LiFi-Based Data Transmission Using Visible Light Communication

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***Abstract*—Visible Light Communication (VLC) leverages the visible light spectrum for secure and efficient data transmission, offering an alternative to traditional radio-frequency systems. This project implements a VLC system using modulation techniques like On-Off Keying (OOK) and Color Shift Keying (CSK) to encode binary data into light signals emitted by a TriLED, which are captured by a Google Pixel 7 Pro camera, processed with OpenCV, and decoded into binary data. K-Means clustering and the HSV color space enhance color detection accuracy by improving the robustness of the system against varying lighting conditions. Evaluated under various lighting environments and transmission distances, the system achieves throughputs of 600 - 700 bps for 4-CSK and 900 - 1000 bps for 8-CSK, with error rates ranging from 2% to 25%. These results highlight the system's scalability, robustness against ambient light interference, and potential for secure VLC applications in both indoor and outdoor settings. Future work involves integrating RSA encryption for enhanced data security, further optimizing modulation techniques, and expanding the system to support higher-order encoding schemes to achieve even greater data rates. This project demonstrates the feasibility of VLC as a reliable and secure communication method, paving the way for its use in diverse real-world applications.**

I. Introduction

A. Background

Visible Light Communication (VLC) is a type of optical wireless communication that uses visible light, typically emitted by LEDs, to transmit data. By rapidly modulating the intensity or color of the light at speeds undetectable to the human eye, VLC enables simultaneous illumination and data communication. Receivers, such as cameras or photodetectors, decode these light signals into digital information.

VLC offers several advantages over traditional radio-frequency (RF) communication. It utilizes the visible light spectrum, which is larger and less congested than the RF spectrum, providing scalability for high-demand applications. Additionally, VLC is immune to electromagnetic interference, making it suitable for sensitive environments like hospitals and airplanes. Its line-of-sight nature enhances security by confining signals to the illuminated area, and modern energy-efficient LEDs make it a sustainable communication solution.

While promising, VLC faces challenges such as interference from ambient light, achieving high data rates, and maintaining synchronization between transmitters and receivers. This project addresses these challenges by integrating advanced modulation techniques, such as On-Off Keying (OOK) and Color Shift Keying (CSK), with robust image processing methods. The goal is to demonstrate the potential of VLC as a secure and efficient communication technology for various real-world applications.

B. Motivation

The rapid expansion of wireless communication networks has resulted in a congested RF spectrum, raising concerns about scalability and performance. VLC, which utilizes the untapped visible light spectrum, offers a solution to these issues while providing inherent security benefits. Unlike RF signals that propagate in all directions, VLC signals are line-of-sight and confined to the area illuminated by the light source. This characteristic significantly reduces the risk of unauthorized access or eavesdropping, making VLC an attractive option for secure data transmission.

- **Potential Applications** This project's implementation of secure VLC-based communication has several real-world applications:
  - Smart Homes: VLC can enable secure communication between IoT devices in smart homes, leveraging existing LED lighting infrastructure to transmit sensitive data without the risk of RF interference.
  - Automotive Communication: VLC can be used for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. For example, headlights and taillights can serve as transmitters for exchanging information such as navigation data or traffic updates securely and efficiently.
  - Indoor Navigation: VLC can support precise indoor positioning and navigation systems, where visible light is used to guide users in places like airports, shopping malls, and museums.
  - Secure Data Transmission: Environments such as hospitals, where RF interference can disrupt critical equipment, can benefit from VLC to securely transmit sensitive data without electromagnetic interference.

The goal of this project is to design and implement a VLC system capable of secure, reliable, and high-speed communication. By using efficient modulation techniques such as

On-Off Keying (OOK) and Color Shift Keying (CSK), the project aims to transmit binary data using a TriLED while addressing common challenges like increasing the bit rate, mitigating ambient light interference, and improving decoding accuracy.

C. Overview of the Main Problem

The primary problem addressed in this project is to establish a secure and reliable communication channel using VLC. This involves overcoming several technical challenges related to data transmission, decoding, synchronization, and performance. Additionally, one of the critical objectives is to increase the data transmission rate while maintaining accuracy and robustness.

