that LEDs are capable of transmitting binary sequences at elevated speeds, while photodiodes demonstrate proficiency in detecting and decoding these signals, even amidst noisy conditions [20]. V2V communication systems utilizing Li-Fi technology hold significant promise for improving road safety by minimizing accidents, easing traffic congestion, and advancing intelligent transportation systems. Earlier prototypes employed transmitters and receivers based on Arduino technology, integrating LED arrays and PIN diodes for the short-range transmission of digital information [21]. Nevertheless, current systems face constraints due to elements like LED brightness, photodiode configurations, and the absence of advanced modulation methods that could enhance efficacy over extended ranges and in difficult conditions [22]. Although certain research has shown that Li-Fi can achieve data transmission over distances of up to 40 meters in controlled environments, issues like alignment, interference from ambient light, and the expansion of range have yet to be adequately tackled [23], [24].

This research addresses a significant gap by integrating Manchester coding with hardware prototyping specifically for V2V safety applications. In contrast to previous research that tends to examine modulation or hardware separately, our study presents an innovative methodology that combines these components to enhance the speed, reliability, and range of V2V communication systems in dynamic, real-world settings. Furthermore, we emphasize the robustness of the system in the face of spectrum congestion, a notable benefit of Li-Fi compared to conventional Wi-Fi, which improves the system’s efficiency in densely populated urban settings. This integration facilitates the swift dissemination of essential safety information, including braking signals, collision alerts, and lane-change notifications [25]. Furthermore, this research broadens the scope of Li-Fi utilization by integrating it with positioning technologies such as global navigation satellite systems (GNSS), aiming to improve the precision and efficiency of vehicular networks, an area that has not been thoroughly investigated in earlier studies [26]. Prior research has utilized

optimization methods, including gray relational analysis (GRA) and Taguchi techniques, to assess system performance and create robust prototypes [27]. This research advances the field by utilizing a practical hardware-based methodology to assess real-world performance, offering fresh perspectives on the viability and efficiency of Li-Fi in V2V communication systems across various driving scenarios.

The construction of a prototype system for collision avoidance purposes is the primary focus of this section, which lays out a systematic approach to integrating V2V communication utilizing Li-Fi technology. Incorporating Manchester coding to reduce noise and guarantee dependable data transfer, the suggested framework makes use of vehicle headlights for transmission and photodiodes for reception. Quick data transmission and reception are made possible by this study's persuasive implementation of a Li-Fi-based vehicle communication system. The suggested theoretical framework was validated through simulation studies conducted using Proteus. After that, we used a digital storage oscilloscope (DSO) to do experimental verification and put the hardware into action. The findings back up Li-Fi's potential as an efficient and cost-effective way to improve road safety.

This study advances the area by creating a thorough system model, building and modeling the framework, and testing it with hardware. This articles future section follows this pattern. Section 2 gives an overview of the system, section 3 describes model development, section 4 covers system design and simulation, section 5 covers hardware implementation and testing, and section 6 concludes with key findings and future research.

2. SYSTEM OVERVIEW

With a capacity 10,000 times higher than that of conventional Wi-Fi communication, Li-Fi is a sophisticated wireless network that uses the visible light spectrum for data transfer. This method is efficient and effective for encrypted communication, as light can unable to penetrate walls, and inexpensive LED lights facilitate the transfer of information.

In the last few decades, a notable design proposed for wireless optical communication is the VLC method. Figure 1 illustrates the spectrum of VLC. The electromagnetic spectrum encompasses light signals within the wavelength range of 380-780 nm, which are detectable by the human eye. Illumination and data transfer can be achieved through VLC. VLC refers to an optical wireless communication system that transmits information through the modulation of visible light. Communication is achieved through the rapid modulation of LED lights, toggling them on and off at a frequency beyond human visual perception.

