MIDDLE EAST TECHNICAL UNIVERSITY

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE 493-DESIGN STUDIO 1

CONCEPTUAL DESIGN REPORT

COMPANY NAME: REVOLUSYS

PROJECT NAME: GIMME FAST

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1.EXECUTIVE SUMMARY

In this era, we are all aware of that accessing to information has a crucial importance, but the more important and challenging part is how to transfer that information. Although RF transmission has been the conventional mean of data transmission up to these days, due to the increasing mobile data transmission RF technologies started to struggle on resolving our needs. In addition to the highly occupied bandwidth RF technologies suffer from speed, security and power efficiency problems. The best way to accomplish these problems is using a revolutionary method: visible light communication.

As Revolutionary Systems we will design an image transmission platform where VLC is combined with data transportation by a vehicle. The system will consist of two end terminals that can receive or transmit an image as data packets while a vehicle rushes between these terminals to handle the long-distance transmission of the data. While combining communication and transportation the main purpose is to transfer an image as accurately as possible in the shortest time. For achieving this goal, the main tasks and our solutions approaches can be listed as:

- Data Compression and Division into Data Packets
  - Compression of image data to enable faster transmission
  - Division of the image data into smaller matrices to get smaller data packets
- Visible Light Communication
  - Sending and receiving light signals by LEDs and photodiodes
  - Modulation of the original signal for communication
  - Filtering in order to cancel noise
  - Use of preamble signals for handshaking between receivers and transmitters
- Data Transportation by Vehicle
  - Control of the vehicle on physically guided tracks
  - Distance detection by ultrasound sensor
  - Transceiver unit placed and memory chunk on the vehicle

Even though handling all these tasks require knowledge from a diversity of electrical engineering areas, our team contains engineers specialized in the areas of communication, computer, electronics and control. Thus, a correct division of labor between us enables us to handle this big task as smaller and manageable problems and come up with a competitive product build upon the skills of each member.

Our company aims to build up a fast and accurate system for the minimal cost while taking physical robustness and the immunity of the system to variable conditions into account. The project is planned to be finished in 4.5 months with a total budget of about 130$.

As the end product, a vehicle that is moving on a physically guided track with a transceiver on it and two end terminals which are a transmitter and a receiver will be delivered. In addition to these, a camera to take the photo and a display will be supplied to the customer with a user manual and two years of warranty.
This document is a conceptual design report of the described product which contains detailed technical information on how the product will be developed.

2.INTRODUCTION

Radio spectrum is used to transmit data wirelessly for an enormous amount of daily services including but not limited to TV and radio broadcasting, mobile phones, Wi-Fi communications, GPS and radar. The global mobile data traffic has increased by 71 percent in 2017 according to the yearly report of CISCO[1] .In addition, the increasing device connectivity because of IoT also puts more load on RF bandwidth. Hence, the ever-increasing demand for huge amount of information, faster communication and higher quality data, it is crucial to note that the usable radio spectrum is a scarce source where exponentially growing demand surpasses the supply. Apart from the narrow and already highly occupied bandwidth problem, some other issues with the convenient communication systems can be explained as security problems, power inefficiency and interference.

A recently developed communication method which is known as VLC (visible light communication) has a potential to solve these problems. Since VLC uses visible light, the bandwidth is increased tremendously, it is in between 430 THz to 790 THz[2] . Also, since the VLC receiver receives the signal only if the transmitter and the receiver are in the same room, it is more secure than RF communication. What is more, since a visible light source can be used for both illumination and communication, it saves extra power when compared to RF communication.

Although, there are existing communication architectures, they suffer from the aforementioned inefficiencies. A need exists for new communication methods. The design possesses a physically guided vehicle and a VLC system. The goal is to transport a picture from one terminal to the other terminal as fast and accurate as possible while keeping the cost minimal.

The professors of Electrical and Electronics Engineering in METU has requested from us to design a system which can transfer data via two complementing technologies, transportation and communication. From then on, the company have worked solidifying the technical approach on the project. By means of weekly meetings and R&D work conducted at Design Laboratory, currently, Revolusys can modulate the communication signal via OOK (On-Off Keying) and receiving the data packets with the rate of 13kbps at 5-10 cm distance. Tests for communication submodule were also done by company and concluded that the communication system is having %4 of error when it is used at 8 cm under the laboratory condition (normal illumination).

This report contains the technical details of subsystems, critical algorithms for the flow of the project, test plans and requirements analysis of the subsystems. The interaction of the subsystems and project parts like cost analysis, overall dimensions and power analysis will also be given.

By accomplishing this project, we will prove that a VLC system integrated with a transportation vehicle is implementable and this, in turn, will lead to a widespread use of the visible light spectrum. This will allow us to operate on a completely empty frequency band which will increase the amount of data transmission to a greater extent. Therefore, the entire society will reap the benefit of increased and more reliable data transmission and live in a more connected world.

3.SOLUTION PROCEDURE

To develop a solution approach, overall system is divided into sub-systems and a system level flowchart is drawn. Each sub-system has its own solution procedure with alternative methods. At this section, first overall system block diagram and system level flowchart will be introduced. Then, each sub-system will be explained in detail. At the end of the section, sub-system level test results will be provided.

3.1 OVERALL SYSTEM BLOCK DIAGRAM

The solution of Revolutionary Systems Inc. to "Gimme Fast" project is a system that consists of four subsystems. These subsystems are image acquisition subsystem, communication subsystem, transportation subsystem and image reconstruction subsystem. Figure 1 shows the main block diagram of the system.

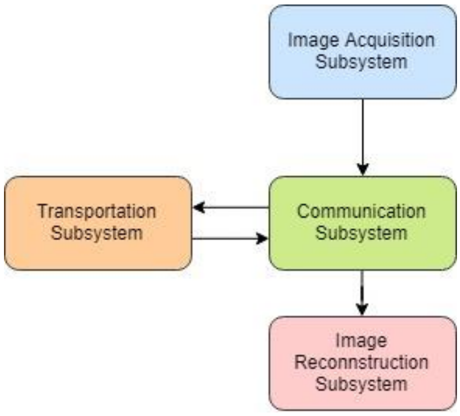

Figure 1: The main block diagram that shows the subsystems of the solution.

The solution proposed and partially tested and by Revolusys is briefly summarized in the following paragraph. This solution and its alternatives are explained in details throughout the entire "Solution" section of this report.

Input of the whole system is an image taken by a camera and inputted to image acquisition subsystem. Image acquisition subsystem compresses the data and sends to communication subsystem. The first part of the communication subsystem transfer data from first terminal to receiver placed on the vehicle. The vehicle moves to second terminal and via utilization of the communication subsystem, data is transferred from transmitter placed on the vehicle to receiver at the second terminal. Vehicle moves back to first terminal while data received by the second part of the communication system is sent to image reconstruction subsystem where image is reconstructed. The reconstructed image is displayed on a screen as the output of the whole system.

This process is visualized in Figure 2 which shows the inputs, outputs and interactions at subsystem level.

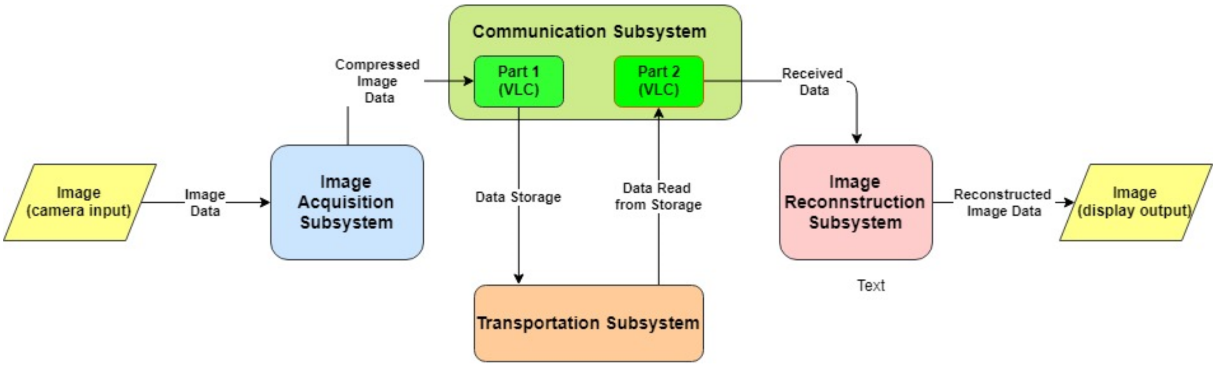

Figure 2: The diagram that shows the inputs, outputs and interactions at subsystem level.

The image compression method is selected as JPEG so that the size can be controllable by making a tradeoff between quality and resolution. It is feasible to have a data image size of 50-80 kB. Test plan will be operated for JPEG compression and alternative compression techniques and the one that successfully compress the image file to size of 50-80 kB will be chosen.

Data is sent at 13 kbps at the tests conducted so far. So, the requirements is met.

For the feasibility of the error detection method, it should be taken into consideration that Hamming method is only detecting one bit errors, therefore alternative methods may be utilized. CRC (cyclic redundancy check) and checksum algorithms are able to detect multibit errors. These three methods will be implemented and tested.

The system level requirements of the solution are classified as functional requirements, performance requirements and physical requirements. These classified requirements are given below.

- *Functional Requirements*
  - The system must be able to take a photo.
  - Some portion of the photo must be transmitted to the vehicle by VLC (Visible Light Communication).
  - The vehicle should go to the receiver terminal on a physically guided track.
  - The data packets carried by the vehicle needs to be delivered to the receiver terminal.
  - The vehicle must go back and forth until the transfer of the full photo is done.
  - As the full photo is delivered, the photo must be displayed at the receiver terminal.
- *Performance Requirements*
  - A minimum DTR (data transfer rate) of 0.013 Mbps will be achieved.
  - The average velocity of the vehicle shouldn’t be lower than 25 cm/sec for the maximum distance case (1.5 meters).
  - The minimum accuracy rate of 90% should be achieved for the reconstructed image.
- *Physical Requirements*
  - The vehicle should be able to move on a physically guided track.
  - The receiver terminal will also be able to move on the track.

- The distance between two terminals should vary between 0.4 meters to 1.5 meters.

Revolusys Inc. defined the design objectives as it is shown on the objective tree, Figure 3. The determined objectives regarding the solution of “Gimme Fast” project are scaled so that the company can assign points to the alternative designs and find the best-matching design considering the company’s milestones. These scales are given in Appendices.1 section.

