JAB: a generic architecture for power efficient, high throughput mobile VLC applications

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July 6, 2022

A Dissertation Submitted to EEMCS faculty Delft University of Technology,
In Partial Fulfilment of the Requirements
For the Bachelor of Computer Science and Engineering

Abstract

Visible Light Communication is a method of wireless communication that avoids the oversaturated frequencies used by radio communication. Prior research typically uses the camera on smartphone for communication, but using a camera is energy-intensive and inefficient. Some alternatives are photodiodes and ambient light sensors, however the former is often not available on phones and the latter is too slow to be useful. This thesis introduces a system, JAB, which combines two sensors to achieve high throughput while keeping energy usage low. The impact of distance, modulation frequency and light are measured on the system implemented on an Android smartphone. Overall, the system is usable and does greatly improve the energy effiency of using VLC. An important next step is creating a custom hardware setup with a kernel driver implementation for a full system test.

1 Introduction

Humans have an innate desire to communicate with each other and, since the arrival of the Telegraph in 1937, this has been done mass scale using digital means. Over the past couple of decades, it has been common to use Radio Frequencies (RF) for communication using protocols such as Bluetooth, WiFi, and GSM. This has led to an oversaturation of the radio frequency band [1].

One alternative to the radio frequencies is the spectrum used by visible light, which is large, safe, and has been relatively unused [2], [3]. In literature, this has been commonly referred to as *Visible Light Communication* (VLC). The visible spectrum has proven to be effective medium to implement a wide variety of applications including localization [4], toys [5], hardware diagnostics [6], battery-free tags [7], and the link/physical layers of the OSI model [2], [8], [9]. Visible Light Communication is typically implemented by using a receiver and a transmitter. Often the transmitting sensor (TX) is a LED that alternates at high frequency using a pre-determined code called a modulation scheme. On the receiver-side, five sensors are typically used as a receiving sensor (RX): photodiodes (PD) [10], LEDs [11], cameras [12], rolling shutter [13], and Ambient Light Sensors (ALS) [14].

In this thesis, a closer look will be taken at the possibilities of combining an ambient light sensor and a photodiode to facilitate low-cost and energy-efficient visible light communication. Although ALSes are ubiquitous in modern smartphones [15], little research has gone into their practical applications [16]. Most papers are aimed at increasing the throughput [15] by using different modulation techniques [14] or calibrating the sensor [16]. The underlying reason for this is that, generally, ALSes have a low sampling rate [17], large error range [18], and low throughput [19]. Although some papers claim that the low sample rate is down to kernel restrictions [10], [15], [20], similar frequencies have been found in papers that avoid using the Android API by programming the sensor using an Arduino UNO [17]. However, these same papers indicate that it is possible to communicate over the ALS even if it is slow. This is significant since the energy cost of using ALS (1mW) instead of either a high-speed diode (150mW) or a camera (2000mW) is significant [21].

In this thesis an architecture, JAB is A Backronym (JAB), is proposed that allows for switching between different sensors by sending information packets alongside data packets. This concept is explored in the scenario of a smartphones that contain energy-intensive, fast sensors and energy-saving, slow sensors. Particularly, it aims to answer the question:

"Is it possible to design a network protocol that allows for changing the receiving sensor, how does such a protocol affect the energy use, and how does it perform in different conditions?"

To answer that question, literature research is done on the possible options for RX and TX components available on smartphones. The most promising of those are implementated, tested and evaluated on the Android platform. Important to note is that what is measured is the baseline, or even, the worst-case scenario for the system. In future, a custom platform implementing JAB can use the experiments in this thesis to measure the relative improvement.

The main contribution of the paper is a new architectural design of VLC on smartphones that allows for the pratical use of the technology and maximizes energy use to throughput ratio.

2 Related Work

There are two categories of papers that are related to this thesis: (1) **Mobile VLC** and (2) **ALS-enabled VLC**.

Table 1: Various designs for TX <-> RX VLC communication

System	TX	RX	Speed	Duplex	Energy Use	Modulation
NECAS [22]	Screen	ALS	1kbps	Yes	~1mW	PWM
SBVLC [23]	Screen	Camera	20kbps	Yes	2000mW	RS
Infoled [6]	LED	Camera	60bps	No	2000mW	RS
Bouberazi [24]	Brightness	Camera	100kps	No	2000mW	RS
Aldarkazaly[19]	LED	ALS	6 bit p/s	S	1mW	OOK
JAB	LED	ALS	-	Yes	1mW	Miller Code

2.1 Mobile VLC

Much research into VLC makes use of smartphones as a part of their system design. Typically these are implemented as either Android or iOS applications [15]–[17], [25], [26] Papers of this kind discuss either the phone as a receiver or transmitter. One thing does remain constant, namely that these papers focus on one specific problem rather than offering a generic solution.