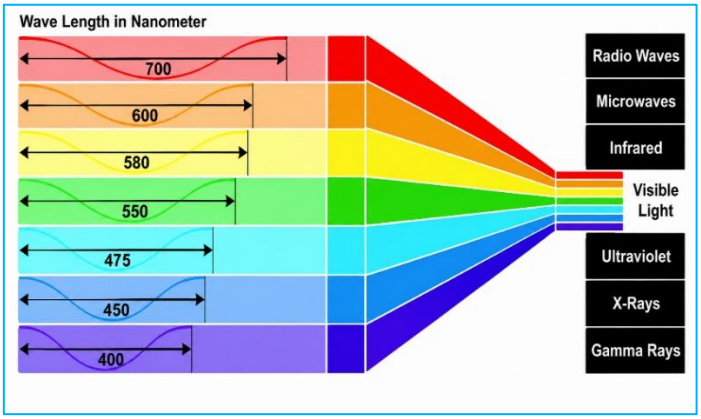


Figure 1. VLC spectrum

It is feasible to achieve simultaneous illumination and data transmission using LEDs, which have emerged as a leading lighting technology in recent times. Illumination and data transmission can be achieved independently, without the need for an additional communication system. Figure 2 illustrates the block diagram of the VLC system. The technology under consideration offers a variety of advantages, including the assurance of human safety, the attainment of high data transmission rates, the provision of substantial breath and width, the improvement of security protocols, and the support of communication reliant on visibility. VLC shows significant potential in a range of applications, such as position detection, intelligent transportation systems, smart retail environments, image sensor communication, audio transmission, networking, and improvements in aesthetic lighting.

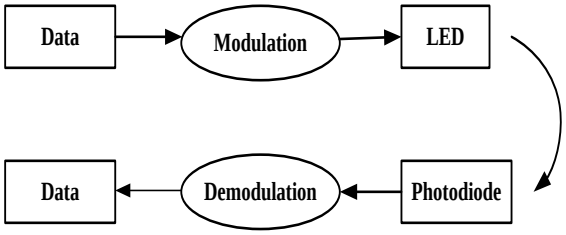


Figure 2. VLC

The system facilitates rapid, economical, and accessible wireless communication, eliminating the necessity for spectrum licensing. Serving as an alternative to traditional Wi-Fi, VLC can be efficiently utilized in various settings, both indoors and outdoors, to ensure dependable data transmission.

A schematic of the Li-Fi network is shown in Figure 3. A transmitter and a receiver are the two main parts of the system. On the receiving end, an ADC converts the data (the speedometer reading) to binary. A high-powered LED then rapidly blinks to enable data transmission by optical pulses across a wireless channel. A photo detector processes the optical pulses and converts them into an electrical signal at the receiving end. A transimpedance amplifier is used to boost the signal, and a comparator is used to convert it back into binary data.

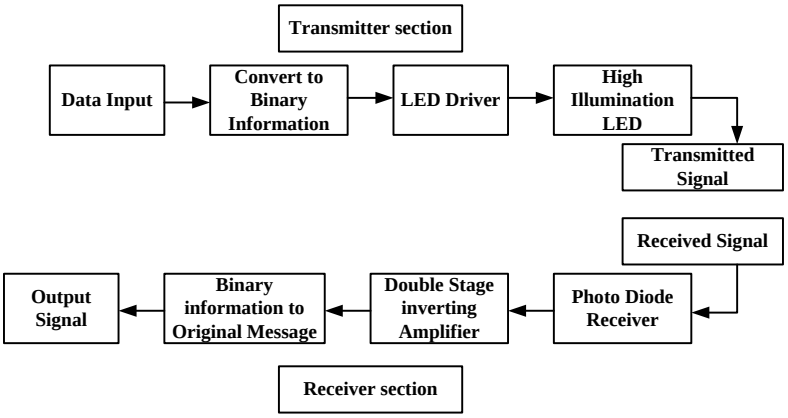


Figure 3. Li-Fi system

3. MODEL DEVELOPMENT

The modulation techniques utilized in VLC are markedly distinct from those used in RF communication, mainly due to the fact that information in VLC is not encoded via changes in the phase or amplitude of the optical carrier. Modulation is accomplished through the adjustment of the emitted light's intensity, with variations in light intensity reflecting the information embedded in the message signal. Two significant elements that affect modulation in VLC systems are dimming control and flicker mitigation.