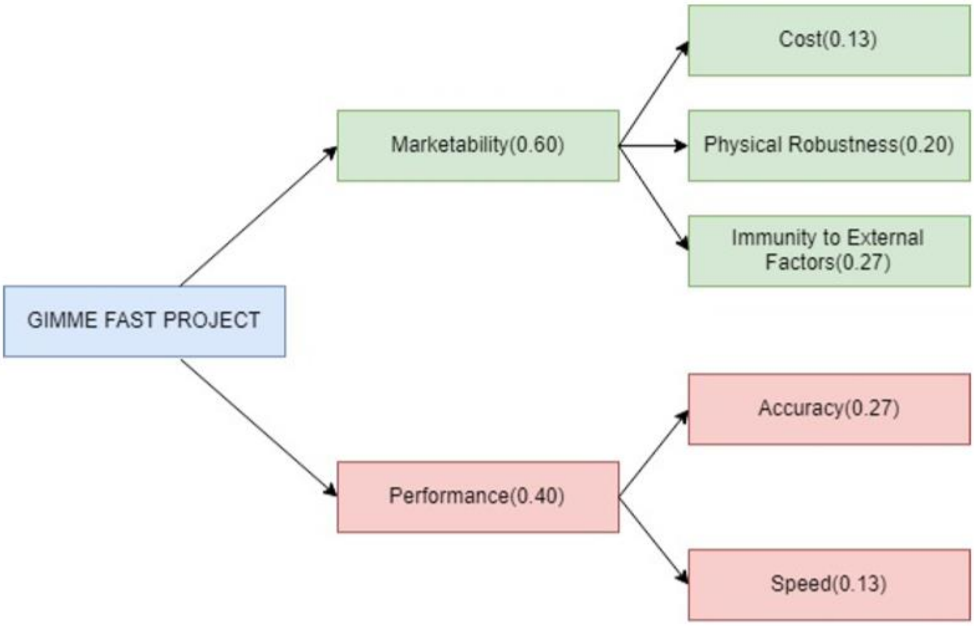

Figure 3: Objective tree for the evaluation of the overall system.

The constraints on the solutions to “Gimme Fast” project are listed below.

- There must be 5 cm between transmitter and receiver during the light communication.
- Maximum time for the total data transfer is 2 minutes.
- Microcontroller’s memory shouldn’t exceed 10 kB.
- Data transfer must be handled with 5 full round.
- Up to 8 LEDs and 8 photodiodes/LDRs can be used in the whole system.
- The distance between two terminals should be convertible up to 1.5 meters.
- The size of the vehicle shouldn’t exceed 20 cm.
- Motors of the vehicle must be on-board.

3.2 SYSTEM LEVEL FLOWCHART

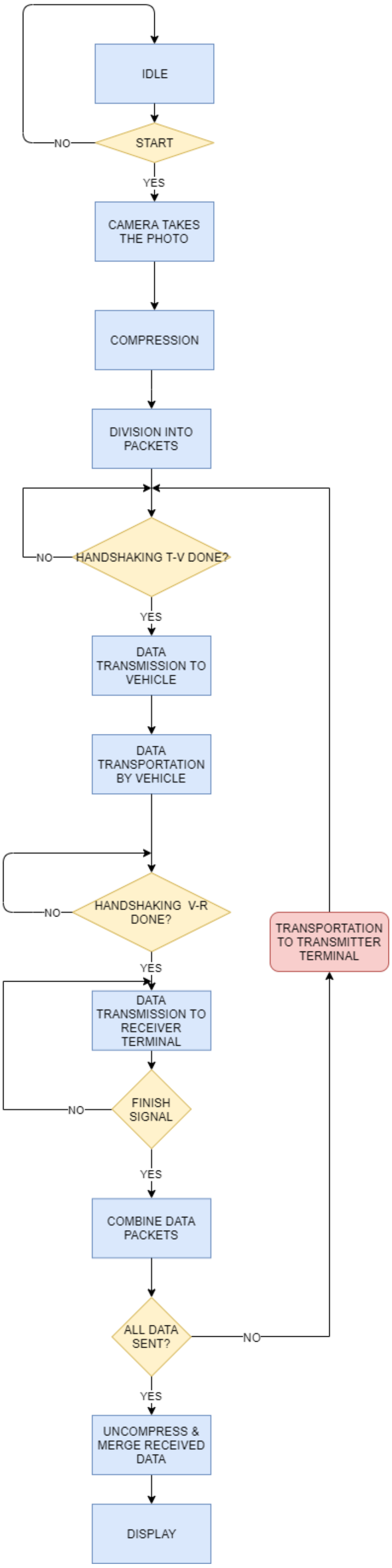

Figure 4: System Level Flowchart

In the idle state of the system, the transmitter terminal is waiting for the start signal which is an on-off button. After taking the start signal the system waits for the camera taking photo. Next state is the compression of the image and its division into data chunks. The length of the chunks' is 10 kB.

Handshaking between transmitter and vehicle is waited to be completed. Here a preamble signal is generated by the transmitter so as to get the vehicle ready for the data transmission. If handshaking is done, data transmission starts. The data packet to transmit is also sent to vehicle in packets such that each packet is checked for error via Hamming method. If there is any error, the communication for the related chunk of data is retransmitted. After data transmission is done, vehicle is initiated for transportation to the receiver terminal. Here, the critical part of the transmission is the ultrasound sensor which will stop smoothly at a distance of 5-10 cm to the terminals on a distance-convertible rail. After reaching the receiver terminal, handshaking protocol is started via sending preamble signal to the receiver terminal. Following the preamble signal, data transmission is initiated. Again, the data is sent by portion by portion, checking each portion via Hamming method. If any error is met, the transmission of that portion is canceled and the related portion is resent. The acknowledgement of the fallacies in data transmission can be solved by using a led at the receiver side so as to acknowledge the transmitter. After data transmission is done the packet end signal is generated by the transmitter. If unique end signal is generated, it means that all the data packets are sent and the image data is ready for the image reconstruction submodule. If unique end signal is not generated, then vehicle is transported back to the transmitter terminal in order to get the new data packet. Meanwhile, the data chunk on the vehicle is deleted in this phase.

After taking the unique end signal by the receiver terminal, the image file in binary form is merged into a file and then JPEG decompression is operated on the file. Finally, the image is sent to the display part and the photo is displayed on the screen.

3.3 SUB-SYSTEMS

As it can be seen from the Section 3.1 (Overall Block Diagram), system consists of 4 main sub-systems: Communication Subsystem, Image Acquisition Subsystem, Image Reconstruction Subsystem and Transportation Subsystem.

3.3.1 Communication Subsystem

The communication subsystem is where the data transmission between the vehicle and the terminals take place. Based on the requirements defined in the Proposal Report, it is expected to reach a data transmission rate of 13 kbps (kilobits per second). Additionally, it should be able to work under different lighting conditions which are defined as sunlight condition, laboratory light condition and dark light condition. Also, the bit error rate should be lower than 10% since according to the requirements defined in the Proposal report, the accuracy rate of the reconstructed image should be higher than 90%.

Based on these requirements, the communication subsystem is designed. The subsystem consists of two parts, the software part and the hardware part.

-Software Part of the Communication Subsystem

In order to successfully transmit the bits, the software part of the communication subsystem must accomplish the following tasks:

i. Modulation

ii. Protocol establishment between the terminals

iii. Error checking

Each of these tasks deserves its own treatment under a separate topic since they are critical concepts on which the entire project is constructed.

i. Modulation

For this purpose, OOK (On-off keying) is used. OOK is an easy-to-implement modulation type when compared to other modulation schemes such as frequency shift keying or phase shift keying. Therefore, it was the first consideration and the solution is devised around this modulation type.

In OOK, bit value 1 corresponds to HIGH state in the transmitted signal and the bit value 0 corresponds to LOW. Therefore, the LED gives light when it is transmitting a 1 and it doesn’t give a light when it is transmitting a 0. The Arduino at the transmitter side is configured to operate the LED driver circuit based on this situation.

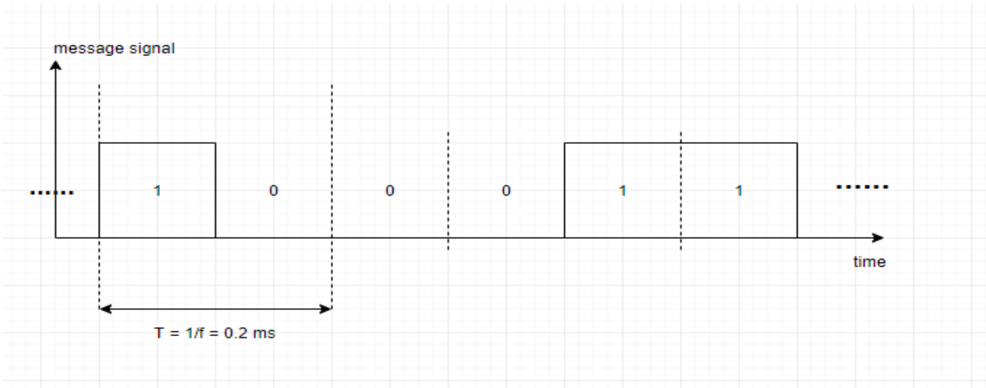

Figure 5: A Sample Message Signal Waveform

We have used OOK at a frequency of 5 kHz and an example message signal used for transmission can be seen in Figure 5. According to this Figure, during one period, T, two bits are transmitted. Therefore, the bit transmission speed is double of the frequency used for OOK, which corresponds to 10 kbps. Hence, we can state that in addition to its ease of implementation, OOK also allows us to come close to the required transmission speed, which is 13 kbps. The speed can be improved by increasing the modulation frequency. In fact, we have managed to send data at 10 kHz, which corresponds to a speed of 20 kbps; however, the systematic testing is done for the 5 kHz case. So, right now we merely state the fact that increasing the speed is possible.

To understand the meaning this obtained speed, it is necessary to consider a realistic scenario. Consider the vehicle is to make five turns, with 10 kB of data transfer occurring each time. In each turn, the data is transferred two times and there are five turns in total. Thus, total **transmitted data length is 100 kB.**

$$time = 8 * \frac{lenght}{speed} \quad (Equation\ 1)$$

In Equation 1, length specifies the length of the data, which is 100 kB in this case. 8 is there to convert byte to bit and dividing it by the speed of the transmission (10 kbps), we obtain time as eighty seconds. In this case, forty seconds of travelling time for the car is left. Remembering that we have a two-minute limit for the entire transmission and transportation, we conclude that 66% of the total time is spent for communication.

OOK Frequency(kHz)	Speed(kbps)	Time(sec.)	Percentage of the total time
5	10	80	66%
10	20	40	33%
15	30	20	16.5%

Table 1: Comparison of speed and time for different frequencies

In Table 1, it is possible to see the results obtained for different OOK frequencies based on the calculation above. The frequency values below 5kHz are unacceptably slow and the frequencies above 15 kHz are not possible to be produced under current circumstances. Therefore, the data is provided for the most commonly used frequencies in the 5-15 kHz range. Based on this data, we can safely say that the time allocated for the communication can be greatly reduced by increasing the speed of the OOK. Therefore, OOK modulation is sufficient for our purposes.

ii. Protocol establishment between the terminals

After the modulation is taken care of, the question arises: How does the receiver know that some data is being sent by the transmitter at a given time and how does the receiver understand whether the data transmission has ended? How are the receiver and transmitter coordinated? To overcome these problems, a protocol between the receiver and transmitter must be employed.

For this issue, the following signal structure is proposed:

$$r(t) = rand(t) + sync(t) + m(t) + end(t)$$

where r(t) is the received signal, synch(t) is the synchronization signal, m(t) is the message signal and end(t) is the ending indicator.

