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Design of a Light Fidelity (Li-Fi) Prototype Using Raspberry Pi

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ABSTRACT

With globalization and the thirst for connectivity across society, the demand placed on wireless infrastructure and the associated resource is growing exponentially. Very soon this resource will reach saturation point, due to the finite bandwidth available in the Radio Frequency (RF) spectrum. A method of countering the impending saturation needs to be found. That method can be Visible Light Communication (VLC).

Light Fidelity (Li-Fi) is a research field within VLC that utilizes the visible light band within the electromagnetic wave spectrum. This band is 10,000 times larger than the RF band and cannot be 'leased' or saturated with users. Light waves can be modulated to carry an enormous amount of simultaneous data, at speeds faster than current consumer equipment can handle.

This paper describes in detail the research, construction and testing of a Li-Fi prototype using Raspberry Pi. The prototype is compact, low cost, uses accessible components and provides a solid foundation for other students to follow on with further work in this field.

The prototype successfully demonstrates the principle of Visible Light Communication and shows the viability of using Python for coding, SPI for data transfer and lists suitable electronic components to process bit-wise data signals. The prototype shows that while it is possible to use addressable LED's as the transmitting element, paper concludes that they are not suitable outside of a heavily constrained environment.

Keywords: *Li-Fi, Wi-Fi, Visible light communication, Raspberry Pi, LED, Radio Frequency, Transmitter and Receiver.*

INTRODUCTION AND BACKGROUND

We now live in a world that is infinitely connected through a multitude of invisible, networked pathways. They stretch and travel across houses, towns, countries and continents. We are a truly global society that now has an insatiable appetite for connection, information and convenience.

This intrinsic appetite has fuelled the proliferation of connection technology from crude military beginnings at DARPA (Dennis et al. 1988), through excruciatingly slow networks of public computers and onto networks increasing in speed and computational power, now without the use of cables.

Almost exponentially the world has developed and embraced technology that now allows us to carry super-advanced, micro-computers in our pockets. The majority of these devices are connected wirelessly to internet service providers, who in turn connect to the World Wide Web. With a swipe of our finger we can find out the weather at that exact moment in Nairobi, St Petersburg and Honolulu.

Aside from the developing detrimental effect this has on us socially, there is a price we are paying in the airwaves. This 'wireless' communication is carried out across the Radio Frequency (RF) band (ACMA, 2013) and limited by blocks of frequencies, each of a finite bandwidth. There will

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be a point in time when all of the available bands are all allocated, meaning the consumer blocks are clogged and causing ineffective and disrupted communication. Although a 'First World Problem' this will have a negative impact on society, with deeper exclusivity creeping into signal allocation and wireless communications.

A supplementary or superseding method of communication needs to be developed to combat the inevitable RF band saturation. There is such a method and it utilizes a relatively untapped source of waves, with an extremely large bandwidth. This method uses the visible light spectrum band, which is shown (not to scale) in Figure 1 below.

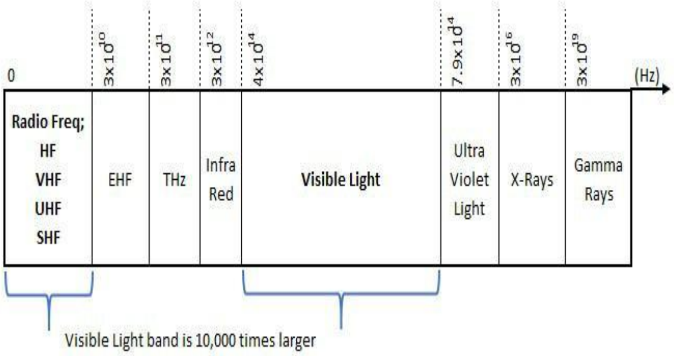

Figure 1 - Radio Frequency vs. Visible Light Frequency Bands. Courtesy of author.

Model	Luminous Flux	Addressable	Type	Voltage/ Current	Frequency	Cost
Cree XML XLamp	260 Lm	No	W	3.1V	unknown	$7.60 ea.
APA102 DotStar	18 Lm	Yes	RGB WWW	5V/120mA	20kHz PWM	$4.5 (10LEDs)
WS2812 NeoPixel	18 Lm	Yes	RGB	5V/60mA	400Hz PWM	$25 (60LEDs)
SK6812	7 Lm	Yes	RGB	5V/60mA	1.1kHz	$25 (60LEDs)
Kingbright NSPW500	20 mcd	No	W	3.2V	unknown	$1.50 ea.
Lumileds LXML	180 Lm	No	W	3V	unknown	$4.25 ea.