The adjustment of light intensity should be executed to prevent variations that can be detected by the human eye. The IEEE 802.15.7 standard mandates a switching frequency exceeding 200 Hz to avoid visible flicker and ensure safe, comfortable lighting conditions. VLC systems employ several modulation techniques, including OOK, pulse modulation methods, and CSK. Among these methods, on-off keying is often preferred due to its simplicity and ease of implementation.

Nonetheless, the presence of surrounding light sources can diminish the effectiveness of VLC systems. In order to tackle this challenge, Manchester coding is frequently employed to enhance signal reliability and mitigate the effects of background noise. Figure 4 depicts the creation of the Manchester-coded signal.

The Manchester coding technique is used in VLC systems to control illumination and reduce flicker in LED applications. Throughout the data transmission process, the average optical power of LED light is kept constant thanks to the Manchester coding approach. The development of baseband VLC systems can benefit greatly from this simple approach, which guarantees flicker-free operation, permits illumination control, and shows robustness against noise from adjacent light sources.

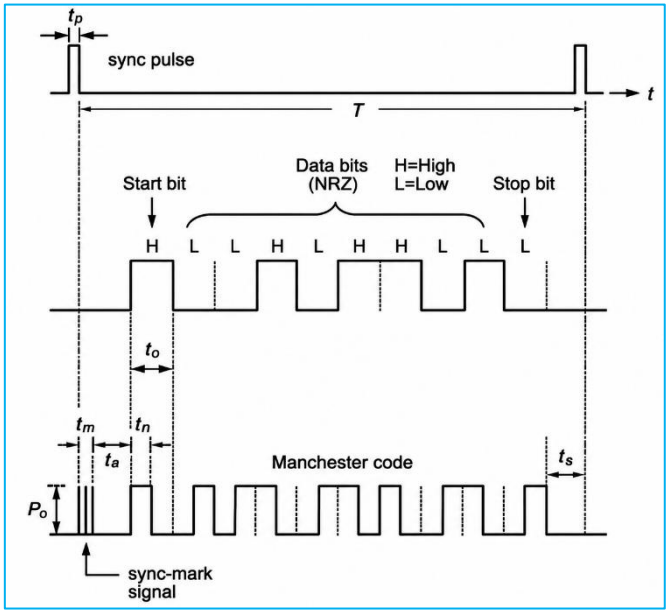


Figure 4. Generation of the Manchester code signal

In order to ensure the circuit operated safely and steadily, the current-limiting resistance for the LED was computed. The voltage drop across the LM317 regulator is roughly 3 V, and the LED requires an operational current of 20 mA. In the LM317 constant-current arrangement, the forward voltage drop of the LED is 3.2 V, while the voltage drop across resistor R_1 stays at 1.25 V. Consequently, 3.2 V+3.0 V+1.25 V=7.45 V is the overall voltage loss in the circuit. A 9 V battery was chosen as the power source in order to offer enough operating margin. The system's LED has a 400 mA current rating. The relationship between the reference voltage of the LM317 and the intended LED current is used to calculate the value of the current-setting resistor R1. Consequently, the resistor value is computed as shown in (1):

$$R_1 = \frac{\mathrm{V}_{R1}}{\mathrm{I}_{LED}} \quad (1)$$

Thus, a resistor of approximately 3.1 Ω is required to maintain the desired LED current in the circuit. The current-limiting resistor's value was found to be 3.125 Ω. Furthermore, a new technology for visible light transmission was created, which uses a spike detection mechanism for data retrieval in the VLC receiver and the duty factor of the Manchester code for illumination management in the VLC transmitter.

