Optical Data Transfer Using Laser and PV Panel

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ABSTRACT

Optical data transfer using commodity embedded devices is a promising approach for low-cost communication in resource-constrained systems. However, the use of Commercial Off-The-Shelf (COTS) optical sensors such as LEDs has limited the achievable sampling rates, and distance in these systems. This paper presents a low-cost, low-latency, and robust optical data transfer system using commodity embedded devices. We present a pulse-duration modulation based approach for embedding data in optical signals using COTS sensors, with the goal of optimizing signal demodulation and decoding at the receiver. Our approach utilizes a laser module and a photovoltaic cell as the transmitter and receiver, respectively, and allows for the transfer of any ASCII characters using 7 bits per character. We demonstrate a transmission distance of 76.2 meters and a data transfer rate of approximately 1333 bits per second with 100% accuracy in our experiments using Arduino Uno R3 boards. The system flashes the laser for 500 microseconds to denote zeros and 1 millisecond to denote ones. Our results show that our system is able to provide a reliable and efficient data transfer system for resource-constrained devices.

INTRODUCTION

VLC, or visible light communication, is a technology that allows for the transmission of data using light waves in the visible spectrum. This technology has a number of potential applications, including indoor positioning systems, high-speed data transfer, and even security and surveillance systems. VLC systems operate by modulating the intensity of light waves in the visible spectrum, which allows for the transmission of data. This is done using a variety of techniques, including pulse width modulation, frequency shift keying, and amplitude shift keying.

One of the key advantages of VLC technology is that it can transmit data at very high speeds, making it suitable for applications where large amounts of data need to be transferred quickly. Additionally, VLC systems can operate over relatively long distances, making them suitable for use in a variety of different settings. Another advantage of VLC technology is that it can be used in areas where other forms of wireless communication, such as radio frequency (RF) or infrared (IR), may not be possible or practical. Areas like hospitals that contain devices sensitive to RF communication can benefit from VLC technology. VLC technology has the potential to revolutionize the way we communicate and transfer data, and it is likely to have a number of important applications in a variety of different fields in the future.

In the field of VLC technology, there has been an increase in interest in the use of COTS devices for low cost optical data transfer. Optical data transfer using commodity embedded devices is an increasingly popular method for low-cost communication in resource-constrained systems. It has the potential to provide high data rates, low latency, and robust performance in a variety of environments. However, the use of COTS optical sensors such as LEDs has typically been limited by their low sampling rates, which can impact the performance of the communication system.

Recent research has focused on establishing VLC channels between devices using customized front-ends with high sampling rates at the receiver. These approaches have shown promising results in terms of data rate and distance, but often require specialized hardware and can be sensitive to environmental interference.

In this paper, we present a low-cost and robust optical data transfer system using commodity embedded devices. Our approach is based on pulse-duration modulation, which allows us to embed data in optical signals using COTS sensors and optimize signal demodulation and decoding at the receiver. Our system utilizes a laser module and a photovoltaic cell as the transmitter and receiver, respectively, using Arduino boards, and allows for the transfer of any ASCII characters using 7 bits per character.

Our system addresses the challenges of low sampling rates and environmental interference by using a pulse duration modulation approach, which requires fewer samples to represent data compared to other modulation schemes. Additionally, our system is resilient to distance-based variations and robust to sensor-specific environmental interference, such as fluorescent light, which can be a major source of interference in VLC systems.

In summary, the main technical contributions of the paper are as follows:

- A low-cost, low-latency, and robust optical data transfer system using commodity-embedded devices.
- A pulse-duration modulation based approach for embedding data in optical signals using COTS sensors.
- Demonstration of a transmission distance of 76.2 meters and a data transfer rate of approximately 1333 bits per second using 7 bits per character with 100% accuracy in our experiments using Arduino Uno boards.
- Resilience to distance based variations and robustness to sensor specific environmental interference.
- Platform with potential for wide adoption in a variety of applications.
- Transmit any ASCII character without the need to define an explicit array or binary tree of characters.