- **Data Encoding and Transmission:** Efficiently encoding binary data into light signals is essential to achieve higher data rates. The project explores modulation techniques like On-Off Keying (OOK) for simplicity and Color Shift Keying (CSK) for higher throughput by encoding multiple bits into each transmitted signal.
- **Signal Decoding and Processing:** Decoding high-speed data signals requires precise and efficient algorithms to interpret the light signals captured by the receiver. As the data rate increases, maintaining decoding accuracy becomes more challenging due to the potential overlap or distortion of signals.
- **System Synchronization:** Accurate synchronization between the transmitter and receiver is critical for high data rates. Misalignment in timing can result in corrupted or missed data, especially when operating at faster modulation speeds.

D. Challenges in Solving the Problem

- **Ambient Light Interference:** Variations in environmental lighting can distort the transmitted signals, leading to decoding errors. Bright or fluctuating light conditions add complexity to accurate signal interpretation.
- **Light Modulation:** Encoding binary data into light signals requires precise modulation techniques like On-Off Keying (OOK) and Color Shift Keying (CSK) to balance speed and accuracy while ensuring reliable transmission.
- **Receiver Sensitivity:** The receiver must differentiate between transmitted signals and background light effectively. This is especially challenging in high-interference environments or when dealing with subtle color variations.
- **Decoding Colors:** Mapping transmitted colors to binary sequences is crucial for data reconstruction. Challenges arise due to variations in lighting, camera sensitivity, or noise, requiring robust methods like K-Means clustering and HSV color space analysis to ensure accurate color detection.

E. Methods and Algorithms Used to Solve the Challenges

To address these challenges, the project employs the following techniques:

- **On-Off Keying (OOK):** For encoding binary data into multi-color light signals.
  - Encodes binary data using the presence or absence of red light. A red light indicates binary 1, and its absence indicates binary 0.
  - Provides simplicity and efficiency for basic data transmission.
- **Color Shift Keying (CSK):**
  - Encodes binary data using specific colors of light emitted by the TriLED. For example:
    - 000 : Red
    - 001 : Green
    - 010 : Blue
  - Enables higher data rates and more complex encoding schemes compared to OOK.
- **OpenCV Integration:** Captured frames are processed using the OpenCV library to enhance the decoding process. OpenCV converts images into matrices for efficient analysis, facilitating precise color detection and binary mapping for data reconstruction.
- **K-Means Clustering:** K-Means Clustering is an unsupervised machine learning algorithm used in the decoding process of Visible Light Communication (VLC) to group pixels into clusters based on their RGB values. In VLC, it plays a crucial role in classifying the colors used in modulation schemes like Color Shift Keying (CSK).

F. Summary of Implementation and Results

The system implementation comprises two main components: the transmitter and the receiver. The transmitter, controlled by an Arduino Uno, utilizes a TriLED to encode binary data into light signals using On-Off Keying (OOK) and Color Shift Keying (CSK). OOK represents binary values using the presence (ON) or absence (OFF) of red light, while CSK encodes multiple bits into distinct colors like red, green, and blue for higher data rates. The receiver captures these signals using a Camera, processes them through OpenCV in an Android application, and decodes the binary data using custom logic. K-means clustering, an unsupervised machine learning algorithm, is employed to group pixels into distinct clusters based on RGB values, enabling precise color detection. This clustering technique enhances the decoding accuracy by mitigating variations in captured colors due to lighting inconsistencies.

Experimental results demonstrated reliable data transmission with a throughput of 600 - 700 bps (75 bytes per second) for 4-CSK and 900 - 1000 bps (112.5 bytes per second) for 8-CSK, with an error rate of up to 15% under controlled conditions. The system showed resilience to moderate ambient light interference. These findings validate the system's potential for secure and efficient VLC-based communication, showcasing its scalability for higher-order modulation schemes.