4. STUDY SYSTEM DESIGN AND SIMULATION

The next one presents an in-depth examination of the simulation process for the Li-Fi system. The proposed system design was simulated utilizing Proteus 8 Professional software. Transmission and receiving modules make to the system's architecture. The model implies that vehicle A's back lights broadcast binary data pulses of 0 s and 1 s. The LED modulation frequency is high enough to hide the fast switching. A photodiode in front of vehicle B converts the optical signal into an electrical current for processing. In circumstances where vehicle A brakes, the back lights notify vehicle B, allowing vehicle B to respond quickly and avoid crashes. Figures 5 and 6 illustrate the block diagrams for the transmitter and receiver modules, respectively.

To measure the car's speed, an infrared speed sensor was employed. A continuous current was supplied to the LED by the Arduino UNO, which processed the data and transferred it to the LED driver, in response to the application of the brakes. When the brake was used, an alert would be activated and the liquid crystal display would show the speed. The photo detector picked up the data signal that the LED was putting out. The received signal was so weak that it could not be detected. To solve this problem, we used a trans-impedance amplifier to boost the current pulse and make it easier to convert it to a voltage pulse, which the Arduino could process with ease. The pulse beep went off and an LCD warning about needing to brake came up as soon as it was detected.

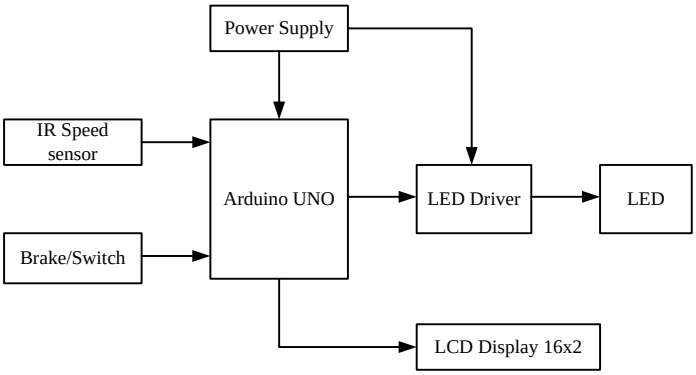


Figure 5. Transmitter section

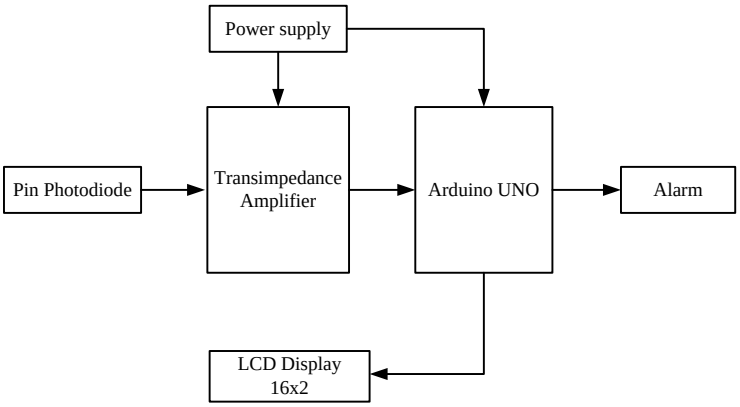


Figure 6. Receiver section

Figure 7, which uses Proteus 8 software to simulate the transmitter, depicts the basic transmitter circuit. The transmitter's simulation results as seen on a digital oscilloscope are displayed in Figure 8. The PWM signal that activates the LED is sent by the function generator employed in this investigation. For the LED to operate, the BC547 transistor served as a tiny signal switch. A 9 V battery, in conjunction with current-limiting resistors, was deployed to assure the safe operation of the LED. The voltage drop across the resistors and LEDs was measured using a voltmeter.