LITERATURE REVIEW

Laser communication compared with traditional radio frequency communication methods can in theory provide much higher bandwidth with relatively small mass, volume and power requirements. This is possible because a laser enables the beams of photons to be coherent over longer distances. The LADEE Spacecraft demonstrated the advantages of laser communication, providing high bandwidth for a relatively small sized spacecraft [1]. However, LADEE utilized a laser system onboard the spacecraft to perform high-speed bidirectional communication and consumes between 50 and 120 Watts. This is too high for most applications, even in the realm of space-craft and our proposed design offers a low cost, commodity hardware based option.

In most VLC systems, LEDs are used as transmitters due to their fast switching ability compared to traditional light sources like incandescent bulbs and fluorescent lamps. These systems can use either a single-chip approach with phosphor-coated LEDs (pc-LEDs) or a multi-chip approach with red-green-blue (RGB) LEDs as the source. The authors in [3] described how to build and test an LED module for transmitting and receiving text data. Utilizing an LDR as the detector, their system was able to achieve data transmission distances up to 2m. The authors of [4], similarly built a Li-Fi based wireless communication system using VLC, where the transmitter is comprised of an array of LEDs connected to an ArduinoUno circuit, while the receiver is comprised of an array of PNP diodes (BPW34) wired to an ArduinoUno circuit. Because of ambient light penetration, their current effective data transmission speed is 100 bits/sec, with a distance between transmitter and receiver no more than 1 foot. Lastly in [5], In a project most similar to ours, the authors design a PC to PC text data transmission system utilizing one LDR and one laser diode where they state they were able to achieve a data rate of 2 Megabits per second at a distance of 21 meters. Our system was able to greatly surpass all of the distance metrics of these prior systems with an improved data rate compared with the systems described in [3] and [4]. We propose that by utilizing a single solar panel to provide a larger target surface and a faster response than an LDR, as well as a laser diode in place of LEDs in order to send data with less ambient light interference and with lower power consumption. Our solution is more robust compared with other commodity systems in the space.

DESIGN ALTERNATIVES

We initially started off with a Morse code based approach. It was similar to the binary logic that our system implemented but it required explicit declaration of the character array that could be sent. This was a time consuming and complex process as it required a corresponding binary tree to decode the characters. This Morse code approach ended up being slower and did not have consistent length for encoding the characters. We instead shifted to a binary logic that converts all the characters of the inputted string into zero's and ones' matching the characters corresponding ASCII values.

Utilizing multiple laser diodes to transmit a byte worth of data at the same time was an ideal alternative to the existing solutions. This would increase the communication speed significantly. However, when we tried to put together 8 laser modules in an array, we realized that the lasers had a huge internal focus shift. This would prevent us from focusing all the lasers on the LDRs or solar panels. As we increased the distance, the deviation of the laser would grow substantially. Solutions like this would work well when using fiber optic cables, but the entire purpose of our project was to create a wireless laser-based mechanism for communication.

After we began testing our system with LDRs, we discovered that the LDR modules had high latency and huge input-to-output mismatch. Also, it was very difficult to focus the laser on the tiny surface of the LDR module, especially at long distances. Hence, we decided to go forward with a photovoltaic cell instead of incorporating a bare analog LDR which would have performed better than the digital LDR module.

Lastly, we tried modulating the brightness of the laser to communicate a variety of data to the receiver. The problem with this approach was that the photovoltaic cell is not able to distinguish between minute changes in the brightness of the laser, especially with the interference of ambient light. This result can be verified from figure 1.

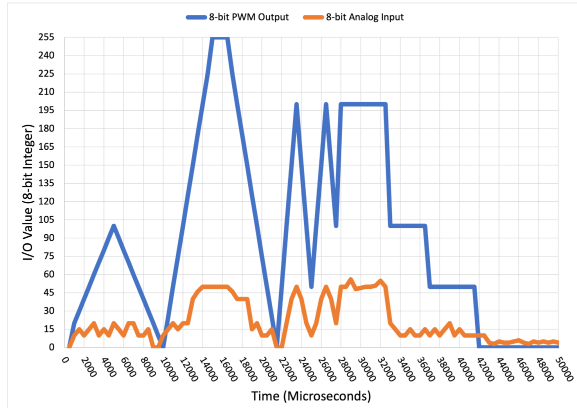

Figure 1. Plot of variable laser intensity output and the corresponding PV cell input.