It can be seen that the available electromagnetic spectrum of RF and Visible Light are disproportionately assigned in current communication methods. Not only is there larger space to grow into, it is 'greener', the band cannot be regulated, leased or saturated, it does not create electromagnetic interference with other devices and modulation of data can occur at frequencies that the human eye cannot detect (Stefan& Haas 2014). There is even research underway by Rajagpol et al. (2012) where data streaming is being conducted at light levels such that the light appears to be off according to the human eye. This could account for daytime or purposefully dark environments where people may use their devices.

With such a relatively new, green technology, the bounds are at the outer limits of current electrical equipment, much like Wi-Fi was when it was emerging. The applications appear endless, ranging from vehicle to vehicle communication, line of sight secure data networks, underwater communication (Rani et al. 2012) and all at communication speeds (>3GB/s) currently not accessible to everyday society (Stefan & Haas 2014).

Motivation and Significance of the study

Upon detailed investigation of Li-Fi research, it was found that not a lot of research has been done to develop this technology for commercial use. But because research into Li-Fi is relatively new, the possibilities are wide open. A lot of research is being done to make this technology available for commercial use in various fields, including Internet access and vehicle-to-road communication using traffic signal lights. From my review of the literature, it became evident that work should be done to look into the possibility of designing a new model that could fit the present infrastructure for indoor applications.

Scope of the study

The scope of the project was to research, develop, build and test a prototype system that would modulate Light Emitting Diodes (LED) such that the integrity and quality of information was preserved across free space and in turn received, then displayed on a suitable device.

A Raspberry Pi microcontroller could be incorporated to allow a compact, yet powerful tool to handle the system demands. This could help to put the prototype components within low budget reach of other students, consumers and researchers.

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One of the foundations of the project was to enhance research in the area of Light Fidelity (Li-Fi) such that a wider, functioning architecture could be developed and implemented domestically, commercially or where the benefits of Li-Fi could be realized.

The scope of this project did not include;

- Streaming audio and video signals.
- Bi-directional Li-Fi communication between the devices. Integration with Wi-Fi and internet services.
- Configuration of a video to interface with a mobile or portable device
- Creation of an application to provide a User Interface.
- Multi-channel communication**.**

Problem Statement

The current wireless communication systems make use of the **Radio Frequency Spectrum**. These wireless communication systems are carried out across the Radio Frequency (RF) band (ACMA, 2013) and limited by blocks of frequencies, each of a finite bandwidth. There will be a point in time when all of the available bands are all allocated, meaning the consumer blocks are clogged and causing ineffective and disrupted communication. Although a 'First World Problem' this will have a negative impact on society, with deeper exclusivity creeping into signal allocation and wireless communications.

Thus, a supplementary or superseding method of communication needs to be developed to combat the inevitable RF band saturation. There is such a method and it utilizes a relatively untapped source of waves, with an extremely large bandwidth. This method uses the visible light spectrum band, which is known as **light fidelity (Li-Fi).**

Aim of the study

The project aim was to produce a functioning, 'proof of concept' prototype that utilizes VLC technology to send information to a related device across free space. The prototype should be low cost, compact and simple to implement.

2. *Specific Objectives*

In order to arrive at the final aim, there were a number of key objectives to satisfy during the project.

These included:

1. Undertake a literature review on visible light communication, modulation and signal conditioning.
2. Undertake a basic requirements analysis
3. Critically evaluate alternative implementations and identify suitable components for the prototype implementation.
4. Build a basic prototype with physical components and achieve high speed square wave transmission.
5. Evaluate the performance and investigate improved modulation techniques for video transmission. Transmit basic video and improve to HD (720p).
6. Measure distance and video quality to define optimal prototype parameters.
7. Identify future research direction.

Research Questions

The study was guided by the following research questions:

1. To what extent does the current school management system impact the day-today school activities?
2. What actions should the school take to ensure smooth, efficient, secure and reliable operation of day-to-day school activities?
3. What is the most significant effect of managing school management processes manually?
4. To what extent does the current system impact the pupils, parents, teachers and administrators work performance?

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Summary

The need for designing a system which gives the application model of Li-Fi Technology using Raspberry Pi is inevitable. Li-Fi uses the visible light spectrum which is better than Radio frequency spectrum. With the use of LED data can transmit at very high speed. If this technology can be put in practical, every LED bulb can be used as like Wi-Fi hotspot to transmit data more secure and safe.

