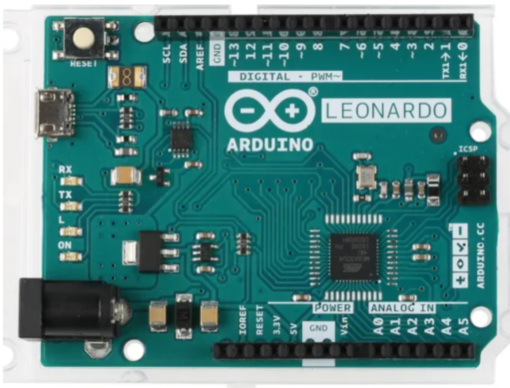
TÉCNICO LISBOA

MEEC

Optoelectronics

Project - Visible Optical Communications



Authors:
Franisco Matias (99936) francisco.m.matias@tecnico.ulisboa.pt
Hugo Rabuge (99959) hugo.rabuge@tecnico.ulisboa.pt

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1 Introduction

In the academic year of 2023/2024, the Optoelectronics course at Instituto Superior Técnico embarked on an ambitious and cutting-edge project titled "Li-Fi: Visible Optical Communications." Spearheaded by Paulo André, this project offers students a unique opportunity to delve into the world of light-based data transmission, exploring the vast potential of Li-Fi technology.

Li-Fi, or Light Fidelity, utilizes visible light communication (VLC) for wireless data transmission, offering a promising alternative to traditional radio-based systems with the potential for faster speeds, improved security, and reduced electromagnetic interference. This innovative project is structured to provide students with hands-on experience in designing, implementing, and evaluating a Li-Fi system, encapsulating the essence of practical learning and real-world application.

The project is meticulously divided into three phases, ensuring a comprehensive understanding and skill development in Arduino programming, theoretical foundations, collaborative implementation, and critical evaluation through presentations and reports. With a blend of individual and group work, the project emphasizes the importance of teamwork, specialization, and accountability, reflecting the dynamics of real-world engineering tasks.

Students are equipped with essential hardware, including Arduino Leonardo, sensors, LEDs, and other components, fostering an environment of creativity and experimentation. The course's laboratory sessions serve as a cornerstone for guidance, learning best practices, and direct application of theoretical concepts.

This project not only aims to enlighten students on the technological intricacies of Li-Fi but also prepares them for the challenges and opportunities in the evolving field of optoelectronics. Through a rigorous evaluation process, encompassing both practical and theoretical aspects, the project seeks to cultivate a generation of engineers well-versed in innovative communication technologies.

As we venture into the demonstration phase, our teams are poised to showcase their achievements, reflecting their hard work, ingenuity, and the collaborative spirit fostered by the Instituto Superior Técnico. The journey through the Li-Fi project not only signifies a leap towards advanced optical communications but also embodies the institute's commitment to excellence, innovation, and the holistic development of its students.

2 Theory

2.1 Modulations

2.1.1 Pulse Width Modulation (PWM)

Pulse Width Modulation (PWM) is a modulation technique used to encode information in the width of pulses and control power supplied to electrical devices, without an increase in signal noise. This method is particularly effective for managing the energy efficiency and precise control of various types of electronics, from LED lighting to motors. The process of PWM can be broken down into several key components:

1. **Generation**: In PWM, a high-frequency square wave serves as the base for the modulation process. This constant frequency wave is crucial for maintaining a consistent signal upon which the modulation can act.
2. **Duty Cycle Adjustment**: The core of PWM lies in the variation of the duty cycle of the pulse wave. The duty cycle refers to the proportion of time during which the signal is in a high (on) state as a percentage of the total time of one cycle. By adjusting the duty cycle, PWM effectively changes the average power delivered to the device. A higher duty cycle increases the average voltage (and thus power) supplied to the load, while a lower duty cycle reduces it.
3. **Control and Regulation**: Through the manipulation of the duty cycle, PWM allows for precise control over the amount of power sent to an electronic device. This method is especially beneficial for applications that require a variable but stable power input, such as dimming LEDs or controlling the speed of motors.
4. **Efficiency and Noise Reduction**: One of the significant advantages of PWM is its efficiency. Since the power is controlled by switching between fully on and fully off states, there is minimal power loss in the

switching devices. Additionally, PWM can be less susceptible to the noise compared to analog control, as the power is delivered in digital pulses.

PWM is widely appreciated for its simplicity and effectiveness in controlling electrical devices, offering an excellent solution for energy-saving applications and precise control over electronic devices. Its use extends across various fields, including lighting control systems, power delivery systems for electronic devices, and speed control for electric motors, highlighting its versatility and importance in modern electronics and communication systems.