PROJECT BACKGROUND

Optical data transfer using laser diodes and photovoltaic (PV) panel technology has gained significant attention in recent years as a potential alternative to traditional methods of transmitting data wirelessly [8]. This is because it offers several benefits over traditional methods, including higher speeds, higher security, and greater distance coverage.

The use of lasers for data transfer has a long history, dating back to the 1960s when lasers were first used for military communication [9]. In the decades since, laser communication has been developed and refined for use in various applications, including satellite communication [1], terrestrial communication, and even personal communication devices.

SYSTEM DESIGN

Our proposed system model is displayed in figure 2. The system is composed of two individual microcontroller units (MCUs) one for transmission and one for reception, a laser diode on the transmitter side, a photovoltaic panel on the receiver side, and a serial monitor that can be used to display the output from the receiver. In this proposed system, MCU-1 is responsible for taking a string of ASCII characters and converting each character to a 7 bit binary value. MCU-1 is interfaced with the laser diode and causes the laser diode, which is pointed at the photovoltaic panel, to flicker rapidly at a speed that is unnoticeable by the human eye. The photovoltaic panel is interfaced with MCU-2, which is connected to the serial monitor on the receiving end. The photovoltaic panel acts as an optical sensor, and MCU-2 translates the flickering of the laser diode into 7 bit binary values. MCU-2 then converts these 7 bit values back into ASCII characters. These characters are then displayed on the serial monitor. Revealing the message that was sent by the transmitter.

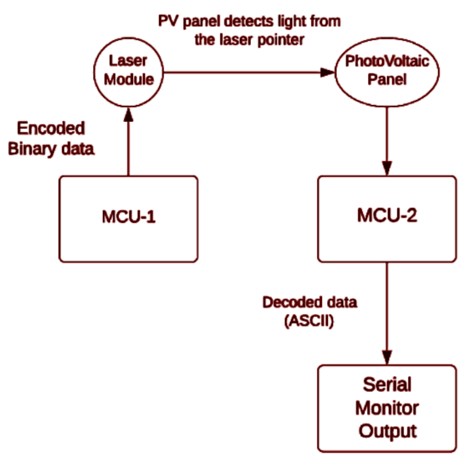

Figure 2. Block diagram of proposed system for optical data transmission using a laser diode and a photovoltaic panel.

The major technical contribution of our proposed system is the use of a photovoltaic panel to act as a receiver. The photovoltaic panel provides a larger surface area to account for the diffraction of the laser as the distance between the transmitter and receiver increases. This adaptation also allows for the alignment of the system to be more forgiving when calibrating at longer distances. The major tradeoff that comes with the use of a photovoltaic panel in our system is the increased sensitivity to ambient light interference.

IMPLEMENTATION

The main components that are used in the implementation of our system are as follows: two Arduino Uno R3's, one KY-008 Laser Module, one 9.5x9.5cm 5V photovoltaic panel, Arduino Serial Monitor, jumper wires, and Arduino IDE for software development. Our prototype was tested in the first floor hallway of Marcus Hall in the University of Massachusetts Amherst, shown in figure 3. The hallway was straight for roughly 100 meters which was perfect for testing the distance of our system. In addition, the brightness of the ambient lighting could be adjusted (using portable desk lamps if necessary in addition to ceiling lights), along with the angle of the flaps on the housing of the receiver to measure different levels of ambient light interference. We were also able to alter the color of the laser to get valuable information on how that affected our accuracy readings in relation to the distance. When testing accuracy we sent 100 ASCII characters from the transmitter and the number that arrived unaltered at the receiver were counted. The accuracy percentage was calculated using these two values.