II. System Overview and Data Collection

A. Main Devices and Hardware

The Arduino UNO microcontroller controls the light modulation process, encoding data into signals using Color Shift Keying (CSK). It drives the Chanzon 10mm RGB Multicolor Diffused LED Diode Light, a 4-pin TriLED that transmits data by switching between colors—red, green, and blue—to represent binary states. The frosted design ensures uniform light dispersion for accurate color detection. The Google Pixel 7 Pro Camera captures these light signals in real-time and sends them for decoding and analysis. Its rolling shutter mechanism, which captures frames row by row, enhances the detection of rapid changes in light signals modulated using On-Off Keying (OOK) or CSK. This setup provides high-speed data transmission, while ensuring accuracy by keeping the transmitter and receiver stationary to avoid motion artifacts.

B. Software Components

The Arduino IDE is used to write and upload code to the Arduino Uno, implementing the logic for modulation techniques, timing, and control of the TriLED. OpenCV, an open-source computer vision library, is integrated with Android Studio to process the visual data captured by the camera, enabling real-time image processing and decoding on mobile devices. The custom decoding logic interprets the light patterns captured by the camera into binary data, mapping each detected color (e.g., red, green, blue) or light intensity to its corresponding binary value. The use of the HSV color space further enhances the system's robustness, allowing accurate color detection under varying lighting conditions and ensuring reliable reconstruction of the original transmitted data.

C. System Communication

The system comprises two main components: the transmitter and the receiver (see Figure 1). The transmitter, controlled by the Arduino Uno, uses the TriLED to emit data-encoded light signals. These signals are modulated using techniques like CSK and OOK, where each color or pulse duration corresponds to specific binary data. On the receiver side, the Camera captures these light signals as RGB frames. The frames are processed using OpenCV, where K-Means clustering is employed to group pixels into clusters based on color similarity. This clustering method identifies dominant colors in the captured frames and maps them to their respective binary values according to the modulation scheme, ensuring accurate decoding of the transmitted data.

D. Data Collection

Experiments were conducted under varying conditions to evaluate system performance: Data collection was conducted to evaluate the performance of the system under various configurations and environmental conditions. Experiments were performed using On-Off Keying (OOK), 4-CSK, and 8-CSK modulation schemes. The TriLED emitted light signals representing binary data, which were captured by a Camera configured with optimized settings, including a shutter speed of 1/10000 second and low ISO to reduce noise.

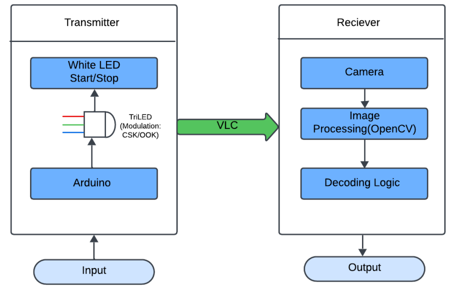

Fig. 1: System Architecture of the VLC Setup

Figure 2 captured frames contained multiple regions corresponding to transmitted symbols, with each region representing binary values through distinct colors. For example, in 4-CSK, colors such as red, green, blue and yellow encoded 00, 01, 10, and 11 respectively. In 8-CSK, additional colors enabled higher data rates while maintaining the same frame structure.

Experiments were conducted at varying transmission distances, ranging from 3 cm to 30 cm, under different lighting conditions, including dark, indoor, and outdoor environments. Captured frames were processed using OpenCV, which converted the images into matrices for efficient analysis. K-Means clustering, an unsupervised machine learning algorithm, was employed to group pixels into clusters based on their RGB values, enabling precise classification of colors used in modulation schemes like Color Shift Keying (CSK).

(a) OOK (b) 4-CSK (c) 8-CSK

Fig. 2: Overall caption for the two figures

E. Data Representations

Data is encoded into binary format for transmission using two modulation techniques: On-Off Keying (OOK) and Color Shift Keying (CSK). In OOK, the presence of red light (ON) represents binary '1', while the absence of light (OFF) represents binary '0', providing a straightforward encoding method using a single color. In CSK, specific colors or color combinations represent binary values; for example, red maps to '000', green to '001', and blue to '010', with additional colors enabling the encoding of more binary values. The Camera captures the emitted light signals as RGB frames, where each frame contains color and intensity information. These frames are processed to extract the binary values, such as red frames in OOK corresponding to '1' and black (off) frames to ‘0‘, while in CSK, each detected color is mapped to its respective binary sequence for accurate data reconstruction.

