Communication by Analogue Optical Wireless Audio Transmission

Report

Abstract

Light, sound waves, how they are used to communicate. The advantages and applications of optical wireless communication, when compared to radio. How I designed and built an analogue optical wireless audio transmission system.

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Supervised and guided by Mr Storchart & Dr Ancharova

ACKNOWLEDGEMENTS

First, I would like to thank my thesis supervisors **Dr Ancharova** and **Mr Storchart** for their dedication, patience, and assistance when completing this research paper.

I would also like to thank my teachers and classmates, with whom I had the pleasure to spend six years, which were critical to my academic growth and development.

A special thanks to **Kasper van Maasdam**, **Timo de Kok**, and **Luke Kuijpers**, who have graciously helped me in the numerous tests and experiments that were required for this paper.

Last, but not least, a big thanks to my family, who have supported me throughout the making of this paper, and all experiments that were done beforehand, without which none of this would have been possible.

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INTRODUCTION

Electromagnetic waves, such as radio waves, surround us. Radio and microwaves are mostly used as a means of communication, but could we use other forms of electromagnetic radiation? Could a narrow-beamed LASER diode be used to transmit a piece of music or important secret messages? Therefore: **How to communicate by analogue optical wireless audio transmission?**

In this paper, I will explore the basics of wave physics, the advantages, and applications of a light-based communication system and how I was able to create such a device. The sub-questions will thus be divided in the following parts:

CHAPTER ONE: What are characteristics of waves?

This question is important to understand all the distinct factors, which influence optical wireless communication. Those factors include *reflection*, *refraction*, *diffraction*, *interference,* and the *Doppler Effect* (more information: CONCLUSION OF CHAPTER ONE).

CHAPTER TWO: What are the possible applications and advantages of light-based communication when compared to radio?

Before fabricating an analogue optical wireless audio transmitter, it is important to understand what it can be used for. Optical wireless communication has various advantages when compared to radio which must be explored before trying to build such a system. Based on the characteristics of line-of-sight and radio propagation, possible applications for such systems can be determined,

CHAPTER THREE: How to build an analogue optical wireless audio transmitter?

Once it is known what the optical wireless transmitter will be used for, and the wave effects and properties are known, it is finally possible to start prototyping the analogue optical wireless audio transmitter. This is crucial to the main question because it is the final product of this research, and partially the answer to the main question, which aims to find out how to communicate by analogue optical wireless audio transmission.

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MOTIVATION

I have been interested in electronics forever since I was a child. When I was still a baby, I would try to push on all buttons just to try out what they did. My grandfather and uncle were electrical engineers, who taught me about the physics of electricity at an early age. I built my first electrical circuit when I was 6 years old.

I got my first laptop when I was 7 -I remember it even had Microsoft Windows XP ® on it-. This is the first time I got interested in computers and ICT in general. I wrote my first program when I was seven and have never stopped programming since then.

At the age of eleven, I made my first computer-controlled radio transmitter, which I used to amaze my friends, but I had to reduce its emitting power to comply with the law. I remade a version of this project for the SDL's 2020 *Treasure Hunt*, in which it was used as the last step towards victory.

In the spring break of 2018 I had an idea: Could light be used as an alternative to radio to communicate a simple audio signal? Could I make a simple system that would use a light beam to transmit audio? I had never heard of such a system before and could not even find a Wikipedia page explaining anything related to it. Therefore, I have spent weeks thinking and prototyping such a system, which, three years later, lead to this research paper.

When I showed the first working prototype of this system to my teachers, the multitude suggested that I make my research paper about this. This was the best motivation to continue improving on this system and author this paper. The first video of myself explaining my mk. 1 prototype of the analogue optical wireless audio transmission system is available at: https://youtu.be/6Bi8ASEOcZI.

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1 WAVE PHYSICS

1.1 BASIC DEFINITION

Wave: "propagation of disturbances from place to place in a regular and organized way." (Hosch, Gregersen, & Grinchenko, 2016)

The waves which are most familiar to us are the waves that travel on water, however, both sound and light exhibit wavelike properties. In the simplest of waves, the disturbance has a fixed *amplitude* and oscillates periodically, so with a fixed *period*, *frequency,* and *wavelength*. Mechanical waves require a medium through which they can travel, but electromagnetic waves do not and can thus be propagated through a vacuum. The speed at which a wave propagates is dependent on the medium's properties.

1.2 TYPES

1.2.1 Transverse

A transverse wave is a wave in which the direction of disturbance is perpendicular to the direction of propagation. A local maximum of a transverse wave is called a crest and a local minimum is called a trough. Electromagnetic waves, such as radio and light, are examples of transverse waves. These, however, consist of two transverse waves: the oscillation of the electrical and magnetic fields. See FIGURE 1 below for more information.