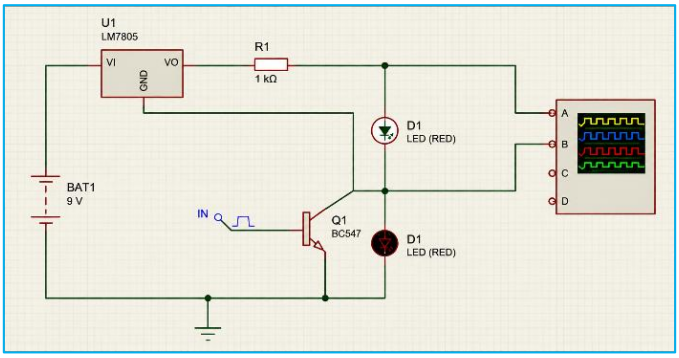


Figure 7. Transmitter side simulation on Proteus 8 software

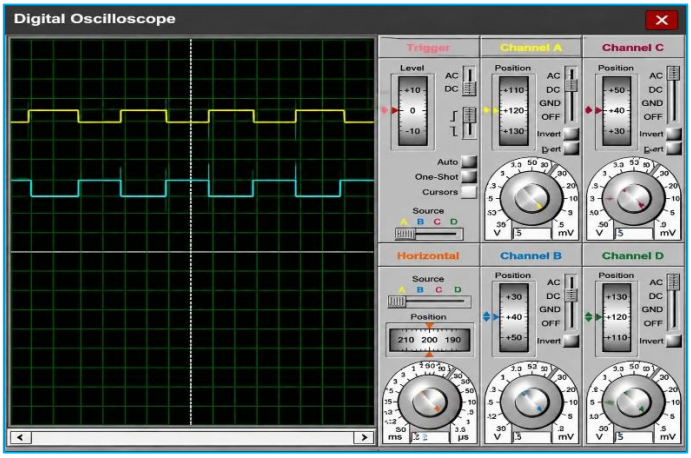


Figure 8. Simulation results of transmitter on digital oscilloscope

The yellow waveform shown in Figure 9 represents the simulation on the receiver side, performed with Proteus 8 software, utilizing input from the signal generator. The blue waveform illustrated in Figure 10 depicts the simulation outcomes of the receiver section, as recorded on the digital oscilloscope output of the LED. A single LED at 1 Hz was analysed for the preliminary assessment. Findings show that a lit LED indicates logic state 1 and a non-illuminated LED represents logic state 0. In digital systems, information is conveyed through varying voltage levels. The voltage spectrum spans from 0 to 5 V. When the voltage is at zero, there is an absence of current flow through the LED.