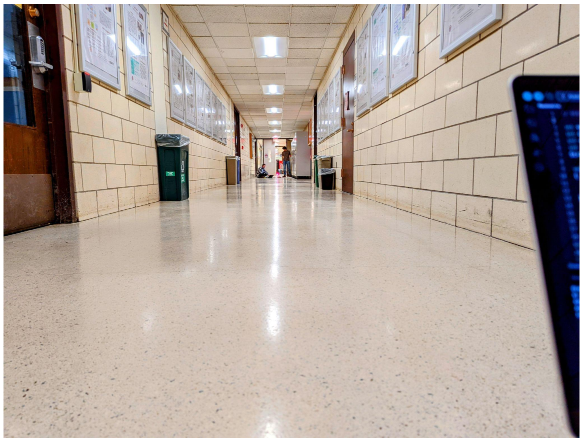

Figure 3. First floor of Marcus Hall, used for testing the implementation of our prototype.

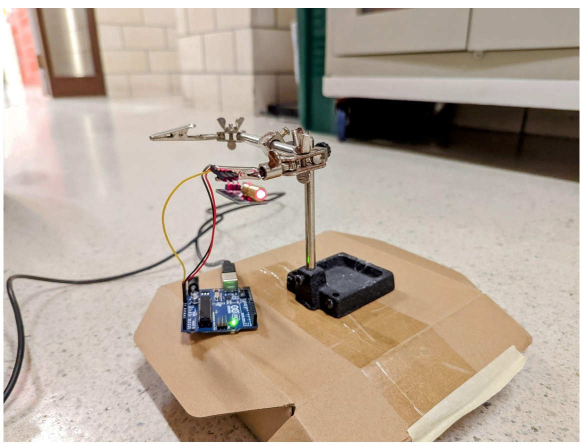

Figure 4. Transmitter hardware setup consisting of Arduino Uno, laser module, and adjustable stand.

Transmitter Hardware

The transmitter portion of our system is composed of one Arduino Uno and the KY-008 laser module which was secured to an adjustable stand as shown in figure 4. The stand was used to keep the laser module steady, as any movement could drastically alter the alignment as distance from the transmitter to receiver increases. The KY-008 laser module is connected to Pin 13 of the Arduino Uno, and to ground via jumper wires. The Arduino Uno is connected to a laptop via USB which acts as both a power supply and the data source.

Transmitter Software

Before writing the software for the transmitter, the first decision that had to be made was to choose a modulation scheme.

We settled on pulse duration modulation (PDM) which is a modulation in which the duration of the pulse, also known as the pulse width, is varied to encode information. PDM has several advantages over other pulse modulation techniques, such as pulse code modulation (PCM) and pulse amplitude modulation (PAM) [6]:

- High resolution: PDM has a higher resolution than PCM, as the pulse width can be varied in finer increments, allowing for more precise encoding of the input signal.
- Simplicity: PDM is a simple and straightforward modulation technique that does not require complex circuitry or signal processing.
- Robustness: PDM is resistant to noise and interference, as the pulse width is not affected by changes in the amplitude of the signal.
- Power efficiency: PDM requires less power than PAM, as the pulse width is not affected by the amplitude of the signal.
- Bandwidth efficiency: PDM is more bandwidth-efficient than PCM, as it requires fewer pulses to transmit the same amount of information.

The code for the transmitter was written in the Arduino IDE and flashed to the Arduino Uno. Pin 13 was set to output, as this was the pin the laser module was connected to and the serial monitor was initialized to enable input. The main function in the code is a loop that constantly checks to see if there is anything in the serial buffer using the "Serial.available()" function. If there is something in the buffer, we read it byte by byte using "Serial.read()". Each byte is then converted to a seven bit binary value using a function called "chartobin()" which makes use of the bitread() function. The resulting seven bit binary string is then used as input in our "flashlaser()" function that blinks the laser on and off. This function iterates through the 7 bit string and for each "0" it blinks the laser for 500 microseconds, and for each "1" it blinks the laser for 1000 microseconds. After exiting the "flashlaser()" function we add a delay of 1.5 milliseconds before restarting the loop. These delay values were the result of significant testing on the solar panel response time. Attempting to shorten these delays any further would result in errors during demodulation.