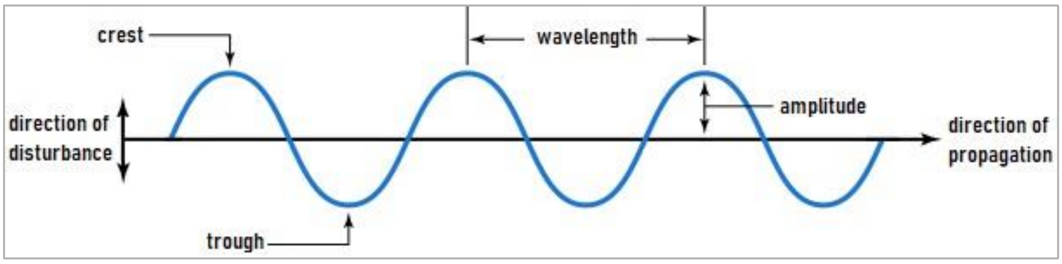

Figure 1: Transverse

1.2.2 Longitudinal

A longitudinal wave is a wave in which the direction of disturbance is the same as the direction of propagation. Longitudinal waves consist of series of compressions (increase in density, analogous to crests) and rarefactions (decrease in density, analogous to troughs), as seen in FIGURE 2. Sound is an example of a longitudinal wave.

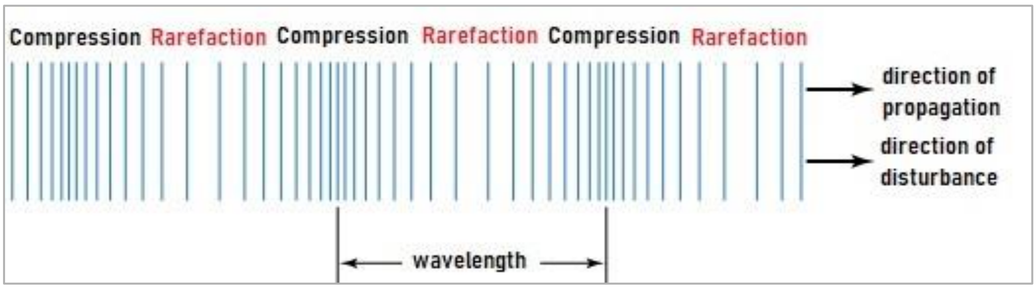

Figure 2: Longitudinal

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1.3 KEY FEATURES

The *amplitude* is the maximum deviation from the wave's equilibrium position. The *wavelength* is the distance between two crests or troughs. The *period* is the time it takes for one *wavelength* to travel through a specific point. The *frequency* is the reciprocal of the *period*, so the number of waves passing through a specific point per time unit, as seen in EQUATION 1.

Equation 1: Frequency

$f = \frac{1}{T}$ where:

f is the frequency in hertz ($Hz = s^{-1}$)
T is the period in seconds (s)

The *propagation speed* or *velocity* of a wave can be described as the *frequency* multiplied by the *wavelength*, as seen in EQUATION 2.

Equation 2: Propagation speed

$v = f\lambda$ where:

v is the propagation speed of the wave in meters per second (ms^{-1})
f is the frequency in hertz ($Hz = s^{-1}$)
λ is the wavelength in meters (m)

1.4 BEHAVIOUR

1.4.1 Reflection

When a wave hits a surface and is reflected (whether it is reflected or not depends on the size and smoothness of the object and the *wavelength* of the wave), the *angle of incidence* equals the *angle of reflection*, as seen in EQUATION 3.

Equation 3: Law of Reflection

$\theta_i = \theta_r$ where:

θ_i is the angle of incidence in degrees (°)
θ_r is the angle of reflection in degrees (°)

The *angle of incidence* is the angle between the direction of propagation of the wave and the *normal* (which is a line perpendicular to the surface). See FIGURE 3 below for a visual representation of the Law of Reflection.

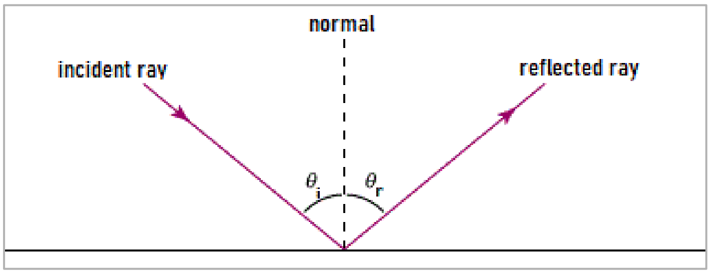

Figure 3: Law of Reflection

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1.4.2 Refraction

Waves travel at different speeds depending on which medium they are travelling through. For example, light travels slower through water than in a vacuum. When a wave enters a medium through which its *propagation speed* would be lower, the wave is "bent" towards the *normal*. When a wave enters a medium through which its *propagation speed* would be higher, the wave is "bent" away from the *normal*. See FIGURE 4 below for a visual representation of the principle of *refraction*.

