Optical Wireless Communication (OWC) between smartphones with LED/Camera pair

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ABSTRACT

The target is to explore the development and implementation of an Optical Camera Communication (OCC) system using smartphones. Using the LED flashlight as a transmitter and the smartphone camera as a receiver, it demonstrates a cost-effective and energy-efficient solution for short-range data communication. The system has two distinct protocols—binary and Type-Length-Value (TLV)—to transmit messages encoded into light patterns, which are decoded through real-time image processing techniques.

The study achieved a maximum transmission speed of 3.33 bits per second over a reliable range of 15 cm, highlighting the potential of OCC for low-data-rate applications. However, challenges such as sensitivity to ambient light, limited communication range, and the inherent constraints of smartphone hardware were identified.

Despite its limitations, OCC presents a promising alternative to traditional wireless communication, particularly in scenarios requiring secure, low-power, and proximity-based data exchange. Potential applications include IoT systems, indoor positioning, and smart environments. Future improvements, such as integrating high-intensity LEDs, optical lenses, and advanced signal processing techniques, could significantly enhance the system's capabilities and broaden its range of applications. This work underscores the viability of using everyday consumer devices for innovative communication solutions and lays the foundation for further advancements in OCC technology.

Keywords: *Optical Camera Communication (OCC), Visible Light Communication (VLC), Smartphone communication, Binary encoding, TLV protocol, Ambient light interference, Signal processing.*

Link to the source code: https://github.com/wasasawa/Low_energy_binary_communication

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1 – INTRODUCTION

Optical Camera Communication (OCC) is an innovative solution for low-energy communications. Given that we have explored every other type of electromagnetic information transfer, it would only be normal to consider the use of the visible light spectrum. Conveniently, hundreds or thousands of visible light emitters are primordial to every building, meaning that with or without the OCC they would consume energy. So why not use those light sources to transfer information?

Even though this solution doesn't achieve high transfer rates, it could be very promising for short distance information sharing (e.g: a factory with multiple IoT devices that share telemetry and other types of data periodically), mobile robot navigation or indoor positioning… These are all applications where the transfer of data doesn't need very high speeds or to reach very long distances and using OCC in these cases would be very beneficial in terms of energy consumption.

Another advantage for OCC is the fact that it can operate in areas where the RF communication faces challenges, such as areas with high RF interference or where RF spectrum use is restricted. OCC can be employed in crowded urban areas, hospitals, or aircraft cabins without adding to the congestion of RF channels.

OCC presents an innovative and energy-efficient solution for short-range communication, but its practical implementation, particularly using smartphones, faces several critical challenges. Since smartphone cameras are not designed for high-speed communication, the rolling shutter effect of these cameras limits achievable data rates. OCC is also highly sensitive to ambient light interference, which can degrade signal quality in environments with variable lighting conditions. The strict requirement for a direct line of sight between the transmitter and receiver limits its applicability in dynamic or obstructed environments. Furthermore, data extraction on smartphones is constrained by hardware limitations, such as limited camera frame rates and processing power, resulting in latency and inefficiency in decoding transmitted signals. It remains a significant challenge to maintain synchronization and accuracy during handovers in multi-device scenarios, such as IoT networks or dense indoor environments. Overcoming these limitations is essential in order to unlock the potential of OCC for practical applications in real-world scenarios.

The primary objective of OCC using LED patterns as a transmitter and a smartphone camera as a receiver is to establish a reliable and cost-effective method for short-range data exchange. OCC aims to leverage the ubiquity of LEDs and smartphone cameras to enable communication without the need for additional hardware. This technology seeks to facilitate low-data-rate communication by modulating data into light patterns, which are then captured and decoded by the camera. Key objectives include achieving efficient data transmission and reception, ensuring compatibility with existing consumer devices, and optimizing system performance in terms of range, accuracy, and robustness under various lighting conditions. Additionally, OCC aims to provide a secure and energy-efficient alternative to traditional wireless communication, offering practical applications in areas like the Internet of Things (IoT), smart environments, and augmented reality systems.

This presentation divide this report into four core parts, starting with a literature review where we will go over some state-of-the-art documents in the OCC field. Afterwards we'll dive into our proposal's methodology, in this part we will explore the transmitter side of our system, the receiver side and the different protocols used between them. We will finish that part with a review of the limitations and some potential improvements we could have made. As a last part we will expose the results achieved during this work.

2 - LITERATURE REVIEW

This section highlights the key references that guided this project, covering principles, challenges and advancements in Optical Camera Communication (OCC) systems and tools like OpenCV for computer vision implementation.