2.1.1 Smartphone receiving

A popular choice for papers with the smartphone as a receiver is the use of the camera as an RX [12], [27], [28], however basing a general mobile VLC system on camera communication may be infeasible due to the high energy cost [21].

One approach to avoid the energy cost of continuously use of the camera was proposed by the authors of GLITTER [27]. In the aforementioned paper, they only detect the location with the camera and then use Bluetooth Low Energy for further communication. Although successful at decreasing the energy consumption, such a mixed system requires an additional hardware module and still uses mostly RF signals. The latter can be a problem in scenarios where a spectrum crunch can occur, like a crowded train station, or where RF signals are best to be avoided like in airplanes.

A light sensor was used in Epsilon [10], which makes use of a breakout board with a PD. The authors of Epsilon did assume that the characteristics of the ALS approximates that of a PD, which later research has disproven. This thesis lifts this assumption and instead designs a system that treats the ALS as a separate type of sensor.

2.1.2 Smartphone transmission

There are two common methods used to transfer data from a smartphone: modulation using the backlight and colors corresponding to bit sequences. The former was applied first in televisions where it was used to encode QR codes into the display [29]. In Boubezari et al [24], [30] messages are encoded by changing the brightness of the screen.

Encoding using a color-based system has been implemented for applications like QR codes [31], videos [32], displays [33], and LCD shutters [1]. Most applicable are displays whereby the colors of a few pixels are subtlety altered to change the overall color of the light without changing the scene. Most systems are a variant of Pulse Amplitude Modulation (PAM) whereby each color is assigned a bit sequence. They then split the display into different sections, which all rapidly alternate between colors. This gives a throughput equivalent to the length of the bit sequence times the number of sections used.

A full exploration of communication by smartphone displays is given in Blinkcomm [34] which describes a "smear frame" problem where frames can be repeated causing a double send problem. They circumvent this by introducing a modulation scheme using various gray shades and guard frames, which allows for the correction of errors. This increases throughput from 10bps to 100bps, but they indicate that according to their calculations the speed should go up to around 300bps on a 60Hz display.

On the operating system level, other interesting modulation schemes could be used. In Inframe++ [35] frames of data are embedded every twelve frames which allows for flicker-free transmission at 240Kbps. Alternatively in Chromacode [32] two complementary frames are shown that cancel each other for human eyes but still allow for data to be embedded. Furthermore, in Smart Display [29] pixels are slightly alternated in key parts of the image, which allows for non-obtrusive changing of the overall light that hits a sensor while allowing for data transfer. Finally, Hi-Light [36] embeds data into the alpha channel of the LEDs of the display. All of these solutions, however, require a much more intricate control over the display than possible for a mobile application. Therefore, they are not considered in this thesis, but their addition to the Android ecosystem is highly recommended.

These works differ from the present thesis since they use the camera to receive the data, while this paper makes use of a photodiode. Modulation using both backlight and colors is explored.

2.1.3 General Smartphone system

JAB is similar to the NECAS [22] system for Near-Field Communication using Visible Light (NFC/VL). It makes use of a duplex system that allows for back and forth communication between the phone and the transmitter. Sending data to the transmitter is done by splitting the screen into four separate blocks with color-coded bit sequences. Receiving data on the phone is done using an ALS sampling at 100Hz. SBVLC [23], a later NFC/VL system, expands on NECAS, but exchanges the ALS for a camera and proposes security schemes.

JAB is inspired by these two papers, but combines multiple sensors rather than using one. It is also aimed at general VLC use cases rather than just Near-Field Communication. Therefore, JAB makes use of less screen estate, faster displays, and a different modulation scheme.

2.2 ALS-Enabled VLC

Some research has been done on the use of the Ambient Light Sensor for VLC. However, these typically focus on the sole use of such a sensor as RX for VLC [15]–[17], [20]. Overall these papers conclude that the ALS is largely unsuitable to be used as an RX due to a low sampling rate of ~100Hz, which results in a data rate of just 6 bit p/s [19].

In Abe et al [21] the limitations of the ALS for use as RX is given together with an estimation of the sampling frequency at around 18Hz. ALS-P [17] introduces a transmitter system that allows for the sending of data without any flicker by aliasing low frequencies, which may be picked up by the ALS, to higher frequencies that are not visible to the human eye. To mitigate the low-frequency Kim & Chung [14] introduce a novel modulation scheme that makes use of the time intervals between the minimum and maximum values of a LED to achieve flicker-free communication. One problem that is unmentioned in these papers is the high error rates present with using an ALS, which may cause additional noise [18].

This thesis differs from these by only using the ALS to find transmitters to connect to, similar to the approach taken by GLITTER [27]. It differs from the aforementioned paper by only making use of VLC technology, lower energy cost, and is meant to be able to run continuously in the background.