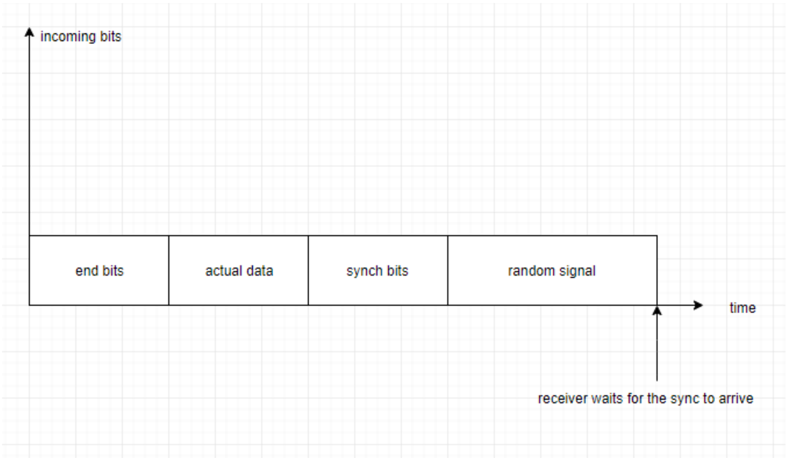

Figure 6 : The receiver waiting for the synch to arrive

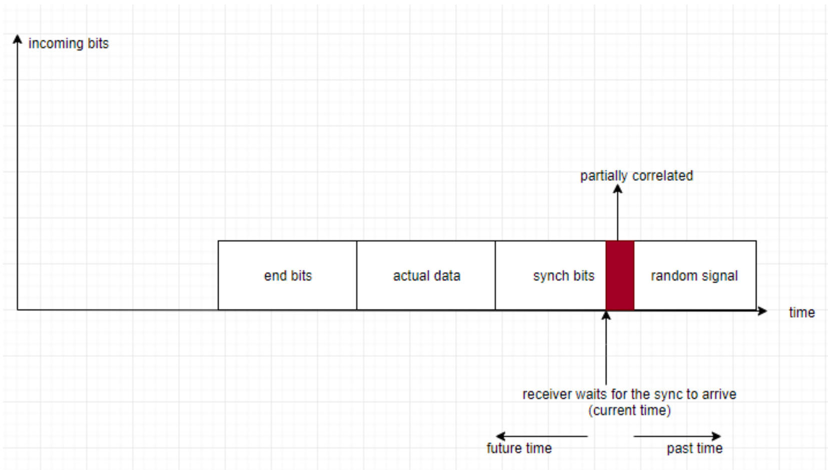

Figure 7 : The receiver is detecting the synch signal

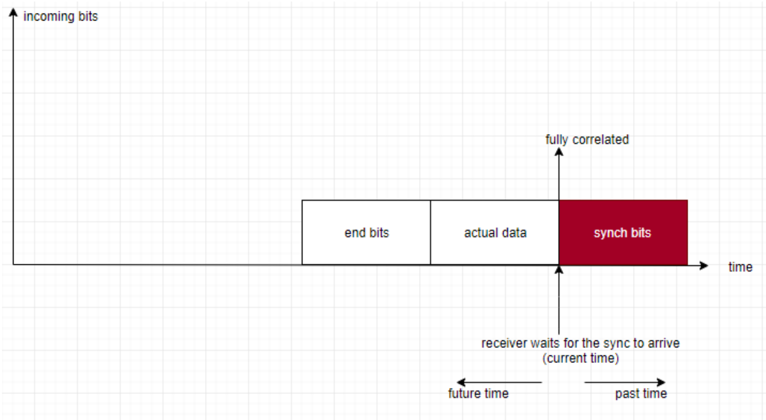

Figure 8 : Receiver fully detected the synch bits

The receiver has two states, idle state and the receive signal state. It waits for the data to arrive until the sync(t) signal arrives. Sync(t) is a special hard-coded signal which is known both by the transmitter and the receiver beforehand. Therefore, in the idle state the receiver constantly correlates the random signal with the sync(t) signal that it has. Full correlation occurs only when the sync(t) signal arrives and matches completely with the sync signal of the receiver. At this moment, the receiver changes state and it starts to read the incoming bit stream. The receiver reads and stores the bits until the end signal arrives. After the end signal, it stops reading data. This way, a portion of the bits are sent successfully. The detection of the synch bits can be seen in the Figures 6, 7 and 8.

However, an important thing here to note is that a unique end signal is required which indicates the transmission of the entire picture is completed. This unique end signal will enable the image reconstruction subsystem to start decompressing and obtaining the original image. Therefore, the last packet of data is sent with a unique end signal after it. The operation of the receiver can be seen in the Figure 9 below.

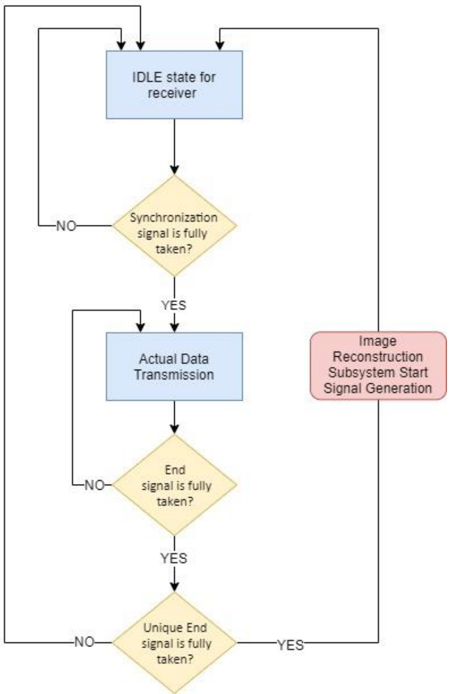

Figure 9: The flow diagram for the receiver part

iii. Error Checking

In coding theory with applications in telecommunication, error detection and correction are techniques that enable the delivery of digital data over communication channels, via VLC in our case.

For error-checking and correction, Hamming Code is utilized. For implementation of Hamming code, the redundant bits are added to raw data. Redundant bits are extra binary bits that are generated and added to the information-carrying bits of data transfer to ensure that no bits were lost during the data transfer.

The number of redundant bits can be calculated using the following formula:

$$2^r \geq m + r + 1 \; where, r : redundant\ bits, m{:}\, data\ bit$$

All the bit positions that are power of 2 are marked as redundant bits and further, they are waiting to be filled with parity bits which are parity checking the related bit positions of the raw data. Even parity check is utilized. As an instance, parity bit 1 covers all the bit positions whose binary representation includes a 1 in the least significant position (1,3,5,7,9,11 etc.). Therefor parity bit 1 is 1 if the number of 1's in the set of bits covered by parity 1 is odd. Similarly, parity bit 2 covers the bit positions having 1 in the second position from the least significant bit (2,3,6,7,10,11, etc.). And the same operation for the parity 1 is realized for parity 2 to select the binary value.

Bit position		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Encoded data bits		p1	p2	d1	p4	d2	d3	d4	p8	d5	d6	d7	d8	d9	d10	d11	p16	d12	d13	d14	d15	
Parity bit coverage	p1	✗		✗		✗		✗		✗		✗		✗		✗		✗		✗		
	p2		✗	✗			✗	✗			✗	✗			✗	✗			✗	✗		...
	p4				✗	✗	✗	✗					✗	✗	✗	✗					✗	
	p8								✗	✗	✗	✗	✗	✗	✗	✗						
	p16																✗	✗	✗	✗	✗	

Table 2: Parity bits' coverage of data bits

For the error correction, simply parity bit check is utilized. XORing the related bits (the one's having 1 in the first bit position, and the one's having 1 in the second bit position, and the followings in the same manner), the result is recorded. It is better to give an example.

Data to transmit: 10101001110

Data received: 10101**1**01110

Parity check for the bit positions having 1 in LSB: 0

Parity check for the bit positions having 1 in one bit after LSB: 1

Parity check for the bit positions having 1 in two bits after LSB: 1

Parity check for the bit positions having 1 in three bits after LSB: 0

In this example, by means of Hamming Code, it is found that 6th (0110) bit position in the data element is wrong and to correct that toggling the value is enough.

-Hardware Part of the Communication Sub-System

For OOK:

In the communication submodule, there is two parts. The first part of the communication submodule provides data transfer from first terminal to the vehicle. The second part of the communication submodule provides data transfer from vehicle to second terminal. Both parts of the communication submodule consist of a transmitter circuit and a receiver circuit. The Figure 1 illustrates the communication system, the data transfer directions and vehicle positions. In this figure, “Terminal 1” represents the terminal where the input to whole system, which is an image, is taken and “Terminal 2” represents the terminal where the output of the whole system, an image, is displayed. “T1” and “R1” represents the transmitter and receiver of the first part of the communication submodule while “T2” and “R2” represents the transmitter and receiver of the second part of the communication submodule. The data transfer between Terminal 1 and vehicle is performed when vehicle is at position 1 while the data transfer between terminal 2 and the vehicle is performed when vehicle is at position 2.

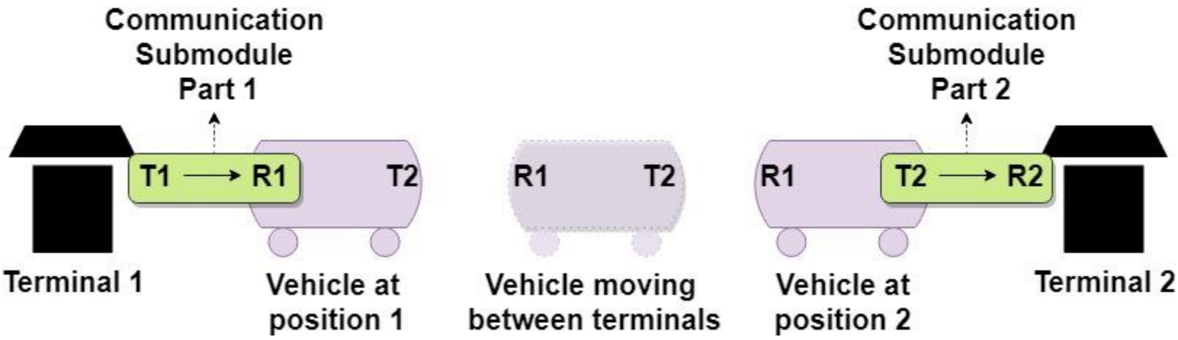

Figure 10: The parts of the communication submodule.

The circuitry that used in first part and the second part of the communication submodule is same and it is given in Figure 10. This schematic is prepared in LTspice XVII. In this figure, supply voltage 9V and input voltage (square wave) are seen at the left side of the figure. The 9V supply voltage is provided by a DC power supply at the communication module tests conducted till this stage but this voltage will be provided by a 9V battery in the final product. The input signal of the transmitter circuit will be provided by Raspberry Pi pins at the first part of the communication submodule and by Arduino pins at the second part of the communication system. The output signal of the receiver circuit will be provided to Arduino pins at the first part of the communication submodule and to Raspberry Pi pins at the second part of the communication submodule.