Receiver Hardware

The receiver portion of our system was composed of one Arduino Uno, one 9.5x9.5cm 5V photovoltaic panel, and a serial monitor to display output. Due to the increased susceptibility to ambient light interference, we chose to secure the photovoltaic panel inside a cardboard box housing which is shown in figure 5. The photovoltaic panel was connected to Pin A4 of the Arduino Uno and the ground pin. The Arduino Uno was connected to a laptop via USB which acts as both a power supply and the data source.

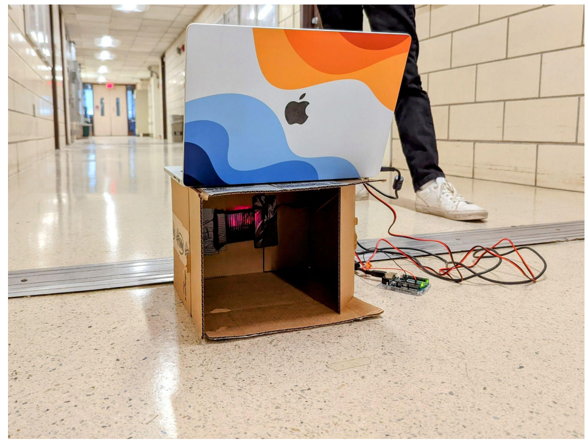

Figure 5. Receiver hardware setup consisting of Arduino Uno, photovoltaic panel secured inside cardboard box, and laptop with serial monitor

Transmitter Software

The code for the receiver was written in the C language using the Arduino IDE and flashed to the Arduino Uno. The main function in the code is a loop that is constantly using "analogRead()" to read Pin A4 which is connected to the photovoltaic module. When the value of A4 is greater than a threshold value, in our case 30, we continue to increment a counter variable "ctrHigh". When the value at Pin A4 drops below the threshold we begin incrementing a new counter variable "ctrLow". While this new counter is being incremented we perform checks to determine if the pulse we received was a zero or a one. If "ctrHigh" is between 4 and 8 the value of the pulse is a zero, and if it is greater than 8 the value of the pulse is a one. We arrived at these values after rigorous testing that determined that it takes approximately 4 iterations through the loop to detect a 500 microsecond pulse. The zero and one values are appended to a string and once the "ctrLow" counter hits 12 (predetermined value based on delay implemented in transmitter code) we convert the string to an integer which is then converted to an ASCII character and printed to the serial monitor.

EVALUATION AND RESULTS

To evaluate the performance of the system, we set up a testbench in a 100 meter long hallway and sent a 100 character long string including symbols from variable distances. Our system was able to transmit all the ASCII characters with 100% accuracy up to the distance of 76.2 meters. We performed this experiment with 3 different colored lasers. Where our best results were observed with the red laser diode as it has the maximum wavelength, which helps it travel longer distances without dispersing when compared to the green and blue lasers. This can be seen in figure 6 below.

All the tests were accompanied with a desk lamp or ceiling lighting as a source of ambient light and the system performed with great accuracy under those conditions. However, the accuracy dropped down below 40% under some extreme brightness environments, for example when flashing a flashlight directly on the PV Panel.This can be seen in figure 7. This we believe, is due to the PV Panel not being able to distinguish between the laser and the alternate light source.

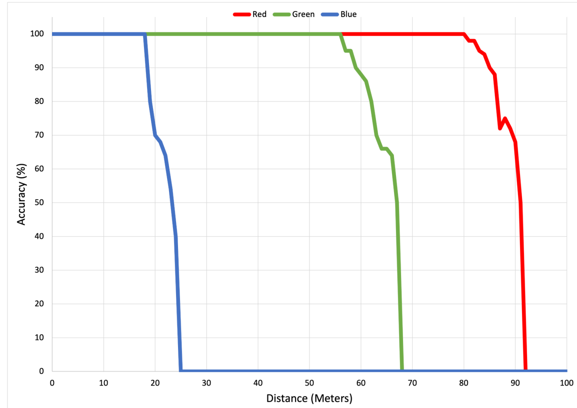

Figure 6. Relation of distance and communication accuracy for blue, green and red lasers.