3 Responsible Research

Due to the low sampling rate of the ALS it is not possible to get near to the danger zone around 200Hz mark [37] where flickering can cause health issues. There exist solutions that can mitigate the flickering by aliasing low frequencies to high frequencies [14] or by utilizing the space between two symbols as proposed in Section 10. Utilizing these techniques are recommended in any replication studies since fast flickering lights may be dangerous to researchers and users suffering from photosensitive seizures. Special care might need to be taken to ensure that the frequencies of 180-220 Hz cannot be accidentally reached.

Table 2: Components used for experiments

Type	Name	Brand
Laptop	ThinkPad S1 Yoga	Lenovo
MCU	STM32F411CEU6 "black pill"	Feiyang
Phone	Poco X3 Pro	Xiaomi
PD	OPT101	Unknown
LED	LED transparent	Unknown
RGB sensor	TCS34725	Unknown

Code for the research can be found on github and can be used to verify or expand on the results. To aid future researchers, Table 2 details the exact specifications of hardware used in the research. Additionally, in order to give an accurate description of the reliablity of the results any the limitations of the study are given in Section 9.

4 JAB System Design

In evaluating various use cases of visible light communications systems three things can be noticed: (1) most of the systems are built on an ad-hoc basis without thought to larger architecture, (2) there is an energy-speed trade-off, and (3) most systems are designed around a single type of RX.

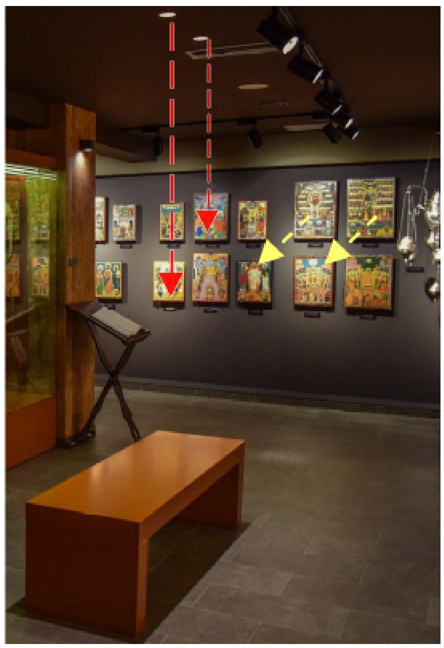

Figure 1: Example of the system where the red arrows indicate a streamed video and the yellow arrows indicate a scannable art piece

Some of these observations are self-evident. A design of a general architecture relies on the existence of a large corpus of prior research that can be drawn on and generalized. Similarly, the increase in speed is directly correlated to the components involved and the sampling rates of those components. An ambient light sensor is slow precisely because it gets sampled infrequently, but this is also the reason why the energy cost is low. Improvement to the sensor would lead to a similar rise in the energy cost, defeating the purpose of using the sensor to begin with. This leads to the first key insight of the paper: **by combining sensors with different performance characteristics, throughput and energy-effficiency can be maximized**

Such a system implies the creation of a handshake system that first connects to the ambient light sensor which then enables a high-speed RX or vice versa. This allows for system flexibility to choose between sensors and provides additional opportunities for security mechanisms. This idea is the foundation of the second set of insights: **sensors can be combined using a handshake mechanism**, **a handshake system allows for system-level flexibility** and **novel security mechanisms are feasible in a handshake system**. These ideas are explored in the paragraphs below.

One of the benefits of using a handshake is that the message that is sent allows for the setting of a variety of options to create the connection. Take a museum with two different AR systems shown in the Figure 1. The first are tables where a guest may put their phone and a short video is streamed to the device. A second may be VLC-enabled QR codes on the art pieces themselves that can be scanned with your phone. For the former, you want to use a photodiode due to the lower energy and higher throughput, while for the latter using a camera offers a more convenient user experience. In the proposed system this could be done using one transmitter design, but where one receiver asks for the PD and the other the camera.

A handshake system inside of a VLC system has been explored for NFC-like systems before [23], but this is just one way to use such a system for security purposes. Another mechanism would be displaying a secret key that uniquely identifies a transmitter on the screen of the receiver. This allows a user to verify with which device they are connecting before meaningful data may be transferred.

Related to this is that requests to connect may be rejected by the user if they opt to not allow the application to make use of the high-speed RX. This gives control over connections and alleviates privacy concerns.

JAB is a basic protocol which allows for the switching between sensors in order to reduce the overall energy cost. Additionally it allows for the creation of dynamic VLC systems, novel security measures and designs similar to the museum example.