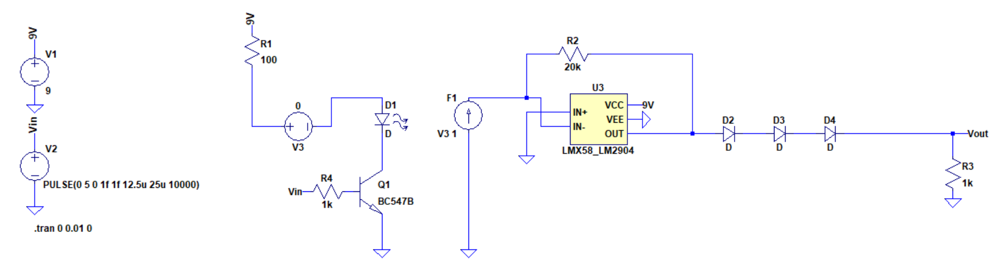

Figure 11: The circuitry of the first part of the communication submodule.

The transmitter circuitry (led driving circuit) is seen in Figure 11. Here 0V DC V3 source is put there only to use it in the receiver circuitry as the input of the current controlled current source which is used to simulate the output of photodiode. The input voltage is supplied to the base of a BC 547 NPN BJT to drive the led. The intensity of the outputted light depends to current flowing through the led. Here, 10R3HD-15 LEDs are used. When input is high, BJT is in SAT and there is a current flowing through the LED which makes it illuminate. When input is low, BJT is in CUT-OFF and there is no current flowing through the LED thus there is no illumination by LED. When there is illumination, this represents "logic 1" information while when there is no illumination, this represents "logic 0" information.

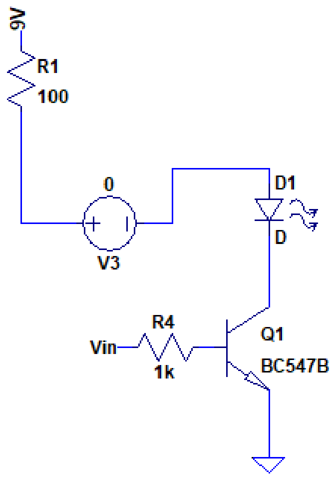

Figure 12: The transmitter part of the circuitry seen in Figure 11.

The receiver circuitry is seen in Figure 13. Here, F1 is current dependent current source and used to represent photodiode. Photodiode provides current as its output which is proportional with the intensity of the illumination detected. A trans-conductance amplifier is used to turn current information at the input to voltage information at the output. This trans-conductance amplifier is built with LM358 OPAMP. When there is current flowing through photodiode, output voltage is [I*R2] and when there is no current is flowing through photodiode, output voltage is "logic 0". Experimental observations show that there is 7.5 V voltage reading at the output pin of the LM358 when LED is shining and 2.5 V voltage reading at the output pin of the LM358 when LED is not shining. This is due to light exists at the environment. To decrease the output low voltage, 3 diodes is connected in series as a simple solution. These diodes decrease the output low voltage to 0.5 V and output high voltages to 5.4 V.

The pins of Arduino are used in the first part of the communication submodule and "digital read" function is utilized. This function takes voltages lower than 1.5 V as logic low and voltages higher than 3.0 V as logic high. The output high and output low voltages of the receiver are in the limits of high and low definitions of the "digital read" function of the Arduino.

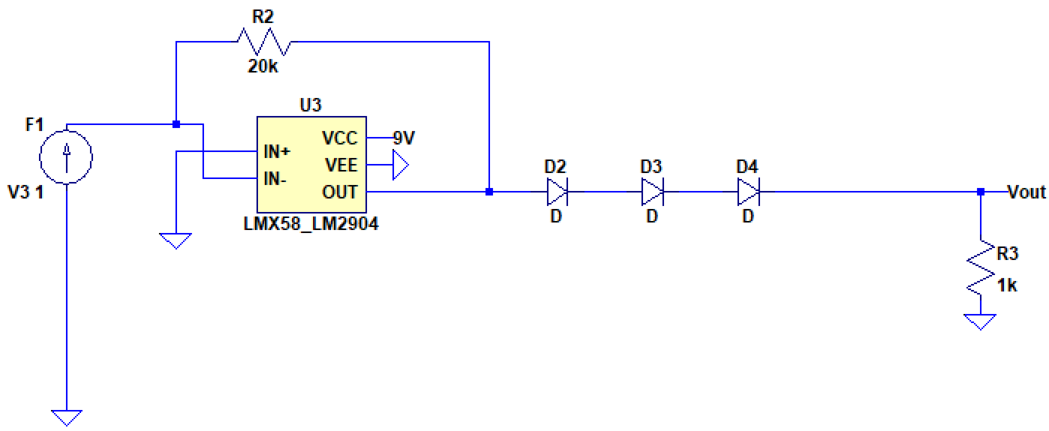

Figure 13: The receiver part of the circuitry seen in Figure 11.

The simulation results of the communication submodule circuitry are presented from Figure 14 to Figure 17. These simulations are taken via utilizing LTspice XVII and output waveform is observed for square wave input with different frequencies.

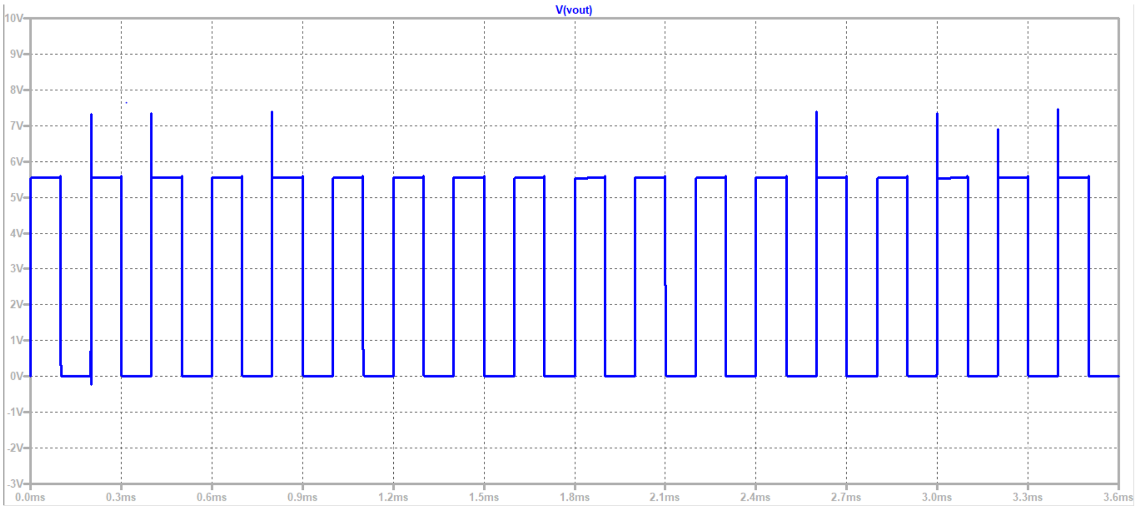

Figure 14: The output waveform for 5 kHz square wave input.

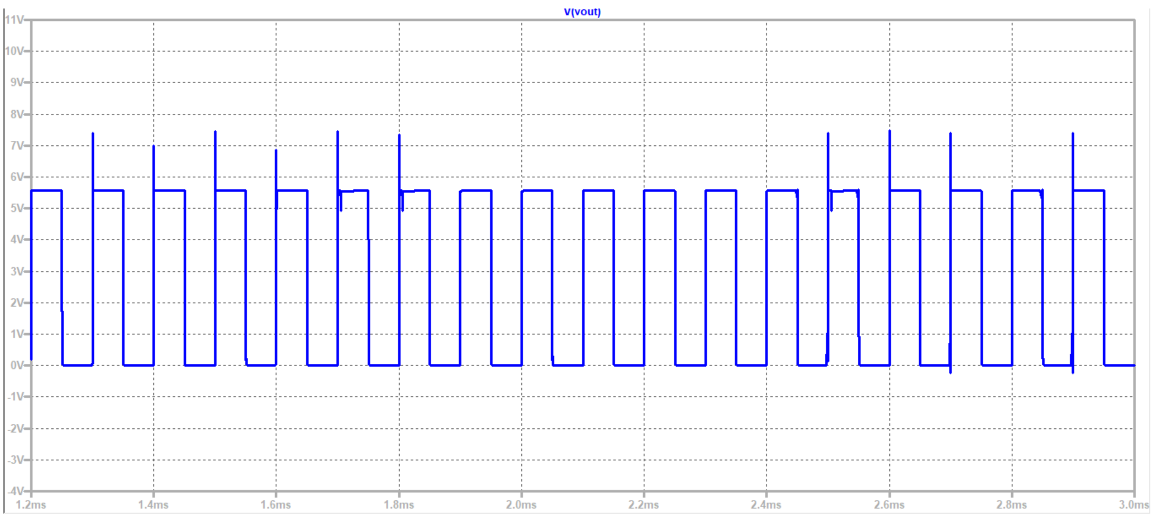

Figure 15: The output waveform for 10 kHz square wave input.

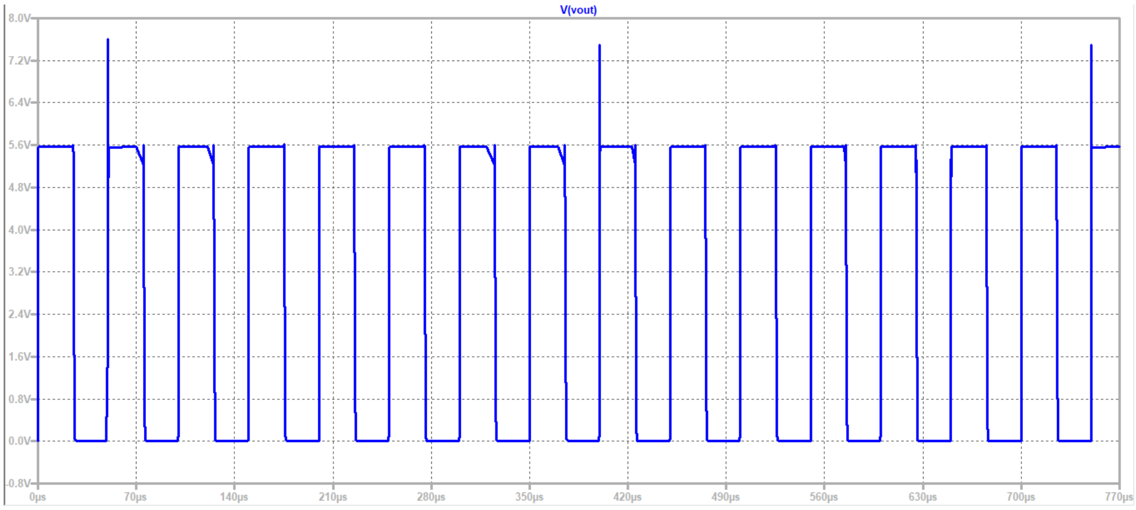

Figure 16: The output waveform for 20 kHz square wave input.