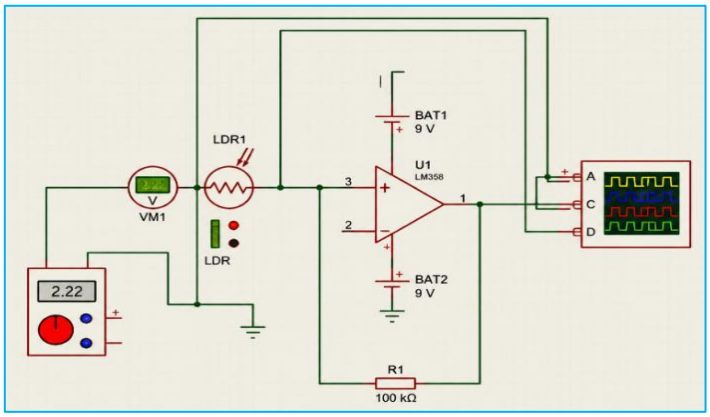


Figure 9. Receiver side simulation on Proteus 8 software

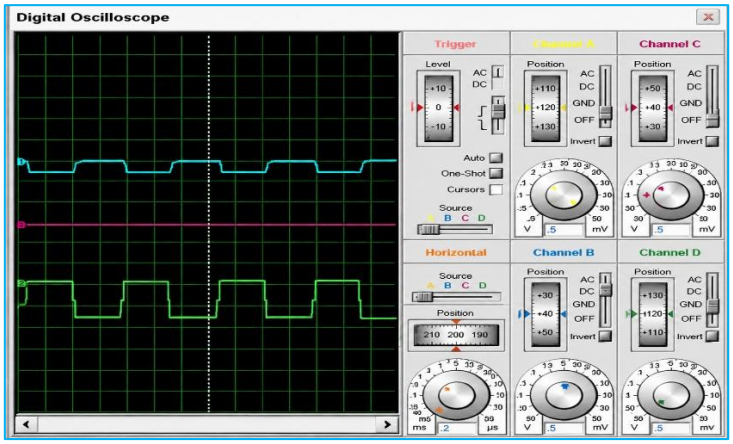


Figure 10. Simulation results of receiver section on digital oscilloscope

The LED remained off under this condition. Conversely, 5 V supplied voltage activated the LED by flowing current. Figure 11 shows the transmitter-receiver circuit simulation, whereas Figure 12 shows the simulation results for the same configuration. Waveform analysis shows the transimpedance amplifier's input data as blue and the amplified output waveform as green. Blue represents data broadcast from the transmitter module, while green represents the amplified signal received at the receiver end. The transmitter and receiver module design methods and simulation are thoroughly examined in this work. DSO experiments verified system operation. The proposed communication method worked because all transmitted data were received and accurately rebuilt at the receiver end.

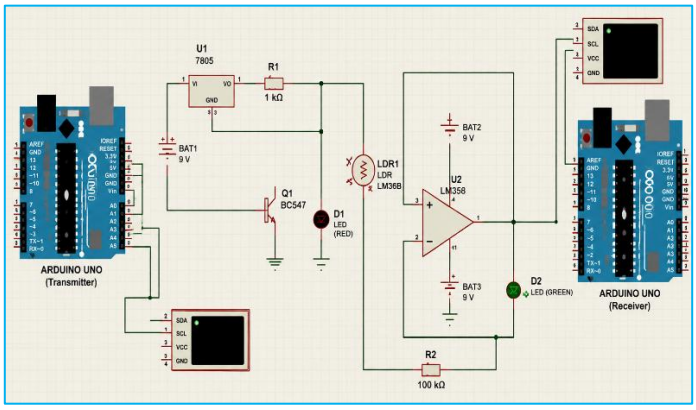


Figure 11. Combine simulation of transmitter and receiver circuit

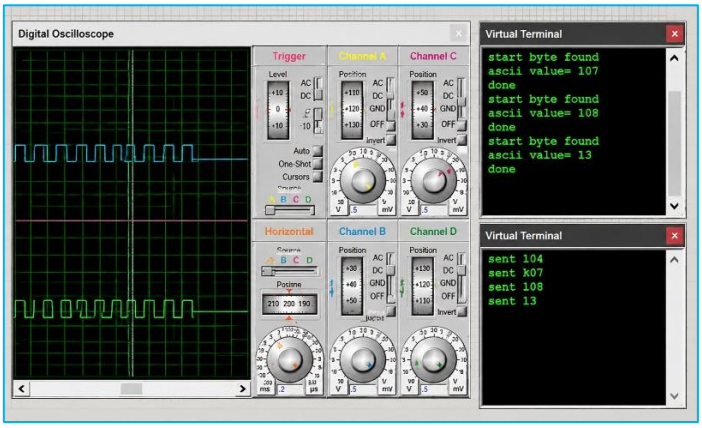


Figure 12. Combine simulation results of transmitter and receiver circuit

5. HARDWARE IMPLEMENTATION AND TESTING

Converting digital data into visible light is the transmitter's job. We opted for an LED because we saw a clear relationship between the amount of current flowing through it and the amount of light it produced. Modulating the LED's brightness is the main idea, with the brightness being proportional to the data being conveyed. When it comes to achieving sufficient light intensity quickly, the Arduino ports just can't cut it. The use of a transistor as a switching mechanism allowed for the quick control of a bigger current, which solved this problem. The receiver uses a photodiode to convert incoming light into electricity. It's crucial to remember that the Arduino's maximum voltage threshold for reception is 5 V when discussing digital communications. The electrical circuit that connects the photodiode to the Arduino must efficiently handle the electrical signal in order to solve this problem and guarantee precise interpretation. The current must be converted into voltage by the receiver portion in order to be amplified and compared.