An outline of a JAB system is given in Figure 2 which describes a video streaming application. Such an application may be an in-flight media system, an info video at a museum display or scannable video at a concert. First the transmitter attempts to connect with nearby receivers continously. After a receiver connects, it exchanges an encryption key that is used to exchange an unique identifying fingerprint for the device. This is checked by the user which can then choose to connect with the transmitter, receive the data using a PD and then disconnect.

5 Protocol Design

Due to heavy restrictions on the amount of data that can be transmitted using an ALS, care must be taken with the protocol used to send data. Assuming that the data rate is at a maximum of 6 bit p/s, only around 360 bits or 45 bytes can be transmitted per minute. A more reasonable waiting period of around 15 seconds yields around 11 bytes, which is significantly less than what traditional protocols like Bluetooth [38], WiFi [39] and Zigbee [40] require. Therefore, a minimalist protocol is proposed here which requires a mininum of only 5 bytes to function.

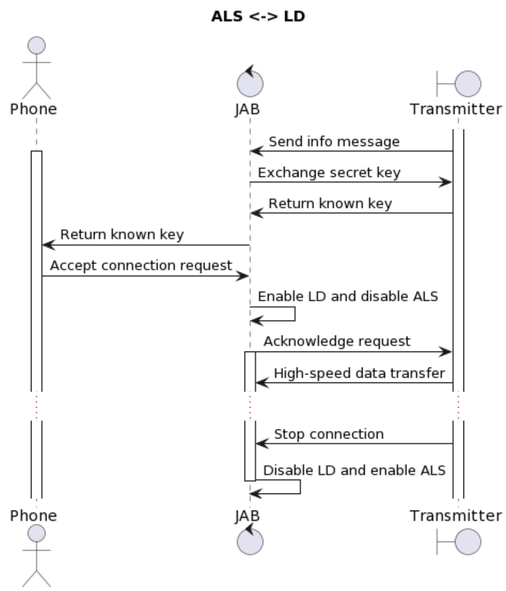

Figure 2: Sequence diagram of the interaction between two devices

5.1 Connection Details

The proposed protocol is conceptually similar to the system used by Bluetooth Low Energy [41]. It establishes a connection using a *Connect* packet, which contains information about the link that it wants to establish. Afterward, data is exchanged using simple sequenced data packets. Each transmitter can be connected to multiple receivers in a client-server setup. Each receiver is given a number to identify the device.

5.1.1 Connect Packet

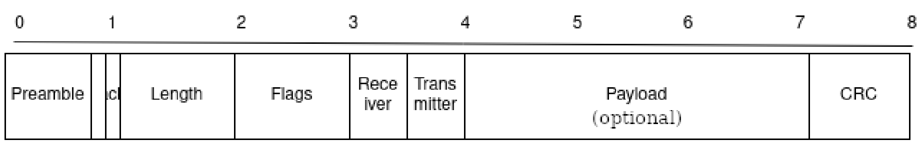

Figure 3: Diagram of the connect package used to establish the connection

The first 6 bits are used as preamble to synchronize the clock and allow the system to identify the values of 0 and 1. A preamble is only sent in the connect packet since the lifespan of each connection is limited to at most a minute, highly decreasing the chance of significant clock drifts to occur. The preamble is set to 101101 which corresponds to twice the longest delay possible using Miller encoding.

1 bit is reserved and 1 bit represents whether there is a payload. 1 byte defines the number of packets that will be sent. 1 byte sets various header options. 4 bits define an unique ID to identify the transmitter and the 4 bits as the number for the transmitter. The transmitter

ID is always equal to 1 plus the highest numbered active receiver. 4 bytes is an optional application-defined payload. 1 byte is allocated as the CRC.

The transmitter and receiver fields exist to allow for the creation of a multiplexed version of JAB. Each transmitter is assigned an unique ID at installation. Receivers are assigned the lowest unused number in use by the transmitter that they have connected to. In total this allows for 16 transmitter with each 16 receivers for a combined 256 concurrent connections.

5.1.2 Data packet

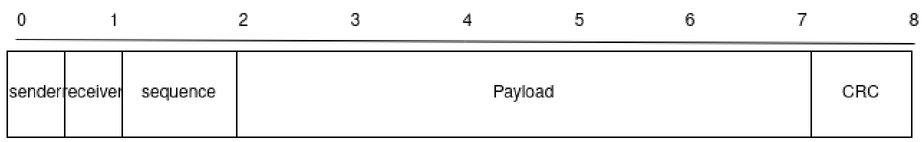

Figure 4: Diagram of the packet used for data transfer

4 bits are used to identify the sender and 4 bits the receiver. Both values are the same values used in the initial connection package. 1 byte is used store the sequence number of the message. 6 bytes are used as the (padded) payload and 1 byte as the CRC.

