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ACKNOWLEDGMENT

As a believer my first thank goes to God almighty who has allowed me to see another milestone on my journey through life.

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And last to my colleagues who we have gone through this journey together we supported each other through the journey and we are all better off for it at the end.

ABSTRACT

The phenomenal global demand for wireless communication links with greater bandwidths is motivating engineers world over to come up with alternatives communication links. One of such system that has received a great deal of attention and has shown evidence of a promising future is infrared optical communications.

This project explores the fundamental aspects involved in designing and building a transmitter and a receiver as part of an infrared optical wireless link for indoor use. It is mainly concerned with extracting as much bandwidth as possible from the circuit designed.

The system built in this project is capable of data transmission of over 20Mbits/second but this is however nowhere near the limit of the systems as will be discussed in the dissertation. Optical communication links have been developed which are capable of data transfer rates of 1.25Gbits/second (Jeganthan, 2001).

The work done in this project and that which have been done by others present a compelling argument as to why infrared optical wireless communications is a formidable form of wireless communications and as a matter of fact a worthy alternative to the well known radio frequency(RF) systems.

Chapter 1

1 INTRODUCTION

The concept of using infrared light for wireless communications was first proposed about three decades ago (Ramirez, 1999) but it is only over the last decade or so that it has received attention as a serious form of wireless communications.

This interest has been partially driven by the ever increasing demand for more bandwidth to transfer data within buildings such as offices, hospitals, and schools and even within machines such as laptops and printers. The cable clustered areas wherever computers, scanners, printers and other work machines were present was a common feature in every office till about a decade or so ago. The cost of maintaining and replacing these cables burdened organizations with huge bills and hours of inconvenience whenever they had to be replaced. Optical wireless communications promises to do away with the need for physical wires while delivering bandwidths that could only have been imagined a decade ago at a fraction of the cost.

Optical wireless communications is now a commercially viable alternative to the well established radio frequency (RF) systems. The use of infrared light circuits required very simple and inexpensive electronic components which are small and consume very limited power, which in today's ``mobile world'' and an ever increase interest on climate change are highly welcome.

This dissertation presents the design, building and testing of a simple infrared system which is capable of at least data rates in the order of megabits per second and proposes ways of improving upon the system that has been developed so far. It also shows work which has been done in the field of wireless optical wireless communications and the direction in which current research is heading.

OBJECTIVES

Optical wireless communications uses light sources such as infrared lighting to transmit data, proposals have been made to use LED's in this way to transmit data. The major objectives of the project are:

- Build a system using LEDs that is capable of transmitting and receiving a signal.
- Find ways to extract maximum bandwidth from the system.

- Build a laser optical transmitter and receiver and compare with the LED system.

1.1 BACKGROUND

1.2 HISTORY

Optical communications have been used in various forms for thousands of years, from the polished shields used to send signals in battles by the ancient Greeks to modern wireless solar telegraphs and now advances into optical wireless communications (OWC) (Duarte, 2002).

At the newly established Bell's Volta laboratory in Washington D.C, Alexander Bell and his assistant Charles Sumner Tainter created the `photophone' in 1880. It allows sound to be transmitted on a beam of light. On June 3, 1880, Bell conducted the world's first wireless telephone between two buildings separated by a distance of about 213 meters (Carson, 2007), however this was not used in any real life practical applications till the US military adopted it several decades later (Smyth, 1993)

The German army in world war II also used an anti aircraft defence unit called *Lichtsprechgerät 80* which directly translates into; *light speaking device. The system was developed by Carl Zeiss Jena (*Bapts,1997)

The 1960s looked to be the decade optical wireless communications was going to break into mainstream communication with the invention of lasers, which could potentially deliver more power, as designers had more freedom to in controlling the shape and size of the emitted beam. However, interest in the use of lasers for free –space communications lost momentum when installation of optical fibre networks for civilian use was at its peak.

Today optical wireless communication systems are used in both indoor and outdoor applications, short range indoor applications (typically 0-1 meter) usually use infrared light emitting diodes (LEDs) for high data rate transfers, examples can be found in portable devices such as Laptops and PDAs and Local area network (LAN) to LAN internet connections.

Infrared lasers have a wide range of application today including communication between spacecrafts, For terrestrial links the maximum range is typically 1- 2 miles (Carson, 2007), but the quality of the links are considerably dependent on atmospheric such as rain, fog, snow and dust(Kahn, 1998). Experiments carried out using incoherent high intensity LEDs have achieved distances greater than 170 miles (Tsaur, 1994). In outer space, free space optical applications achieve distances of several thousand kilometres but could theoretically cover interplanetary distances in the order of millions of kilometres with the aid of optical telescopes (Tsaur, 1994).

Figure 1: An early photophone (freespaceoptics.org, 10/7/2010)

There are three forms fuzzy groupings of optical wireless communications;

- Free space optical communications (FSO),
- Visible light communications(VLC),
- Optical wireless communications (OWC).

Although this project only involves optical wireless communications, the other forms of optical communications will also be introduced briefly in this chapter.

1.21 FREE SPACE OPTICAL COMMUNICATIONS (FSO)

Originally developed by the US military and NASA, FSO provides licence free high capacity super fast communication links. It is a line of sight technology that uses invisible beams of light to provide optical bandwidth. FSO combined with microwave has become very important for high availability, point-to-point links. FSO links fail in low visibility conditions, particularly fog. Microwave links fail in moderate rain. The combined (or dual) system will fail when both these conditions are present simultaneously. As it is unusual (but not unheard of) for fog and moderate rain to occur together, these dual links can achieve near 100% availability. Free space links usually make use of infrared lasers.

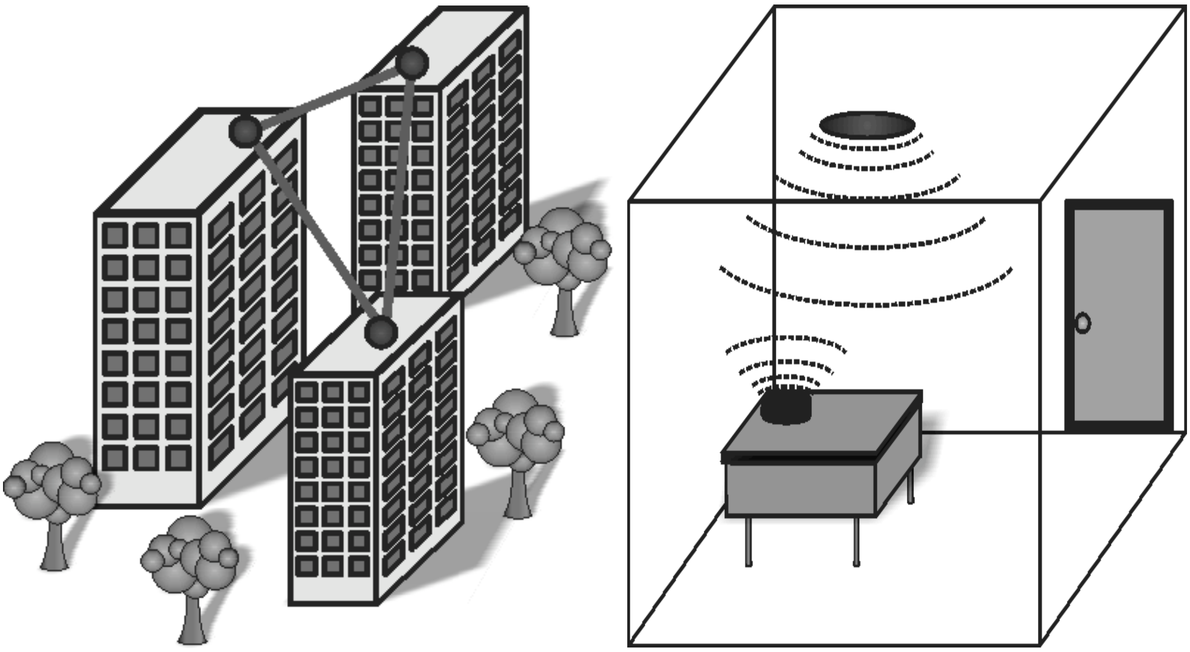


Figure 2: Two operating schemes of FSO communication: (a) Point to point Free space link (b) multi point free space link (Xian 2009)

1.23 VISIBLE LIGHT COMMUNICATIONS (VLC)

Humans rely heavily on 'visible' light to gather information in our daily lives. Visible light sources such as street lights, lamps, and commercial displays can be used to transmit to data. VLC uses visible light between 400TeraHetsz (THz) and 800 THZ (1 THz = 1000GHz).Experiments carried out using ordinary fluorescent lamps achieved low data rates of 10 kilobits per second (Kbit/s) between 1 – 2 kilometres (km)(Dominic, 2007).(*give applications*)

Unlike the light emitted by LEDs which are also used for optical communications, visible light is not harmful to the human eye and unlike radio waves does not interfere with other similar devices operating in the vicinity.

VLC requires a clear direct line of sight between transmitter and receiver, although it is not as essential as in the case of OWC. VLC suffers from severe multipath distortion and the capacity is also limited by delay spread.

1.24 OPTICAL WIRELESS COMMUNICATIONS (OWC)

OWC which is the main focus of this project is a form of free space communication which uses infrared LEDs and lasers.

OWC systems could be point to point or multipoint depending on the application, infrared (typically 750 nm wavelength) LEDs are usually at the transmitter.

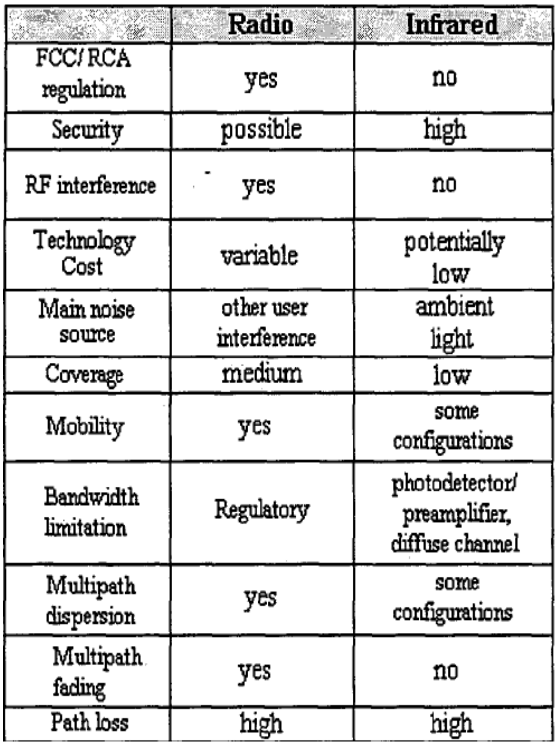
1.3 COMPARISON BETWEEN INFRARED AND RADIO SYSTEMS

Radio frequency electromagnetic waves have been used for long time for short range communication applications, however over the past decade or so infrared radiation has been increasingly used as they present certain advantages over radio frequency. In the UK radio frequency transmission is regulated by the Ofcom (Abdullah, 2006) and with increasing congestion of the frequency bands, it is becoming ever more expensive and difficult to obtain licences, on the other hand infrared spectrum, which offers potentially vast bandwidth capabilities, is not subject to such regulations.

Just like visible light infrared radiation in its nature is restricted to the room in which it is generated. This helps safe guard against eavesdropping as the radiation cannot be detected outside the room. Unlike radio frequency, infrared radiations do not interfere with devices of similar nature operating in nearby rooms nor does it interfere with radio frequency devices, in addition infrared components are cheap (less than GB£1), easy to manufacture and consume little power. (Ramirez, 1999).

However, just like every piece of technology infrared devices have their disadvantages; as would be illustrated later in this chapter, infrared radiation links are prone to being blocked by objects placed between the transmitter and receiver, the noisy environment owing to incandescent, fluorescent or even sunlight degrade the quality of the signal received at the detector (Abdullah, 2006). Furthermore infrared radiation can damage the retina and regulations are in place which limit the power they can operate at, this restricts the range of the devices. Table 1 below compares infrared and radio frequency.