METHODOLOGY

A. *Introduction*

This project was purely one of research and experimental work. The project was executed as a progressive development of concept following a body of research and expansion of ideas to achieve the aim. The steps generally followed a typical Project lifecycle model from the Project Management Book of Knowledge (Stack pole, 2010).

1. **Project Initialization**– research proposal, literature review, design information Project Start Up – procurement, production readiness.
2. **Project Production Phase** – build the prototype
3. **Project Execution** – get the prototype working, test and develop Project Closure – write up dissertation, demobilization.

B. *Project Initialization*

The Project Initialization Phase was a combination of producing a preliminary report, deeper research into prototype specifics and formalization of the project scope and outcomes.

This phase was purely research driven and the investigation carried out defined the general shape of the project. Significant information was gathered during this phase and a thorough search helped to prevent errors or miscalculations during construction.

The outputs of the Initialization Phase were;

A mental roadmap of the Project direction, with alternative routes in reserve, a list of required resources, and Set-up of a Project Diary to track daily progress and the reasons behind the various decisions made throughout the Project.

C. *Research Approach*

1. **Start-up**

The Project Start-Up phase took the outputs from the Initialization Phase and built on them to begin the procurement of Project resources, allocation of Project space, Project management systems and to mark the start of the physical work phase of the Project.

This phase moved the Project from an idea, theory and research-based Project to one that was tangible.

Outputs of the Start-Up Phase were;

An allocated workspace to construct the prototype, Focused research to a preliminary modulation technique, understood how to drive the LED's from a 3.3V Raspberry Pi output signal to a LED i/p signal All necessary software downloaded and installed, and Purchased and procured all test equipment, power supplies, components, devices, cables and frame work.

2. **Production**

The Production Phase marked the start of the actual building of the prototype. This was undoubtedly one of the most exciting aspects of the project and brought with it the start of the major challenge to get it working.

The outputs of the Production Phase were;

Build and develop the LED driver circuit to deliver the required voltage to modulate the LED's, and to completely construct all power supplies, equipment and components.

3. **Execution**

This phase contained the largest amount of work, frustration, technical demand, support and investigation. The primary focus was to get it working and then to look for optimization and improvement, time permitting.

The planned sequence of work was;

i. Connected power supply and signal management circuits to drive LED's on,
ii. Confirmed that photodiodes could receive the LED's being manually switched on and off,
iii. Used the Raspberry Pi (RPi) transmission module (TX) to create a simple square wave to send to the RPi receiver module (RX) and achieve basic communication, displayed on a screen or other output device,
iv. Increased data speed (via small steps) and maintained expected outputs,
v. Attempted to send a file across free space, maintaining the quality of the original.

The outputs of the Execution Phase were;

A Project Diary that recorded the path followed throughout the Project to provide a resource to build the Dissertation from, a working Prototype that could send files across free space using Visible Light Communication technology, and a final configuration (including software + code used) of the system.

4. **Project closure**

The Closure Phase intends to wrap up the Project and finalize all aspects ready for academic submission. Closure includes decommissioning the prototype system, returning borrowed or loaned equipment and writing up the results. Should the Project provide suitable material, a publishable paper could be written to give information to the wider engineering community.

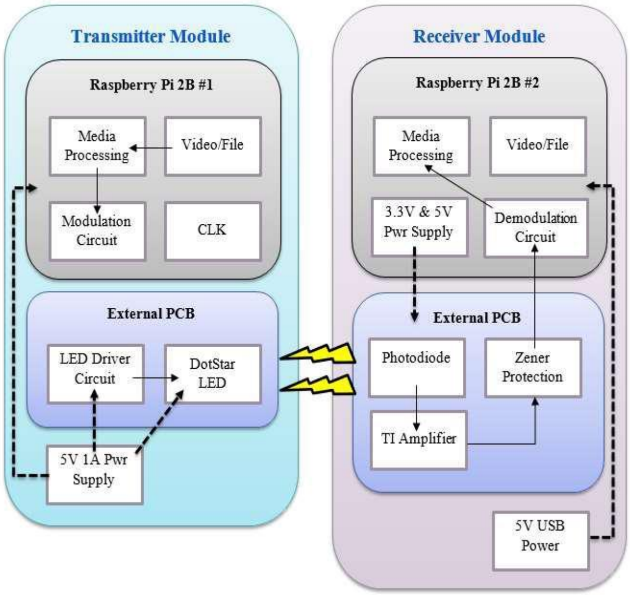
The outputs of the Project Closure phase are;

An academic Dissertation submitted to ICU for B.Sc. Mobile Communication, Decommissioning of the prototype.