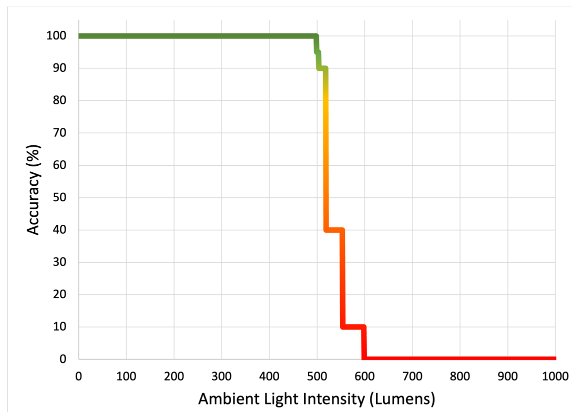

Figure 7. Plot of communication accuracy in percentage versus ambient light intensity in lumens.

The system attained a baud rate of 1333 bits per second. This value was calculated by averaging the time required to transmit a zero (500 microseconds) and a one (1000 microseconds). It takes [500 + 1000]/2 = 750 microseconds on average to transfer 1 bit. This implies that the system can send [1 second / 750 microseconds per bit] = 1333 bits per second on average.

With our system we were able to beat both papers [5] and [3] with their maximum distance being 21 meters and 2.88 meters respectively. Our data rate however was lower than most other similar solutions where papers [5] [3] reported 2 Mb/s and 3.4 Gb/s data rates respectively. It is important to note here that these minimal distances are impractical for the use cases we designed our system to accommodate.

DISCUSSION

As can be seen from our results, our laser diode and PV panel system was able to achieve great distance and still receive reliable communication. However, in our research we discovered that by using our current modulation approach our system is no doubt limited in the data rate we are able to achieve.

Our data rate of 1333 bits per second is adequate for transmitting short messages between transmitter and receiver and accomplishing the task of low power communication for resource constricted devices, and accomplishes our goal. But this data rate is low when considering data types such as video, audio, and large text files. By utilizing a higher order modulation approach for the laser diode [7]. We could possibly achieve a higher data rate given a constrained bandwidth than we could with our current design.

Our laser diode used was a commodity device and highly inexpensive. When conducting experiments for our distance metrics, as stated before, the beam from the laser would grow exponentially with distance making it hard to know if the beam was contacting the PV panel and difficult to center on the panel. We believe that by using a narrow beam laser there would be less beam spread and overall would result in a higher maximum transmission distance.
Another problem our team encountered when performing experiments was aligning the laser with the panel. This problem was amplified greatly when using an LDR in place of a PV panel as the surface needing to be contacted by the laser was extremely small. At longer distances the slightest movement would throw off the beam greatly. We believe that adapting our system in the future with some way to more effectively lock the beam to the panel would be very useful when applying this technology to real world applications.

CONCLUSION

VLC has recently attracted a lot of attention due to its ability to provide fast data speeds, great security, minimal ambient light interference, and decreased energy use when compared with other solutions. This paper combines conventional VLC techniques for text communication from the transmission side to the receiver side.

VLC is helping to deliver fast data speeds, bandwidth efficiency, and a relatively secure channel of communication. Our system is an inexpensive, commodity hardware, wireless communication platform. Our system can transmit any ASCII character via a laser diode positioned in space. This form of communication provides more advantages than WiFi, such as security, long distance communication, and bandwidth efficiency. The information can be transferred based on the coherence and single wavelength characteristics of the laser diode used.

Communication between the transmitter and receiver is accomplished by turning on and off the laser diode for a set amount of time at a faster pace than the human visual system is able to detect. Given the current state of VLC technology, its improving efforts, and the adoption of these techniques, it appears that VLC will have a significant impact on wireless communication within the next few years. Research in the sector of the wireless communication field will move faster toward standardization and laser diode based communication may become the standard for long distance communication in defense, undersea, aerospace, and healthcare environments.

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