Table 1: Pros and cons of infrared and radio frequency.(Ramirez, 1999)



	Radio	Infrared
FCC/ RCA regulation	yes	no
Security	possible	high
RF interference	yes	no
Technology Cost	variable	potentially low
Main noise source	other user interference	ambient light
Coverage	medium	low
Mobility	yes	some configurations
Bandwidth limitation	Regulatory	photodetector/ preamplifier, diffuse channel
Multipath dispersion	yes	some configurations
Multipath fading	yes	no
Path loss	high	high

Table1: Pros and cons of infrared and radio frequency.(Ramirez, 1999)

Both radio and infrared are excellent mediums of communication; it is safe to conclude that one would be preferred over the other depending on the area of application. Generally radio is preferred in long rage communications which require high mobility and infrared is well suited for short range communications which require high data rates.

1.32 TRANSMITTERS

The two most commonly used IR transmitters are: Light emitting diodes (LEDs) and laser diodes (LDs). LEDs are generally cheaper and harder to damage than laser diodes, which is why they are the preferred choice for manufacturers. Also LEDs have higher power capability. Laser diodes on the other hand can be used at higher modulation rates than LEDs

1.33 PHOTODETECTORS (RECEIVERS)

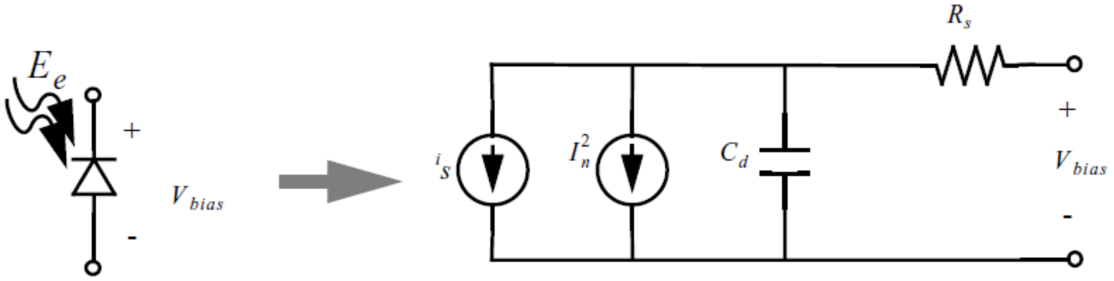
Photodetectors are semiconductors devices which convert incident light into an electric current. There are different types of configurations, the most common type are: PIN diodes and avalanche photodiodes.

The PIN detector is preferred in most systems as it has low-bias-voltage requirement and has a higher operational temperature range. However PIN detectors are about 10 to 15dB less sensitive than avalanche photodiodes (Chu, 1987)

Avalanche photodiodes; on the other hand provide a more robust communications link due to their increased power margin. This reduces the problem of accurate alignment of lenses and allows for reduction of preamplifier noise, laser power and miscellaneous losses.(Personick, 1985)

The aim of this project is to develop a high speed optical communications system which makes photodiodes the preferred detectors for this project as they give greater frequency response. Just like other semiconductor diodes, photodiodes have a finite transit time and are usually operated under reverse bias conditions.

The electrical behaviour of a photodiode can be modelled as a small signal equivalent circuit below:



The chief photocurrent i_s , is generated when photons from the incident light penetrate the diode. The wavelength of the of light used directly affects the sensitivity of the photdetector and therefore, in order to maximize power efficiency, the emission of the wavelength of the optical source is spectrally matched to that of the detecting photodiode.

Figure 4 below normalized spectral efficiency of some typicl photodiodes.

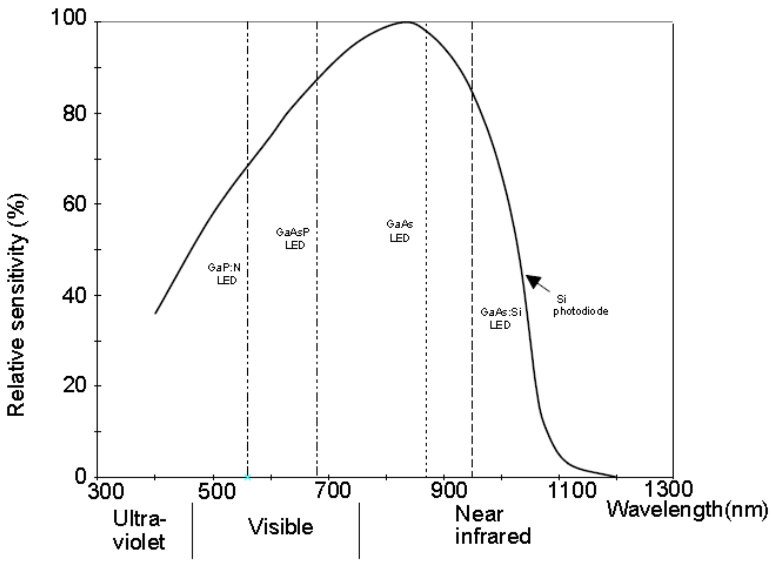


Figure 4: Relative spectral sensitivity of silicon photodiodes and emission peaks of several LEDs (Carson,2007)

The two elements of the model R_s and C_d represent the series resistance of the diode and the diode capacitance, since the photodiode is operating under reverse bias conditions C_d is largely dependent on the applied bias voltage.

1.4 DATA TRANSMISSION LIMITS

There are three main factors that affect indoor optical wireless systems data transmission rate: ambient light, multipath distortion, and LED transient time.

In most indoor communication systems, in addition to the emitted light from the optical transmitter, receiver photodiodes are also exposed to ambient light from lamps which, if not checked, could degrade the link performance. There are three main sources of ambient light:- incandescent lamps, fluorescent lamps and sunlight.

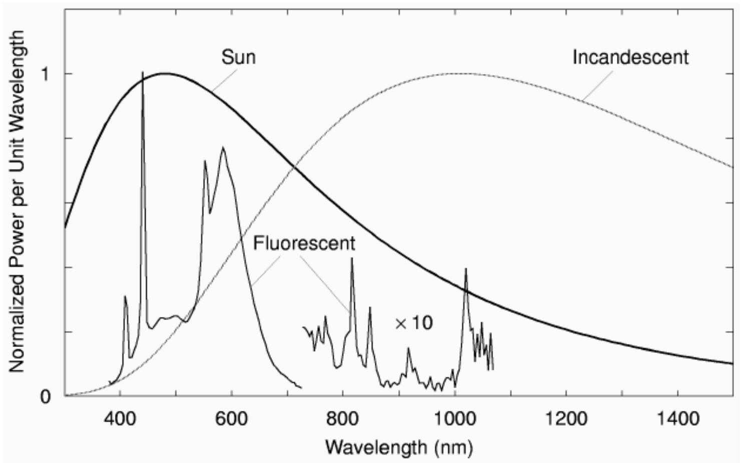


Figure 5: Optical power spectra of common ambient light sources [Kahn, 1997]

Direct sunlight is typically stronger than the two other artificial sources of ambient light. Sunlight is unmodulated and has a very wide spectral with its maximum power spectral density occurring at approximately 500 nm. Artificial ambient light sources are modulated either by the mains frequency or by high frequency switching signal for fluorescent lights.

1.5 LINK CONFIGURATION

Transmission link between transmitter and receiver for Indoor Optical Wireless communications can be classified based on the existence of a line of sight (LOS) path which can be directed LOS and non directed LOS (Chu, 1997), diffused and tracked (street, 1997) as shown in the figure below. (Ghassemlooy 2003)

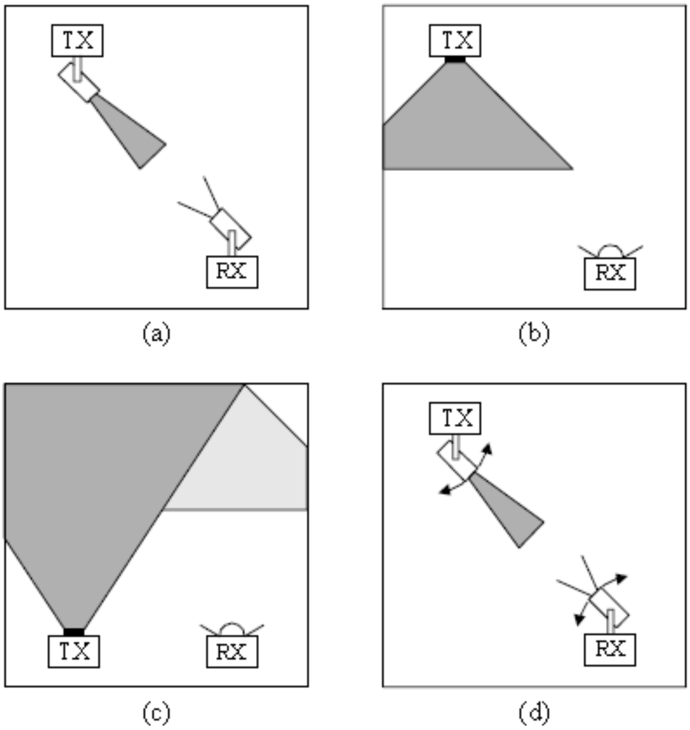


Figure 6: Link configurations: (a) directed LOS, (b) non-directed LOS, (c) diffuse and (d) tracked (Ghassemlooy 2003)

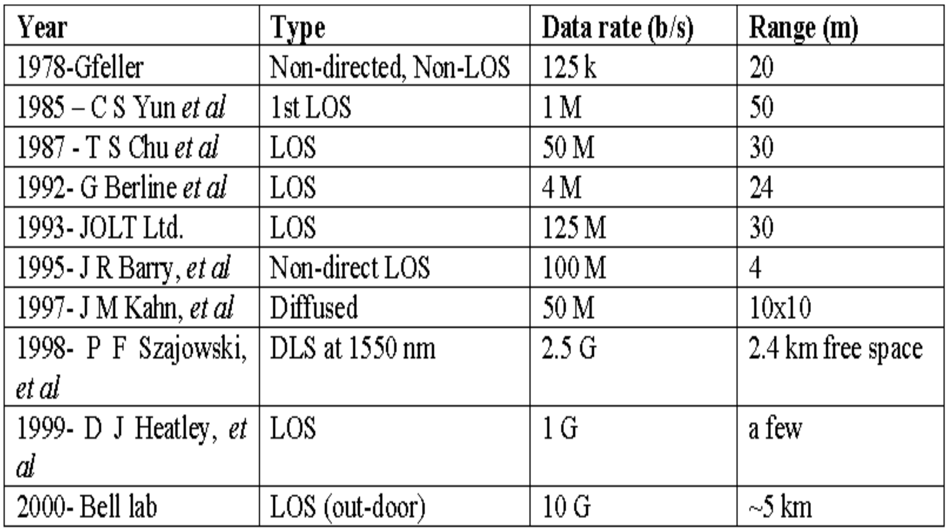
The directed line of sight configuration is the most common for IrDA (Infrared Data Association)links; it achieves very high power by coupling narrow beam transmitters and narrow field of view (FOV) receivers. This means that optical concentrators can be used along with thin film optical filters and since directed LOS configurations do not suffer from multipath dispersion the data rate is potentially only limited by the available power budget. The biggest drawback of directed LOS is the fact that the transmitters and receivers have to be aligned and need an interrupted direct line of sight, which limits the areas of application where this configuration can be applied. However they are perfect for peer to peer communications (Yen, 1985) such as those found in laptops, PDAs and digital cameras(Williams 2000). Portable devices which make use of IrDA operate over a maximum range of 1meter and offer data rates from 9.6Kilobits/second to 4 Megabits/second (Mbit/s).

Non- directed LOS on the other hand uses wide beam transmitters and wide field of view receivers, which means that, unlike the direct LOS, there is no need for an uninterrupted direct LOS. However this advantage comes at a cost of reduced radiance power (Personick, 1985). As wide beam receivers and wife field of view receivers are used means that a proportion of the emitted signal will bounce off walls and other objects within the range of the emitted light, this will give rise to multipath propagation. It is also worth mentioning that since most of the power received at the photo detector is from the direct LOS path, this configuration is not completely immune to blocking (Gfeller, 1979). Non-direct LOS is well suited for point to multipoint such as infrared emitter located on the ceiling of an aircraft and transmitting to the in-flight entertainment sets. By controlling the coverage area of the transmitting source large rooms can be divided into 'optical cells (Ghassemlooy 2003), with a different infrared emitter for each cell. An example of an existing commercial non –directed LOS system is the VIPSLAN-10 by JVC, which has a cell radius of up to 10m and data rates of up to 10Mbit/s (JVC, London). Figure 6(b) illustrates non-directed LOS.