D. System Design

The system can be broken down into two sub-systems; the transmitter (tx) and the receiver (rx). Each one is made up of smaller functions such as the led electrical control circuit and board, the photodiode electrical control and board, the software in the tx and rx modules, the peripherals (keyboard, monitor, mouse etc.) And support software (e.g. mobaxterm).

Figure 2 Illustrates how the prototype is made up from a system point of view and shows the interaction between the varying components.



E. Transmission circuit (PCB)

After deciding to utilize the DotStar LED (APA102c) and the recommended quad level shifting chip (74HCT125), the circuit was constructed on a breadboard. A representative layout of the breadboard is shown in figure 27.

ISSN: 3471-7102, ISBN: 978-9982-70-318-5

GND (Black wiring);

- All ground connections were made common between the +5V power supply and the Raspberry Pi.
- All OE pins used on the 74HCT125 are grounded.
- APA102C pin 3 is grounded.

+5V Power Supply (Red wiring);

- +5V power supply connected to breadboard rail, VCC pin 14 of 74HCT125 and VCC pin 4 of APA102C.

F. Receiver circuit (PCB)

After component selection was completed, the circuit was constructed on a breadboard and connected to the RPi GPIO when the output levels were known. A representative layout of the breadboard is shown in figure 35. The wiring technique is described below.

GND (Black wiring);

- All ground connections were made common.
- Anode of S5973 Photodiode grounded.
- Pins 3 and 4 of OPA380 TIA are grounded.
- Anode of 1N4728 Zener grounded.

+5V RPi (Red wiring);

- +5V supply from RPi GPIO pin 2 connected to breadboard +V rail.
- Pin 7 of OPA380 TIA connected to +5V.
- 1uF ceramic capacitor connected across +5V rail and ground

DATA Signal (Blue wiring);

- 1MΩ resistor connected across Pins 2 and 6 of OPA380 TIA.
- Cathode of S5973 Photodiode connected to Pin 2 of OPA380 TIA.
- Cathode of 1N4728 Zener connected to Pin 6 of OPA380 TIA.
- 330Ω resistor connected between OPA380 TIA Pin 6 and RPi GPIO MISO pin 21 (BCM9).

G. **Raspberry Pi**

The Raspberry Pi was selected as the micro-controller over the Arduino family of devices due to its ability to handle faster processes, its versatility across all aspects of computing, low cost and simple to use package. The Arduino family does tick off the low cost and actually has a wider range of supporting devices such as sensors, displays, lights, data processors, but it was assessed for this project as not suitable for the potential media handling and general computing requirements of the project. Arduino's are very popular with robotics and hobby projects, more targeted to smaller engineering-type projects.

Raspberry Pi offered the diversity to prevent the project arriving at a roadblock that was unable to be overcome, such as processing speed or data management. The RPi 2B CPU has a clock speed of 900MHz and can be overclocked to 1000MHz whereas the Arduino's (in the same price bracket) have CPU speed <100MHz. Additionally, the RPI came as a complete package, with Arduino requiring 'bolt-on' components which would have increased the cost and complexity. Other micro-computers were considered, but the support documentation, availability, cost and function removed them from final selection and purchase. A table of these has been presented earlier in this document.

H. **Power supply**

DotStar LED's are a +5V device and the initial plan was to utilize the Raspberry Pi's +5V power supply to light the LED and power the quad level shifting chip. On AdaFruit's DotStar Overview webpage (Burgess, 2016), they discuss that it is possible to power the LED's off +3.3V but that it is not

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recommended. I attempted to do this initially, but was unable to get a single LED to respond.

For the first trials, the Raspberry Pi +5V supply from the GPIO was used, with light output significantly lower than what would be expected from a bright LED. Without modulation, the LED was observed to flicker. Through research this was found to be a result of the Raspberry Pi's current sharing scheme with other internal processes. The RPi was powering a Wi-Fi USB dongle, running Python code on the desktop, using SPI, and also providing power to the quad level shifter. This unreliable nature of current sharing forced the purchase of a separate +5V, 1A power supply.

Although this was openly discussed on online forums as necessary when powering an entire LED strip, it did improve the brightness and robustness of illumination from the circuit. Implementing a separate supply was at the expense of my compact prototype objective, but could be removed on future revisions by a higher rated USB supply or a new model RPi with USB3.0.