In theory this modulation can be described as follows:

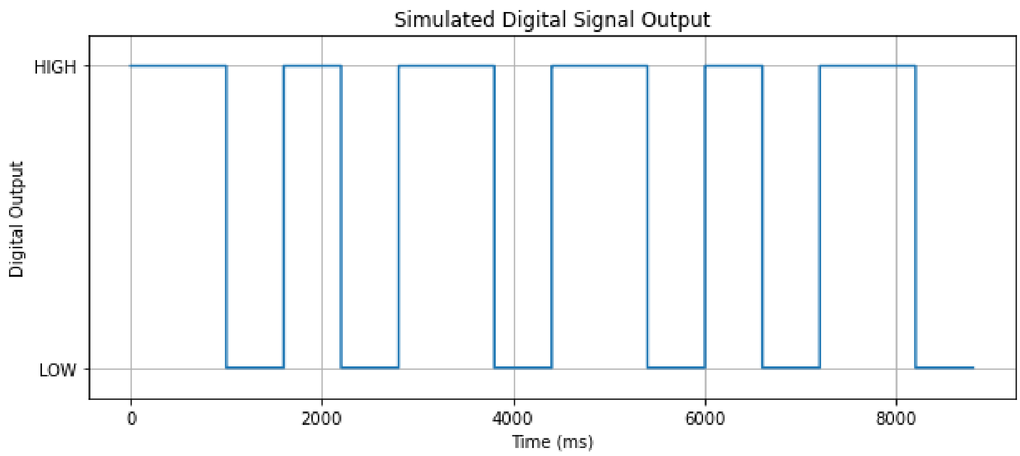

Figure 1: Digital output of PWD for the vector [1, 0, 1, 1, 0, 1]

2.1.2 Pulse Code Modulation (PCM)

Pulse Code Modulation (PCM) is a digital scheme for transmitting analog data. The basic idea behind PCM is to convert analog signals into a digital form to improve signal reliability and ensure efficient data transmission. The process of PCM involves three main steps: sampling, quantization, and encoding.

1. **Sampling** is the process of capturing the amplitude of an analog signal at regular intervals. According to the Nyquist theorem, to accurately capture the signal, it must be sampled at least twice the highest frequency present in the signal.
2. **Quantization** involves mapping the amplitude of each sample to the nearest value within a range of discrete levels. This step introduces quantization noise, which can be minimized with sufficient bit depth.
3. **Encoding** converts the quantized values into a binary form for digital transmission. Each quantized sample is represented by a unique binary code.

PCM is extensively used in audio and video transmission systems due to its resistance to noise and interference, making it a robust method for digital communication.

In theory this modulation can be described as follows:

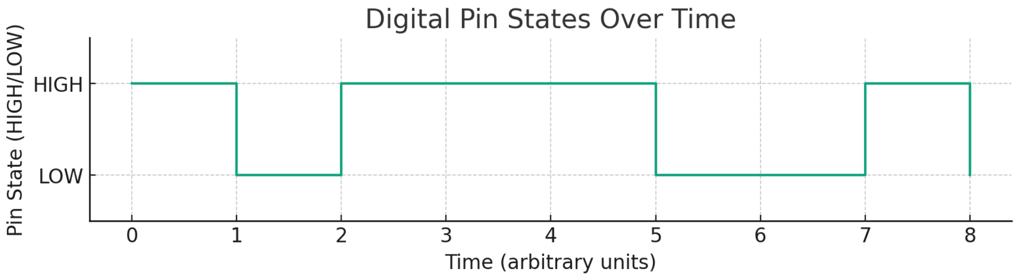

Figure 2: Digital output of PCM for the vector [1, 0, 1, 1, 1, 0, 0, 1, 0]

2.1.3 Pulse Position Modulation (PPM)

Pulse Position Modulation (PPM) is a modulation technique that varies the position of a pulse within a fixed time frame to encode information. This approach is distinct from other modulation techniques, such as PWM, which modulates the width of pulses, or PCM, which encodes information in a digital form. The unique aspects of PPM make it particularly suitable for certain applications. The process and advantages of PPM include:

1. **Pulse Position Variation**: The essence of PPM is the shifting of pulse positions within a predetermined time frame to represent information. Unlike amplitude or width modulation, PPM encodes data by altering the timing of each pulse, making it less susceptible to noise and amplitude variations.