The third configuration known as diffuse was first proposed in 1978 by Gfeller (Gfeller, 1978) and Bapst (Bapst, 1979). Just like visible light infrared signals can also be absorbed by dark surfaces, directionally reflected from shiny surfaces and diffusely reflected from bright surface (Kahn, 1997). This configuration relies on the reflections in a room to provide coverage, as shown in figure6(c). A typical diffuse transmitter points vertically upwards emitting a wide area infrared signal, the receiver would also have a wide Field of View (FOV) and gathers signals which are reflected off the walls and surfaces in the room. Gfeller and Bapst have carried out experiments to determine the reflection coefficient of a variety of materials ranging from 0.4 to 0.9, they found white plaster walls range from 0.7 to 0.85 depending on texture and angle of incidence (Gfeller, 1978) (Bapst, 1979). Diffuse link configurations are quite convenient from a user point of view as it does not require the transmitter and receiver to be pointed nor does it require a direct LOS, which makes them suitable for both infrastructure and ad-hoc networks (Street, 1997). Just like non-directed LOS, diffuse links suffer from high optical path loss, typically 50-70 dB for a 5 m horizontal separation (Kahn, 1995), the losses become even greater if a person stands next to the receiver and blocks the main signal path, a phenomenon known as `shadowing'. Diffuse links suffer from severe multipath propagation. "Intersymbol interference limits the maximum unequalized bit rate to ≈260 Mbit/s"(Gfeller, 1979)".Thus, for a coverage volume of 10 x 10 x 3m, the unequalized bit rate would be limited to ~16Mbit/s"(Smyth, 1993). Even so the diffuse configuration enjoys the greatest attention from the research community, experiments have reported data rates up to 50 Mbit/s (Tsaur, 1994)(Lee, 1998). It is also the IEEE 802.11 infrared physical layer standard. A wireless network system manufactured by Spectrix Corporation which covers an area of 1000 square feet and is capable of data rates up to 4Mbit/s is an example of commercially available diffuse system (Spectrix, 2000).

Figure 6(d) shows the final link configuration; the tracked system, it combines the high power efficiency of the directed LOS with the wide area coverage of the non-directed LOS systems. Experiments carried out by B.T labs have achieved data rates of 1Gigabit/second (Gbit/s)(Wisley, 1996). The tracking was done using mechanical steerable optics, these are however quite expensive and difficult to miniaturise. In response Heatley (Heatley, 1998) proposed a solid state tracked system, using multi-element transmitter and receiver arrays along with a lens arrangement. Steering becomes simply an issue of choosing the correct array element. Experiments carried out using solid state tracked systems have achieved data rates of 34Mbit/s (Parand,1999), 100Mbit/s(Wisley, 1996) and 155Mbit/s (Bellon, 1999). Implementing diffuse links using multiple-beam transmitters and angle diversity receivers or tracking systems opens the doors to potential space-division multiplexing, which would also multiple users to communicate without suffering a loss of per user capacity, as each user is allocated a different cell.

Table 2: some practical results showing different link configurations (Ghassemlooy 2003)



Year	Type	Data rate (b/s)	Range (m)
1978-Gfeller	Non-directed, Non-LOS	125 k	20
1985 – C S Yun *et al*	1st LOS	1 M	50
1987 - T S Chu *et al*	LOS	50 M	30
1992- G Berline *et al*	LOS	4 M	24
1993- JOLT Ltd.	LOS	125 M	30
1995- J R Barry, *et al*	Non-direct LOS	100 M	4
1997- J M Kahn, *et al*	Diffused	50 M	10x10
1998- P F Szajowski, *et al*	DLS at 1550 nm	2.5 G	2.4 km free space
1999- D J Heatley, *et al*	LOS	1 G	a few
2000- Bell lab	LOS (out-door)	10 G	~5 km

1.6 STANDARDS AND EYE SAFETY

To standardize and promote safety in Infrared communication links, an international organisation called IrDA(Infrared Data Association) was formed in 1993 which regulates hardware and software used in Infrared communication links (Ramirez, 1999).

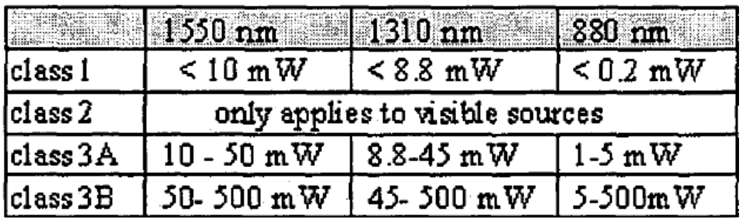
The first standards were released in 1993 and 1994, which consisted of a number of mandatory and optional protocols, these protocols dictated the PHY (physical signalling Layer), IrLAP (Link Access Protocol) and IrLMP (Link Management Protocol and Information Access Service (IAS)) (Barry, 1997).

Standards in force today cover a wide range of data rates from 9.6kb/s to 4Mb/s. All links covered by the standard must have a direct line of sight (LOS) and are specified to work only over a short range (0 -1 m). (Ramirez, 1999).

For example, in IR LANs the standards specifies 3 physical layers, two using radio with spread spectrum modulation and one layer using IR, it also specifies that the signal from the IR physical layer be 780-950nm wavelength range and a data rate of 1 or 2 Mbps.(Halsall, 1996)

However infrared radiation within this range can potentially damage the retina and the cornea by thermal radiation, and for a lot of Optical wireless communications applications this is the single biggest factor that limits the legal power of the system (Heatley, 1998). The standards treat lasers and LEDs sources equally but make distinction between point sources (which the eye can focus) and large area sources. The potential damage to the eye is a function of the power, wavelength of the emitting source and the duration of exposure (Street, 1998). The allowable exposure limits (AEL) which ensures that IR sources are safe under all circumstances is set by the International Electrotechical Commission (IEC).Point source emitters such as lasers must have reduced power levels in order to satisfy the IEC 825-1 standard (Ramirez,1999). The commission classifies IR sources into classes; table 1.3 shows the classes and the allowable wavelengths.

Table 3: Safety classification for a laser source (Street, 1998)



	1550 nm	1310 nm	880 nm
class 1	< 10 mW	< 8.8 mW	< 0.2 mW
class 2	only applies to visible sources		
class 3A	10 - 50 mW	8.8-45 mW	1-5 mW
class 3B	50- 500 mW	45- 500 mW	5-500mW

Class 1 products are regarded as being inherently safe even when viewed directly. Emitters used for optical wireless communications are required to belong to this class. LEDs which are the industry's preferred photodiodes are large area emitters. This means they can be used at fairly larger power emission levels safely, they are also remarkably cheap (40 – 80 pence from Farnell) which makes them the ideal emitters.

Lasers diodes which are point source emitters are made safer by placing a screen after the laser which changes the point emission to a large area emission. Another way of mitigating the point emission problem is by using holograms (Heatley, 1998) which can break up the point beam and disperses it over the retina, another advantage of using holograms is the ability to define the shape of the emitted beam which cannot be done by the screens (Smyth, 1993), this gives the designers the ability to achieve greater power levels safely by choosing the direction and shape of the emitted beam.

Chapter 2: Theories governing wireless communication links.

2 OPTICAL WIRELESS COMMUNOCATIONS

The design complexity of an optical wireless communication system depends on its applications and the degree of accuracy the system is expected to achieve. The design usually consists of a transmitter section and a receiver section, the components which will be included in each section depends on the systems intended are of application. For example a system designed for communications within a room is less complex than one that is designed to communicate between different rooms in a building.

The circuitry required for this project is relatively a simple design as the system is required to communicate only over a few centimeters. Figure 7 below shows a typical optical wireless communications schematic.

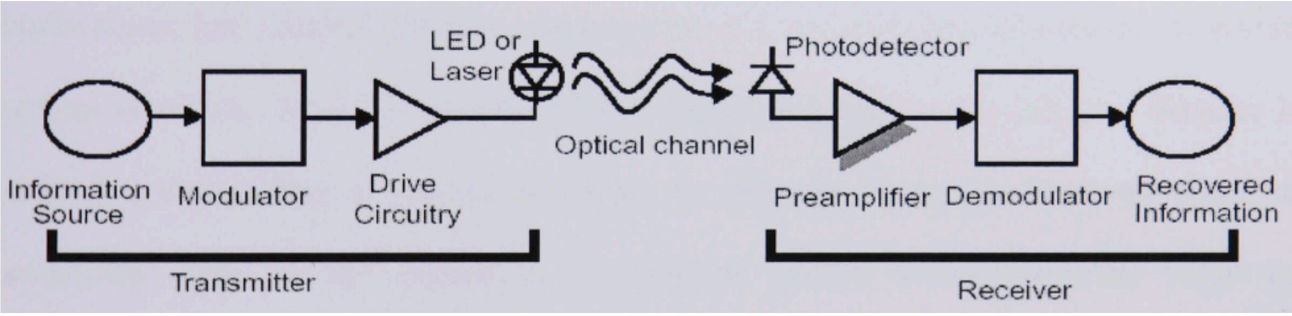


Figure 7: Typical optical wireless communications link components (Abdullah, 2006).

The transmitter section consists of an information source which generates a data stream which is sent to the appropriate drive circuit which inturn modulates the optical signal, generated by either and LED or laser. The modulated optical signal travels through free space and is received by the photodetector which converts the signal into a current. The preamplifier amplifies the signal to a usable voltage level and the signal is then demodulated to retrieve the original signal.

As discussed in the previous chapter IrDA has established standards that govern the use of wireless links, one of which is receivers must be able to resolve signals between 0 – 1 meter. This has lead to varying lengths in the distance transmitter and receivers operate from, in some applications like this projects design, the transmitter and receiver are only a few centimeters apart, and in some applications they could be on different floors in a building (Pandya, 1995). Since photocurrent is a direct function of the incident signal intensity, over this distance it means that the preamplifier current can vary through five orders of magnitude (Abdullah, 2006). Additionally as wireless links components become less expensive, in addition to innovation which makes them well suited for integrated circuits technology has made it beneficial in realizing receivers (Xian, 2009).

2.1 Theorem:

2.12 Channel capacity:

Channel capacity is defined as the highest rate of information that can be reliably transmitted through a channel, it is denoted by *C.* (Moloney, 2008)

$$C = \frac{\log_2\left(n^{T/\tau}\right)}{T}\,\text{bits/s} = \frac{1}{\tau}\log_2(n)\,\text{bits/s}$$ [2.1] (Paulson)

From the above equation, there are two ways of increasing channel capacity:

1. Increasing *n*, or
2. Decreasing *τ.*

2.13 Shannon's capacity theorem:

Considering a band limited channel operating in the presence of additive noise:

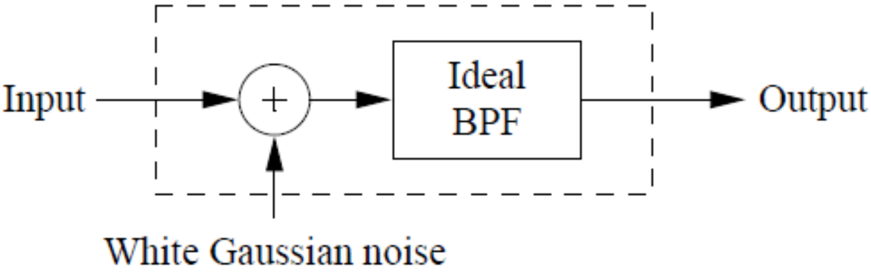


Figure 8: The Shannon- Hartley theorem states that the channel capacity is given by: (Xian, 2009)

□=□□□□21+□□ **[2]**

(Yen, 1985) .

Where:

C is capacity in bits per second.

B is channel bandwidth in Hertz

S/N is the signal to noise ration.