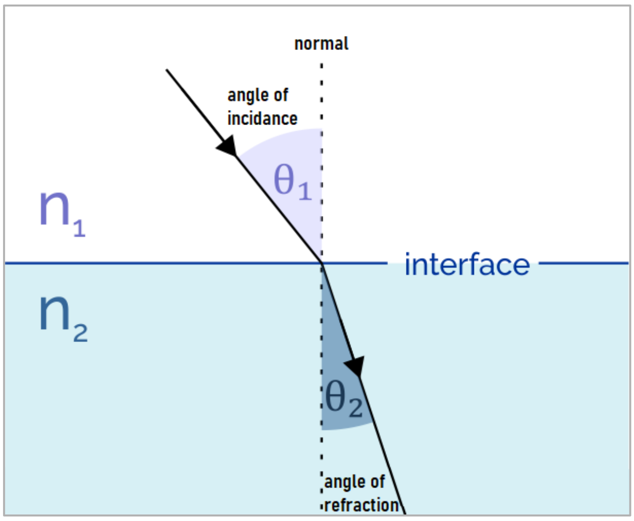

Figure 4: Refraction

With light, this "bending" can be expressed using Snell's law, which states that the *refractive index* of the first material times the sin of the angle of incidence equals the *refractive index* of the second material times the sin of the angle of refraction, as seen in EQUATION 4.

Equation 4: Snell's law

$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$ where:

n_1 is the refractive index of the first medium ($unitless$)
θ_1 is the angle of incidence in degrees (°)
n_2 is the refractive index of the second medium ($unitless$)
θ_2 is the angle of refraction in degrees (°)

The refractive index of a material x is equal to the velocity of light in a vacuum divided by its velocity in material x, as seen in EQUATION 5.

Equation 5: Refractive index

$n = \frac{c}{v}$ where:

n is the refractive index ($unitless$)
c is the velocity of light in a vacuum in meters per second (ms^{-1})
v is the velocity of light in a substance in meters per second (ms^{-1})

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1.4.3 Diffraction

When a wave hits an obstacle or opening that is small or comparable to its *wavelength*, the wave will bend around the obstacle or spread out after the opening. This is called diffraction. The reason *diffraction* happens is that, as soon as a wave hits an object, the object will function as a wave source itself, thus causing *interference* in the original wave. This causes the blurring of shadow edges, for example. See FIGURE 5 below for a visual representation of the principle of *diffraction*.

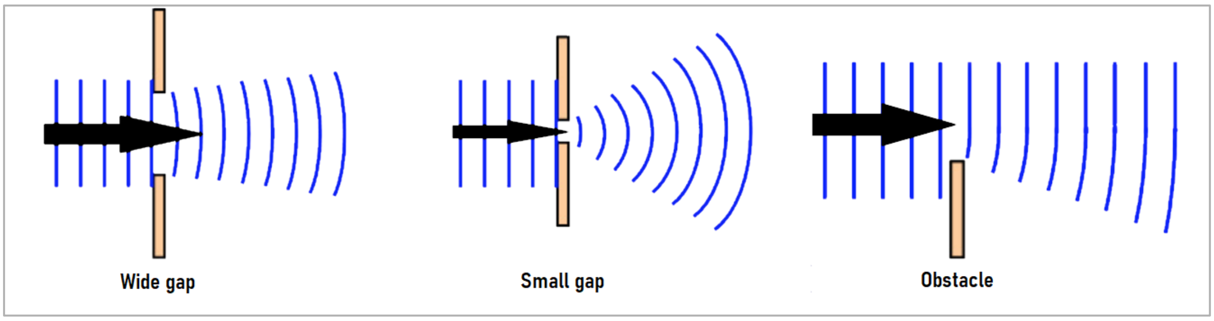

Figure 5: Diffraction

As one can see in the figure above, the wider the gap, the smaller the angle of diffraction, and vice versa. This can also be seen in the following EQUATION 6, which can be used to calculate the diffraction angle with a single slit.

Equation 6: Diffraction

$d \sin(\theta) = n\lambda$ where:

d is the width of slit meters (m)
θ is the angle of diffraction in degrees $(°)$
n is the order number for the maximum diffraction $(unitless)$
λ is the wavelength in meters (m)

1.4.4 Interference

When two waves meet, the resulting wave will be the sum of both *originating waves*. This is what we call *interference*. See FIGURE 6 on the next page for a visual representation of the principle of *interference*.