I. GPIO protection

In order to prevent against damage due to inadvertent supply of current back through the output GPIO's (MOSI, SCLK), 470Ω resistors were placed between the GPIO and the input to the level shifting chip. Because the LED was powered by the +5V power supply, the value of resistor had no bearing on the brightness, which was set by the 32-bit data signal.

To see if there was an effect on the data and SCLK signals from the GPIO, 330Ω, 470Ω and 1kΩ resistors were tested as protection. The value of resistor had no measurable or detrimental effect on the signal strength or quality coming out of the GPIO. The quad level shifter also just boosted the value to +5V and passed to the LED.

RESULTS

With the successful processing of square waves, the script was finished off to process the binary data of a file. This file was a picture of the raspberry pi logo in a jpeg format. The file was uncomplicated, but it didn't matter as the only meaningful aspect was that it contained binary data to extract and send.

When the file data was first transmitted, the concept of data encoding was not at the forefront of the project. However, once the output was seen, it was clear that this aspect was critical to the success of sending and processing any information. A screen capture of the data at the output of the receiver can be seen in section 5.3.8.

It shows the long sequences of similar bits and unless the original clock signal or timing is known, the bits cannot be separated into the original stream. Note that this is only a small snapshot of the data that gets transmitted and received.

Because of the boot-up failures of the raspberry pi modules, the final testing to determine transmission bit rate and actual frequency were unable to be performed. Timing of the transmission and confirmation of the bit-wise size of the file data array (i.e. how many elements) could have been used to determine this system performance characteristic.

Figure 3: Block Diagram for Transmitter and Receiver Modules

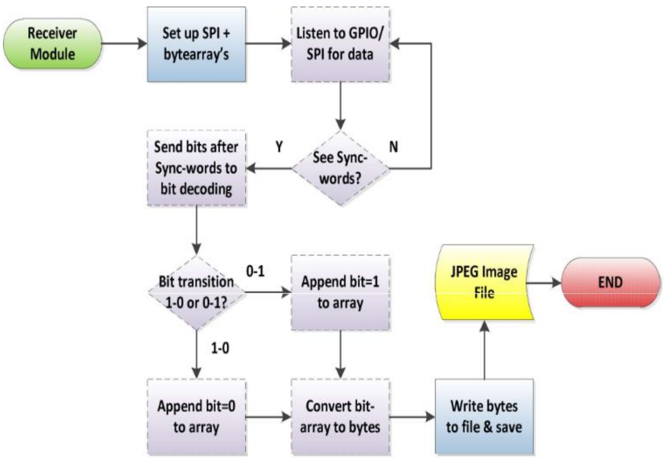

Figure 4 - Software Diagram for Transmission Module

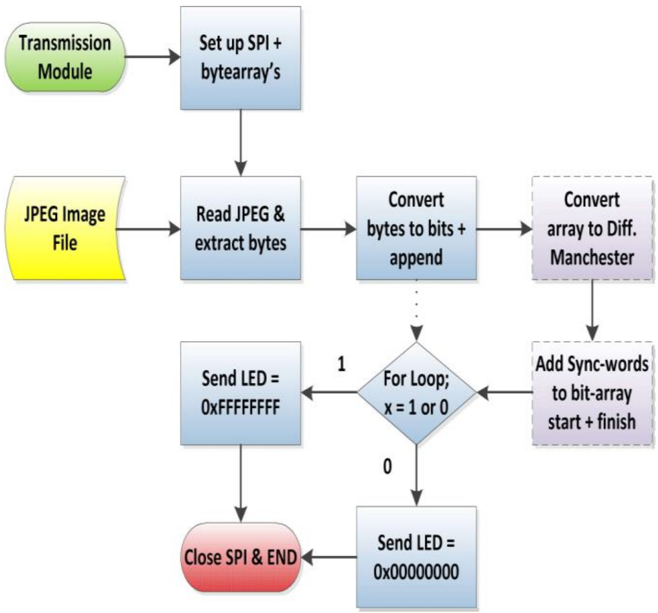

Figure 5 - Receiver Module Breadboard Layout
Source: developed system

Aside from measuring the system capability, it was able to successfully extract a file and transmit the data across free space using modulation of an LED.

Due to the nature of communication with addressable LED's, they are not suitable as a transmission element, unless for low speed applications. These speeds would have to be above those perceptible by the human eye and also those that are likely to cause medical events such as seizure triggers, headaches and nausea. Transmission speeds with a clock signal of 32MHz are therefore limited to 1MHz before any bandwidth or circuit limiting conditions.