III. Methods, Techniques, and Algorithms

A. Modulation Techniques

The project employs two primary modulation techniques to encode binary data into light signals, as shown in Figure 2:

- **On-Off Keying (OOK):** On-Off Keying (OOK) is a simple modulation technique where binary data is encoded using the presence or absence of light. In this project, red light is used to represent binary states:
  - Red Light ON: Encodes binary 1.
  - Red Light OFF (Black Light): Encodes binary 0.
- **Color Shift Keying (CSK):** Encodes binary data using colors emitted by the TriLED. Each color represents a specific binary sequence:
  - **4-CSK:** Uses 4 colors (e.g., red: ‘00‘, green: ‘01‘, blue: ‘10‘, and yellow: ‘11‘) to encode 2 bits per symbol.
  - **8-CSK:** Expands to 8 colors, encoding 3 bits per symbol for higher throughput.

  CSK enables scalable data rates and efficient use of the light spectrum.

B. Error Detection and Correction Mechanism

- **Reed-Solomon Encoding:** Reed-Solomon encoding is incorporated to enhance data reliability by detecting and correcting multiple errors in the transmitted data. This error correction mechanism ensures robust communication, particularly in environments with ambient light interference or signal degradation over distance.

C. Decoding Process

The decoding process is a critical component of the system, converting captured light signals into binary data.

1) Android Application: The CameraX API is utilized within a custom-developed Android application to capture light signals in real-time. The application ensures optimized settings for accurate signal detection. Shutter speed is configured to $1/10000$ second, allowing precise capture of rapid light transitions, while ISO is set to a low value to minimize noise and enhance the signal-to-noise ratio. Focus is locked at infinity to maintain clarity, and exposure is manually adjusted to prevent light over-saturation. The captured frames are streamed directly to the Android application, where they undergo processing using OpenCV for decoding and data reconstruction. This integration highlights the seamless interaction between hardware and software components, enabling efficient and accurate signal decoding.

2) OpenCV Integration: Captured frames are processed using the OpenCV library to enable efficient analysis and decoding. Each frame is converted into an OpenCV `Mat` object, allowing for pixel-level manipulation and detailed examination. To streamline the processing workflow while retaining critical information, frames are resized (e.g., 100×1

Fig. 3: Resized Image 100 X 1

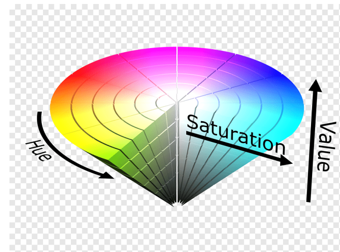

Fig. 4: HSV Color Space

Figure 3) to focus on essential data such as color and intensity. This approach ensures that the processing pipeline remains computationally efficient without compromising the accuracy required for detecting and decoding the transmitted signals.

3) Color Clustering: To decode the light signals into binary data, **K-Means Clustering** is employed to group pixels into distinct color clusters corresponding to the modulation scheme (e.g., red, green, blue, yellow). The algorithm minimizes the intra-cluster variance using the objective function:

$$J = \sum_{i=1}^{k} \sum_{x \in C_i} \|x - \mu_i\|^2$$

where k is the number of clusters, x represents a pixel in the color space, μ_i is the centroid of cluster i, and C_i is the set of pixels in that cluster. The centroids are updated iteratively as:

$$\mu_i = \frac{1}{|C_i|} \sum_{x \in C_i} x$$

This ensures that dominant colors in each frame are identified and mapped to their corresponding binary sequences based on the CSK modulation scheme (e.g., red $\rightarrow$ ’000’, green $\rightarrow$ ’001’).