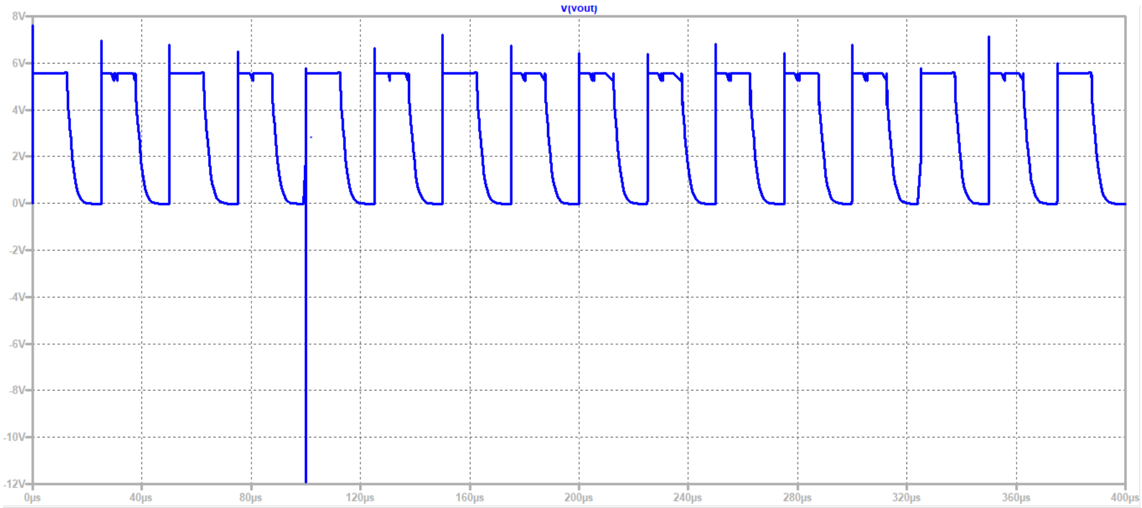

Figure 17: The output waveform for 40 kHz square wave input.

Alternative Solutions for Communication Subsystem

Alternative approaches can be developed for the communication subsystem. Each alternative will bring its own implementation and challenges. However, it is still important to note them in case if the current developed solutions partly or completely fail.

The alternative solutions should be developed without losing our perspective on the communication system, that is the alternatives should be investigated under their corresponding section and their effects to the other sections should also be analyzed. Keeping these points in mind, alternative solutions are presented as follows:

i. Alternative Modulation Types

Modulation schemes other than OOK can also be considered for the VLC system. BPSK, QPSK, FSK and PWM can be candidates.

In PWM, each symbol is assigned to a square wave with a unique duty cycle. This way, in the demodulator side, they can be detected by making use of their different duty cycles. This method does not require a change in the circuitry and be constructed rather easily. It can provide more reliability in terms of bit error rate but since a PWM modulated bit occupies a time duration which is equal to two OOK modulated bits, it suffers from speed. However if, in the future, OOK fails, PWM can be considered as a viable back up plan.

In FSK, each one or zero is allocated to a distinct frequency and a sine wave of corresponding bit frequency is transmitted during a bit period. However, there is no need to utilize this method as binary FSK. For example, four different frequency values can be used to represent 00, 01, 10, 11. This can increase the transmission speed but introduces more complexity. Furthermore, employing FSK also requires changes in the transmitter and receiver circuitry.

BPSK and QPSK aim to change the phase of the carrier frequency for each corresponding symbol. In BPSK, there are two symbols (0 and 1) whereas in QPSK there are four different symbols (00, 01, 10, 11). They can be implemented using root raised cosine filters and its matched filter at the receiver end; however, their modulation and demodulation is even more complex than FSK.

In conclusion, alternative modulation types can be realized by first trying PWM, then FSK, BPSK and QPSK in the given order.

ii. Alternative Protocols

Firstly, the amount of bits to be sent from the transmitter can be kept fixed each and every time. This way, the need for an end signal can be avoided. As a result, the transmission signal would look like this:

$$r(t) = sync(t) + m(t)$$

Other than that, the 3-way handshaking protocol can also be used. In this protocol, the transmitter first sends a sync signal. It is a randomly generated number and it is picked up by the receiver. Then, the receiver responds by sending and acknowledgement signal and its own synch signal. Finally, the receiver acknowledges that it received the last synch signal and then the communication starts. Although it is sophisticated, 3-way handshake protocol has the potential to securely form a communication channel and therefore, it can be preferred over other protocols. However, it requires detailed change in circuitry.

A problem which was encountered during testing was that the receiver side sometimes missed the first data bit of the incoming data stream. Therefore, guarding bits in the beginning of the sequence can be placed and the receiver can specifically check for them. If it realizes that the guard bits are mistaken, it can request the transmitter to send the data packet again.

iii. Error checking

As a matter of fact, according to our test results, the system meets errors more than once. However, Hammington method of error check corrects only one-bit position. It doesn’t suit to our system.

Checksum error detection and cyclic redundancy check methods can also be alternatively used. In checksum error detection scheme, data divided into k segments each of m bits. In the transceiver's end the segments are added using 1's complement arithmetic to get the sum. The sum is complemented to get the checksum. The checksum segment is sent along with the data segments. At the receiver's end, all received segments are added using 1's complement arithmetic to get the sum. The sum is complemented. If the result is zero, the received data is accepted; otherwise discarded.

Unlike checksum scheme, which is based on addition, CRC is based on binary division. In CRC, a sequence of redundant bits, called cyclic redundancy check bits, are appended to the end of data unit so that the resulting data unit becomes exactly divisible by a second, predetermined binary number. At the destination, the incoming data unit is divided by the same number. If at this step there is no remainder, the data unit is assumed to be correct and is therefore accepted. A remainder indicates that the data unit has been damaged in transit and therefore must be rejected.

3.3.2 Image Acquisition Subsystem

<u>Camera Part:</u>

In the image acquisition submodule, the photo is captured by **Raspberry Pi Camera 3**. The code required for this operation will be written in Python. It is important to note that **2 seconds** will be needed to spend before taking the photo in order to give the camera's sensor time to sense the light levels.

<u>Image Compression and Division into Packets:</u>

The size of the raw data of the image file can be found via the equation below:

$$\#\,of\ Pixels * \frac{Bit\ Depth}{8 * 1024^2} = File\ Size\ in\ Megabytes$$

The maximum resolution of Pi Camera 3 is 2592x1944(5 MP) and the minimum resolution is 64x64. Resolution of the image is the parameter for the user to select how many pixels to use for the image capturing. Also via the Python Image Library, the quality of the photo can be arranged. In this way, JPEG compression is used. JPEG compression use lossy compression to reduce file sizes. By doing optimizations on the tradeoff between data amount (resolution) and photograph quality(compression), the image file will be saved in JPEG format.

To transfer an image, it is required to convert an image to a string in such a way that the string represents the image. The binary data will then be splitted into 5 packets of data chunk by simply splitting the array of data into five blocks of arrays and then the first data packet will be sent bit by bit to the transceiving circuitry with the required rate (**13 kbps**). Five data packets will be sent one by one at each phase of the communication with the vehicle.

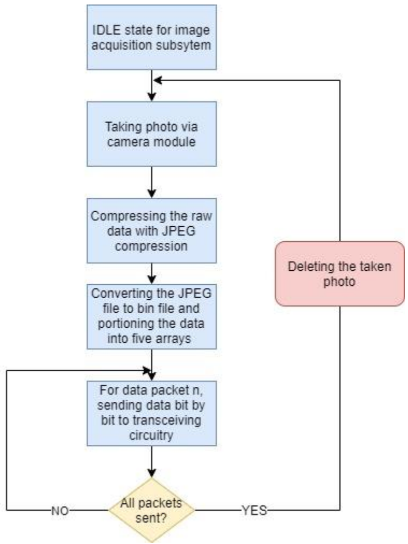

Figure 18 : Flowchart of the Image Acquisition Subsystem

3.3.3 Image Reconstruction Subsystem

Data Collection:

Throughout the transportation phase, as the vehicle comes to the receiver terminal, data packet on the vehicle is taken by the receiver side and stored as binary files to the Raspberry Pi 0 on the receiver terminal.

When the unique end signal is generated at the end of the receiver-side communication process, the merging and decompression process is initiated.

Merging:

The bin files are merged on the general purpose computer as a JPEG file via PIL library of Python. Since JPEG is a lossy medium for the images, decompression is not fully operatable. As image file is merged the proper signal is generated to initiate the display process.

Display: Raspberry Pi LCD screen, having a resolution of 128x128, can be utilized by using SPI(Serial Peripheral Interface) via its drivers. The screen operates with 3.3 V.

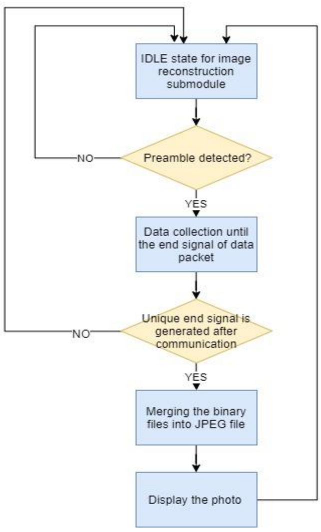

Figure 19: Flowchart of the Image Reconstruction Subsystem

3.3.4 Transportation Subsystem

The transportation subsystem is a complementary part to the Li-Fi communication in order to achieve image transmission between two end terminals where a vehicle transports the data between transmitter and receiver terminals. As the vehicle receives the data from the transmitting terminal with the methods explained in the communication subsystem description it transports the data towards the second terminal, while moving on physically guided tracks, to the location where again Li-Fi communication would take place. When the transported data is transferred to the receiving terminal the vehicle is required to go back to the transmitting terminal to receive the new packet.

The vehicle has a limited memory of 10kB and expected to do at least five laps between the end terminals in order to transport a single image. By considering the fact that the whole data transmission must be done under 2 minutes, by also taking the Li-Fi communication time into account, we decided that the average velocity of the vehicle must be at least 25cm/s for the maximum distance case when the distance between two terminals are equal to 1.5 meters. Also the vehicle has to stop at least 5cm away from each terminal while the distance between the two terminals can vary up to 1.5 meters.

The whole image transmission process is required to be done under 2 minutes in which both VLC communication and data transportation by the vehicle must be handled while the distance between the two end terminals are varying up to 1.5 meters. The maximum amount of data that the vehicle can carry is limited to 10kB while the vehicle is expected to do at least 5 laps, going back and forth between the terminals on physically guided tracks, for the transportation of the whole image. By considering the number of minimum laps and the time limitations we decided that the average velocity of the vehicle must be at least 25cm/s for the maximum distance case when the two terminals are 1.5 meters away from each other. In addition to these, the vehicle must come to stop at least 5cm away from the terminals which requires a sensor fed controller considering that the distance between the terminals is variable.

To accomplish all these tasks the design of this subsystem can be divided into three parts which are the control loop design, physical structure of the vehicle and the design of the physically guided tracks that the vehicle will travel on.