Shannon's theory states that for a given communications system:

- There is a maximum a rate of information C
- If the information rate is less than C, by using intelligent coding arbitrarily small error probabilities can be achieved

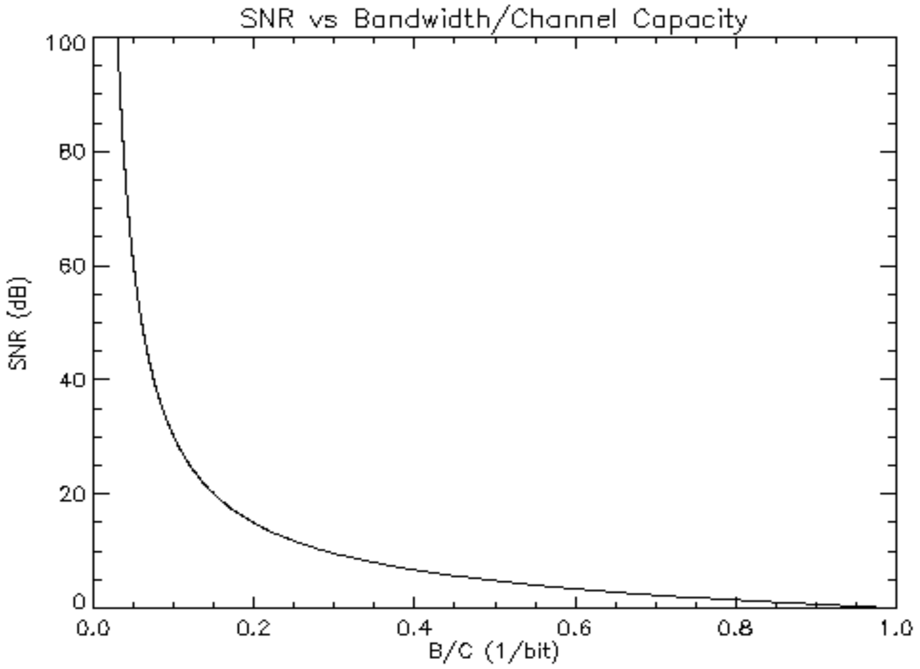


Figure 9: Bandwidth requirement for a given channel as a function of Signal to noise ratio (Paulson)

Shannon Hartley's theorem is undoubtedly one of the most important equations in data communications. In a single formula it links the three most important parameters in data communications: (Moloney, 2008)

- Channel bandwitdth
- Received signal power
- Noise level at the received output.

For a given system the channel capacity C, increases as the available bandwidth increases and as the signal to noise ration improves.

2.2 CAPACITY VERSUS BANDWIDTH

Upon examining Shannon’s equation **[2]** it would seem as if bandwidth increases proportionally to increase in capacity C. However, In practice this is not the case because increasing the bandwidth B also increases the noise power $N=N_0B$ which gives(Moloney, 2008):

�=����21+��

�=����21+��0�

=��0 �0������21+��0�

=��0���21+��0��0��

To further illustrate the above stated point, consider where a bandwidth increases from B to ∞, that means �/�0�→0. The expression limit ���� → 0(1+�)1�=�. This means that as the bandwidth goes to infinity, S/N_0B goes to 0 and $(1 + S/N_0B)^{NoB/s}$ goes to *e* .

The channel capacity therefore goes to(Moloney, 2008):

lim� →∞�=lim�→∞��0���2(1+�/�0�)�0�/�

=�����2�

=1.44��0

From the above expressions it is clear to see that as the bandwidth goes to infinity, the capacity goes to 1.44�/�0, that is it goes to finite value!(Moloney, 2008)

2.3 LED EMISSION OPERATING PRINCIPLE (band gap theory)

From basic chemistry we know that each molecule consists of atoms and electrons. Each electron in an atom has a distinct energy level figure 10. In some elements such as silicon photodiodes, light emission or absorption can be a byproduct of transition as the electrons move from one level to another with wavelength λ:

$\lambda=Cf0=CE2-E1/h=1.2398E2-E1$

(Kressel, 1995)

where:

C is light velocity

E_1 is energy level before transition

E_2 is energy level after transition

H is Planck constant

f_0 is emission frequency.

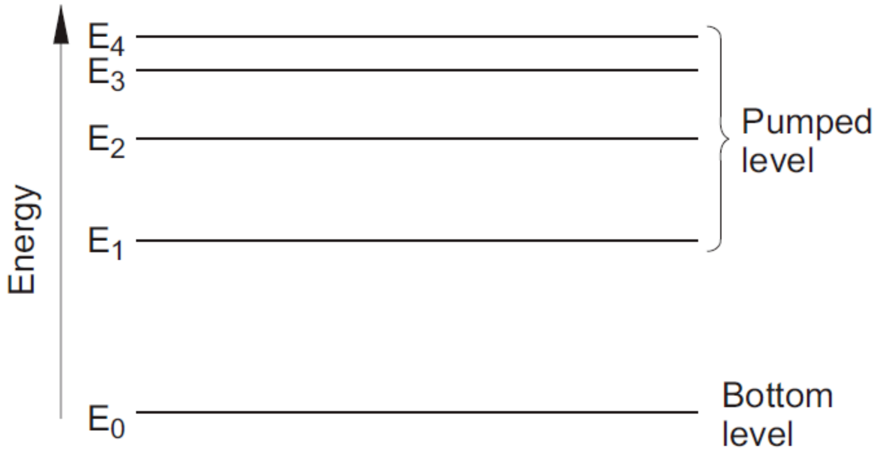


Figure 10: Electron energy levels.(Lee. 2000)

There are fundamentally three types of electron transition: Resonant absorption, spontaneous emission and simulated emission.

In resonant absorption, an electron moves from the stable low energy level E_0 to the higher energy level E_1 by light absorption (see figure 11)

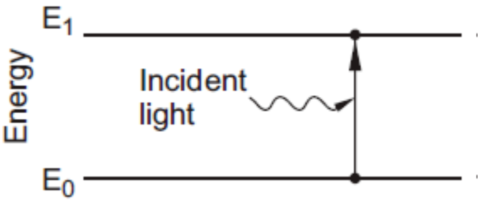


Figure 11: the resonant absorption electron transition.(Lee, 2000)

The second type of electron transition is spontaneous emission, which is opposite of resonant absorption (see figure 12). An electron transits to a more stable low energy level E0 from a high energy level E1. At the same time the energy balance E1 – E0 is released as light. However since each electron transits free of influence from other electrons, the light emitted is random and could be out of phase, this type of emission is known as incoherent light radiation as is typical in spontaneous emission. An example is Infrared light emission.

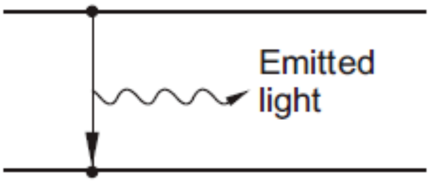


Figure 12: spontaneous emission (Lee, 2000)

Figure 13 shows the third transition type: stimulated emission. There is a forceful transition of electrons from higher energy level E1 to lower energy level E0, as a result of exposure to incident light. The light emitted is in phase with the incident light, because the stimulated light is emitted resonant to the incident light. This type of light emission is referred to as coherent light emission.

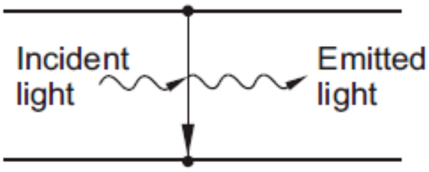


Figure 13: stimulated emission.(Lee, 2000)

2.32 THE IDEAL PHOTON DETECTOR

Optical photodetectors are devices that sample incident radiation and produces and equivalent current proportional to the power of the incident radiation upon the surface of the detector. Radiation from other bodies near the detector add background noise to the received signal which in many cases determines the eventual sensitivity level a detector can attain. Experiments carried out have shown that under normal ambient conditions the detector will receive radiation at 300K and peaks near the 10µm wavelength (Smith, 1968). As long as the noise amplitude remains constant it is possible to isolate the noise from the signal. However, in practice the noise amplitude always fluctuates. This will set the minimum detectable signal level for the ideal photo detector in which the detector is completely free from internal fluctuations or noise (Putley, 1973). No real detectors are able to achieve this but the best modern detectors can differentiate wanted signal from noise within a factor of two or three of its ideal limit (Putley, 1973).

2.33 PHOTO EFFECT IN PHOTO DETECTORS:

The phenomenon in which electrons are emitted by a metal or semiconductor (such as photodetectors) as a result of short wavelength electromagnetic energy absorption of visible or infrared light is known as the photon effect (Abdullah, 2006).

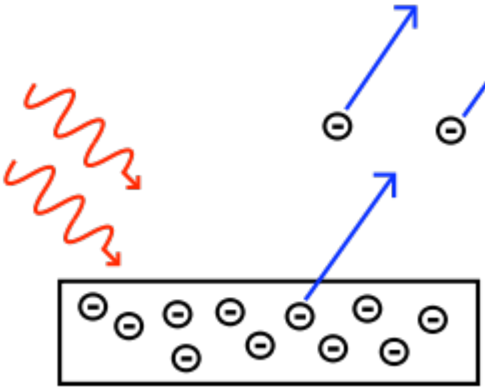


Figure 14: Showing incident rays causing electron emission from a matter such as metal or semiconductor. (wikipedia, 25/7/2010).

In photodetectors the presence of incident light on the p-n junction leads to the generation of electron – hole pairs within the diode (see figure 15) Under reverse-voltage conditions, a depletion region is formed when an electric field is applied. All incident light with the same energy as the semiconductor bandgap energy are absorbed in the depletion region.

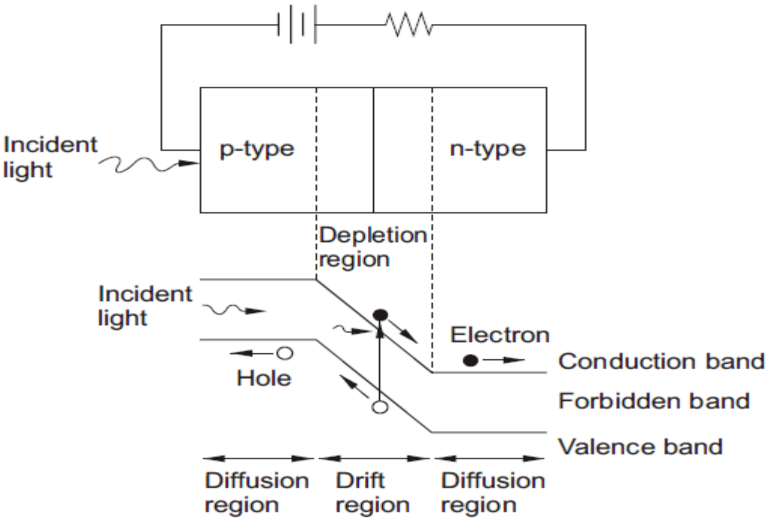


Figure 15: carrier generation in a photodetector (Moloney, 2008).

If a carrier gains enough energy it can create other carriers by collision ionization, when this happens the newly created carries could also gain enough energy to create new carriers through the same process. This sets off a chain reaction of carrier creation (Graeme, 1985). The carriers collect on opposite sides of the diode. Electrons move towards the cathode and, and holes move towards the anode. Consequently current flows through the load resistor and light signals are converted to electric signals. (Personick,1985).

The type of carrier, the voltage across the diode and the material from which the diode is made from determines if a carrier is going to produce another carrier pair (Smith, 1968). The light wavelength which will produce a response is determined by the depth of the junction and the size of the depletion region (Putley, 1973).

For a given photodiode and a given wavelength, the responsivity expresses the resulting efficiency as:

□□=□ø□ 2.2 [Graeme, 1985]

Where:

R is the diode's flux responsivity and;

$\emptyset_c$ is radiant flux received energy in watts.

2.4 CIRCUIT DESIGN AND EXPERIMENTAL PROCEDURE

The main objective of project was to test the bandwidth limit of the system developed and as such the circuit design was intended to be as efficient as possible while maintaining simplicity.