The transmitter section's hardware design is shown in Figure 13, while the receiver section's hardware design is shown in Figure 14. Although the distance between the transmitter and receiver can be changed, a transimpedance amplifier is used to avoid abnormally high or low signal levels. A variable

potentiometer resistor is incorporated into the design. To reach a certain output voltage level, a transimpedance amplifier either amplifies or attenuates the input voltage. In this case, an op-amp comparator is used to confirm the signal's digital stability before it is fed into the Arduino.

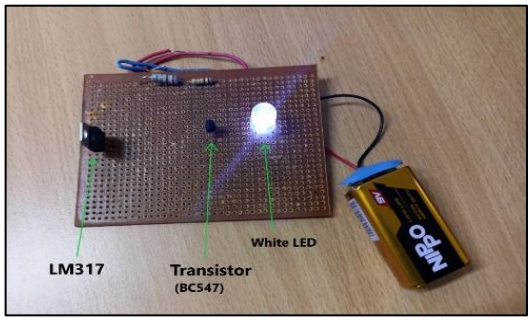


Figure 13. Hardware design of transmitter section

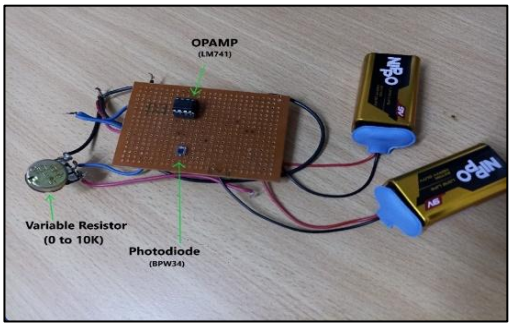


Figure 14. Hardware design of receiver section

The design was validated and the desired qualities were assessed by experiments. For the most part, these assessments made use of Proteus 8 Professional. To adjust the prototype's resistance settings for amplification, text is transmitted as a test signal during calibration. The results of the full system's design validation, which included the software, receiver, and transmitter, are shown in Figure 15. Perform hardware testing.

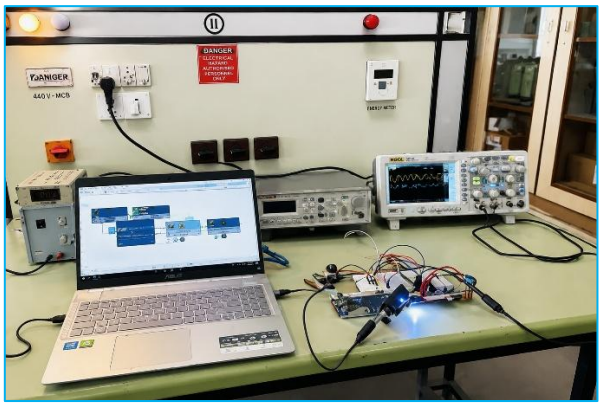


Figure 15. Testing of hardware

The performance of the transmitter and receiver in the Arduino-based Li-Fi system is described in detail in the following sections. The waveform acquired on the DSO for the transmitter part is shown in Figure 16, while the waveform obtained on the DSO for the reception section is shown in Figure 17, which shows the Arduino signal as it passes through both the transmitter and the receiver. The acquired propagated signal was nearly identical to the initial broadcast signal. When compared to the sent signal, the received signal showed a little phase discrepancy and a change in duty cycle. This phenomenon can be linked to interference inside the wireless channel and the influence of capacitive effects.

A completely functional Li-Fi model has been put into place. Figures 18 and 19 show the VLC concept of Li-Fi. With the help of Arduino, a Li-Fi transceiver with an array of LEDs was created to make digital data transmission easier. In hardware testing, the waveforms shown on the CRO seemed to match the ones obtained from simulation.