2. **Noise Immunity**: One of the primary advantages of PPM is its high immunity to noise. Since the information is encoded in the time position of pulses, it is less affected by signal amplitude changes or disturbances, making it robust against environmental noise and interference.

3. **Energy Efficiency**: PPM can be more energy-efficient in certain contexts, particularly in optical communication systems like Li-Fi, where it enables precise control over light pulses without significantly altering power consumption.

4. **Complexity and Precision**: While offering several benefits, PPM also introduces complexity in terms of timing precision and synchronization between the transmitter and receiver. The accurate positioning of pulses requires precise control, making the implementation of PPM more complex than some other modulation techniques.

PPM is especially advantageous in environments where robustness against noise and interference is critical, and where precise control over the timing of signal transmission is possible. Its applications range from optical communication systems, such as Li-Fi, to various forms of wireless communications where signal integrity is paramount. Despite its complexity, the benefits of PPM in terms of noise immunity and efficiency make it a valuable technique in specific communication scenarios.

In theory this modulation can be described as follows:

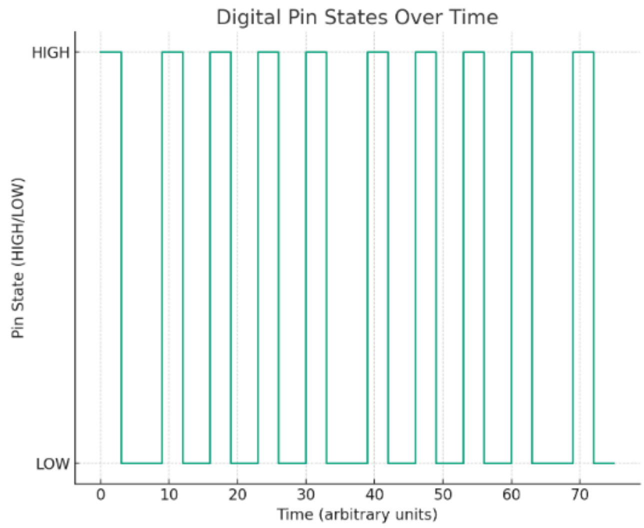

Figure 3: Digital output of PWD for the vector [0, 1, 0, 1, 0]

2.2 Visible Light Communication (VLC)

Visible Light Communication (VLC) utilizes the visible spectrum for data transmission, offering a potential alternative to RF (Radio Frequency) communication, particularly in RF-sensitive environments. VLC is characterized by its use of light-emitting diodes (LEDs) to transmit data by modulating the light intensity, which is received and demodulated by photodetectors.

VLC has several advantages, including high bandwidth, low interference with existing RF systems, and inherent security due to light's inability to penetrate opaque objects. Moreover, VLC leverages the existing lighting infrastructure, making it a cost-effective solution for indoor wireless communication.

2.3 Application in Li-Fi

Li-Fi (Light Fidelity) is a technology that utilizes VLC principles for wireless communication. By modulating the intensity of LED lights at speeds imperceptible to the human eye, Li-Fi can transmit data between devices.

2.3.1 Pulse Width Modulation (PWM)

PWM is primarily used to modulate the brightness of LED lighting for data transmission in Li-Fi systems. By adjusting the width of the light pulses emitted by LEDs, PWM can encode data through variations in light intensity. This method is particularly advantageous for applications that require the simultaneous use of LED lighting for illumination and data transmission, as it allows for the control of light brightness to suit environmental needs while transmitting data. The encoded information is then decoded by a photodetector at the receiving end. PWM's ability to precisely control the duty cycle of LED emissions makes it an effective method for adjusting data transmission rates and optimizing energy consumption.

2.3.2 Pulse Code Modulation (PCM)

PCM finds its application in Li-Fi by converting analog signals into a digital format, which is then transmitted through light pulses. This technique involves sampling the analog signal at uniform intervals and quantizing each sample into a series of binary digits (bits). In a Li-Fi context, these bits correspond to the presence or absence of light pulses, enabling the transmission of digital data over light waves. This digital representation of data is particularly beneficial for ensuring the integrity and security of the transmitted information. PCM's compatibility with digital systems makes it ideal for a wide range of applications, including secure communications and integration with existing network infrastructures, providing a reliable method for transmitting complex data payloads.

2.3.3 Pulse Position Modulation (PPM)

PPM is used in Li-Fi to encode data by altering the position of light pulses within a given timeframe, rather than changing their intensity or width. This technique modulates data onto a light source by varying the timing of pulse emissions. The unique advantage of PPM in Li-Fi applications lies in its high immunity to interference from ambient light conditions and its robustness against signal attenuation, making it suitable for environments where light intensity can vary significantly. By encoding information in the timing of pulses, PPM can achieve high data rates with reduced error rates. This method is particularly valuable in scenarios where maintaining consistent light intensity is challenging, allowing for reliable data transmission across varying lighting conditions.