Control of the Vehicle

In order to control the vehicle, we will design a closed loop controller where the distance of the vehicle to the terminals measured by a sensor would be used as feedback. We are going to use DC motors as the actuators of our vehicle whose speed can be controlled by applying a variable duty cycle PWM input to them. So, the main aim of our controller is to produce the appropriate PWM output which will then be fed to the four DC motors located at each wheel through a motor driver. The motor driver that is to be used is simply an H-Bridge which enables turning the motors in both directions by changing the polarity of the applied voltage using switches as shown in Figure 20. Thus, the vehicle can go back and forth between the terminals without turning around.

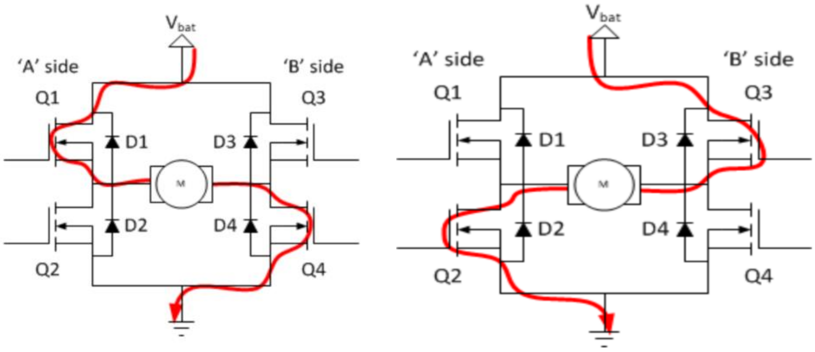

Figure 20 : H-Bridge circuitry which enables the rotation of DC motors in both directions

The vehicle would understand that the data is transmitted to its receiver as the specific end signal is received and then it would rush towards the receiving station. At this point, the duty cycle of the PWM would be increased to its maximum value gradually in order to allow soft start of the motors. This is crucial in order to prevent any damage on the motor or the physical construction and make the subsystem more robust. Throughout the transportation, the controller would get the distance data of the vehicle and as the distance gets smaller than a certain threshold the duty cycle of the PWM would be decreased gradually so that the vehicle comes to a soft stop at 5cm away from the terminal. This time the sending of the specific end signal would indicate that the data transmission is over after which the vehicle goes back to the transmitting terminal to receive a new packet while measuring its distance to the terminal by another sensor located on the opposite end of the vehicle. Similar to the data carrying step the controller will manipulate the duty cycle of the PWM so the vehicle comes to a soft stop 5cm away from the transmitting terminal, ready to receive the new packet.

This procedure would repeat itself again and again until all of the data packets are transmitted to the receiving terminal.

<u>Physical Structure of the Vehicle:</u>

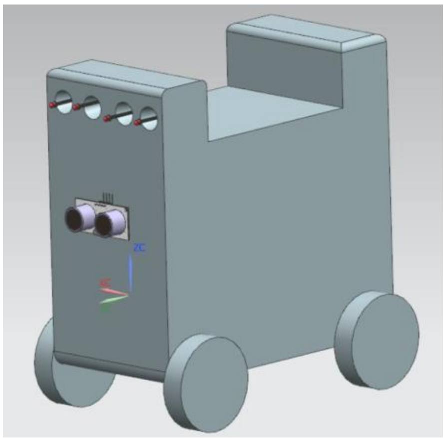

Figure 21: Rough CAD Drawing of the Vehicle

Vehicle's rough CAD drawing is given in Figure 21. At front and back ends of the vehicle, there are distance sensors to calculate the distance between vehicle and the terminals. At the upper parts of the vehicle, there are slots for photodiodes/LEDs for communication between transmitting/receiving terminals respectively. There is an empty place on the vehicle reserved for the controller and driving circuitries. Inside the main body of the vehicle, batteries and motors will be placed. Wheels of the vehicle will be suitable for operating on the rail. Length of the vehicle is 20 cm and overall height (calculated from the bottom of the wheels to the top of the vehicle) is 20 cm.

Physically Guided Tracks:

For the physically guided track, two parallel u-aluminum profiles with 3 meters length and 3 cm width will be used. Terminals will be located on the profile ends and their position will be adjustable on the profile. Vehicle moves on the rail. An example of U-Type profile is provided at the Figure 22.

Figure 22: U-Type Aluminum Profile

Alternative Solutions for Communication Subsystem

Alternative approaches can be developed for the transportation subsystem in case our first plans fail our cause any unexpected problems. Again, the alternatives can be developed for the three main parts of the transportation subsystem which are the control loop design, physical structure of the vehicle and the design of the physically guided tracks that the vehicle will travel on.

1) *Alternative Control Loop Structure*

Putting the sensor on the vehicle and applying a closed loop control based on the distance measurement made on the vehicle seems to be the best and the most straightforward solution. However, in case of any failure with the use of proximity sensors we might use a IMU or decoder to identify the location of the vehicle while measuring the distance between the terminals by a single sensor which is placed on one of the end terminals.

2) *Alternative Physically Guided Track Structure*

Although our first plan which is limiting the movement of the car by using U-profile guides seems to be the easiest solution we are considering the fact that it might increase the rolling resistance of the wheels considerably. This would decrease the speed of transportation which is a crucial problem as speed makes up an important criterion for the success of the project. As an alternative to this approach we may put wheels directly on the ground and separate the rails from the traction mechanism and use them as only movement limiters. In order to achieve this, two freewheels that are parallel to the ground should be fixed on the bottom of the vehicle. Then again two U-profile rails should be fixed to the ground so that added freewheels can just slide between them. By this way the vehicle won't be able to do any lateral movement while the freewheels enable minimal friction between the rails and the vehicle.

3.4 TEST PROCEDURES, EXPERIMENTS AND TEST RESULTS

There are four main subsystems to be tested in solution proposed by Revolutionary Systems Inc. to "Gimme Fast" project. These are image acquisition subsystem, communication subsystem, transportation subsystem and image reconstruction subsystem. Up to this point, communication subsystem is tested. The procedure followed during the tests of communication submodule, results of these tests and evaluation of test results with respect to the requirements set for the communication subsystem are explained in the following sections.

3.4.1 Test Procedures

In tests of communication subsystem, Revolusys demonstrated the communication system that utilizes the on-off modulation at 10 kBit/sec data transfer rate.

The test data stream was upload to input as input and output of the system for transmitter led to receiver photodiode distances from 5 cm to 10 cm (with 1 cm steps) and for different light conditions (dark, lab light , intense light) was observed. This process was repeated 50 times for lab light condition and dark light condition at all distances and for intense light condition for 5 cm and 8 cm transmitter to receiver distances.

In these, to illustrate the proper operation of the commination system, 150 bit message signal was transmitted. This deterministic 150 bit message is given in Appendices.2 section. The number of message bit was selected arbitrarily, the communication system will transmit more than 150 bit at once on its operation. The transmitted stream starts with 6 bit preamble array, "1-1-1-1-1-0". After this 6 bit of array, "1" bit is sent. After receiving last bit of preamble, "0", receiver searches for a rising edge. With the rising edge, transmitter arranges its sampling point to mid-point of the high or low durations, to decrease the error. After this 7 bit of information, 150 bit message signal is sent. After 150 bit of message signal, transmitter stops transmitting.

The received data (with digital read command of Arduino), was read on the COM screen of Arduino and compared with the message signal in MATLAB. The number of error in the received 150 bit message signal was determined and recorded for different trials.

The setup for lab light condition test is seen in Figure 23. The setup for dark condition test is seen in Figure 24 and Figure 25. In this test, a dark environment was reached via using wooden pieces seen in Figure 24. The light level at this test condition is seen in Figure 25. The setup for intense light condition is seen in Figure 26. "1" in these figures shows the LED while "2" shows the photodiode and "3" shows the source of intense light, a telephone flash light.

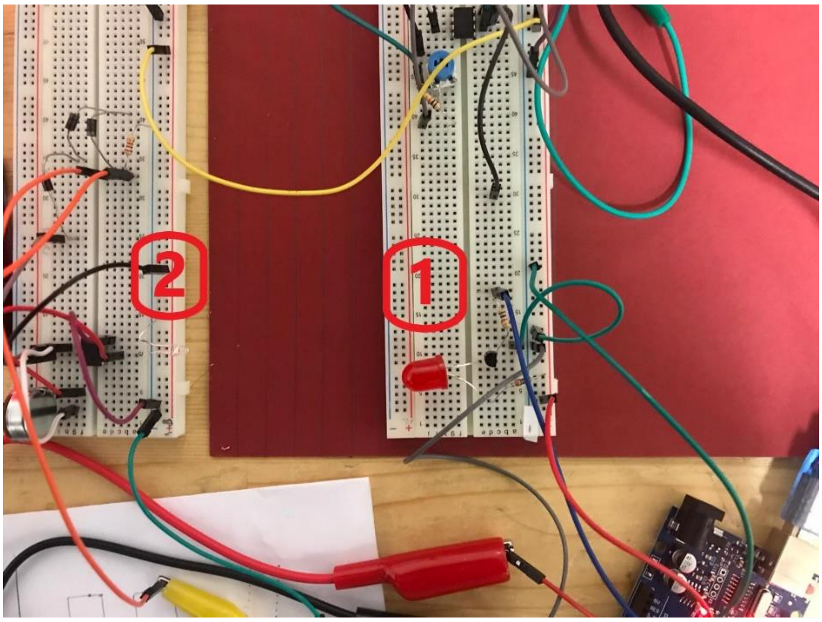

Figure 23: The setup for lab light condition tests.

Figure 24: The setup for dark condition tests. (1/2)

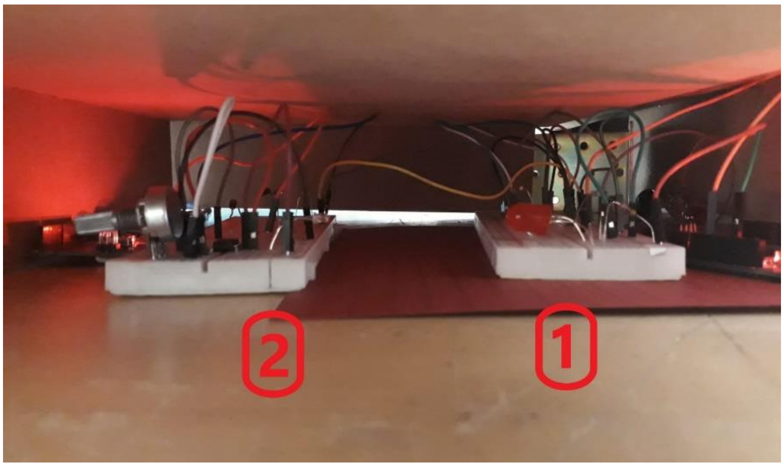

Figure 25: The setup for dark condition tests. (2/2)

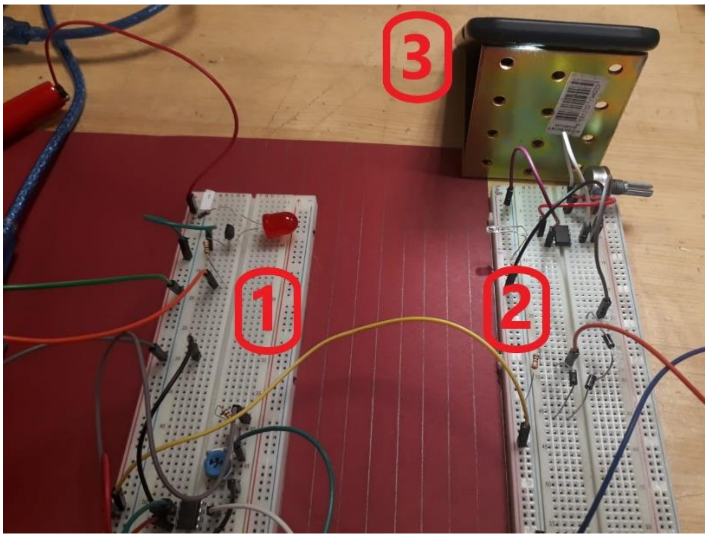

Figure 26: The setup for intense light condition tests.