Data packets are used mostly as responses to the *Connect* packets during the handshake. The only other time that they would be used are in scenarios where the ALS is the primary receiver for the application. With other sensors, it is assumed that the system switches to another protocol for further communication. This is because there exists a IEEE standard which defines a VLC protocol [9] which too heavy for this use case but could be used at higher stages. This would allow for better interoperability with other systems in the future.

6 Example Transmitter Design

JAB is a generic system design and protocol which can be implemented in many ways, but in this thesis only the bare minimum is assumed to give an indication of how the system would work in a worst-case scenario. An additional benefit is that it ensures the system is cheap, flexible and extendible. In fact, for the design only two real elements are needed: (1) transmission of binary data using light and 2) a sensor to detect the modulation scheme used on the phone.

6.1 Transmission of binary data

To transmit data to the phone JAB makes use of a LED connected to a microcontroller. Sending data is done by alternating between two symbols that each represent a bit. One of these symbols is the "low" value that represents the 0 bit and the other is a "high" value which represents the 1 bit.

One scheme is to turn the LED on or off entirely, which is called On-Off Keying (OOK). Another variant is Pulse Width Modulation (PWM), which is a mechanism whereby a peripheral is turned on or off so fast that it appears dimmed to humans. By choosing two frequencies that seem visually similar, it may appear less abrupt when the switch occurs. Both of these schemes are used in experiments to determine which performs better in JAB.

6.2 Modulation Scheme

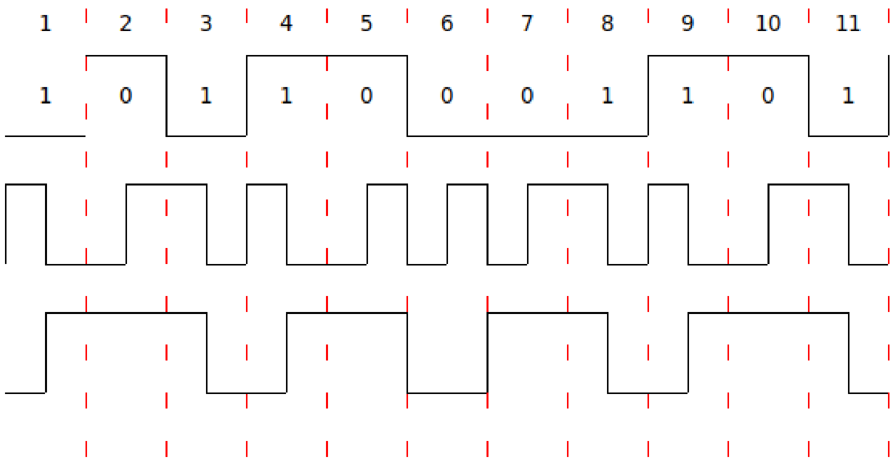

Figure 5: Comparison of On-Off Keying, Manchester Encoding and Miller Code

The proposed system makes use of the Miller Code. This encoding has been shown effective at increasing the data rate for other VLC use cases [42] and has some distinct advantages over other encoding systems. Miller encoding can use the entire bandwidth, offers easy clock recovery, and gives a remarkably stable data stream [43], [44]. The latter is important since it reduces flicker.

Miller Code is a code that communicates the transitions between the current and the next bit, unlike most other codes which look at absolute values. There are three options for possible signal patterns or symbols. If both bits are zero, it inverts the signal at the edge. If the last bit is one it inverts in the middle of the interval. Otherwise, if the last bit is zero it keeps the same value. This ensures that there is a change in signal every other bit, decreasing the transitions required, and keeping the needed bandwidth low [44]. Clock rates are also easy to recover since the longest possible interval can only happen in one case: the sequence 101 [43].

7 Receiver Design

The design of the transmitter values the use of widely available components, extensibility, and low cost. Primary to the usage of the receiver in the context of JAB is that it switches between the different sensors. In this section three options which can receive VLC signals and two methods of sending signals are discussed. These methods are later tested in Section 8.

Table 3: Comparison RXs

Name	Speed	Energy cost	Distance	Modulation
ALS [19]	9bps	1mW	15cm	OOK
PD [8]	2.2Kbps	150mW	~1m	OOK+Manchester
Camera [45]	71bps	2000mW	-40m	Polarization Intensity Modulation

7.1 Choice of Receiving Sensors

The three sensors in Table 3 are typically applied in VLC contexts. A common choice for mobile applications is the back camera, [6], [7], [28]. One downside is that a camera is rather energy-intensive and is bit clumsy to use since you need to point it towards the transmitter. Typically it also has a requirement to use computer vision algorithms to extract the relevant part of the picture, which can be computationally expensive.

Photodiodes are a typical choice for embedded projects [1], [32], [34] since they are flexible, cost-effective, energy-efficient, and allow for the highest throughput [2]. Although they could be easily added to a phone they are, at the moment, rarely included. It has had some use in smartphone-based VLC, but typically on a breakout board connected to the phone [10].