3 Project

3.1 First Phase

The initial phase of the project was dedicated to acquainting each group with the necessary components and the foundational skills required for Arduino programming. This was achieved by engaging with provided examples and theoretical underpinnings relevant to the project's focus on visible optical communications.

To achieve the objectives of the project, a variety of materials were utilized, taking an important role for the construction and testing of the system, and software tools for programming and data analysis:

3.1.1 Hardware Components:

- Arduino Leonardo: The core microcontroller board responsable for providing the necessary digital and analog I/O pins for interfacing with LEDs, sensors, and other components.
- 330 Ohm Resistor: Employed to limit current through the LED, ensuring optimal operation without damaging the component.
- Red LED: Served as the light source for transmitting data through visible light communication.
- Flexible Cables with Connector (x4): Used for making connections between the Arduino, LED, resistor, and sensor.
- USB Cable Type A/B: For connecting the Arduino Leonardo to a computer, enabling programming and data communication.
- KY-039 Sensor Module: Consisting of an IR LED and photodiode, this sensor was used for detecting the modulated light signals emitted by the LED.
- Si Photodiode – Thorlabs DET10A2: Employed in the final demonstration to accurately detect light signals.
- Light Torch – Lexman 2500 lm: Integrated with a current amplification stage, this high-intensity light source was used during the final demonstration to test the system's capability at higher transmission powers.

3.1.2 Software and Resources:

- Arduino IDE 2.3.2: The development environment for writing and uploading code to the Arduino Leonardo.
- Example Codes and Schematics: Provided in Fenix which facilitated initial experimentation and understanding of basic concepts related to the project.

3.1.3 Demonstration and Testing Equipment:

For the final demonstration of the project in lab sessions, additional materials were required:

- Oscilloscope: Used in conjunction with the Si Photodiode to visualize and measure the modulated light signal.

3.2 Second Phase

During the second phase, which occurred in week 6, our group progressed from individual learning and preliminary work to a collaborative approach where each member focused on specialized tasks within the project.

In this step, the group worked on the amplitude modulation of the signal, aiming to increase the data transmission rate, after implementing Pulse Width Modulation (PWM) for more effective data communication.

After that, the group decided to implement another modulations processes: Pulse Position Modulation (PPM) and Pulse Code Modulation (PCM), in order to find out the main diferences between them.

The code developed for the different modulations is present at the end of the document in the Attachments section.

3.3 Third Phase

The final phase of our project, coinciding with week 6 class session, was dedicated to the demonstration of our work.

In preparation for the demonstration, we conducted extensive testing to ensure that it would performed as expected under various conditions. This involved fine-tuning the light torch modulation, verifying the signal integrity with the photodiode and oscilloscope setup, and making any necessary adjustments to the amplitude and PWM schemes.

The demonstration itself was an opportunity to showcase the practical application of our system. It was a synthesis of our theoretical knowledge and the hands-on skills we had honed over the preceding weeks.