3.4.2 Test Results

The data obtained from the measurements taken for lab light condition and dark condition are tabulated in Table 1. The data obtained from the measurement at 5 cm and 8 cm transmitter to receiver distance are tabulated in Table 2. It is observed that for lab light condition at 10 cm, data transfer was not successful.

Table 3: The data obtained from the measurements taken for lab light condition and dark condition.

	The Lab Light Condition		The Dark Condition	
The Distance Between Transmitter and Receiver	The Average Number of Error	The Standard Deviation	The Average Number of Error	The Standard Deviation
5 cm	7.2	13.95	8.2	9.33
6 cm	11.4	12.15	11.4	12.05
7 cm	10.0	14.35	0.5	1.23
8 cm	2.6	5.10	11.4	15.08
9 cm	28.5	16.92	21.6	25.02
10 cm	X	X	0.8	1.17

Table 4: The data obtained from the measurement at 5 cm and 8 cm transmitter to receiver distance.

	The Lab Light Condition		The Dark Condition		The Intense Light Condition	
The Distance Between Transmitter and Receiver	The Average Number of Error	The Standard Deviation	The Average Number of Error	The Standard Deviation	The Average Number of Error	The Standard Deviation
5 cm	7.2	13.95	8.2	9.33	12.8	14.70
8 cm	2.6	12.15	11.4	15.08	5.5	7.94

The data tabulated in Table 3 is shown as a line graph in Figure 27. The tabulated data in Table 4 is shown as a line graph in Figure 28. Note that data in Table 3 and Table 4 is number of error in 150 bit received message signal while Figure 27 and Figure 28 shows % error rate.

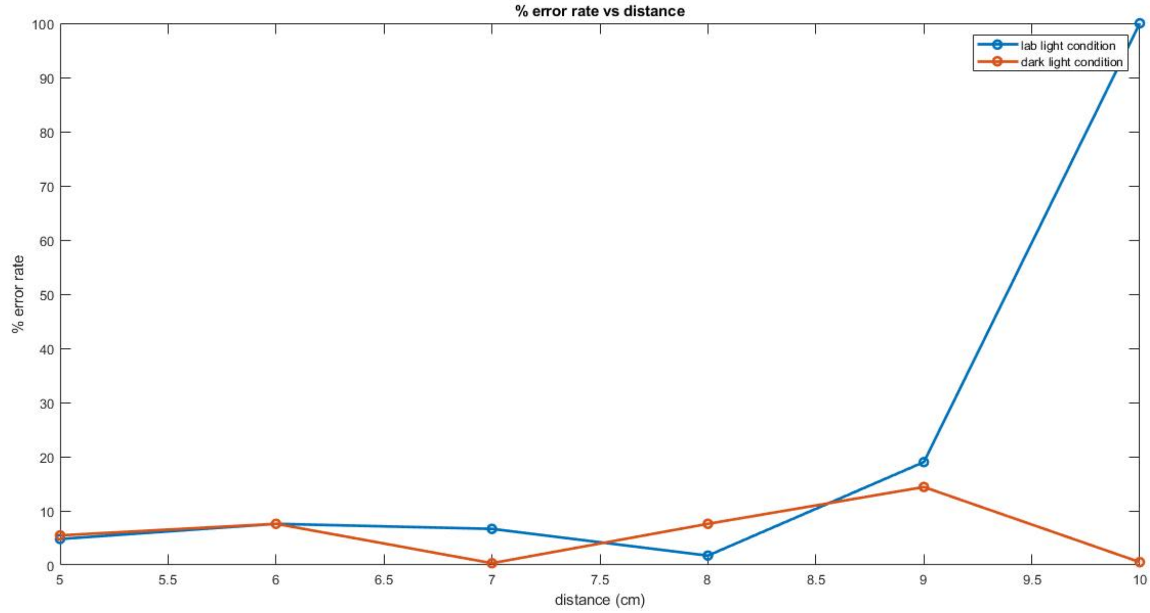

Figure 27: The data tabulated in Table 1 as a line graph.

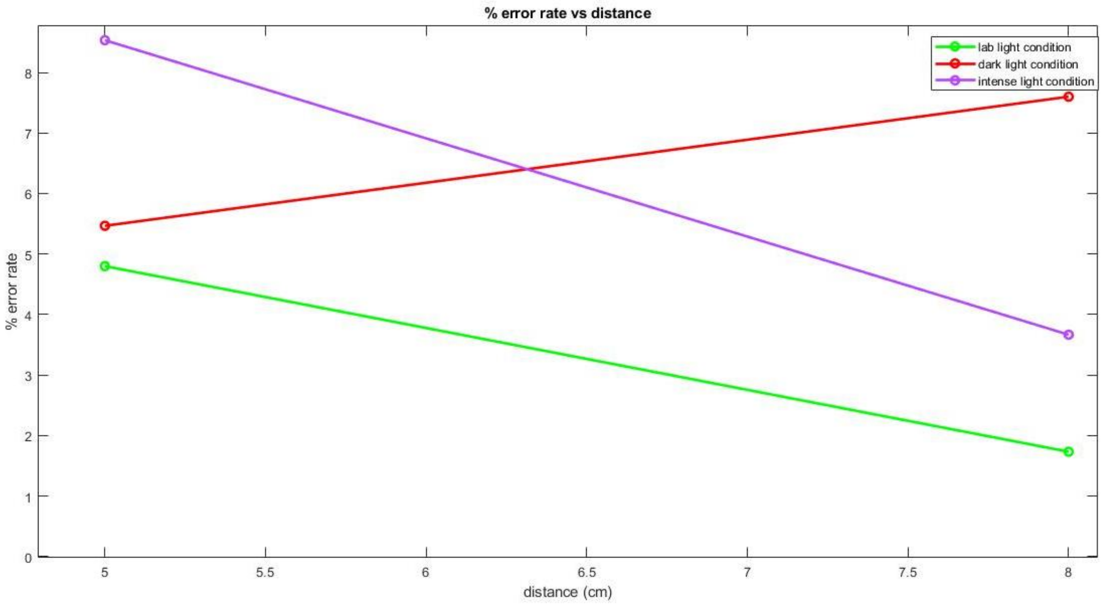

Figure 28: The tabulated data in Table 2 as a line graph.

3.4.3 Evaluation of Test Results

The requirements which are determined, proposed in the Proposal Report of the Revolutionary Systems Inc. regarding “Gimme Fast” project and related with the communication subsystem are listed and the results of the conducted tests are related with them in the following paragraphs.

a. *Some portion of the photo must be transmitted to the vehicle by VLC (Visible Light Communication). (functional requirement)*
b. *The data packets carried by the vehicle needs to be delivered to the receiver terminal. (functional requirement)*

In the conducted tests, a photo is not transmitted but a 150 bit message signal is successfully transferred from transmitter part to receiver part.

c. *A minimum DTR (data transfer rate) of 0.013 Mbps will be achieved. (performance requirement)*

In the conducted tests, data transfer rate was 10 kb(kilobit)/sec which is equal to 0.0098 Mb(megabit)/sec. This data transfer rate is for one LED. Since data transfer will be performed by four LEDs, data transfer rate of the tested communication system is 40 kb/sec which is equal to 0.0391 Mb/sec. Thus, communication system was successful at reaching the requirement regarding the data transfer rate.

d. *The minimum accuracy rate of 90% should be achieved for the reconstructed image. (performance requirement)*

In the conducted tests, no picture was reconstructed but considering the percentage error at the received data, communication system was successful at all three light conditions at a distance varying from 5 cm to 8 cm.

4.PLANS

4.1 TEST PLANS FOR NOT BUILT SUBSYTEMS

There are four main subsystems to be tested in proposed solution. The communication subsystem is tested and the results are presented in the "Test Results" subsection of the "Solution" section, in this report. The other three subsystems will be tested upon their completions. The procedures that will be followed during the tests of these subsystems, the measure of success at the planned tests for subsystems, the plans regarding to integration of the submodules to build the whole system as the final product, the procedure that will be followed during the test of the whole system and the measure of success at the planned tests for whole systems are explained in the following subsections.

4.1.1 Test Plans for Image Acquisition Subsystem

Upon completion of the image acquisition subsystem, the main tasks of this subsystem will be tested as described below.

1. Photo Taking: The output produced upon taking a photo via camera will be examined. If the camera output is not suitable considering the size and the data format of this output, the camera will be replaced with another camera.
2. Compressing the Data: The output of camera will be stored in Raspberry Pi and this stored data will be compressed. The expected size of this data is 50-80 kB. The output of the compression algorithm will be tested both for predetermined data and data obtained from camera. If the compression algorithm does not work properly, other compression algorithms will be utilized.

3. Data Division: The data division code will be tested for both predetermined data and the data obtained from the output of the compression unit.

The requirements of the image acquisition subsystem are listed in the 3.1 section of this report. The measure of success for the tests described above will be measured according to degree of satisfying these requirements.

4.1.2 Test Plans for Image Reconstruction Subsystem

Upon completion of the image reconstruction subsystem, the main tasks of this subsystem will be tested as described below.

1. Merging Data Packets: The code written to merge data packets will be tested for varying number of predetermined data packets and output of the code will be observed.
2. Displaying Reconstructed Image: The display unit will be tested with predefined data regarding its quality.

The requirements of the image reconstruction subsystem are listed in the 3.1 section of this report. The measure of success for the tests described above will be measured according to degree of satisfying these requirements.

4.1.3 Test Plans for Transportation Subsystem

Upon completion of transportation subsystem, the main tasks of this subsystem will be tested as described below.

1. Distance Sensing: The distance sensor will be tested in 0-10 cm range. If the sensor cannot provide sensitive distance measurement with low error rate, the sensor type will be changed.
2. Soft Start/Stop: The starting and stopping moments of the movement of the vehicle will be observed taking the stagger of the vehicle into account.
3. Achieving Aimed Speed: The speed of the car will be measured at the maximum terminal to terminal distance and will be compared with the predetermined speed requirement.

The requirements of the transportation subsystem are listed in the 3.1 section of this report. The measure of success for the tests described above will be measured according to degree of satisfying these requirements.