2.1. Optical Camera Communications: Principles, Modulations, Potential and Challenges

Optical Camera Communication (OCC), a subset of Optical Wireless Communication (OWC), offers an innovative solution to the increasing limitations of Radio Frequency (RF) technologies. OCC uses LEDs as transmitters and standard cameras as receivers to enable cost-effective low-speed data transmission and positioning without hardware changes. OCC has been integrated into the IEEE 802.15.7m standard [1] and uses visible, infrared, and ultraviolet light spectrums to enable a variety of applications including indoor positioning, vehicular communications, and IoT systems. Key modulation techniques such as Nyquist sampling, region of interest signals, hybrid camera-PD, and rolling shutter-based schemes increase data rates and efficiency. However, challenges such as limited data rates, interference, and mobility restrictions remain. This paper highlights solutions such as advanced modulation schemes and interference mitigation strategies to pave the way for integrating OCC into new technologies.

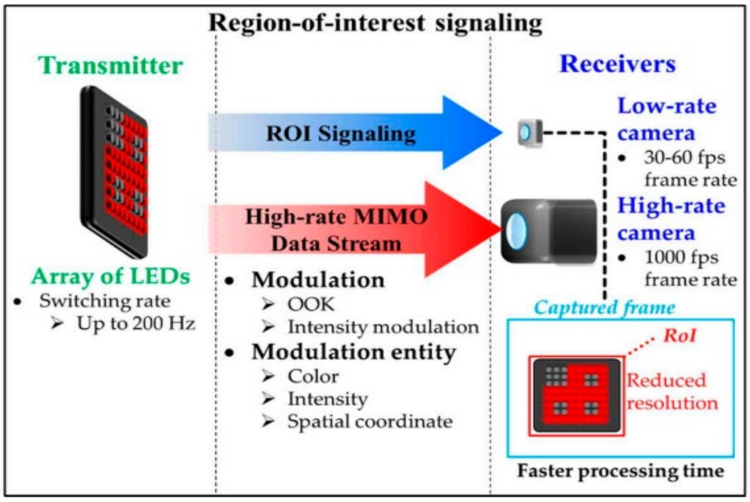

Figure 1 : Optimizing data processing with region-of-interest signaling in OCC systems [1]

2.2. Requirements and Implementation Challenges in OCC

Optical Camera Communication (OCC) is a promising technology within the field of Optical Wireless Communication (OWC) that leverages LEDs and camera sensors for data transmission. The study by Shahjalal et al. [2] provides a comprehensive overview of the requirements and challenges associated with implementing OCC systems, particularly those using smartphone cameras.

The paper highlights the essential components for OCC systems. High-speed LEDs are used to encode data into modulated light signals, while CMOS cameras with rolling shutter mechanisms capture these signals. The rolling shutter effect, while effective for encoding, imposes limitations on the achievable data rates due to the frame rate of the cameras. Efficient modulation schemes, such as On-Off Keying (OOK) and Manchester coding [2], are necessary to process these signals effectively. Furthermore, error correction protocols are critical for maintaining data integrity, especially in environments with noise or interference.

The authors identify several challenges in OCC systems. These include limited data rates caused by the rolling shutter mechanism, susceptibility to ambient light interference, and dependency on a direct line of sight (LoS) for effective communication. External light sources, such as sunlight or artificial lighting, can degrade signal quality, reducing system robustness. These challenges highlight the importance of optimizing both hardware and software components to improve performance.

Despite these limitations, Shahjalal et al. note the advantages of OCC systems, such as enhanced security due to the use of light-based communication and compatibility with widely available consumer devices like smartphones. The study also suggests potential improvements, including advanced modulation techniques, the use of global shutter cameras to overcome rolling shutter constraints, and machine learning approaches for dynamic interference mitigation.

In summary, the study provides a detailed framework for understanding the requirements and challenges of OCC systems, paving the way for further research and development in this emerging field.