The circuit that we developed was,

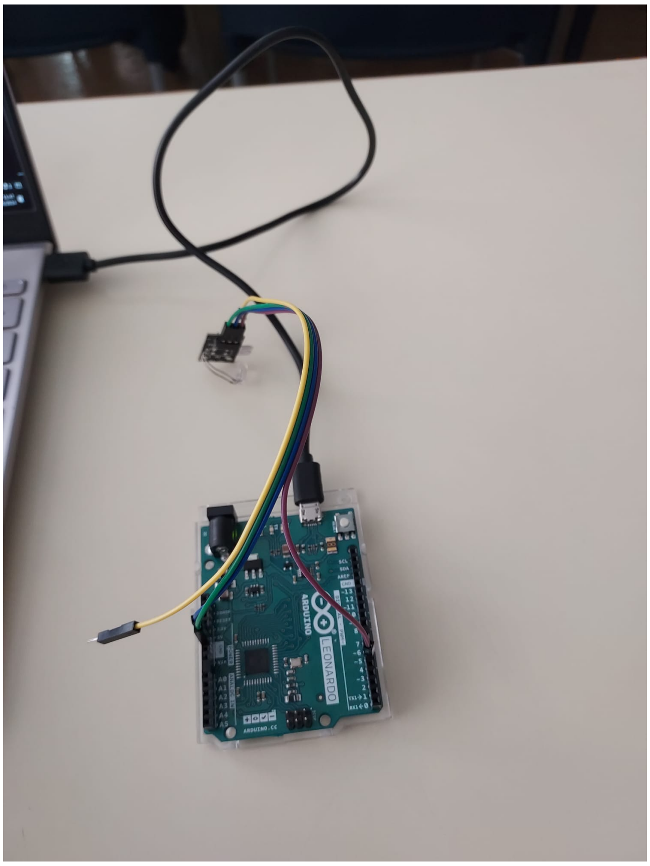

Figure 4: Arduino Leonardo used in this project

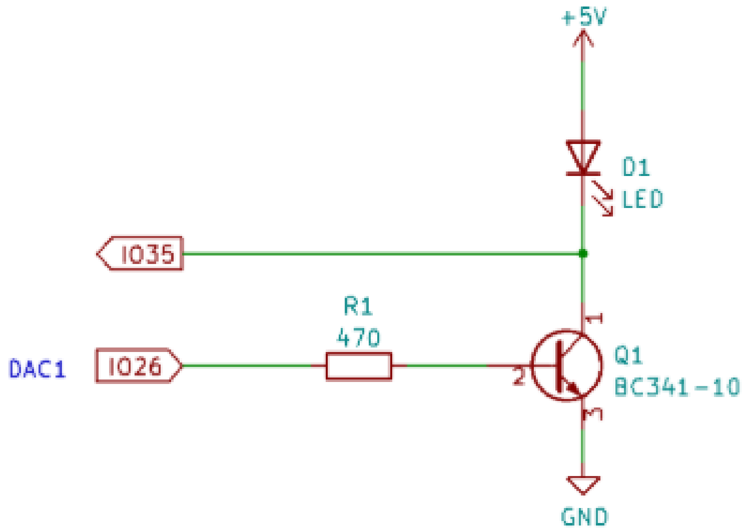

Figure 5: Schematic of the circuit

The picture above depicts a simple transistor switch circuit, and was used for our experimental results. It shows a BC341 NPN transistor labeled Q1, which is being used to control a LED (D1). The LED is connected to a +5V power source through a current-limiting resistor (R1, labeled 470 ohms). The transistor's base is connected to DAC1, likely a digital-to-analog converter output, through a resistor labeled 1026, which is probably meant to be the resistance value in ohms.

The transistor acts as a switch that turns on the LED when a sufficient voltage is applied to its base relative to the emitter. When DAC1 outputs a voltage that is high enough to overcome the base-emitter threshold voltage (usually around 0.7V for silicon transistors), current flows from the base to the emitter. This allows a larger current to flow from the collector to the emitter, which in turn lights up the LED. When the voltage at DAC1 is low, the transistor switch is off, and no current flows through the LED, so it remains off.

This type of circuit can be used in various applications where electronic control of power to a device (like an LED) is needed, often controlled by a microcontroller or other digital circuitry. The actual values of the resistors (1026 and I035) are unusual and would need to be chosen based on the desired current for proper operation and to protect the DAC and the transistor from excessive current.

With this, together with the code in the attachments we got the following graphics for the two modulations tested in class (PWM and PPM respectively). Firstly there are the results for Pulse Width Modulation (PWM):