2.41 TRANSMITTER

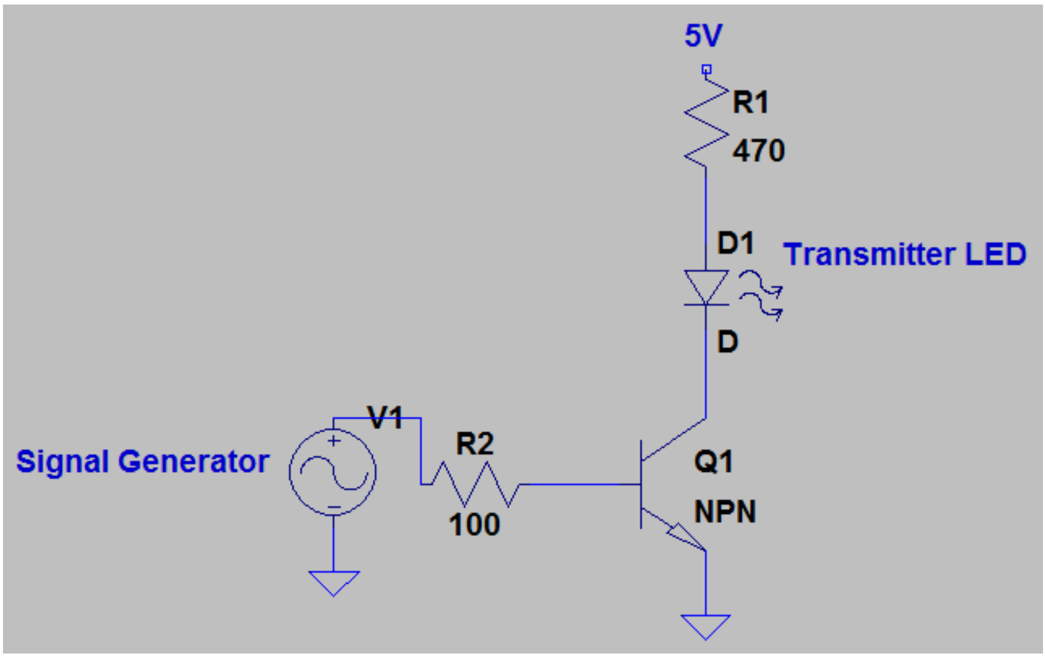


Figure 16: LTSpice representation of transmitter circuit.

The above figure shows the transmitter design on LTSpice. R1 which is connected between the power source and the LED had to be at least 380Ω from the datasheet in order to protect the LED, but 470Ω was the closest available resistor. A signal generator is connected to the base of the transistor which is the source the pulse train (square waves) used to drive the signal, although R2 is not absolutely necessary it was placed between the signal generator and the transistor as a precautionary measure to protect the transistor, and naturally the emitter pin is grounded.

This seemingly simple circuit is the transmitter of the system, the desired operating frequency can be chosen directly from the signal generator and the LED is powered from the mains. Most LEDs like the one used here have a voltage limit of approximately 9V, increasing the input voltage to the LED increases the light intensity but running it at any voltage above 9V risks burning out the LED.

Although it is not possible to see infrared light with the human naked eye, it can be seen through a digital camera and this was used to ensure that the LED was actually lit when the circuit was turned on as figure 18 shows:

±10V.

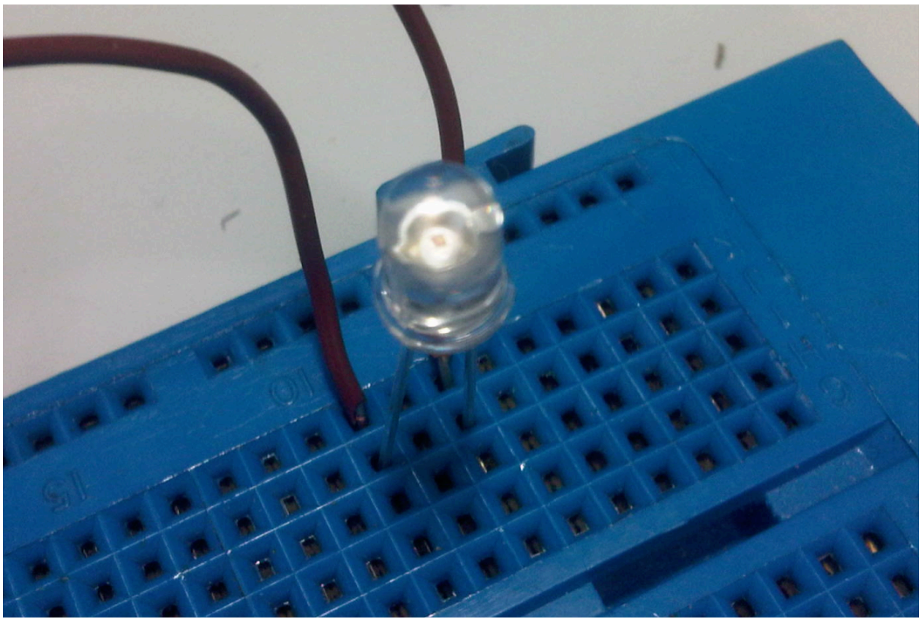


Figure 17: Showing infrared LED when lit as seen through a digital camera.

2.42 RECEIVER (DETECTOR)

In keeping with the general theme of the project circuit design, the receiver circuit was also intended to be as simple as possible while delivering on the objectives of maximum possible bandwidth.

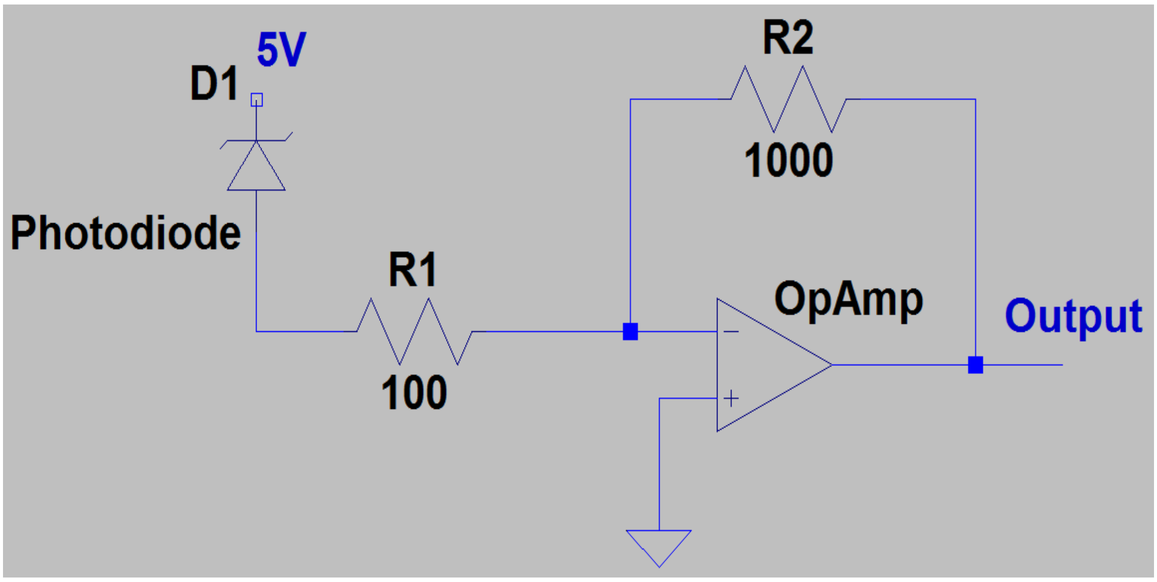


Figure 18: Showing LTSpice layout of the receiver section.

The photodiode is powered by 5V from the mains, and the operational amplifier is powered with ±10V.

Once the transmitter section is turned on and the LED is checked to ensure it is transmitting, it is pointed toward the photodiode.

The light from the transmitter that falls on the photodiode is converted into current as passed along the receiver circuit for further processing.

The resistors R1 and R2 are known as the gain control resistors. The ratio of these two resistors is what determines the amplification gain of the operational amplifier (OpAmp)

Gain = $\frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1}$ (Parand, 1999)

Therefore the closed loop gain is 10 or 20dB.

An oscilloscope or spectrum analyzer can be connected to the output pin where the results can be analyzed.

It is worth pointing out that because the PIN photodiode only has a half angle of 22°, it is absolutely paramount that the transmitter and the receiver are pointed towards each other for the photodiode to detect the transmitted signal.

Chapter 3

3 RESULTS

This chapter will present the experimental results obtained from the circuits. The results will consist mainly of the output from the receiver. This will highlight some the characteristics of the system and its limitations.

3.1 SIGNAL DISTORTION

The transmitter circuit is driven by a square wave pulse train from a signal generator; therefore the frequency of the input signal can be varied.

The transmitted signal travels through free space and is received at the detector. The receiver circuit is designed to amplify and invert the signal.

The figure below shows the transmitted signal and the received signal at 100Hz.

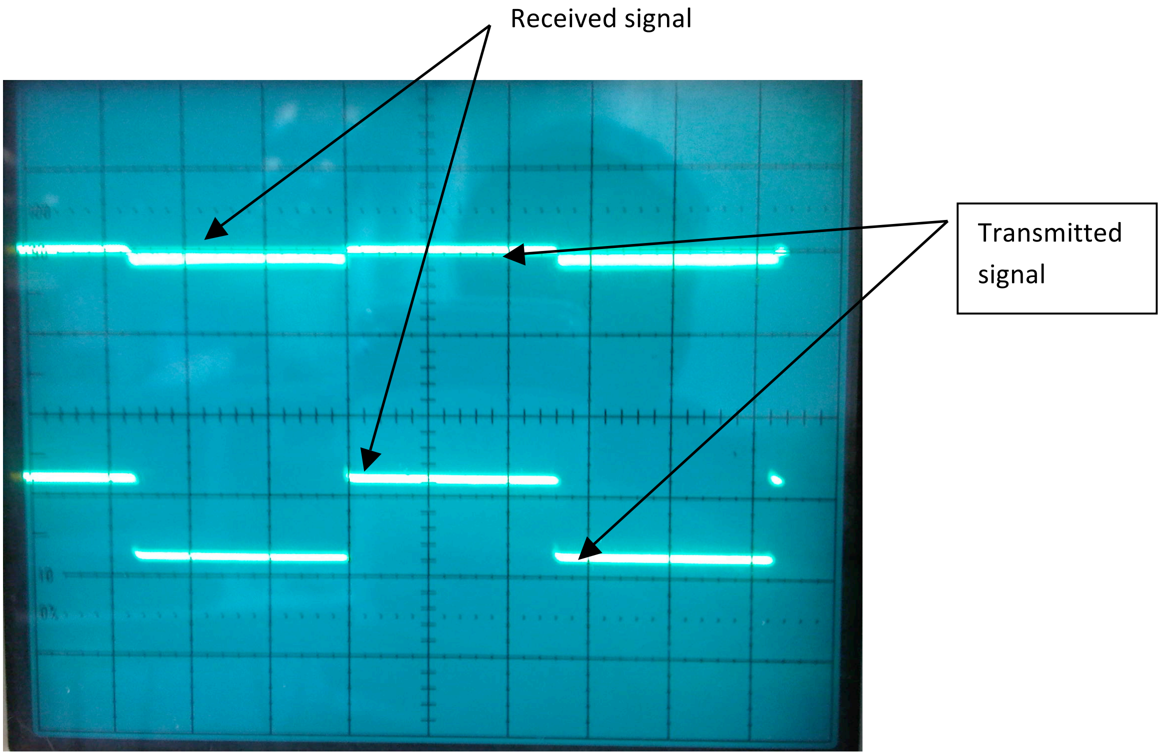


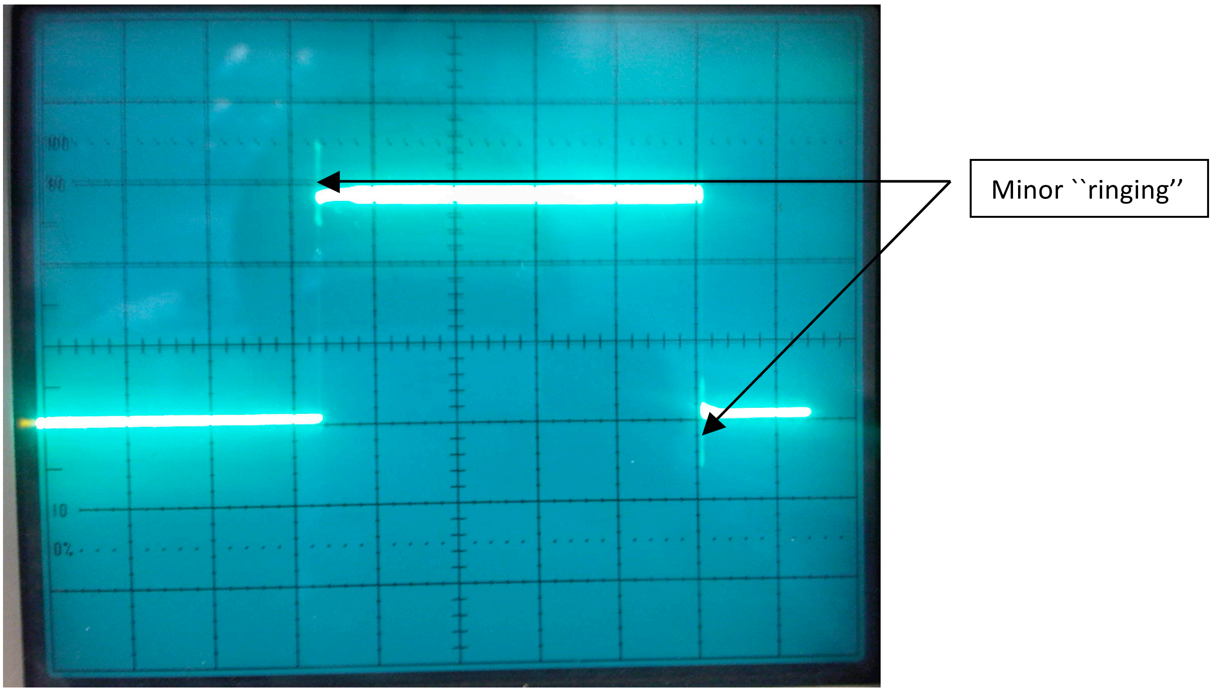
Figure 19: showing the transmitted signal and the received signal at a frequency of 100Hz.