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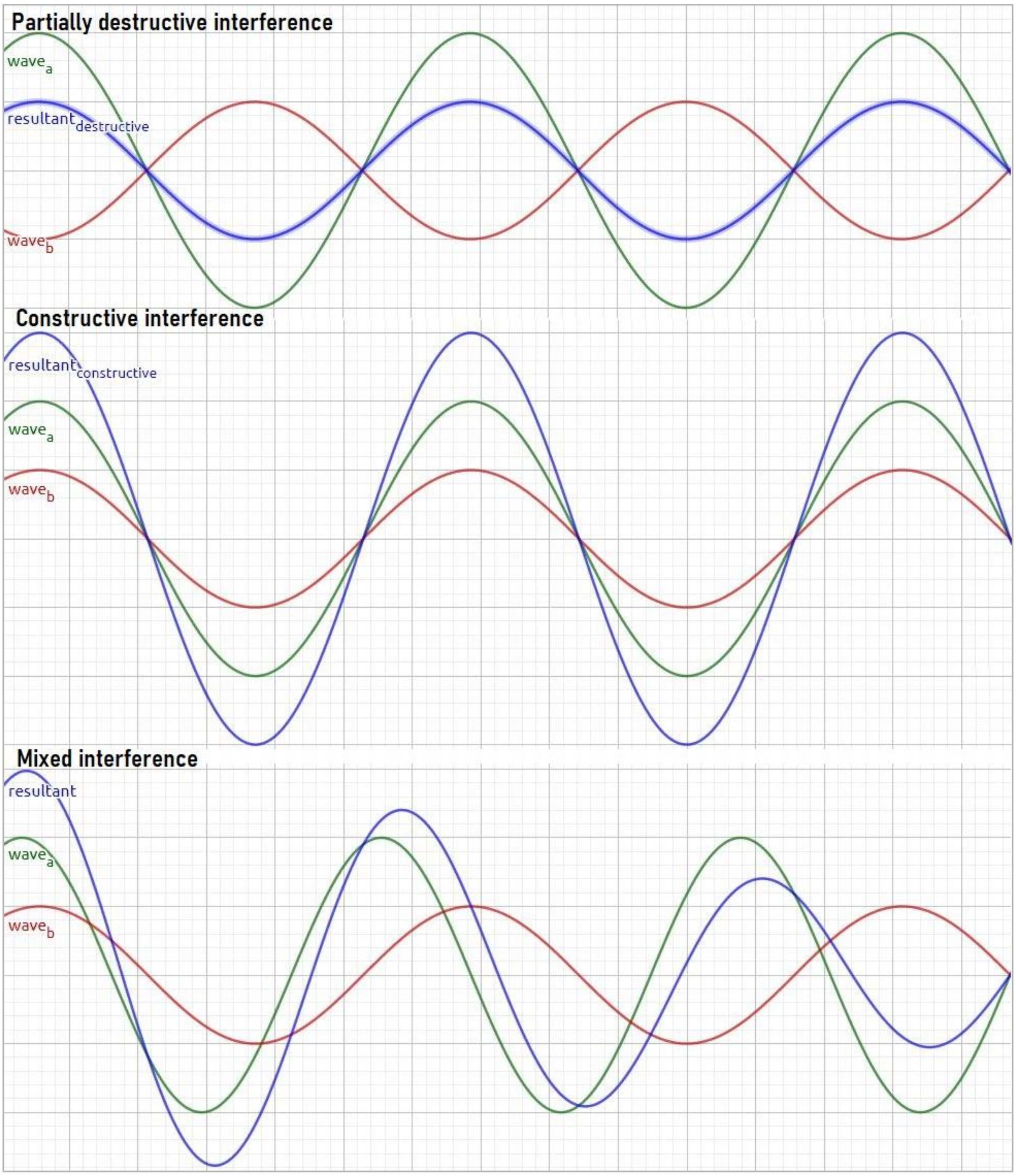

Figure 6: Interference

1.4.5 Doppler effect

When the source of a wave moves relative to an *observer*, a different *frequency* will be observed than the one emitted by the *wave source*. The reason behind this is that when the wave source travels towards the observer, both the source and the wave front are pushed towards the observer, causing a higher *frequency*. The same principle applies when the source travels away from the observer. See FIGURE 7 on the next page for a visual representation of the principle of the *Doppler Effect*.

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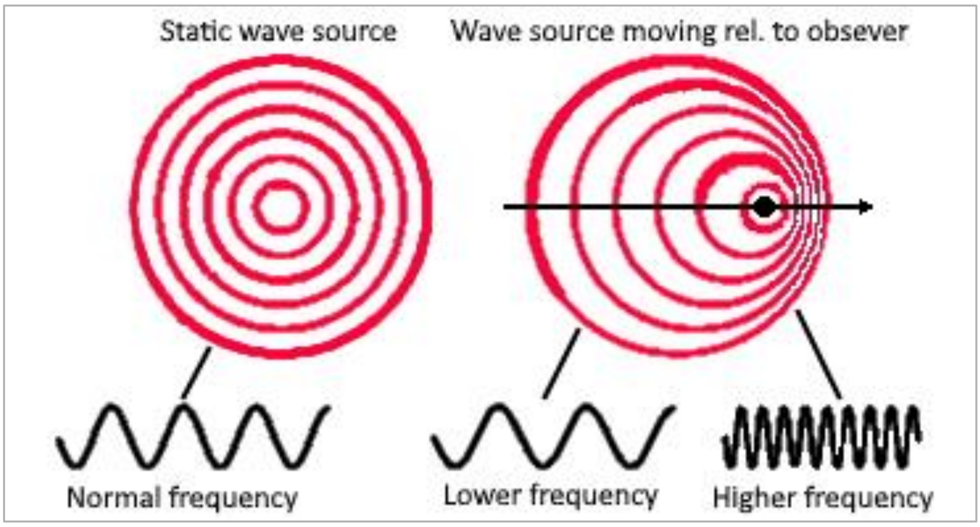

Figure 7: Doppler Effect

With light, this effect can be seen in stars, where their relatively high *velocities* cause what we call *redshift* and *blueshift*. These are caused by the same effect as an ambulance siren passing by and changing *pitch*. The observed *frequency* of light can be calculated with EQUATION 7.