In an addressable LED strip, the proximity of the illuminating elements to each other, may result in difficulties locking onto a particular element or interference caused by adjacent elements. This could be overcome with a rigorous hand-off regime or assigning transmission elements spaced a 1m or greater apart. With a singular element luminous flux of 18 lumens, the luminous intensity does not offer enough 'power' to transmit data over distance greater than 400mm. For a domestic application this does not allow an associated device to be far enough away from a ceiling mounted lighting installation. An opportunity does exist for smaller installations such as desk lamps.

System Implementation Results

System implementation involves all the activities starting from the installation of the new system, in order to implement the full operation.

Figure 6 - Software Diagram for Receiver Module.
Source: developed system

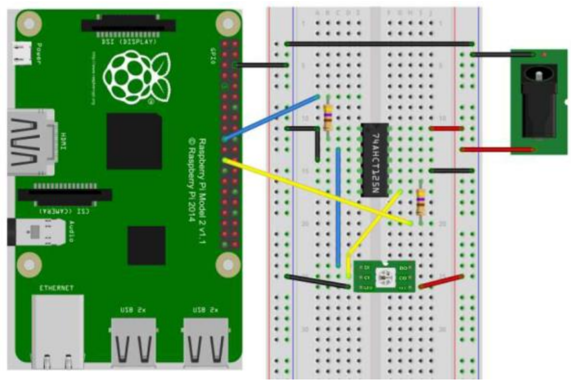

Figure 7 - TX Module Layout Diagram.
Source: developed system

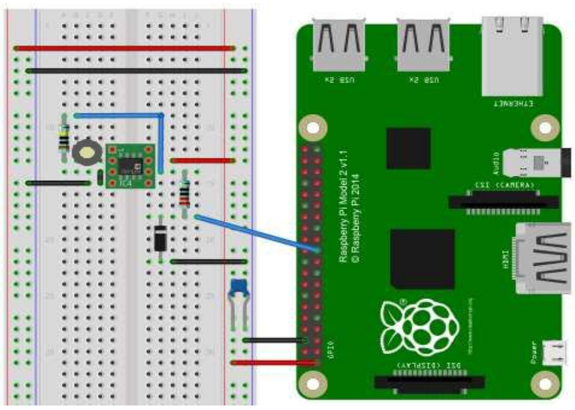

Figure 8– Prototype System Diagram
Source: developed system

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1. Programming Language and Program Design

The programming language used in this project is python. The system was designed in models which is the structure it should be. The source and object code are provided in appendix column.

2. System Evaluation and Maintenance System maintenance is the process of monitoring, evaluating and modifying a system to make desirable changes. System maintenance involve the constant review of output from the system and updating its format as well as the need of the changing the current situation. Therefore, evaluation ensures improved performance and great efficiency. If the system performance is below the desired standard set in the design. Then, it will need to identify the faults by the application of relevant maintenance methods.

3. Documentation

Documentation it is the detailed information about a system design specification, its internal workings and its functionality. It includes information on how to use the system and how it works.

DISCUSSION

The first step in the implementation of the project was to conduct a literature review, conduct a requirements analysis and identify suitable components for prototype implementation.

The literature review was comprehensive and covered all aspects of Visible Light Communication, alternative technology as well as the State of the Art. Light Fidelity is a fast-moving research field with it gaining in popularity through the media and topical journalism. Nevertheless, a knowledge gap was identified and targeted with this prototype.

Components were reviewed in light of the requirements analysis and selected to fulfil the various roles within the prototype. Aside from the addressable LED (which formed some of the knowledge gap) there were no other components selected that were deemed inappropriate.

Another significant objective was to build a basic prototype with physical components and to achieve high speed square wave transmission. This was achieved with the transmission of a 1MHz square wave between the two modules. The square wave was at the correct level and was clamped to +3.3V to prevent damage to the Raspberry Pi GPIO.

The original project intent was to transmit and receive video files, but the complexity of this task as well as building a light fidelity prototype from scratch meant that this goal was unobtainable in the timeframe available.

The complexity of transmitting video signals at a bit level was found to be at a significantly difficult level for an undergraduate project. Just transmitting a video file is complex enough, but to stream the video and mixed audio signals is very advanced work. In hindsight (and only discovered through research) this should have been put into the 'as time permits' section rather than a project objective.

As such, the goal was amended to transmitting a file across free space and that was partially achieved. There was also difficulty encountered with implementation of an encoding scheme, with the realization coming late in the project development. With other academic commitments, the ability to deliver a coherent report took precedence over implementing the chosen encoding scheme.