The ALS is on paper an attractive option to explore for VLC use cases. Almost every phone includes one, they are by far the least energy-intensive and can, in theory, support frequencies high enough to be undetectable by human eyes. However practical experiments have shown to be unstable, with large error margins and an unpractically low data transfer rate of merely 6 bit p/s [18], [19].

7.2 Choice of Transmission Sensors

JAB includes a duplex system whereby the receiver and the transmitter exchange information in order to setup the connection. Three options for transmission on a smartphone are typically used: flashlight, backlight and display. The latter two are relevant for the creation of a connection using the ALS and are explored in this section.

7.2.1 Backlight Modulation

Most conveniently from the perspective of the smartphone would be to use the screen brightness of the display since these are an integral part of a smartphone. Another benefit is that typically, when communication is relevant, the display would be already on and, therefore, does not incur additional energy costs. With a sensitive photodiode, only small differences between two brightness can be detected which can avoid visible flicker. Sadly, due to restrictions in the Android API, the screen brightness is linked to the framerate of the screen which limits the throughput [30]. However, if integrated into the OS, the screen brightness may be an obvious choice for transmission.

7.3 Display Modulation

From the perspective of a user application manipulation of the interface is the easiest way to communicate. Since smartphone UIs are already made to be able to quickly change their view, they require the least amount of modification at an OS level to establish. Such modulation has been popular in the field of Smartphone-to-Smartphone which uses the camera to receive the signals [22]–[24].

Typically, the screen can drive at 30Hz, 60Hz or 120Hz. Using OOK with Miller encoding data can be sent with a throughput of 30/60/120 bps. As explored by Blinkcomm [34], Frames on smartphones are occasionally repeated which causing problems with the double sending of data. To mitigate this you can send guard frames every other bit, but this decreases your transmission speeds by half.

8 Experiments & Results

JAB is designed around applications where a small amount of data needs to be exchanged to create an initial connection. Typically, this should be done with only a singular message. The receiver, pictured in Figure 6, is implemented on an Android phone and the transmitter on Micropython. Testing is done with the ALS as the RX.

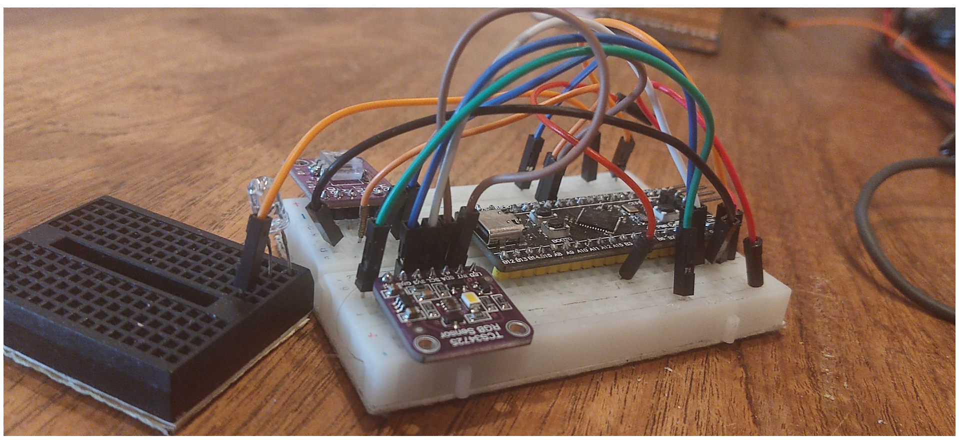

Figure 6: Picture of the experimental setup

8.1 Sending Data using the Display

In Section 7.2 two schemes for sending data are described. Measuring performance is done by repeatedly sending the bit sequence 101101 and calculating the Bit Error Rate (BER). Brightness modulation is tested using OOK and three combinations of PWM frequencies.

Table 4: Bit error rate depending on low-high pair for brightness modulation

Frequency	(0, 100)	(0, 20)	(80, 100)	(20, 80)
1Hz	4%	15%	85%	0%
5Hz	100%	100%	100%	100%
20Hz	100%	100%	100%	100%
40Hz	100%	100%	100%	100%

In Table 4 the BER for various frequencies is given. BER is the probability that a bit is incorrectly received. Modulation from brightness work well at rate of 1Hz, but stops working at any higher frequency. This is because Android does not allow for the immediate change of the brightness at the user application level, but imposes a transition. Even at low frequencies it causes two symbols to infere with each other making communication near to impossible.

Table 5: Bit error rate depending on low-high pair for color-based PAM.