4) Region Analysis: Region analysis utilizes the HSV color space(Figure 4) to enhance decoding accuracy by separating color information (Hue) from brightness (Value), making it more reliable under varying lighting conditions compared to RGB. The Hue channel identifies colors, ranging from red (0°) to green (120°) and blue (240°), while Saturation measures the intensity of the color from vibrant (1) to grayscale (0). The Value channel indicates brightness levels, scaling from black (0) to full brightness (1). Each frame is divided into vertical bands, with each band representing a portion of the transmitted signal. The system analyzes these bands to determine the dominant color based on Hue and Saturation, ensuring accurate signal decoding while minimizing sensitivity to brightness variations.

IV. Evaluation and Results

1) Hardware Configuration:

- **Transmitter:** Arduino Uno was programmed to modulate light signals using OOK, 4-CSK, and 8-CSK. The TriLED emitted data-encoded signals with a white LED marking the start and end of each transmission session.
- **Receiver:** A smartphone Camera was used to capture light signals with settings optimized for VLC:
  - Shutter Speed: $1/10000\,\mathrm{s}$
  - ISO: Low value for noise reduction
  - Focus: Infinity to maintain clarity of transmitted light.

2) Frame-Based Transmission: For each frame:

- OOK: 1 bit per symbol (10 symbols per frame, 10 bits/frame).
- 4-CSK: 2 bits per symbol (10 symbols per frame, 20 bits/frame).
- 8-CSK: 3 bits per symbol (10 symbols per frame, 30 bits/frame).

The frame rate was fixed at 30 FPS, resulting in the following data rates:

- OOK: 10 bits/frame $\times$ 30 FPS $=$ 300 bps.
- 4-CSK: 20 bits/frame $\times$ 30 FPS $=$ 600 bps.
- 8-CSK: 30 bits/frame $\times$ 30 FPS $=$ 900 bps.

3) Experimental Conditions:

- **Ambient Light:** Under varying ambient light conditions, the system's performance was evaluated in three distinct environments. In a dark room, minimal interference provided ideal conditions for benchmarking, ensuring accurate signal detection and decoding. Under indoor lighting, moderate interference from artificial light introduced some challenges, requiring the system to mitigate noise effectively. In bright outdoor conditions, high interference from sunlight posed significant challenges to signal clarity, testing the system's robustness and ability to handle adverse environments.
- **Data Transmission:** Binary data sequences of varying lengths (10, 100, and 1000 bits) were transmitted using OOK, 4-CSK, and 8-CSK modulation schemes.

4) Software Integration: The Android application processed received frames using **OpenCV**. Data reconstruction utilized K-Means clustering for color detection and image processing.

A. Metrics for Performance Evaluation

The system performance was evaluated using the following metrics:

1) Throughput: Throughput (T) represents the rate of successful data transmission and is measured in bits per second (bps). It is calculated as:

$$T = \frac{\text{Bits Transmitted Per Frame} \times \text{Frame Rate (FPS)}}{\text{Time (s)}}$$

2) Error Rate: The error rate (E_r) is defined as the percentage of incorrectly decoded bits in the reconstructed binary data. It is influenced by the distance between the transmitter and receiver, ambient lighting conditions, and the modulation scheme used. The error rate is given by:

$$E_r = \frac{\text{Number of Incorrect Bits}}{\text{Total Number of Bits Transmitted}} \times 100$$

3) Accuracy: Accuracy (A) measures the percentage of correctly decoded bits and is defined as:

$$A = \frac{\text{Number of Correct Bits}}{\text{Total Number of Bits Transmitted}} \times 100$$

Alternatively:

$$A = 100 - E_r$$

These equations provided a quantitative basis for evaluating the performance of the Visible Light Communication (VLC) system across various experimental setups, ensuring a robust analysis of its throughput, error rate, and reliability.