The oscilloscope display above shows the output in channel 1: 0.2V/div which gives a peak to peak value of 0.6V. The input is on channel 2: 1V/div which has a peak to peak value of 3.8V.

The input and output signals are similar with the only difference being in amplitude, the received signal is significantly lower than the transmitted signal. The transmitted signal strength is subjected to attenuation losses as it is transmitted between transmitter and receiver, circuit characteristics also reduces the power of the received signal.

As the frequency of the input signal is increased, it could be seen that the amplitude of the received signal decreased, the reason why this happens is explained further in the discussion section.

It was also evident that the received signal was increasingly distorted as the signal frequency of the signal increased as shown in figures 21 and 22.



Minor ``ringing’’

Figure 20: shows the received signal at 1KHz, with early evidence of ringing.

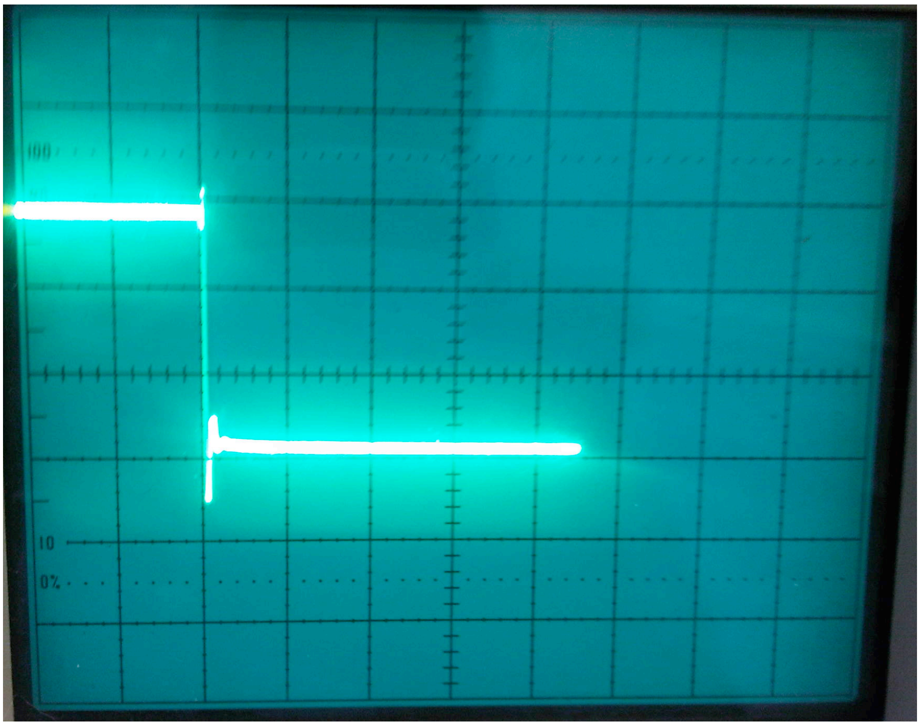


Figure 21: Received signal at 10kHz.

Figures 21 and 22, show the distortions to the received signal as the frequency of the transmitted signal increases. The overshoot or ``ringing'' is known as Gibbs phenomenon; this will be discussed further in the discussion section.

There are several factors which cause ringing in communication systems. In this system the most likely causes are:

- Step response as signal is generated from an oscillator.
- At higher frequencies the detector and transmitters capabilities are exceeded.
- High resistance will cause time response to slow down, *change resistances and check time response.

Figure23 below shows the ringing effect is exacerbated with further increase in frequency.

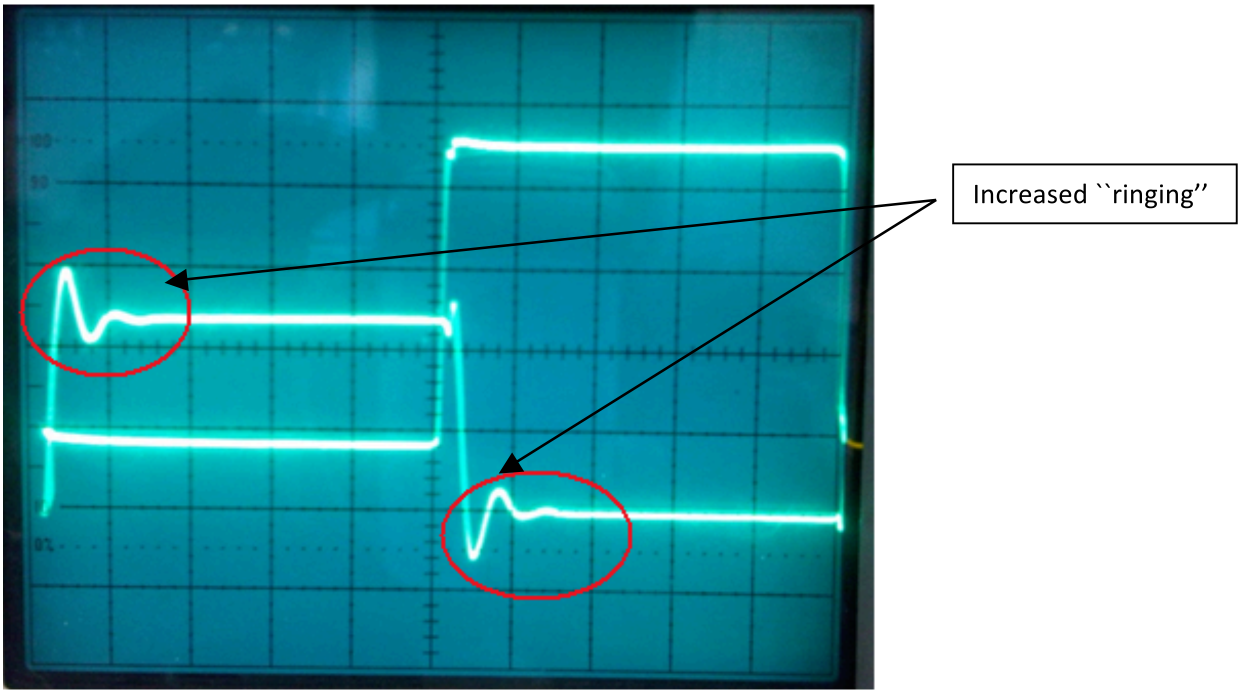


Figure 22: Shows the distortions getting bigger at 100kHz.

The figure above shows the received signal as compared with the transmitted signal at 100 kHz. It is clear to see that the "ringing" effect on the received signal becomes more profound as the frequency of the transmitted signal increases. The amplitude of the overshoot become larger and the time taken for the signal to settle also gets longer. The oscilloscope settings for the received signal is 0.2V/div, this means the amplitude has also dropped to 0.44V.

3.12 TIME CONSTANT

All electronic circuits suffer from some form of time delay from when an input is applied to when the output responds accordingly to the input, this delay is known as time constant (τ). The resultant time constant of any circuit or system usually depends upon the reactive components (either capacitive or inductive) from which the circuit is built. (Wisely, 1996)

The resistors, transistor, LED and photodetector all contribute to the time delay in this system. According to the data sheet, the PIN silcon photodiode used has a rise and fall time of 5ns while the GaAls infrared emitter has rise and fall times of 25ns. This means that at high frequencies the other components contribute to the delay by up to 2 orders of mangnitude.

At low frequencies the rise and fall times of the system seem almost instantaneous (as shown in figure 24) even though this is practically impossible.

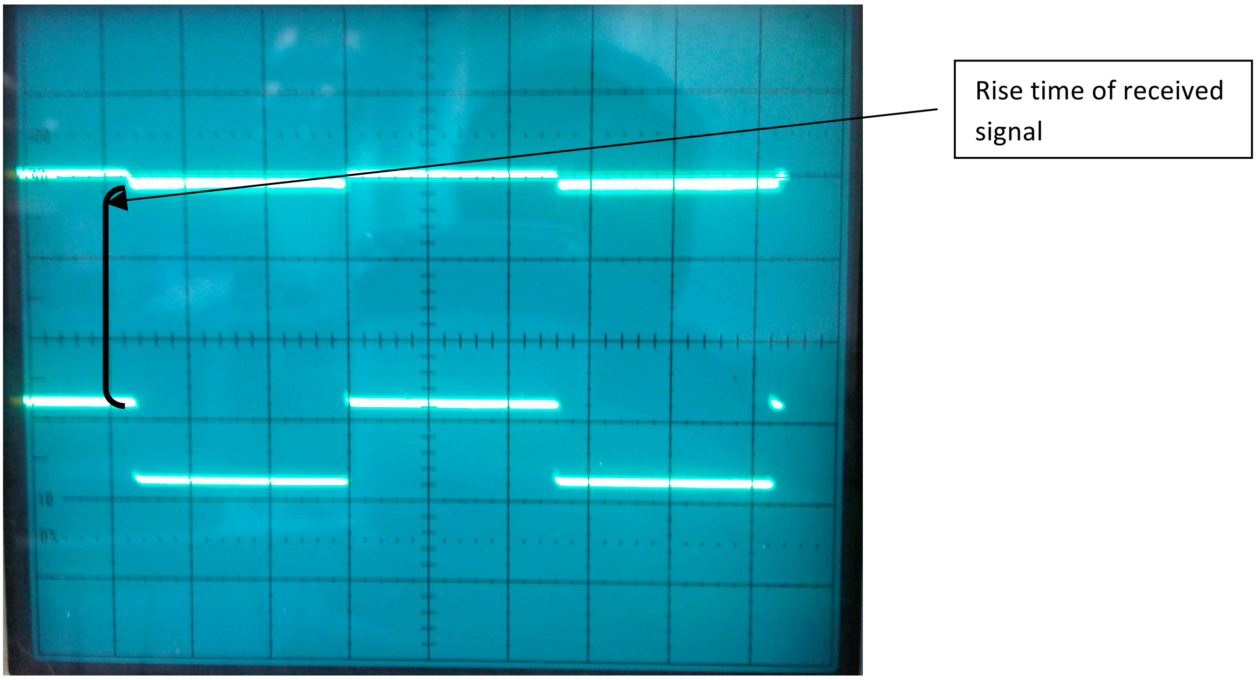

Rise time of received signal

Figure 23: the rise and fall times of both transmitted and recveived signal.

However as the effects of Gibbs phenomenon become more profound, the time constant is clearly seen to increase. Figure25 shows the time constant of the received signal at a frequcny of 100kHz.