Equation 7: Doppler Effect (light)

$f = f_1(1 - \frac{v}{c})$ where:

f is the observed frequency in Hertz (Hz)
f_1 is the emitted frequency in Hertz (Hz)
v is the velocity of the wave source rel. to the observer in meters per second (ms^{-1})
c is the velocity of light in a vacuum in meters per second (ms^{-1})

1.5 CONCLUSION OF CHAPTER ONE

Waves are the propagation of disturbances with a fixed *frequency* and *amplitude* which exhibit wave properties and effects, such as *reflection*, *refraction*, *diffraction*, *interference,* and the *Doppler Effect*. Those wave properties are relevant to the main question due to their influence in *optical wireless communication*, which uses both electromagnetic and sound waves to communicate.

For instance, the *reflection* of a light beam could potentially be used to extend the range of optical wireless communication, by creating relatively long lines-of-sight.

Atmospheric *refraction*, however, caused by the velocity of light decreasing with increasing atmospheric density, can cause a deviation of the beam when communicating at long range, which is why it needs to be predicted and calculated to be compensated for. Additionally, refraction caused by the passing of the beam through different media such as air and glass must also be calculated to be compensated for.

Understanding *diffraction* and *interference*, on the other hand, is required when comparing radio and line-of-sight propagation (as seen in CHAPTER TWO).

The *Doppler Effect* is only important when the emitter moves relative to the receiver. However, it would have to reach *relativistic velocities* to be remotely noticeable.

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2 APPLICABILITY OF OPTICAL WIRELESS TRANSMISSION

Now that wave physics are clarified, the value and effectiveness of an eventual *light-based communication* system need to be explored. Therefore, it needs to be compared to its most close relative: *radio communication*.

2.1 RADIO-WAVE PROPAGATION

Due to *diffraction* and the *wavelength* of radio waves closely matching the size of most encountered obstacles, radio waves *propagate* following the easily understood inverse *square law*, as seen in EQUATION 8.

Equation 8: Inverse Square Law

$I = \frac{P}{4\pi r^2}$ where:

I is the received intensity in Watts per meter squared (Wm^{-2})
P is the power in Watts (W)
$4\pi r^2$ is the outer area of the projected sphere in meters squared (m^2)
r is the distance from the source (radius) in meters (m)

This means that, any antenna from which *radio propagation* occurs will result in *omnidirectional emission*, which can then also be received omnidirectionally. However, due to *beam divergence loss*, which is caused by the *geometric spreading* of the *electromagnetic field*, the *received intensity* quickly drops, as seen in the previous equation.

From this also follows that radio waves would require emitting antennas hundreds or thousands of kilometres across to achieve *collimation* comparable with that of *LASER*[1] beams.

2.2 LINE-OF-SIGHT (OPTICAL) PROPAGATION

Electromagnetic waves of higher *frequency*, like light, however, are much easier to *collimate*, due to their wavelength being insignificant compared to the size of the emitting device. Due to this, little diffraction of visible and near visible light occurs. This means that light travels in a *line-of-sight propagation* pattern.

Beam divergence loss also plays a role in *line-of-sight propagation* but can be minimised by *collimating* the transmitted light into a narrow beam by using a LASER diode -which typically produces a narrow beam of radiation- as a transmitter.

Additionally, *atmospheric absorption* and *atmospheric scattering* can cause strong *degradation* in emitted signals. While *atmospheric absorption* losses can be minimised by choosing a *transmission wavelength* that lies within a *low-loss window*[2] in either the *infrared*, *visible*, or *ultraviolet* region, significant *atmospheric scattering* losses can be caused by any variability in *atmospheric conditions* such as rain, fog, or dust.

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[1] Light Amplification by the Stimulated Emission of Radiation
[2] Band of wavelength where the signal attenuation is minimum.

2.3 POSSIBLE APPLICATIONS OF OPTICAL WIRELESS COMMUNICATION

Optical wireless communication is obviously not meant for the masses. That would require a *collimated*[3] emitter for every receiver and a *line-of-sight*[4] between each of them, which is obviously not viable.