Frequency	2 (1-PAM)	4 (2-PAM)	8 (3-PAM)	16 (4-PAM)
1Hz	0%	0%	18%	
5Hz	0%	0%	18% (0%)	
41Hz	50%	25%	54% (36%)	
60Hz	100%	100%	100%	
120Hz	100%	100%	100%	

Contrasting the result of the brightness modulation is that of color-based PAM given in Table 5. PAM performs well even at higher frequencies, but it does not work at the maximum frequencies of the display, which is in line with the results of Blinkcomm [34]. The system performs the best at 41Hz, which is the minimal useful integration time that is supported by the color-sensor. With the 3-PAM the error rate in brackets is the BER subracted by the BER at 1Hz.

Table 6: Throughput per low-high pair

Frequency	2	4	8	16
5Hz	5 bits p/s	10 bit p/s	15 bit p/s	20 bit p/s
41Hz	5.25bps	10.5bps	15.4bps	20.5bps
60Hz	7.5bps	15bps	22.5bps	30bps
120Hz	15bps	30bps	45bps	60bps

Combining the BER with the throughput given by Table 6 , it seems that 2-PAM to 3-PAM communication has the required performance characteristics to act as a transmitter. Since the amount of communication that needs to be sent is rather small, it would serve to use 3-PAM at around 5Hz or 2-PAM at 41Hz.

8.2 Receiving data at the phone using the ALS

For this section, the data is received using an ambient light sensor. An arbitrary message is sent from a transmitter using a red LED to a phone at varying frequencies. Both the throughput, time and the BER are calculated for each variation. It is important to note, however, that this number may be misleading due to timing issues caused by the program being implemented using the Sensors Android API and in user-space.

Table 7 shows the bit error rate relative to the values used as low and high symbol. Out of this data, it is noticable that there is little difference between the alternatives. One notable exception in column 3 where the PWM frequency pair is set to 80 and 100. This indicates that, similar to the human eye, the ALS responds logarithmatically to light and that the same distance at the high end seems smaller at low end. Sadly this rejects the hypothesis to mask the modulation in a range not visible to humans.

Table 7: Bit Error Rate depending on PWM frequency

	(0, 100)	(0, 20)	(80, 100)	(20, 80)
1Hz	0%	0%	90%	0%
5Hz	10%	10%	41%	21%
10Hz	24%	35%	65%	95%
18Hz	60%	67%	98%	69%
25Hz	100%	100%	100%	100%
50Hz	100%	100%	100%	100%

Another interesting result is that the experiments confirm 18Hz, given by the ALiSa [20], as the maximum speed that an ALS can function in an Android environment. This is significantly less than the 100Hz achieved by ALS-P [17], which aschews the Android platform in favor of the Arduino. Overall, this is indicating that even further research is required to find the source of the low frequencies of the ALS.

Table 8: Goodput depending on frequency

	Time To Send	Throughput	Messages Per Minute
1Hz	91s	0.7 bit p/s	~0.5
5Hz	18s	3.7 bit p/s	~3
10Hz	9s	7.4 bit p/s	~6
25Hz	4s	2bps	10
50Hz	1s	6bps	60
100Hz	1s	12bps	91

Goodput of the system is given in Table 8, which indicates the time that it takes the system to send one protocol message at the indicated frequency. These values are plotted using the BER rate. Although the BER increases the higher the frequency, it is outpaced by the increase in total throughput.

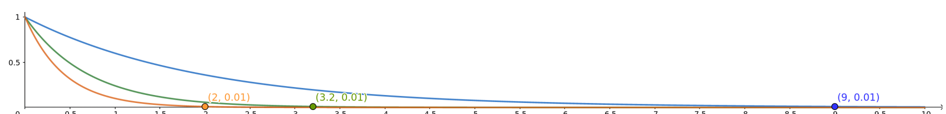

Figure 7: Probability curves for the BER

In Figure 7 the probabilities for 5Hz, 10H and 18Hz are plotted[and the intersection to the point where probability of failure is less than 1% is calculated. This is at 2, 3 and 9 messages respectively. This combined with the baseline of 1Hz yields the following worst case transmission times: 91s (1Hz), 36s (5Hz), 27s (10Hz) and 36s (18Hz). This shows that the optimal frequency to use is 10Hz.

8.3 Impact of the distance and lighting on the bit error rate

All the tests mentioned before are repeated in daylight, night time and living room lighting condition. The results are given in Table 9. Distance to the object seems to make very little difference when it comes to the Bit Error Rate. Instead there seems to be a hard cut-off after which communication becomes impossible entirely. At a no light condition of 0 lux this cut-off point is at 1.5 meters while at 400 lux, this decreases to 30cm.