4.2 INTEGRATION PLAN OF THE SUBSYTEMS

As the first step of the integration of the subsystems, image acquisition subsystem will be integrated with the first part of the communication subsystem and the image reconstruction subsystem will be integrated with the second part of the communication subsystem. As the second step, transportation subsystem will be integrated in between these two separate subsystem couple and the integration of the whole system will be completed. This process is depicted in Figure 29.

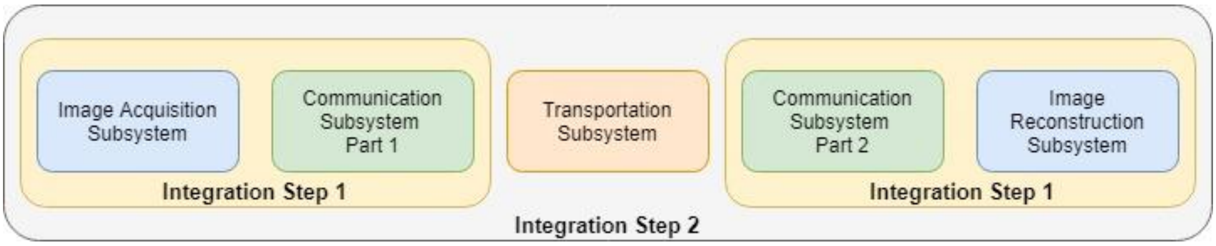

Figure 29: The integration steps of the subsystems.

Upon completion of the integration of the subsystems, the tests described below will be conducted.

1. Test of subsystem couples:
   a. The image will be taken via camera at the image acquisition subsystem and the output of the first part of the communication subsystem (which is the output reading of the first receiver via Arduino) will be observed.
   b. A predetermined data will be uploaded to transmitter of the second part of the communication subsystem and the output of the image reconstruction system (which is a display screen) will be observed.
2. Test of integrated system with no motion: Terminals will be positioned so that vehicle will be at 5 cm distance to both terminals. Without any movement of vehicle, the whole system will be tested. An image will be taken via camera at the image acquisition subsystem and the display screen at the output of the image reconstruction subsystem will be observed.
3. Test of whole system with motion: The whole system will be tested with varying distance between two terminals. An image will be taken via camera at the image acquisition subsystem and the display screen at the output of the image reconstruction subsystem will be observed. The timing of the whole process will be measured.

The requirements of the whole system are listed in the 3.1 section of this report. The measure of success for the tests described above will be measured according to degree of satisfying these requirements.

4.3 PROJECT MANAGAMENT

4.3.1 Gannt Chart and Allocation of The Tasks

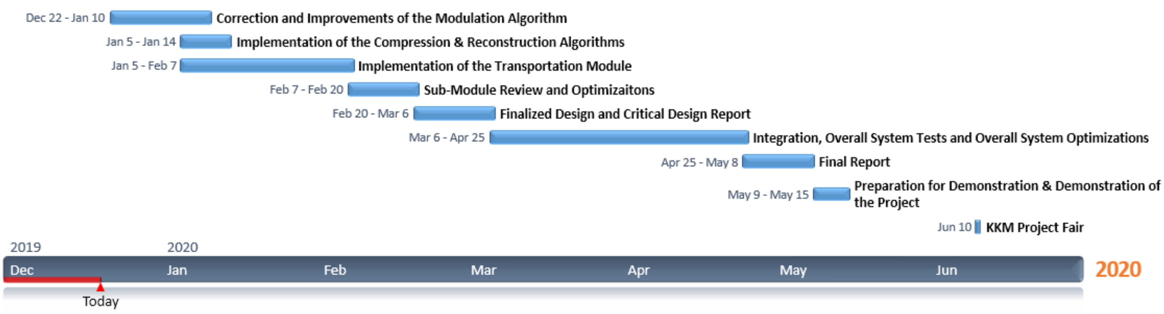

Figure 30: Gannt Chart of the Project Schedule

- Doğukan Atik and Ahmet Demirdaş will be responsible from Correction and Improvements of the Modulation Algorithm.
- Ahmet Demirdaş and Onur Akdeniz will be responsible from Implementation of the Compression & Reconstruction Algorithms.
- Mert Eyüboğlu and Ozan B. Boyraz will be responsible from Implementation of the Transportation Module.
- All members will conduct the Sub-Module Review and Optimizations together.
- Critical Design Report and Final Report will be written with the contribution of all of the members. All members will represent the final product of the Revolusys together at Demonstrations and KKM Fair.

4.3.2 Cost Analysis

EXPENSE ITEMS	COSTS
2 x Raspberry Pi 3 (To be used in receiver and transceiver terminals)	410 TL
Arduino Uno + Vehicle Kit with DC Motor Driver (to implement the vehicle with microcontroller embedded on it)	152.5 TL
Raspberry Pi 3 Camera Module (to take the photo at the transceiver terminal)	16 TL
8 x LED (to be used for VLC at the transceiver terminal and on the vehicle)	1 TL
8 x Visible Light Sensitive Photodiode (to be used for VLC at the receiver terminal and on the vehicle)	12 TL
3.5`` LCD Screen (to display the reconstructed image at the receiver terminal)	50 TL
Aluminium Profiles for Physically Guided Track	28 TL
Others(Jumpers, breadboard, PCB,3D printing costs etc.)	100 TL
TOTAL COST	**769.5 TL (130.4 $)**

4.3.3 Foreseeable Difficulties and Contingency Plans

As stated throughout the report, every solution has its own alternatives. In this section, major probable risk sources will be summarized. Main concerns are about the communication part and transportation part of the project, that’s why, Revolusys Inc. mainly focused on finding alternative solutions for Modulation & Error Checking, Control Loop Structure Physically Guided Track Structure. Image Acquisition and Reconstruction sub-systems of the project are more reliable and easy to implement. Therefore, there are no alternative plans for this sub-systems.

Contingency Plan on Modulation

On the test stage of the project, On-Off Keying modulation was preferred. Tests were conducted for 150 bit data sample and bit-error rate for 150 bit data array was obtained. Test results were admissible and error rate was tolerable for proper communication. But normally, data array will be larger than 150 bits, that's why, in case of failure with On-Off keying, alternative modulation techniques were proposed on the related section of the report.

Contingency Plan on Error Checking

First option for Error Checking for received data is Hamming Code algorithm. Its details were given in the related section of the report. If this method fails, there are two alternatives for error checking algorithm.

Contingency Plan on Transportation Module

First options on the Control Loop and Physically Guided Track Structure design is provided in the related section of this report. If these designs fails, there are alternatives for both of them which is stated in the related section.

5.DELIVERABLES

Equipment

- Vehicle

The user will be provided with a vehicle which has a transceiver embedded on it. The transceiver unit includes 4 LEDs and 4 photodiodes. The vehicle is able to detect the terminal and accelerate or decelerate accordingly.

- Physically Guided Track

The user will be provided with a 1.5 meters long aluminum constructed rail on which the vehicle can move.

- Transmitting Terminal

The user will be provided with a rectangular prism shaped transmitting terminal which contains a camera, to take a photo, transmitter unit which consists of 4 LEDs and its own computational unit.

- Receiving Terminal

The user will be provided with a rectangular prism shaped receiving terminal which contains a receiver unit consisting 4 photodiodes, a 3.5 inch LCD screen to display the taken photo and its own computational unit.

Documents

 Warranty

Revolusys Inc. provides two (2) years warranty in both transportation and communication breakdowns of the system except the user faults.

 Manual

A manual will be provided to the users to get informed about the utilization and the maintenance of the system.

6.CONCLUSION

Revolusys Inc. will design the communication subsystem by using OOK (On-Off Keying). The alternative solutions for this subsystem are also given in the report (FSK, QPSK, BPSK). The tests for alternative modulations will be done. For the error detection and correction, Hamming method is utilized. Alternatively, checksum and CDR (cyclic redundancy check) methods are thought to be implemented for test plans.

Transportation subsystem is also given with its solution approach. Ultrasound sensor will be utilized to limit the distance of the car with terminals.

In image acquisition subsystem JPEG compression is done, alternative compression methods will also be tested. Test plan contains the required tests for camera and compression algorithms' effectivity in transceiver terminal and also decompression algorithms' effectivity in the receiver terminal.

Further details for test plans, subsystem level solutions, requirement analysis, the interaction of the subsystems were given throughout the report.

Taking all the solutions for these topics into consideration, Revolusys Inc. will have a deep R&D work on each subsystem of the project and implement the total system.

7.REFERENCES

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8. APPENDIX

<u>Appendix 1: The objectives of solution and their measure of success.</u>

Performance Objectives:

Speed:

• 5 points – Operation time less than 60 seconds

• 4 points – Operation time between 60 and 75 seconds

• 3 points – Operation time between 75 and 90 seconds

• 2 points – Operation time between 90 and 105 seconds

• 1 points – Operation time between 105 and 120 seconds

• 0 points – Operation time over 120 seconds

Accuracy:

• 5 points – The displayed image has %100-85 accuracy

• 4 points – The displayed image has %85-70 accuracy

• 3 points – The displayed image has %70-55 accuracy

• 2 points – The displayed image has %55-40 accuracy

• 1 points – The displayed image has %40-25 accuracy

• 0 points – The displayed image has under %25 accuracy

Marketability Objectives:

Cost:

• 5 points – Total cost is under 100$

• 4 points – Total cost is between 100-125$

• 3 points – Total cost is between 125-150$

• 2 points – Total cost is between 150-175$

• 1 points – Total cost is between 175-200$

• 0 points – Total cost is over 200$

Immunity to Variable Light Conditions:

• 5 points – Works under sunlight.

• 4 points – Works under indoor lightening.

• 3 points – Works at shadows at daytime.

• 2 points – Works under indoor shady lightening.

• 1 points – Works unsteadily under shady indoor lightening.

• 0 points – Works only under complete darkness.

Robustness:

• 5 points – System is robust for its operation and transportation of the system.

• 4 points – Risk of disintegration of several parts of the system while packing and transporting whole system to another location.

• 3 points – Disintegration of several parts of the system while packing and transporting whole system to another location.

• 2 points – Risk of disintegration of one part of system in operation time.

• 1 points – Disintegration of one part of system in operation time.

• 0 points – Disintegration of several parts of system in operation time.

<u>Appendix 2: The 150 bit deterministic message signal</u>

[0 1 0 1 0 1 1 1 0 0 0 1 0 1 0 1 1 1 0 0 0 1 0 1 0 1 1 1 0 0 0 1 0 1 0 1 1 1 0 0 0 1 0 1 0 1 1 1 0 0 0 1 0 1 0 1 1 1 0 0 0 1 0 1 0 1 1 1 0 0 0 1 0 1 0 1 1 1 0 0 0 1 0 1 0 1 1 1 0 0 0 1 0 1 0 1 1 1 0 0 0 1 0 1 0 1 1 1 0 0 0 1 0 1 0 1 1 1 0 0 0 1 0 1 0 1 1 1 0 0 0 1 0 1 0 1 1 1 0 0 0 1 0 1 0 1 1 1 0 0]