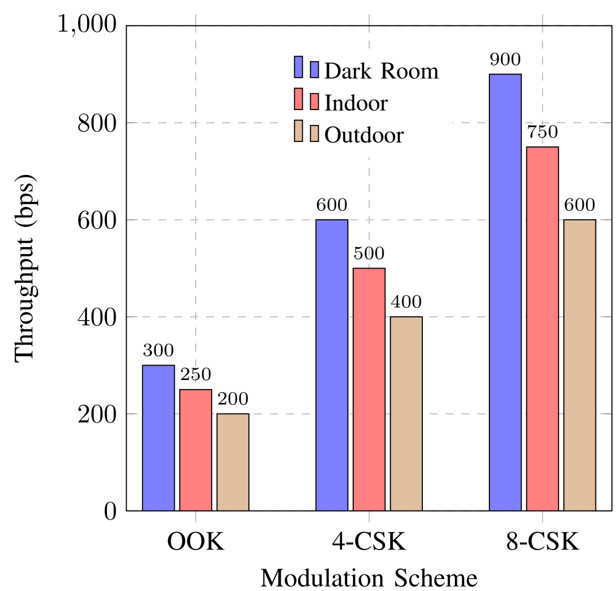

Fig. 5: Throughput Comparison for Different Modulation Schemes Under Various Lighting Conditions

B. Numerical Results

1) Throughput Results: Figure 5 shows the throughput for three modulation schemes—OOK, 4-CSK, and 8-CSK—under different lighting conditions: Dark Room, Indoor Lighting, and Outdoor Lighting. Throughput is measured in bits per second (bps) and demonstrates the impact of modulation technique and lighting on data transmission.

OOK has the lowest throughput: 300 bps in a dark room, 250 bps indoors, and 200 bps outdoors. It encodes 1 bit per symbol, making it robust to noise but limited in data rate.

4-CSK encodes 2 bits per symbol, achieving 600 bps in a dark room, 500 bps indoors, and 400 bps outdoors. It balances data rate and robustness by using multiple colors for encoding.

8-CSK encodes 3 bits per symbol, reaching 900 bps in a dark room, 750 bps indoors, and 600 bps outdoors. Its higher data rate increases sensitivity to interference, especially outdoors.

TABLE I: Error Rates (%) for Different Distances and Lighting Conditions

Distance (cm)	**OOK (%)**	**4-CSK (%)**	**8-CSK (%)**
Dark Room	5	8	10
Indoor Lighting	10	15	20
Outdoor	20	25	30

Lighting conditions affect throughput significantly. In a dark room, all schemes perform at peak throughput. Indoor lighting causes moderate interference, reducing throughput slightly for CSK schemes. Outdoor lighting introduces significant interference from sunlight, resulting in the lowest throughput for all schemes. OOK remains stable due to binary encoding, while CSK schemes decline more noticeably due to reliance on accurate color detection.

2) Error Rate Analysis: **Table I** summarizes the error rates observed under different lighting conditions, illustrating the impact of environmental factors and transmission range on the VLC system's performance. In a dark room, error rates were minimal, with OOK at 5%, 4-CSK at 8%, and 8-CSK at 10%, highlighting the system's ability to decode signals reliably under ideal conditions where the absence of ambient light and close proximity to the transmitter ensures strong signal clarity. However, as lighting conditions become more challenging, error rates increase significantly. Under indoor lighting, OOK error rates rise to 10%, while 4-CSK and 8-CSK reach 15% and 20%, respectively, reflecting moderate interference from artificial light sources. In outdoor conditions, error rates peak at 20% for OOK, 25% for 4-CSK, and 30% for 8-CSK due to sunlight interference and reduced signal intensity. These results demonstrate the trade-offs between lighting conditions and error rates, emphasizing the need to optimize receiver sensitivity, implement robust modulation techniques, and enhance error correction mechanisms to ensure consistent performance across diverse environments.

3) Accuracy Trends: **Table I** shows the accuracy trends for different modulation schemes under various conditions. OOK achieved the highest accuracy, with 95% in a dark room (5% error rate), dropping to 90% indoors (10% error rate), and 80% outdoors (20% error rate). For 4-CSK and 8-CSK, accuracy in a dark room was 92% and 90%, respectively, decreasing to 85% and 80% indoors, and further to 75% and 70% outdoors. These results highlight the trade-off between higher data rates and reduced accuracy in challenging environments.