With the challenges presented by the addressable LED, the distance was only able to be quantified at 200mm with a focusing lens and up to 400mm with a collimator to focus the light beam onto the photodiode. Note that the distance parameter was improved by altering an aspect of the prototype.

Regarding quality of the reproduction, the file was not able to be reproduced in the receiver module due

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to difficulties encountered with the encoding and modulation scheme. The code tested was able to accurately reproduce the original file, but this was within the transmission module rather than across free space.

So, although the performance of the prototype in regards to distance and quality (at this point in time) is poor, this object can be considered partially successful.

COMPARISON OF LI-FI TO OTHER TRANSMISSION MEDIA

Features	Li-Fi	Wi-Fi	WiMAX	Bluetooth
Full form	Light fidelity	Wireless fidelity	Worldwide Interoperability for Microwave Access	Bluetooth full from the epithet of the tenth-century king Herald "Bluetooth"
Operation	It transmits data using light with the help of LED bulbs.	It transmits data using radio waves with the help of Wi-Fi router,	Broadband Wireless access	Anywhere at least two Bluetooth devices exist.
Interference	Do not have any interference issues similar to radiofrequency waves	Will have interference issues from nearby access points (routes)	WiMAX communications pose a significant interference threat to satellite signals transmitted in the C -band frequency	Bluetooth devices interfere with other technologies
Technology	Present IrDA compliant devices	WLAN802.11a/b/g/n/ ac/ad standard compliant devices	Wireless metropolitan area network (WMAN)	WPAN
Applications	Used in airlines, undersea explorations, operation theatres in the hospitals, office and home premises for data transfer and internet browsing	Used for internet browsing with the help of Wi-Fi kiosks or Wi-Fi hotpots	WiMAX serves a larger interoperable network	Bluetooth applications is huge, because we transact business and communication more with people who are close by than with those who are far away
Merits	Interference is less, it can pass through salty sea water, works in a dense region.	Interference is more, cannot pass through sea water, works in less dense region	WiMAX can be used for long range. It provides broadband connectivity up to varied ranges, around 30km.	Setting up a Bluetooth connection between two devices is quick and easy. A Bluetooth headset is compatible with any other device that supports Bluetooth.
Privacy	In Li-Fi, light blocked by the walls and hence will provide more secure data transfer	In Wi-Fi, RF signal can't be blocked by wall and hence need to employ techniques to achieve secure data transfer	WiMAX uses X.509 or PKMv2 as authentication algorithms. Mandatory-3 DES Optical-AES	Bluetooth offers several security modes and device manufactures determine which mode to include in a Bluetooth-enabled gadget.
Data transfer Speed	About greater than 10Gbps	WLAN -11n offers 150Mbps, About 1-5Gbps can be achieved using	Waves at bps/Hz and can peak up to 100 Mbps in a 20 MHz channel.	800Kbps

		WiGig/Giga-IR		
Frequency of operation	10000 times frequency spectrum of the radio	2.4GHz, 4.9GHz and 5GHz	Licensed/Unlicensed 2G to 11GHz	2.4GHz
Data density	Works in high dense environment	Works in less dense environment due to interference related issues	Works in high dense environment	Less dense
Coverage distance	About 10 meters	About 32 meters (WLAN802.11b 11 g), vary based on transmit power and antenna types	Up to 40 miles	About 10 meters
System component	Lamp driver, LED bulb (lamp) and photo detector will make up Complete Li-Fi system.	Requires routers to be installed, subscriber devices (laptops, PDAs, desktops) are referred as antenna	There are three main components of WiMAX network architecture: the mobile stations, an access service network and connectivity service network which is responsible for providing IP functions.	Four major components: Radio Unit (radio transceiver), Baseband Unit (flash memory & CPU), Software Stack (driver software) and Application Software (user interface)
Power Consumption	Medium	Medium	High	Low
Cost price	Low	Medium	Medium	low
Working concept	Direct Binary Data Serving	Various Topologies	Request/Grant	Master-Slave

CONCLUSION

This thesis demonstrated a solution to the problem of integrating Visible Light Communication technology with present infrastructure, without having to make major changes to that infrastructure. The proposed system was segmented into two parts with different interface protocols and was demonstrated practically. Visible Light Communication is a rapidly growing segment of the field of communication. There are many advantages to using VLC. There are also many challenges. VLC will be able to solve many of the problems people have been facing for many years, mainly environmental and power usage issues.

VLC is still in its beginning stages, but improvements are being made rapidly, and soon this technology will be able to be used in our daily lives.