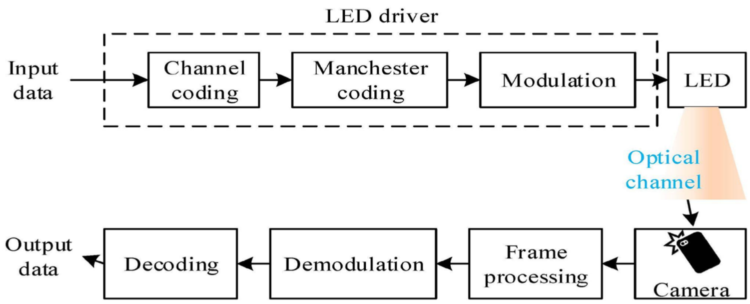

Figure 2 : The block diagram of an optical camera communication (OCC) transmitter and receiver system [2]

2.3. Computer vision implementation in OCC

The paper highlights the important role of computer vision in enabling Optical Camera Communication (OCC), where cameras act as receivers to detect and decode data transmitted via LED light patterns. By using OpenCV and advanced image processing techniques, OCC systems efficiently extract meaningful binary information from visual signals, ensuring reliable and robust communication.

The implementation begins with the camera capturing real-time video frames, which are subsequently processed to isolate the LED signal from environmental noise. The preprocessing pipeline includes grayscale conversion to reduce computational complexity and Gaussian blur to minimize scattering noise caused by ambient lighting. Thresholding follows to create a binary representation of the frame, distinguishing illuminated regions (binary '1') from non-illuminated ones (binary '0'). These preprocessing steps ensure that the LED signal is accurately extracted despite challenging lighting conditions.

A critical aspect is the use of region of interest (ROI) techniques to localize the LED transmitter. By dynamically defining and tracking these ROIs, OCC systems can maintain focus on the transmitter even in environments with multiple light sources or moving components [3]. This capability ensures synchronization between the transmitter and receiver, allowing the system to detect patterns of light modulation effectively.

Real-time frame analysis enables OCC systems to overcome traditional communication challenges, such as ambient light interference and motion-induced misalignment. Techniques like contour detection or bounding box estimation enhance the system's ability to maintain accurate detection of the LED's position, which is essential for decoding the transmitted data. Modulation schemes such as On-Off Keying (OOK) [3] simplify the interpretation of the binary signals, making the system both efficient and scalable.

OCC systems achieve enhanced adaptability and reliability by integrating computer vision. Frame-by-frame analysis allows dynamic responses to changes in lighting, obstructions in the line of sight, and variations in transmission patterns. This adaptability makes OCC a promising solution for applications like IoT, indoor positioning, and secure, low-power communication.

Additionally, scalability is facilitated by reliance on widely available consumer-grade cameras and open-source libraries like OpenCV. This software-driven approach eliminates the need for specialized hardware, making OCC an economical alternative to RF-based communication systems. Visible light, immune to RF congestion and interference, enhances OCC's applicability in crowded urban areas, hospitals, and industrial environments.

In conclusion, computer vision is central to the successful implementation of OCC. By harnessing advanced image processing techniques, OCC systems achieve accurate detection and decoding of light signals, paving the way for energy-efficient, secure, and versatile wireless communication solutions.

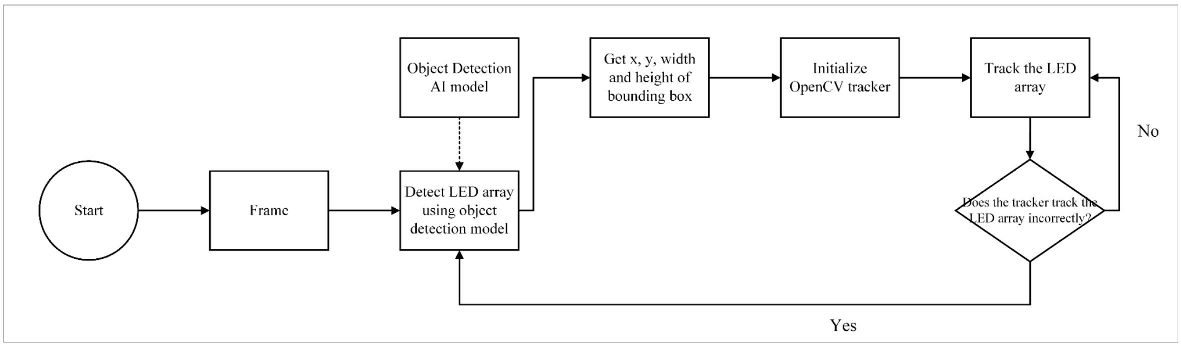

Figure 3 : OpenCV approach for LED array detection [3]

3 - METHODOLOGY

In order to implement the OCC with smartphones, we were provided with 4 Samsung S24 smartphones as hardware, these phones being pretty recent helps with the technically demanding nature of the project (real-time computing and image analysis), the fact that they are based on an Android OS also helps with portability and ease of use/developpement.
In our software development we divided the task into two fairly independent parts, the transmission and the reception. We decided to make two completely different APKs (Android Application Package) to slightly simplify our task and also for us to be able to have 2 groups developing both sides of the project independently. We have also developed two versions of the software: one that uses pure binary packets, and one using the TLV (Type Length Value) protocol.
At the beginning we were evaluating 2 possible solutions for the implementation, the first one using only two phones (one transmitter and one receiver), the second one using a microcontroller and a phone (the microcontroller would be connected to a LED that acts as a transmitter while the phone would be the receiver) we decided that we would only use the phones due to time and material issues.