Table 9: Effect distance on the Bit Error Rate

	0cm	5cm	10cm	25cm	40cm	80cm	1.2m
1Hz	0%	0%	0%	0%	0%	10%	0%
4Hz	0%	0%	0%	0%	0%	0%	0%
10Hz	12%	12%	12%	12%	12%	20%	20%
18Hz	60%	60%	60%	60%	60%	62%	60%

8.4 Energy Use

The energy usage consumed by using the camera is around 2000mW, while that of a photodiode is 150mW and an ALS consumes 1mW. By using the values of Table 3 and dividing it by the wattage a ratio of bits/energy is found. This yields 9 bps/mW, 15 bps/mW and 0.036 bps/mW. Dividing the bps/w together gives the ratio whereby combining the two sensors requires less energy per bit than using just one. For the PD/Camera combination, it takes 416 time units for the photodiode to reach parity with the camera while the ALS takes just 250. The ratio of PD to ALS is around 2, meaning that provided that if at least half of the time that the phone is powered on there is no active connection then using the ALS is more efficient per bit than always using a photodiode.

Total throughput and energy can be calculated by using the following equation: $f(x, y, z) = 1 * x + 150y + 2000z$ and $g(x, y, z) = 9 * x + 2252y + 71z$ whereby x is x the time idling, y in the time spent communicating with the camera and z communication using the PD. This implies that providing JAB is more efficient than using a monosensor providing that the distribution of time spent follows the inequality $x < 150y + 2000z$. Dividing this by the total time gives an equation comparing the idling and the active time. Active time is described by the percentage spent on either a PD or a camera, therefore the worst case scenario for JAB where all time is spent using the PD. In this case $x < 150y$ meaning that JAB is more energy efficient in absolute terms providing that the smartphone is idle once at least one minute per two hours or 10 minutes per day.

9 Limitations

A proof of concept was implemented in user-space on the Android platforms due to time contraints. This approach has two drawbacks, namely, the kernel can interrupt the process which can cause incorrect readings and clock drift. Another issue is that the Android SDK is not designed with this use case in mind, which makes implementating the system awkward and does not give any access to the parameters of the ALS. The latter may be the cause of the low sampling frequencies. Testing of the system was also done using just one smartphone and so only one ALS was able to be tested. In fact, it is not known what the ALS actually is that was tested since this information is not given by the manufacturer. A more comphrensive study may look at a larger selection of phones beyond those by either Xiaomi, used in this thesis, or the Samsung Galaxy S phones which dominate the other ALS-based VLC papers.

10 Conclusion & Future Work

This thesis introduces a new architecture for the design of a smartphone-based VLC system called JAB. By switching between two different sensors to receive VLC communication, the energy cost of receiving such communication can be amortized. In particular, the combination of using the Ambient Light Sensor for connection establishment and a Photodiode for further communication is explored.

Testing was done by developing a prototype for the Android platform, but it is far from ideal. By developing it in userspace, rather than kernelspace, it was not possible to get the exact timing needed in order to get accurate results in all scenarios. Access to the parameters of the ALS was highly restricted which may have lead to it running at lower frequency than that it is capable of.

An ALS/PD combination supports a throughput of 2 bytes per second at 1.25m distance for low ambient light conditions or 30cm at high ambient light. At this speed 1 message takes around 10 seconds to arrive with a bit error rate of 10%. Although slow, this is still within bounds to be useful in some scenarios.

In the future, an implementation of the system should be developed on a system that allows for greater access to the components. A promising platform is the GNU/Linux-based PinePhone, which allows for the connection of custom PCBs to the phone and where the development of a kernel module is more feasible than on an Android platform. In general, an exploration of implementation display-based modulation at the OS level is paramount to the usability of the technology in a real-world scenario. A few interesting avenues would be using the smear frames to transmit data, adjusting individual pictures to modify the total amount of light, or changing of the backlight at a high frequency. Finally, a mitigation to the flicker issue at low sampling rates would be by multiplexing devices by using clock offsets. This eliminates flicker and maximizes the capacity per transmitter while still being at a low frequency.

In conclusion, JAB represents an important step on the road to creating accessible, interesting and useful VLC application on smartphones. However, in order for the architecture to come to its right it must be integrated at the OS level. It is the hope of the author that this thesis can serve as an example as to why such research would be useful and necessary.

11 Acknowledgments

Thanks to Koen Langendoen for his endless patience, kind words and guidance. I promise that one day, I will learn how to properly use which and that. Until then, I hope you can forgive me for the times you had to correct that mistake. Thanks as well to Marco Antonio Zúñiga Zamalloa for giving his wise words of advice when I needed it. My gratitude goes out to all the support staff whose thankless work at the university ensured that the light above my head kept shining. Special thanks to my friends and family for their endless support, especially my recently passed grandparents who I hope look down at me with pride. And, finally, to the stellar staff at the Atoni van Leeuwenhoek whose amazing work kept my mother alive. To them I owe a debt of graditude of which I know that I will never be able to repay.

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