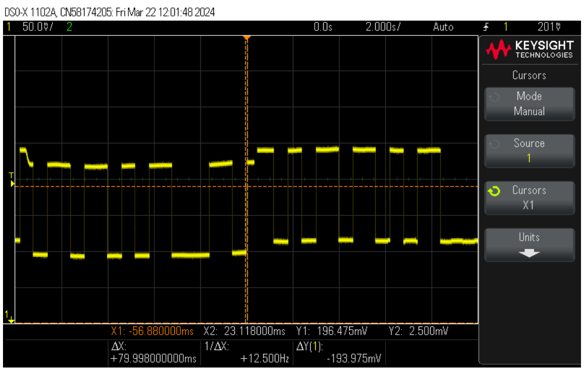

Figure 6: With a delay of 1s when it is 1 and a delay of 0.6s for when is 0

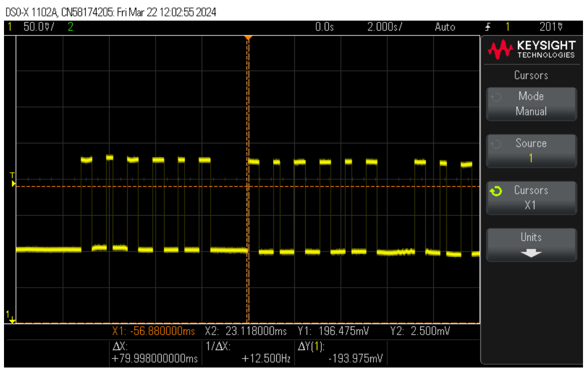

Figure 7: With a delay of 0.5s when it is 1 and a delay of 0.3s for when is 0

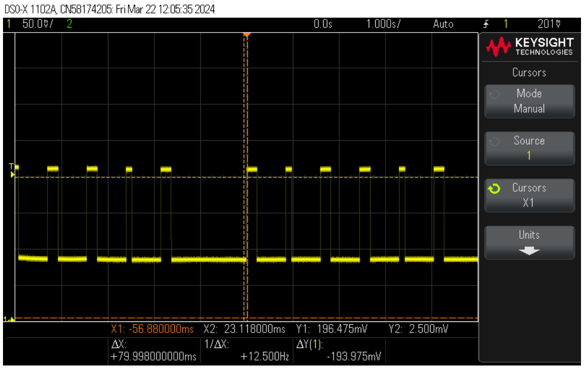

Figure 8: With a delay of 0.25s when it is 1 and a delay of 0.15s for when is 0

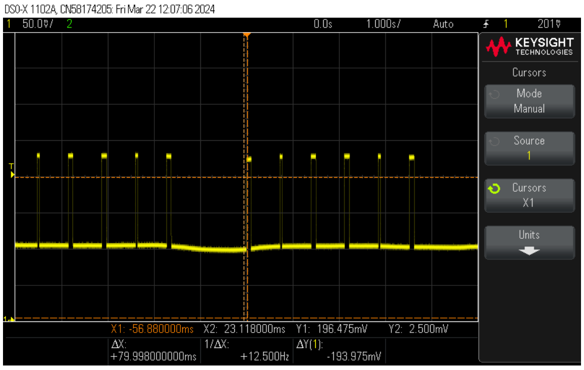

Figure 9: With a delay of 0.125s when it is 1 and a delay of 0.075s for when is 0

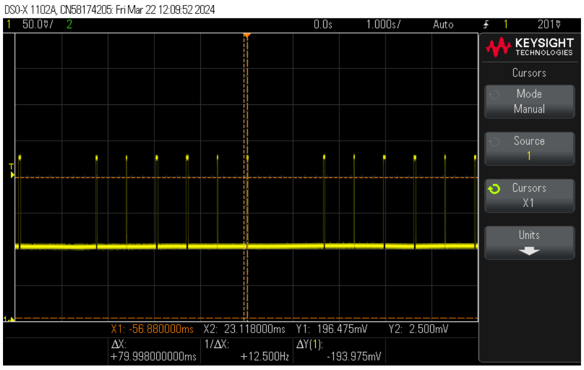

Figure 10: With a delay of 0.0625s when it is 1 and a delay of 0.0375s for when is 0

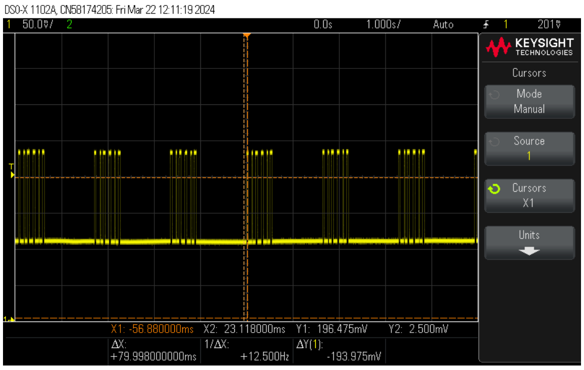

Figure 11: With a delay of 1s when it is 1 and a delay of 0.6s for when is 0

And for the Pulse Position Modulation (PPM):