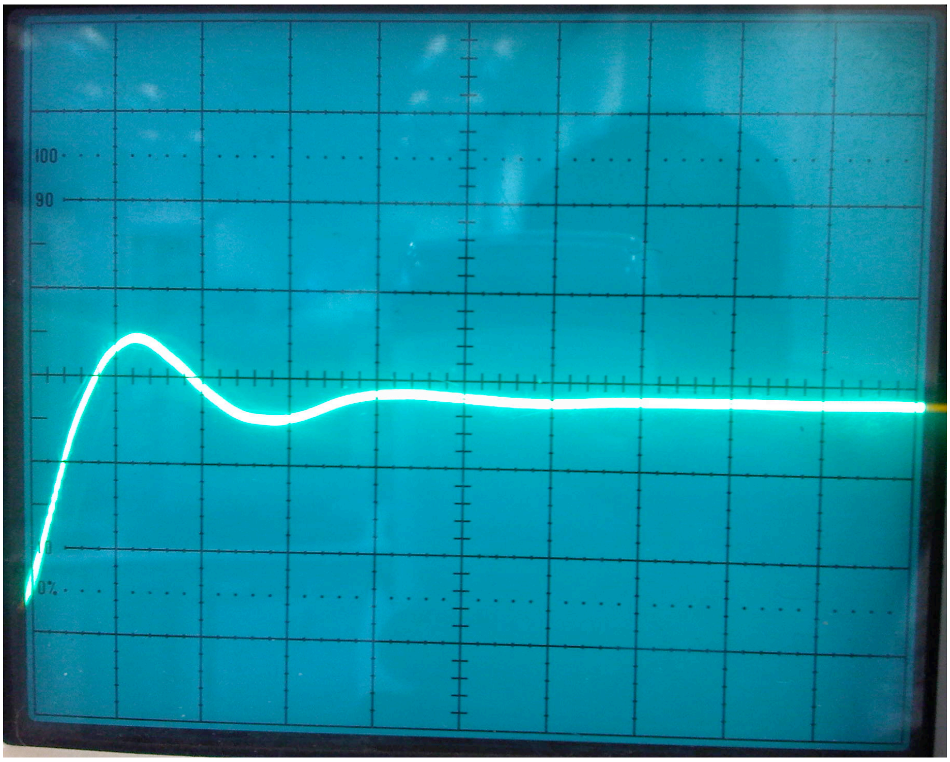


Figure 24: shows rise time of the received signal at 100kHz.

Oscilloscope settings: 0.2µs/div and 0.2V/div.

Figure25 above clearly shows rise time of the received signal at 100 kHz. The time constant (τ) is even much longer due to Gibbs phenomenon. With the stated oscilloscope settings, it takes the received signal approximately 0.84µs to settle.

3.13 SPACE LOSS

The results shown so far are for when the transmitter and receiver have been placed at within touching distance of one another. For true telecommunications the transmitter and receiver have to placed at some distance part. It was observed that the signal decay upon separating the transmitter and receiver was rather abrupt. The received signal power decayed from 0.6V at 100Hz to 0V at a only a distance of 5cm.

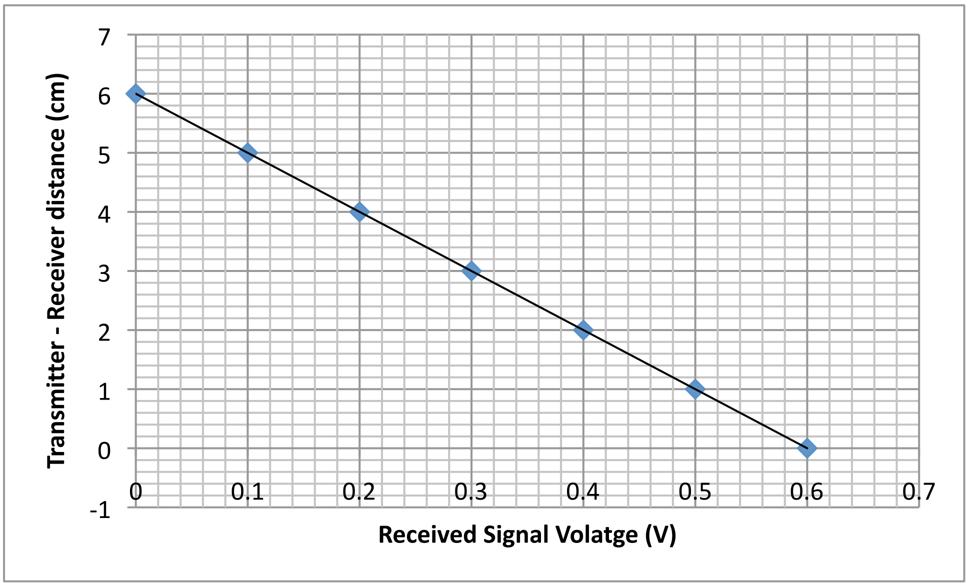


Figure 25: Relationship between received signal power and transmitter- receiver distance.

The results obtained show a linear relationship between the received signal strength and the distance between the transmitter and receiver, as the distance between the transmitter and receiver widened the amplitude of the background noise increased as the signal got weaker until it was completely swamped by noise at 5cm. The signal decays at a rate of 0.1V/cm.

The expected graph if the received signal was proportional to light power arriving at PIN diode is an inverse square relationship. However graph as can seen is linear, the most probable explanation is that the PIN diode receives a signal proportional to the square root of the power.

3.14 BADWIDTH CAPACITY

Recalling Shannon’s channel capacity theory:

$$C=B\log_2\left(1+\frac{S}{N}\right)$$

Where the symbols have their usual meaning:

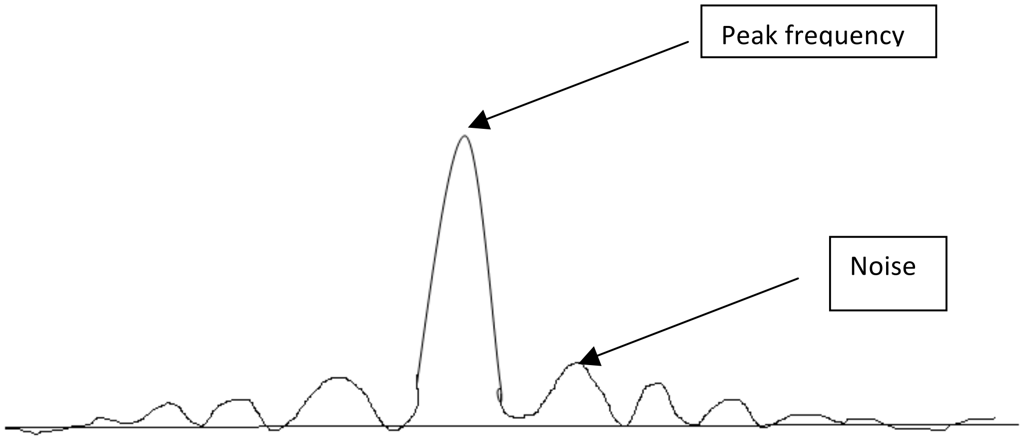


Figure 26: : The signal as seen on a spectrum analyzer.

The figure above shows the output signal of the circuit as would be seen on the screen of a spectrum analyzer. Unlike an oscilloscope which displays signals as a function of time. A spectrum analyzer displays power spectrum over a given frequency range.

To estimate the channel capacity of the system, by Shannon’s theory the bandwidth and signal to ratio has to be obtained. The bandwidth is equal to the input frequency which can be read off the signal generator. At the peak point where the signal flattens, the value of the signal strength can be read in dB. And the noise level can be read at the bottom of the sync function as shown above.

By increasing the input frequency and monitoring both the signal and noise power levels, a map of the bandwidth over a frequency range can be noted and the channel capacity calculated.

The bandwidth limit of the system should be at the point where the signal to noise ratio (SNR) value begins to drop. However, the signal generator used to drive the circuit had a range of 10Hz – 1MHz only, and at 1MHz the SNR value had still not started dropping, so it can be deduced that the system has a bandwidth of at least 1MHz.

To calculate channel capacity at 1MHz:

Bandwidth (B) = 1MHz

Signal strength (S) = -11.97dB

Noise strength (N) = -75.18dB

SNR (dB) = -63.21,

$10 \log_{10}SNR = 63.21$, therefore $SNR = 2 \times 10^6$.

By Shannon's channel capacity theorem:

$C_{max} = 10^6.\log_2(1 +(2 \times 10^6)) = 20931569.29 \approx 21$Mbits/second.

As the maximum bandwidth of the system is not known due to the limited range of the driving signal generator, the maximum channel capacity cannot be calculated but it is safe to say that the system is capable of at least 21Mbits/second. A possible future modification that would allow the limit of the circuit to be tested will be discussed in the future work section.

Chapter 4

4 DISCUSSION

This chapter will present analysis and further discussion of the results obtained from the experiments. Theories governing free space and optical communications will be employed to help better understand the capabilities and limitations of the system.

4.1 LOSES

As the first set of transmitted signals were received and monitored upon setting up and operating the system, it was observed that the received signal had far lower amplitude than the transmitted signal. This due to several contributing loss factors, the main ones are highlighted below:

4.12 Optical losses:

This is a component dependent loss, the bulk of this loss occurs due to the transmitter and receiver optics which attenuate the signal. To manage these losses manufacturers of high end optical devices would minimise the optical surface area of an LED or laser, for example and use ant-reflection coatings (Jeganathan, 2003). However in less expensive systems, such as the one designed for this project; the design is typically for close proximity communications. Manufactures choose a narrow angle beam transmitter so as to concentrate the signal as much data as possible with the aim of reducing attenuation losses. The transmitter used for this project has a typical half angle of ± 22° (for full datasheet refer to appendix).

4.13 Free Space loss:

One of the biggest limiting factors in optical communications is receiving only a fraction of the transmitted signal (lee at al, 2000). This is inversely proportional to the square of the path length. The PIN silicon photodiode used for this project has a wide receiving angle in order to receive the maximum amount of signal possible however for very high capacity systems the introduced multipath delay spread can lead to inter-symbol interference. In more advanced systems, a wave guide such an optical fibre is used to guide the transmitted signal to the lens of the receiver which vastly improves the received signal quality and strength (Moloney, 2008).`` For example, 8 mrad (< 0.5 degrees) beam divergence at 1km, results in an 8 m beam diameter. Therefore, a 150 mm receiver collects less than 0.04% of the transmitted signal – equivalent to a loss of –35 dB. Decreasing the beam divergence to 2 mrad reduces the loss to -23 dB" (Jeganathan, 2003).

4.14 Circuit losses:

the circuit is built with resistive components which all contribute to the losses in the circuit. The detector converts the received light pulses into electric current and passes it through the circuit. Resistive heating which is a form of loss that occurs as a result of electric current passing through a conductor although not very significant in the case of this system is none the less one of the circuitry losses.

Both the transmitter and receiver include amplifiers that increase the electronic signal power before the LED turns it into light power and after the receiver PIN diode to increase the power of the received signal before further processing.

4.2 SIGNAL DISTORTION

From the experimental results, it was observed that the received signal suffered from distortion at higher frequencies (from approximately 100kHz) this phenomenon is known as Gibbs Phenomenon named after the American physicist J. Willard Gibbs. It is a peculiar overshoot or “ringing” of the Fourier series which occur at simple discontinuities periodic functions (Arfken, 1985) due to band-limiting the signal.

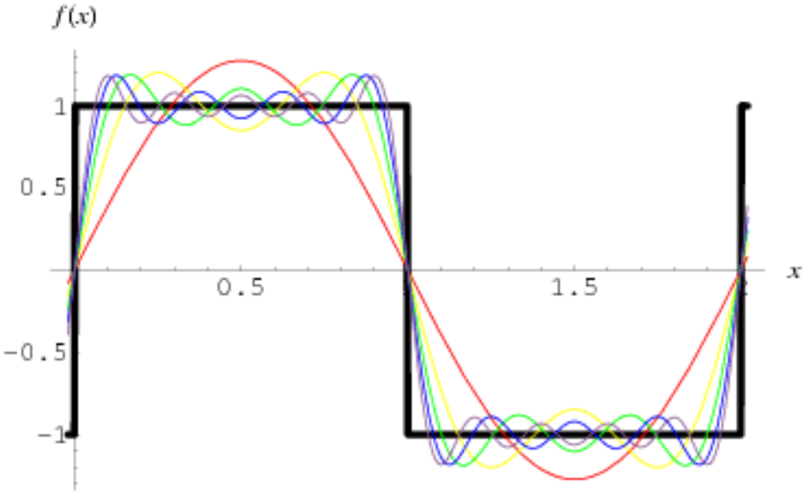


Figure 27: A theoretical example of Gibbs phenomenon on a square wave.(mathworld.com 14/9/2010)

The Gibbs phenomenon occurs due to the fact that Fourier sums overshoot at a jump discontinuity, and the overshoot does not die out even with further increase in frequency.