A possible application would be for discrete military communication. The most common communication methods used by the military are the radio and in rarer cases the internet. Both are relatively accessible by an enemy due to their geometric spread or their worldwide nature. It might seem like that is not a problem, because of the strong encryption used by the military, however, every encryption is breakable within a finite amount of time, which means the rise of quantum computers may lead to the failing of such algorithms[5].

That is where a *collimated* light-based communication system may be a solution. Such a system would be useful in relatively short-range, as a line of sight is required. However, due to that nature, any interruption by an eventual enemy would be instantly detected, and could interrupt the communication, if necessary. This would effectively prevent anyone from stealing the sent information. Another advantage is that LASER diodes also exist in both infrared and ultraviolet variants, which are both invisible to the eye, making them much harder to detect and thus intercept.

Similarly, a satellite could be built with a strong *collimated* LASER diode, which, could send a discrete message to a single person in the world, which is quite unbreakable. However, such a satellite is closer to fiction than to science, as "*both building sway and turbulence dramatically increase the BEP's*[6] *nonlinearity*." (Arnon, 2003)

On the other hand, a much shorter-range system is possible. Short-range wireless optical communications, like LiFi[7] have developed. "*LiFi is a mobile wireless technology that uses light rather than radio frequencies to transmit data.*" (pureLiFi, 2021) The main advantage of LiFi is that the area of connectivity is defined by the area of illumination, meaning that any type of interference is much simpler to be avoided. Additionally, LiFi can be used in areas where radio cannot, such as nuclear power plants, planes, and hospitals.

2.4 CONCLUSION OF CHAPTER TWO

Radio waves spread out in a sphere, while light can be collimated relatively easily. This means that signal intensity stays high at long distances when communicating with light, while radio signal tends to be attenuated very easily.

Optical wireless communication is applicable in short range communication, as a solution to interference problems which occur when multiple radio emitters use the same or a close frequency with too small of a distance.

Additionally, it can be used in long range situations, using collimated light sources, such as LASER diodes. This makes it suitable for military and experimental purposes.

[3] Made accurately parallel.
[4] A line from an observer's eye to a distant point.
[5] (Wood, 2011)
[6] Bit-Error Probability
[7] Light Fidelity

3 FABRICATION OF AN OPTICAL WIRELESS AUDIO TRANSMITTER

3.1 BUILDING THE EMITTER

When first trying to make an analogue light-based audio transmitter, copious mistakes were made. First was tried to connect a *LED*[8] directly to an audio signal. The hypothesis was that the LED would turn on at the positive peaks of *AC*[9], thus potentially transmitting a signal. However, this failed, as in addition to LED's being diodes, which only conduct current in one direction, the relatively low power from the audio signal would not suffice to power any lighting.

Subsequently, an audio signal was connected in series to a power source and a LED. The hypothesis was that the audio signal would *modulate*[10] the power of the LED and send the signal. In practice, this worked surprisingly well, having a significantly high SNR[11]. This was the first working analogue optical wireless audio transmitter prototype, which was thus codenamed Mk. 1, as seen in FIGURE 8.

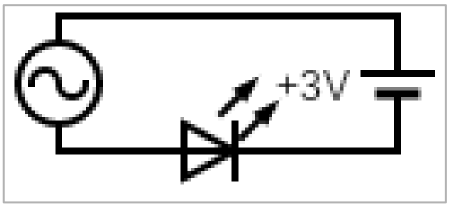

Figure 8: Transmitter Mk. 1

Numerous tests of the Mk. 1 revealed that this relatively simple circuit could only be used with an LED or a LASER diode with a maximum power of 1 mW. From this can be concluded that this circuit is practically unusable at long range.

This led to the hypothesizing of Mk. 2, which uses an *NPN*[12] transistor to modulate the power of a relatively high-power light source, such as a LASER diode. Additionally, an audio transformer is used to both isolate the circuit from the audio source and to significantly increase the signal strength.

As seen in FIGURE 9, when AC flows through the primary coil of the audio transformer, a magnetic field is induced in the ferromagnetic core, which induces AC through the secondary coil. When a current flows through the base and collector of the NPN transistor, a current will flow from the base to the emitter, thus powering the diode and modulating the input signal.

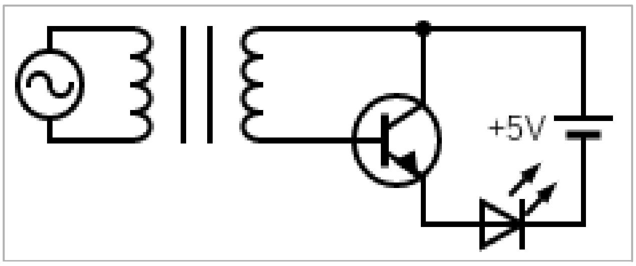

Figure 9: Transmitter Mk. 2

However, the frequent tests of the Mk. 2 revealed that the audio quality was relatively low when compared to that of the Mk. 1, plausibly due to the quality of the NPN transistor and diode used. Due to those same factors, the SNR of this version has proved to be significantly lower.