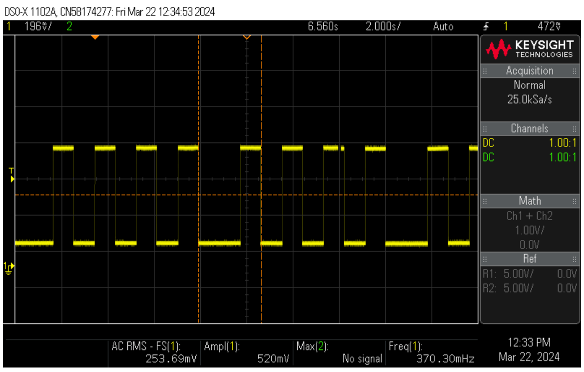

Figure 12: With an interval between peaks of 0.9s for 1 and 1.8s for 0

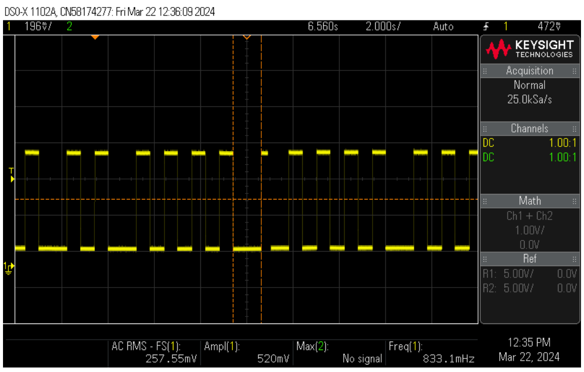

Figure 13: With an interval between peaks of 0.6s for 1 and 1.2s for 0

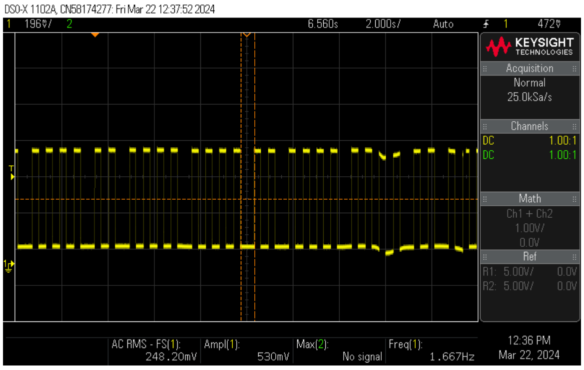

Figure 14: With an interval between peaks of 0.075s for 1 and 0.150s for 0

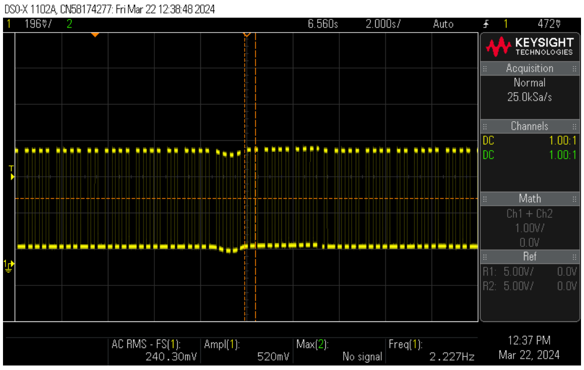

Figure 15: With an interval between peaks of 0.150s for 1 and 0.300s for 0

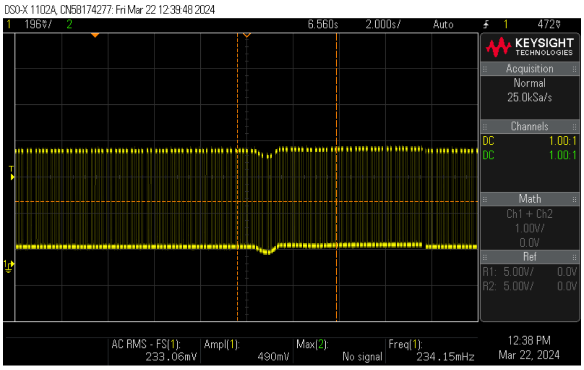

Figure 16: With an interval between peaks of 0.075s for 1 and 0.150s for 0

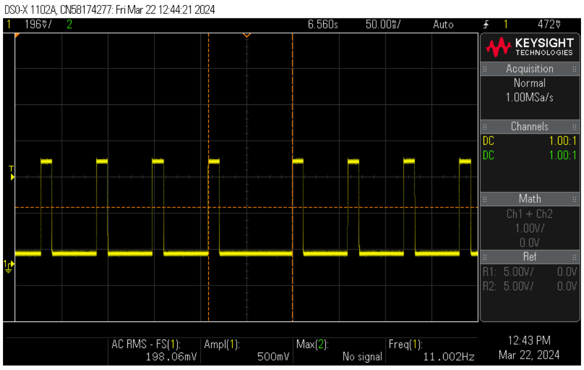

Figure 17: With an interval between peaks of 0.03s for 1 and 0.06s for 0

Figure 18: PPM installation

After testing these two modulations in laboratory wih the photodiode and the light torch, we can verify that, as we decrease the time delay of 0's and 1's it gets worse and worse to verify which one is the HIGH or LOW.