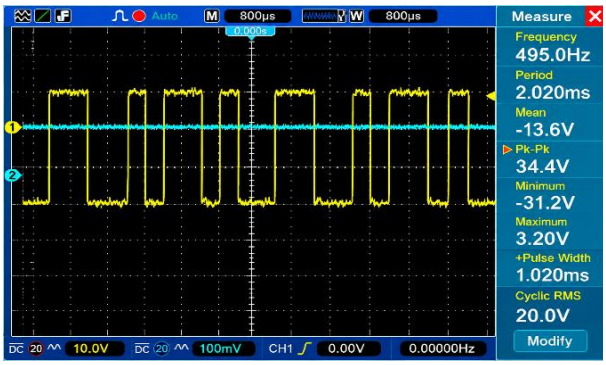


Figure 16. Waveform obtained on DSO for transmitter section

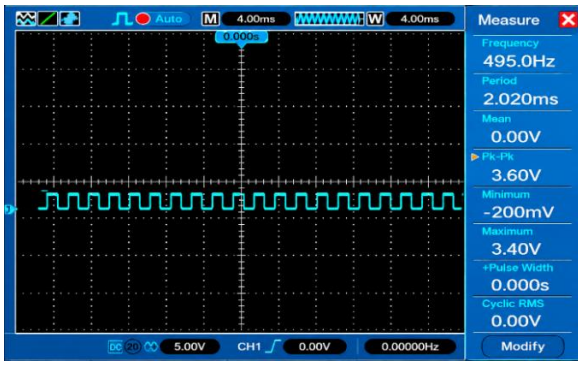


Figure 17. Waveform obtained on DSO for receiver section

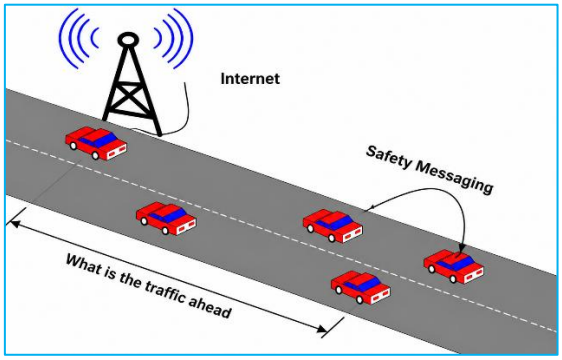


Figure 18. Li-Fi VLC

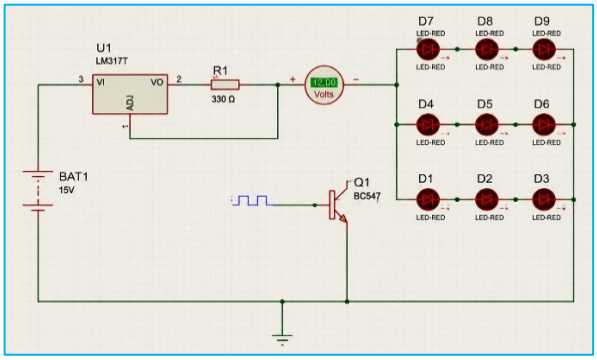


Figure 19. Array of LED's

6. CONCLUSION

This paper describes the design of a Li-Fi prototype with transmitter and receiver modules for vehicular communication. Manchester coding reduced noise and signal distortion for reliable data transfer. Simulation and hardware tests with a DSO showed that photodiodes can accurately receive digital data supplied via LED-based optical signals with low error rates. The proposed system was practicable since simulation and experimental results were consistent.

The results show that the transmitter-receiver separation, light intensity, and photodiode receiver responsiveness mostly affect system performance. The suggested architecture is promising for high-speed optical wireless communication, notably in V2V road safety communication systems. The prototype reliably sent data up to 15 cm. Future attempts will use LED and photodiode arrays to increase communication range to 7 m and use advanced modulation and signal processing technologies to reduce noise and improve system reliability.

The significant potential of Li-Fi allows for its application across various domains, including disaster management in scenarios such as earthquakes and floods, affordable in-flight internet services, biomedical communication, and underwater use. This positions Li-Fi as a promising, dependable, and energy-efficient solution for future wireless communication systems.

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AUTHOR CONTRIBUTIONS STATEMENT

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Prashant Magadum	✓		✓			✓			✓		✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analysed in this study.

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