C. Output

Figure 6 illustrates the end-to-end decoding process of the Visible Light Communication (VLC) system. The first window (top left) displays the binary data decoded from the transmitted signal, where each frame is indexed and mapped to a binary sequence derived from modulation techniques like OOK or CSK. For example, Frame 27 contains the binary sequence '0010100010111011111010100000'. The second window (top right) showcases the dominant colors detected in each frame, directly corresponding to the binary data. Frame 27, for instance, contains the sequence [Green, Blue, Red, Yellow, White, Cyan, Black, Green, Blue, Red]. The third window (bottom) provides a visualization of the resized image for Frame 27, where each vertical bar represents a detected color in the transmitted signal. The resized image simplifies processing while preserving critical color transitions, allowing efficient mapping between the captured colors and the reconstructed binary data. This integrated setup demonstrates accurate signal detection, color decoding, and data reconstruction, highlighting the robustness of the VLC system.

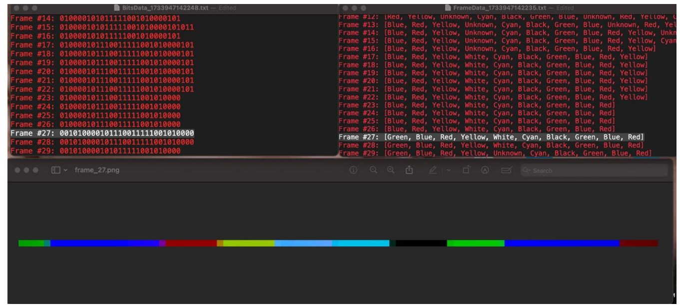

Fig. 6: Output

D. Observations

- **OOK vs. CSK:** OOK is more robust under noisy conditions but offers limited throughput. CSK achieves higher throughput but is more sensitive to interference.
- **Ambient Light Sensitivity:** HSV color space and clustering mitigated ambient light effects, but accuracy decreased with increasing light intensity.

E. Summary of Results

The experimental evaluation demonstrates that the proposed VLC system achieves:

- Reliable throughput of 600 bps for 4-CSK and 900 bps for 8-CSK under controlled conditions.
- Error rates below 10% in ideal environments and up to 25% in challenging outdoor conditions.
- Scalability to higher-order modulation schemes with careful optimization of receiver sensitivity and error correction.

These findings validate the system's potential for secure and efficient VLC communication, particularly in low-noise environments.

V. Conclusion and Future Work

A. Conclusion

This project successfully demonstrated the feasibility of Visible Light Communication (VLC) using a TriLED transmitter and a smartphone camera receiver. By employing modulation techniques such as On-Off Keying (OOK) and Color Shift Keying (CSK), the system achieved reliable data transmission rates of 300 bps, 600 bps, and 900 bps for OOK, 4-CSK, and 8-CSK, respectively. Error rates ranged from 5% to 30% depending on the distance and lighting conditions, highlighting the system's robustness in controlled environments and its sensitivity in challenging conditions. The integration of OpenCV and K-Means clustering ensured effective decoding of transmitted signals.

B. Future Work

While the results of this project validate the practical application of VLC, several areas for improvement and expansion have been identified:

- **Dynamic Environments:** Extend the system's robustness to dynamic scenarios where the transmitter or receiver may be in motion.
- **Higher Data Rates:** Explore advanced modulation techniques such as Quadrature Amplitude Modulation (QAM) or higher-order CSK to achieve greater throughput.
- **Longer Distances:** Investigate methods to enhance transmission distance, such as using higher-powered LEDs or more sensitive camera sensors.
- **Machine Learning for Decoding:** Integrate machine learning models for more accurate and efficient decoding of transmitted data, especially under adverse lighting conditions.
- **Outdoor Optimization:** Develop adaptive noise filtering and synchronization techniques to improve system performance in outdoor environments with significant ambient light interference.
- **IoT Integration:** Adapt the VLC system for integration with IoT devices to enable secure, energy-efficient communication in smart home or industrial applications.

By addressing these aspects, future iterations of this system can achieve greater reliability, scalability, and versatility, paving the way for VLC adoption in a broader range of practical applications.

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