Another important note is that, there will be a moment in time ($\approx$ 15 ms) that we wont be able to verify our sample in full, because some bits will simply not get caught by the photidiode and the light given the speed (data rate) that we are imposing.

4 Conclusion

In conclusion, our project successfully explored the application of various modulation techniques—PWM, PCM, and PPM—within a Li-Fi communication framework. We demonstrated that while PWM, PPM and PCM offer distinct advantages in data transmission and noise immunity respectively, there are inherent limitations when pushing the data rate, particularly in detecting signal states at higher frequencies. Our findings emphasize the need for a balance between speed and reliability in optical communication systems. As we approached the critical threshold of 15ms for signal detection, we observed a degradation in performance, highlighting the physical constraints we must consider in real-world applications. This project not only deepened our understanding of the theoretical underpinnings of Li-Fi technology but also provided valuable hands-on experience in the practical challenges of implementing a visible light communication system.

5 Attachments

Listing 1: Arduino sketch for PWM modulation.

```
int a[] = { 1, 0, 1, 1, 0, 1};

void setup() {
  pinMode(9, OUTPUT);  // Configure pin 13 as an output
  //pinMode(LED_BUILTIN, OUTPUT); // Configure the built-in LED pin as an output

  Serial.begin(9600);  // Initialize serial communication
}

void loop() {

  for (int i = 0; i < sizeof(a) / sizeof(a[0]); i++) {
    //Serial.print("a[i] = ");

    if (a[i] == 1) {
      Serial.println(1);
      digitalWrite(9, HIGH);  // sets the digital pin 13 on
      delay(62.5);
      digitalWrite(9, LOW);
      delay(600);
    } else {
      digitalWrite(9, HIGH);
      delay(37.5);
      digitalWrite(9, LOW);
      delay(600);
    }
  }

  digitalWrite(LED_BUILTIN, HIGH);   // turn the LED on
  delay(500);                       // wait for half a second
  digitalWrite(LED_BUILTIN, LOW);    // turn the LED off
  delay(500);
}
```

Listing 2: Arduino sketch for modified PPM modulation.

```
int a[] = { 0, 1, 0, 1, 0};

void setup() {
  pinMode(5, OUTPUT);  // Configure pin 5 as an output
  //pinMode(LED_BUILTIN, OUTPUT); // Configure the built-in LED pin as an output

  Serial.begin(9600);  // Initialize serial communication
}

void loop() {
  for (int i = 0; i < sizeof(a) / sizeof(a[0]); i++) {
    if (a[i] == 1) {
      digitalWrite(5, HIGH);
      delay(10);
      Serial.println(1);
      delay(10);
      Serial.println(1);
      delay(10);
      digitalWrite(5, LOW);
      Serial.println(0);
```

```
        delay(10);
        Serial.println(0);
        delay(10);
        Serial.println(0);
        delay(10);
        digitalWrite(5, HIGH);
        delay(10);
        Serial.println(1);
        delay(10);
        Serial.println(1);
        delay(10);
        digitalWrite(5, LOW);
        Serial.println(0);
        delay(10);
        Serial.println(0);
        delay(10);
        Serial.println(0);
        delay(10);
      } else {
        digitalWrite(5, HIGH);
        delay(10);
        Serial.println(1);
        delay(10);
        Serial.println(1);
        delay(10);
        digitalWrite(5, LOW);
        Serial.println(0);
        delay(10);
        Serial.println(0);
        delay(10);
        Serial.println(0);
        delay(10);
        Serial.println(0);
        delay(10);
        Serial.println(0);
        delay(10);
        Serial.println(0);
        delay(10);
        digitalWrite(5, HIGH);
        delay(10);
        Serial.println(1);
        delay(10);
        Serial.println(1);
        delay(10);
        digitalWrite(5, LOW);
        Serial.println(0);
        delay(10);
        Serial.println(0);
        delay(10);
        Serial.println(0);
        delay(10);
      }
    }
}
```

Listing 3: Arduino sketch for modified PCM modulation.

```
int a[] = { 1, 0, 1, 1, 1, 0, 0, 1};

void setup() {
```

```
  pinMode(5, OUTPUT);
  Serial.begin(9600);  // Initialize serial communication

  for (int i = 0; i < sizeof(a) / sizeof(a[0]); i++) {
    if (a[i] == 1) {
      digitalWrite(5, HIGH);  // sets the digital pin 5 on
      delay(250);
    } else {
      digitalWrite(5, LOW);  // sets the digital pin 5 off
      delay(250);
    }
  }
}

void loop() {
  // Loop function is intentionally left empty
}
```