[8] Light-Emitting Diode
[9] Alternating Current
[10] To vary the amplitude, frequency, or phase of a carrier wave to transmit information.
[11] Signal-to-Noise Ratio
[12] Negative-Positive-Negative

3.2 THEORETICAL VISUALS

The Mk. 1 analogue optical wireless transmitter works by upshifting the equilibrium of the signal. The value of this upshift is determined by the target voltage of the light source used as an emitter. See FIGURE 10 for a visual representation.

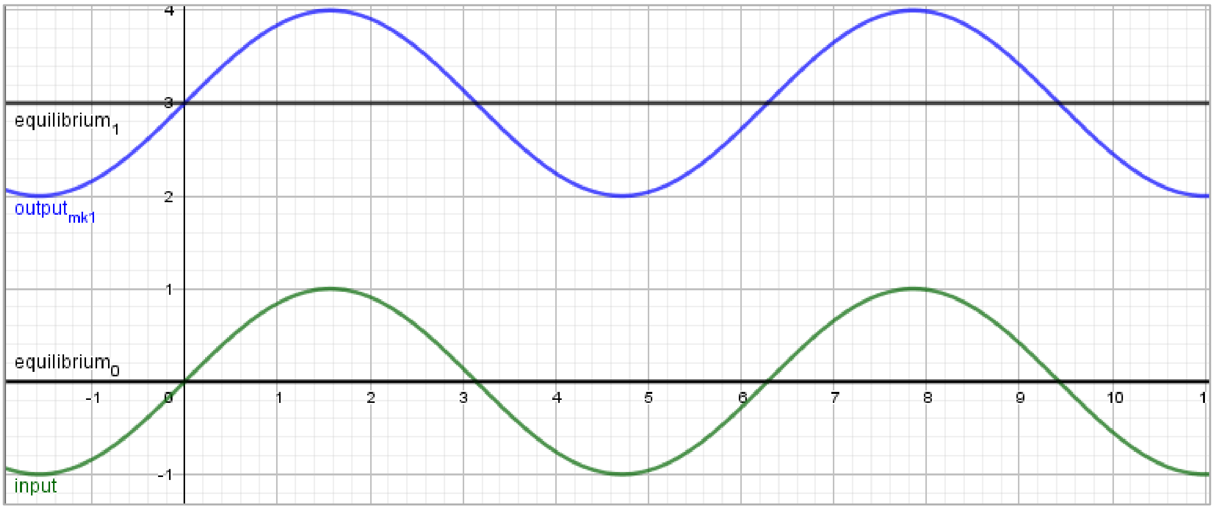

Figure 10: Input vs Mk. 1 Output

The Mk. 2 analogue optical wireless transmitter works quite differently. This transmitter works by turning the voltage off when the signal is negative and turning it on when the signal is positive. The voltage is once again determined by the light source's target voltage, as seen in its specifications.