Figure 4 : Demonstration of OCC communication: smartphone LED transmission and camera detection

3.1- Transmission

For the transmission side of the OCC, the process is simple, we need to code a simple yet functional UI (user interface) where the user can type the message to send, the software then

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converts the message into binary (or TLV) and sends it serially (bit by bit) via the flashlight (flashlight on= 1, flashlight off= 0) with the desired frequency.

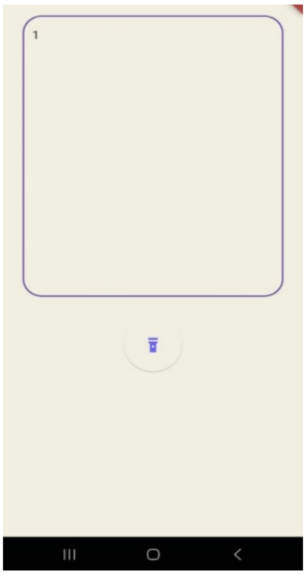

Figure 5 : Tx Interfac

3.2- Reception

The reception side was implemented to capture, process, and decode the light signals emitted by the transmitter. Using the smartphone's camera, the system analyzes the incoming video in real-time to detect and decode the flashlight signal. To achieve this, computer vision techniques were employed using the OpenCV library. OpenCV enabled efficient detection of the LED signals through frame-by-frame image processing.
We can divide this process into multiple stages as of the following:

3.2.1 Installing and Integrating OpenCV in Android Studio:

To enable real-time image processing for detecting and decoding LED signals, the OpenCV library was integrated into the Android Studio project. The process began with downloading the OpenCV SDK and importing it into the Android Studio environment. The library was then configured to work seamlessly with the project by adding it as a module and initializing it during runtime. This integration allowed the system to utilize OpenCV's robust computer vision functionalities, such as frame conversion and brightness analysis, ensuring efficient signal detection. The integration was tested with basic image processing tasks to verify successful setup before being applied to the LED detection process.

3.2.2 Signal Detection:

The receiver application defines a Region of Interest (ROI) around the expected position of the LED transmitter. Using OpenCV, each frame is converted to grayscale to simplify processing and reduce computational load. The brightness levels in the ROI are then analyzed. If the average brightness within the ROI exceeds a predefined threshold, the system identifies the LED as being in the "on" state (binary '1'). Otherwise, it records an "off" state (binary '0').

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3.2.3- Synchronization Mechanism:

To facilitate synchronization between the transmitter and the receiver, we use a synchronization sequence (e.g., "100100"). Once a flashlight is detected, the receiver checks if this synchronization sequence is performed first, if not we assume that it's just background noise, or some other communication that isn't destined to this particular receiver. If it's detected, we start recording the incoming bit sequence in order to decode them later. This mechanism minimizes errors caused by misalignment.

3.2.4- Data Processing:

The captured binary sequence is accumulated based on the period of the communication and processed based on its structure (e.g., binary or TLV):

- For binary messages, the sequence is accumulated until it reaches a length of 8, which is then converted to an ASCII character.
- For TLV messages, we first extract the type and length fields, the system then decodes the value based on its length and reconstructs the original message.

3.2.5- Visual Feedback:

The output of the data processing stage is then displayed on the UI screen.

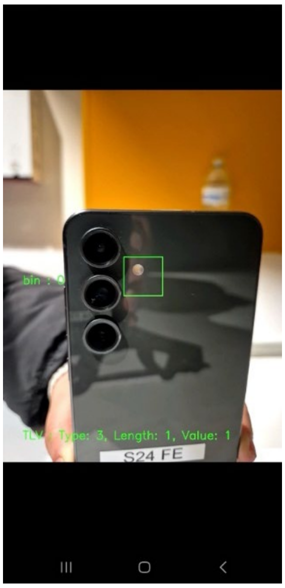

Figure 6 : Rx interface

3.3- Binary/TLV implementations

To explore different approaches for data transmission, we implemented two encoding formats: **Binary Packets** and the **Type-Length-Value (TLV) Protocol**. Each format was evaluated based on its ability to transmit data effectively while meeting the system's flexibility and scalability requirements.