As our system is driven by square waves, the explanation for the Fourier’s theory will be made in reference to a square wave. The Fourier expansion of a square wave is as follows:

$$\sin(x) + \frac{1}{3}\sin(3x) + \frac{1}{5}\sin(5x) + \cdots$$

(Arfken, 1985)

Arfken calculated that for a given square wave, the Fourier function *f* which equals π/4 between 2*n*π and (2*n* + 1) and –π/4 between (2*n* +1)π and (2*n* + 2)π for every integer *n*, such a square wave would have a jump discontinuity of height π/2 at every integer multiple of π. His calculations give an explicit formula for the limit of the height of the error. It states that the Fourier series exceeds the height π/4 of the square wave by:

$$\frac{1}{2}\int_0^\pi \frac{\sin t}{t}\,dt - \frac{\pi}{4} = \frac{\pi}{2}\cdot(0.089490\ldots)$$

Which is about 9 percent. Generally for continuous differential function with a jump of *a,* at any point the Fourier series will overshoot this jump by approximately *a.*(0.089490) (Arfken, 1985).

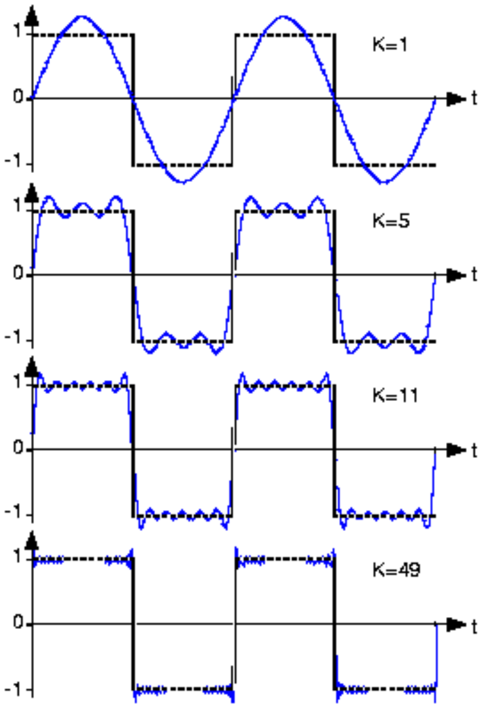


Figure 28: Fourier approximation of a square wave. K is the number of Fourier terms. (cnx.org 14/9/2010)

In Electronic terms the cause of this ringing is a result of the photon effect as described in chapter 2. The effects of this ringing can sometimes be reduced or even completely eradicated by increasing the values of the base resistor in the transmitter section of the system and the gain controlling resistors in the receiver section. In this system doing so did not have that effect and that is because both the LED and the photodiode were operating at their absolute maximum electrical ratings.

Also at high frequencies it was observed that the received signal power decreased, one of the causes of this is as the frequency increases and the width of the pulses get smaller and smaller, it meant that the signal could not rise to its maximum value before the end of the pulse and such had to drop.

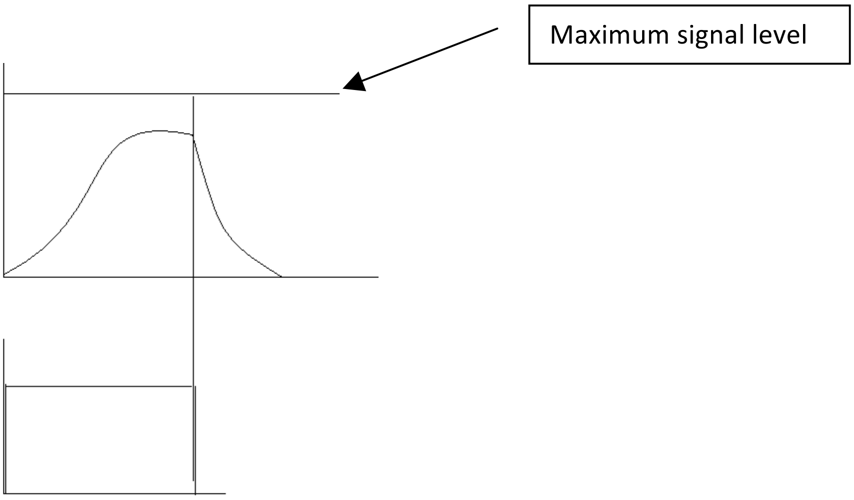


Figure 29: Shows signal drop due to short pulse

4.3 TIME CONSTANT

In an ideal circuit, the output of the system would change instantaneously in response to an input change, however in real circuits there is a delay between the time input changes and the output changes as stated already.

Although there are no capacitors in the circuit, the small signal equivalent circuit of the system has capacitive components and as such RC (resistor-capacitor) circuit conditions apply. The time required to charge a capacitor to discharge to 1/*e* (where *e* is Euler's constant) its initial value is what is referred to as the time constant of the circuit. The figure below illustrates further:

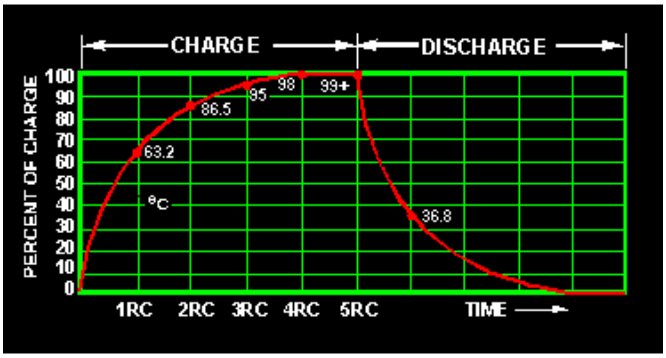


Figure 30: charging and discharge of capacitor depicting time constant (τ).

(http://www.tpub.com/neets/book2/3d.htm 14/09/2010)

This slow rise and fall time is partly the reason why the output signal does not respond immediately to a change in the input. The value of time constant τ (in seconds) is equal to the product of the circuit resistance (in ohms) and the circuit capacitance (in farads). The data sheets for some of the components do not state the capacitance and resistances of the components therefore it is not possible to calculate the total capacitances and resistances of the circuit. Moreover, the resistance of the semiconductor components change with the amount of current passing through them.

However from the experimental results we know the actual time constant of the circuit to be 0.84µs at 100kHz. We have also seen that decreasing the base resistance reduces the time constant.

4.4 LASER DIODE Vs LEIGHT EMITTING DIODE (LED)

The initial project aim was to build a laser system in addition to the LED system and to compare the two systems.

However, attempts to build the laser system were unsuccessful as the emitting laser burnt when the circuit was turned on. Replacement lasers were used in modified circuits but this also proved unsuccessful.

The laser diode used was a AlGaInP from Farnell (full data sheet in appendix). It had a peak wavelength of 635 nm so it is well within the range of the photodiode used for the LED circuit.

A laser diode is characterised by a threshold current I_{th} , for stimulated emission above I_{th} the carrier frequency is very short as the spectral emission narrows to a few angstrom units, the emitted light becomes quite directional and the externally measured quantum efficiency is high (Kressel, 1995) and this leads to power spike.

A similar circuit to that used for the LED circuit is used for the laser circuit. The laser diode conducts initially in a similar manner as the LED below I_{th}. But with an input voltage of 5V the light signal produced by the laser is too weak to be detected by the photodiode and increasing the voltage any further causes the current to spike well above I_{th} and this causes the circuit to burn.

In contrast the LED has a broad emission spectrum and a broad angle beam, and a modulation feature limited by a spontaneous carrier lifetime of about 1ns under optimum condition (Farnell data sheet).

Although both lasers and LEDs can be used for optical communications, their areas of application differ slightly. LEDs are useful for applications requiring limited bandwidth capabilities and short to moderate transmission distances (Muthu 2001, has developed systems capable of 1.25Gb/s over one kilometre). Lasers on the other hand are used for more demanding high data rates and long distance applications, lasers have temperature dependent thresholds and are therefore somewhat harder to use than LEDs (Kressel, 1995).

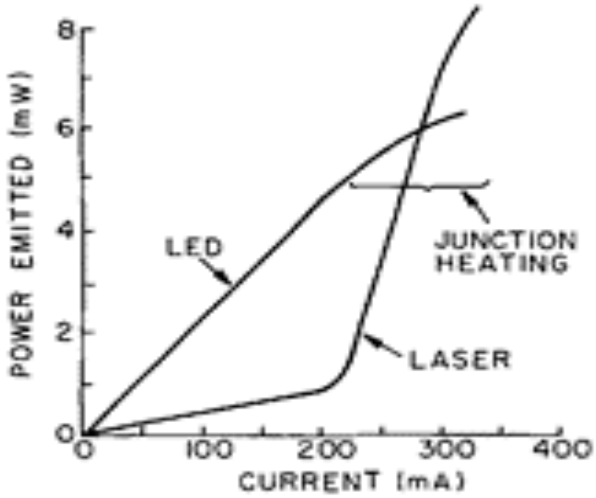


Figure 31: Power emission from an LED and Laser as a function of direct current (Kressel, 1995)

Chapter 5

5 FUTURE WORK

As discussed the channel capacity of this system has not been fully tested as the driving signal generator has a limited frequency. A possible solution would be to introduce a 555 precision timer chip into the circuit. Precision timer circuits have fairly simple circuits and require a relatively straight forward C code to run. They allow the user to set the frequency and pulse width of a driving signal and some are capable of frequencies in the range of 100's of megahertz and are available for less than £10GB. This would allow further tests that could reveal the limit of the circuit and improvements could be made.

Another factor which limits the capabilities of the communication link is the choice of emitter diode and receiver photodiode. Although the data sheets of the diodes used in this project state wireless communications as one of their applications they are by far not the best choice as further research into the area has shown. There are LEDs which are coated with anti reflection material and have lenses that help concentrate and direct the transmitted beam, a more concentrated beam delivers more signal as the multipath dispersion is greatly reduced and signal loss due to internal reflection is greatly reduced. There are also photodiodes which have inbuilt gain systems which amplifies the received signal, this reduces the overall circuitry of the system. At less than £5GB these photodiodes are inexpensive and readily available at most electronic hardware suppliers.

The fundamental operations of optical wireless communications systems have been explored in this project and it has been shown that infrared light can be transmitted and received over free space. A step in further development of the system would be to transmit data over the communication link. With the scale, and amount of resources available for this project a realistic data transfer would be text, this can be achieved by incorporating a PIC microcontroller at the transmitter. If this is done it would eliminate the need for a 555 timer as the microcontroller can be used to control the frequency of the driving signal. The current channel capacity of 21Mbits/second is sufficient for text transmission.

5.1 CONCLUSION

There is currently a huge drive towards wireless communications for indoor transmissions, and optical communications is a very good contender to be the leading form of wireless communications. It offers great advantages over the current more widely used radio frequency systems such as not needing licenses to operate, greater mobility and being far less expensive among other advantages as discussed in chapter 1.

Indoor optical systems are expected to operate within environments with ever present ambient noise from sunlight and artificial sources such as fluorescent light bulbs. The latter being potentially the most disruptive to optical communications as they are capable of producing electrical spectral harmonics in the range of MHz (Ramirez, 1999). The degree to which noise affects an optical communication link is also dependent on the link configuration used, while direct links are less affected they are less mobile, on the other hand indirect links which are more mobile are affected more by noise and are subject to multipath dispersion.

The biggest obstacle to advancing multi- Gigabit /second optical communications is perhaps diminished power at the receiver and reduced receiver sensitivity at higher frequencies (Jeganathan, 2003). This is improved by using bandwidth tracking systems. However it is unlikely that such systems can be developed within the time and resources available to the MSc projects in the near future.

The most productive way towards developing multi-gigabyte systems under these constraints would be to concentrate on finding ways to improve the data bit rates by reducing effects of multipath dispersion and through the use of better electronic components and continuously improving the SNR. The leading researchers in this field are also always looking at ways to improve the range of the system; this area should also receive great attention in future projects.

TIME MANAGEMENT

Activity	**Wk1**	**Wk2**	**Wk 3**	**Wk 4**	**Wk5**	**Wk 6**	**Wk 7**	**Wk 8**	**Wk9**	**Wk 10**
Research components and systems	■	■								
Ordered components			■	■						
Built and tested Tx					■	■				
Built and tested Rx						■	■	■		
Attempted Laser circuit						■	■		■	■
Write thesis										

Table 3: Gantt chart of the project activity time line

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