It is intended that this research will provide the starting steps for further study and development on raspberry pi integration with white LEDs can be used for data transmission.

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In spite of the research problems it is our belief that the VLC system will become one of the most promising technologies for the future generation in optical wireless communication.

Future works

There was a significant process of discovery and learning throughout the project and this has resulted in a clear understanding of where this research needs to go in the future as outlined below.

1. **Internet of Things**: Light Fidelity has a place in the domestic environment to contribute to the Internet of Things. The release of small microprocessors means that similar prototype fundamentals shown here can be implemented on a much smaller scale. The components used in this project are compact and can easily be adapted to fit into a small package such as the Raspberry Pi Zero. An LED transmitter would need to be in line of sight of the receiver and communication can take place between household devices.
2. **Improvement of LED Transmitter Element:** It is clear that addressable LED's are not presently suitable for this application, so research could continue to find a small, bright LED that could be used as the transmission element for a prototype. This would cut down on coding and support components. Consideration should be given to ceiling mounted LED's or even modulation of domestic ceiling lights.
3. **Implementation of Data Encoding Techniques**: This project was not able to successfully implement a data encoding technique to allow data reproduction in the receiver module. The project has suggested that Differential Manchester is suitable and also shown software diagrams of where to integrate it. Other encoding schemes could be trialed.
4. **Possible Introduction of Arduino**: With the success (with some limitations) there is an opportunity to tailor a light Fidelity prototype using Arduino products. These remove the challenges faced with a +3.3V device interfacing with +5V components and remove the current and CPU sharing schemes of the Raspberry Pi.
5. **Alternative Coding Language**: Python is regularly out-performed in coding benchmarks by other languages such as C and C++. Python could present a limitation in a real-time environment particularly if streaming data live. An option would be to explore an alternative coding language to handle the file processing and LED modulation.
6. **Vehicle to Vehicle Communication**: Being able to modulate an LED means that this can be applied to any LED. Many vehicles now come with LED lights in the front and rear and if these could be modulated to carry information, then vehicles could communicate.

This application can lend itself to sending voice activated messages to drivers in front or behind, or warn a trailing vehicle of the speed it is doing, or that a vehicle is too close the one in front. A potential invention could be the sending of SMS-like messages to other drivers, converted from voice to text and sent via modulated head or taillights. Imagine being able to tell another driver that he has one headlight out or he's left his wallet on the roof or that there's a speed camera up the road**.**

7. **Photodiode in Photovoltaic vs Photoconductive Modes**: Test the photodiode in photoconductive mode and a control of photovoltaic mode to observe differences in speed, noise, signals etc.

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PYTHON CODE

1. Transmitter Module Code

```
#!/usr/bin/python
from PIL import Image
import time
import spidev
import RPi.GPIO as GPIO
#set up SPI for LED
spi = spidev.SpiDev()
spi.open(0, 0)
spi.max_speed_hz = 31200000
#define start and finish sync-words
#implement differential Manchester coding with SCLK
#store new encoded data in new bytearray
#append start and finish sync-words to data bytearray
#opening the image file// for the TX module
buffer = bytearray()            #put the bits in an array to rebuild
picture = bytearray()           #this is where I store the final bits
file = open("logo.jpg", "rb")
bytes = bytearray(file.read())
for byte in bytes:
  for i in range(8):
    bit = (byte>>i) & 1
    buffer.append(bit)
    #send bits to the LED using SPI
    if bit == 1:
      resp = spi.xfer([0xFFFFFFF])
    else:
         resp = spi.xfer([0x00000000])
spi.close()
```

2. Receiver Module Code

```
#!/usr/bin/python
from PIL import Image
import time
import spidev

#set up SPI
spi = spidev.SpiDev()
spi.open(0,1)
spi.max_speed_hz = 31200000
#define sync-words for start and finish
picture = bytearray()
buffer = bytearray()
#this is where I store the final bits
#put the bits in an array to rebuild
#Insert GPIO listening for start sync-word
#once start sync-word seen store next data to bytearray fordecoding
#listen for finish sync-word and stop sending to bytearray
#decode bytearray looking for transitions in data.
#send 1's or 0's to new bytearray for conversion back to image
#convert back to right structure// for RX module
for i in range((len(buffer)/8)):
bitstobytes = buffer[i*8:i*8+8]
byte = 0
for x in xrange(8)
byte = byte +
pow(2*bits          obytes[x],x)*bitstobytes[x]
picture.append(byte)
#write to file and display result
refile = open("relogo.jpg", "wb")
refile.write(picture))
```