3.3.1- Binary Packets

In the binary packet format, messages are transmitted as simple binary sequences. Each bit corresponds directly to the flashlight's state, where "on" represents a binary '1' and "off" represents a binary '0'. This format is straightforward and easy to implement, making it highly

efficient for small and simple messages. The lack of additional fields or metadata reduces processing time and transmission overhead, allowing for faster communication. Additionally, the simplicity of this method minimizes the computational requirements for encoding and decoding, making it a lightweight solution ideal for straightforward applications.
However, binary packets have significant limitations. The absence of structure makes them unsuitable for transmitting complex or multi-field data, as they cannot differentiate between types of content or include metadata. This lack of flexibility restricts their scalability, as they cannot accommodate more sophisticated communication scenarios. Moreover, without error-checking mechanisms, the receiver has no way to verify the integrity or completeness of the message, increasing the likelihood of errors in transmission.

3.3.2- Type-Length-Value (TLV) Protocol

The TLV protocol provides a structured format for encoding messages, making it a more versatile solution for transmitting diverse types of data. Messages are divided into three fields:

- **Type**: Identifies the nature of the data being transmitted, such as text, numeric values, or other specific types.
- **Length**: Specifies the size of the value field, ensuring that the receiver knows how much data to process.
- **Value**: Contains the actual message or data being transmitted.

This structured format offers significant **flexibility**, supporting a wide range of data types and enabling adaptability to complex communication scenarios. It is also highly **scalable**, as its metadata facilitates efficient processing of multi-field or larger messages. The **length field** plays a crucial role in **error handling**, allowing the receiver to validate the message's completeness. Moreover, the **modularity** provided by the Type field helps the receiver identify and interpret the data type, enhancing its ability to handle diverse content effectively.
However, TLV has some limitations. The inclusion of the Type and Length fields increases the size of the transmission, resulting in higher overhead, particularly for small or simple messages. The encoding and decoding processes are also more **computationally intensive** compared to simpler formats, requiring additional processing resources. Furthermore, accurate parsing of TLV messages relies on proper synchronization between the transmitter and receiver to ensure each field is correctly identified and processed.

3.4 - Combining the 2 APKs

In order to efficiently use the system, we thought of the possibility to combine the 2 apks into 1, so that each smartphone could be used as a transmitter and receptor at the same, however this was pretty complicated, especially the fact that we need to use both the flashlight and the camera of each phone which could result in pretty significant interference.

4 – RESULTS

We evaluated the system's performance based on key metrics such as transmission speed, communication distance, and error rates under different environmental conditions:

- **Transmission Speed:** The maximum transmission speed achieved by the system was 300 ms per bit, resulting in a data rate of approximately 3.33 bits per second (bps). This limitation primarily comes from the time required for the smartphone camera to capture, process, and analyze each frame. Most smartphone cameras operate at 30 frames per second (fps) or lower, meaning a new frame is captured every 33 ms; however, due to processing delays and the need to confirm light transitions, the effective frame rate for OCC is much lower. Additionally, the receiver application relies on OpenCV-based image processing, including grayscale conversion, thresholding, and ROI extraction, all of which introduce computational overhead. Another factor is the rolling shutter effect, where smartphone cameras scan images line by line rather than capturing the entire frame simultaneously, potentially distorting fast-changing light signals and requiring additional processing. To ensure accuracy, each bit must remain visible for a sufficient duration to avoid frame overlap or missed transitions. Despite these constraints, the transmission speed remained stable across different tests, demonstrating the system's real-time processing reliability.
- **Communication Distance:** The system was tested with distances ranging from a few millimeters to 15 cm. The maximum reliable communication distance achieved was 15 cm, beyond which the signal could no longer be detected accurately. This distance limitation was primarily due to the intensity of the light emitted by the flashlight and the constraints of the smartphone's camera to capture the light at longer ranges. At distances beyond 15 cm, the signal became increasingly susceptible to ambient light interference, which negatively impacted signal detection and decoding accuracy.
- **Environmental Factors:** Environmental conditions, particularly ambient light, played a significant role in the system's performance. In well-lit environments, the signal detection rate decreased, especially when the ambient light intensity was high, leading to difficulties in differentiating between the flashlight signal and background noise. In low-light conditions, the system performed more reliably, with better signal detection and lower error rates.

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