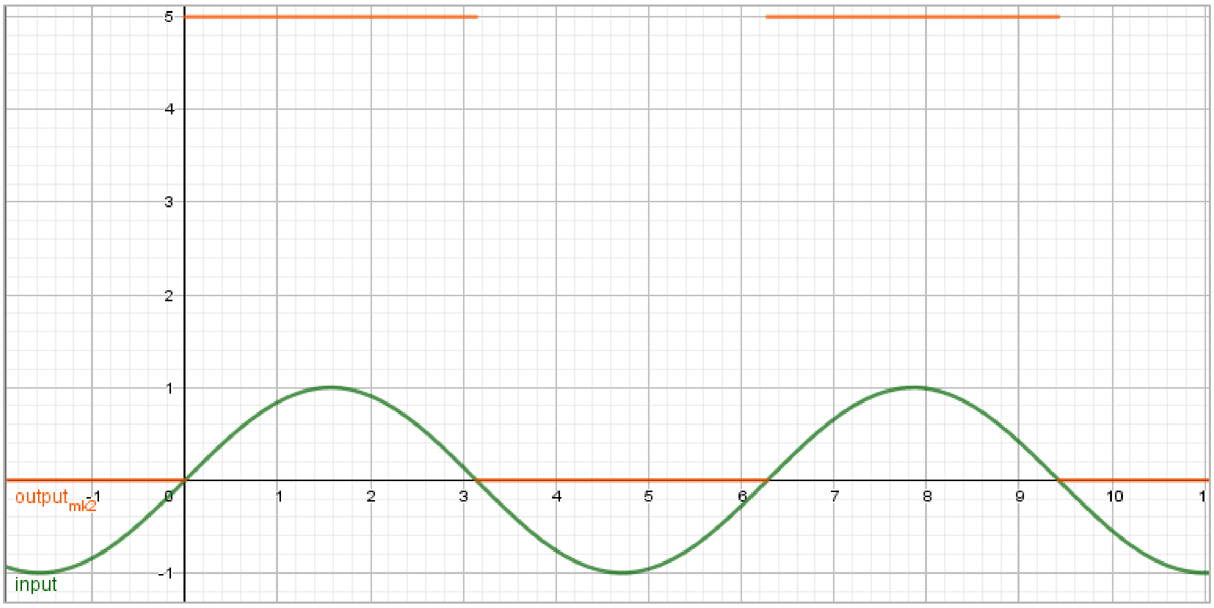

Figure 11: Input vs Mk. 2 Output

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3.3 BUILDING THE RECEIVER

Once the transmitter Mk. 1 was built, a receiver had to be built, which was relatively simple when compared to building the transmitters. First was tried to use a camera to record the emitted light. A program was then made that would detect the variations in light and convert those variations into a *WAV*[13] file. However, most cameras have a maximum framerate setting of 30 *FPS*[14] [15], which means that the maximum detected frequency would be around 30 Hz.

This is insufficient for a usable communicator, as the human hearable frequency range spans from about 20 Hz to 20 kHz.[16]

After concluding using a software was not the most efficient solution, a new hypothesis was made: a series of photovoltaic cells (i.e., a solar panel) connected to an amplifier should be enough to remove any DC voltage and amplify the received signal. An electrical diagram of a simple photovoltaic receiver can be seen in FIGURE 12. This receiver offered a low SNR in low-lighting conditions, however, due to its relatively high surface area, this receiver picked up noise when exposed to ambient lighting sources, such as neon bulbs, causing a constant square-wave 100Hz noise.

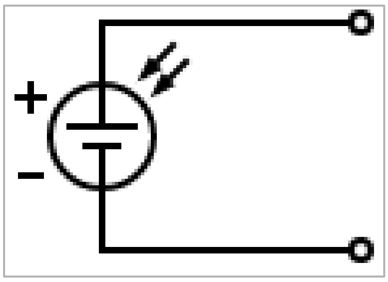

Figure 12: Photovoltaic receiver

To solve this problem, first was tried to use a solar panel with a smaller surface area, which hypothetically would pick up less ambient light, potentially causing less noise in the transmitted signal. However, the relatively small surface area of the solar panel did not significantly increase the SNR.

To increase the SNR, a new hypothesis was made: using an LDR[17] in series to an adequate power source (according to the lighting's specifications) would modulate an incoming signal over a significantly smaller area. This version of the receiver can be seen in FIGURE 13.

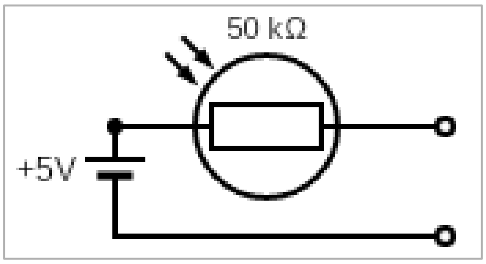

Figure 13: LDR receiver

However, LDR's have a limited resistance reactivity, meaning the transmittable frequency is significantly limited by the usage of such a resistor.

At this point was decided that the original receiver would suffice for the purposes of this paper, as the SNR was relatively high when compared to any other model, and that it can be increased even more by simply turning off any ambient lighting or directing the receiver away from interfering ambient lighting. The definitive version of the photovoltaic receiver can be seen in FIGURE 16.

[13] Waveform Audio File Format
[14] Frames Per Second
[15] (VideoSurveillance.com LLC., 2021)
[16] (Purves, Augustine, & Fitzpatrick, 2001)
[17] Light-Dependent Resistor

3.4 RESULTS

3.4.1 Short-range test of Mk. 2 + Definitive photovoltaic receiver

In this test, a 12 V LED strip, with a 12 V LED power supply were used with the Mk. 2 circuit, equipped with one multimeter measuring the voltage across the LED strip and another measuring the current (in mA) going through the same LED strip.

The LED strip caused the voltage drop to about 10 V at the power supply, which means the current was too high and the power supply decreased the voltage to regulate the current, to about 50 mA.

A test song (*Bad Guy – Billie Eilish*, chosen because of its relatively high number of low-frequency sounds) was then played on the circuit and received with the definitive photovoltaic receiver. The receiver is then moved up and down, which demonstrates the unfocussed LED's propagation to be analogous to that of radio (following the inverse square law), causing a direct decrease in signal intensity when brought further from the receiver.

This test demonstrates that LEDs or any unfocussed/uncollimated light sources can only be used at relatively short distances, because of significant signal attenuation.

For convenience of access, a video of this test was made and uploaded to YouTube at: https://youtu.be/k2tEKeeLna4

3.4.2 Long-range test of Mk. 2 + Definitive photovoltaic receiver

In this test, a $5\ mW$ Red ($650\ nm$) LASER diode, with a $5\ V$ power supply were used with the Mk. 2 circuit, which were both clamped in place so it would not move while testing.

The diode was pointed at the receiver, and a test song (*Never Gonna Give You Up – Rick Astley*, chosen because it contains frequencies in the whole hearable spectrum) was then played on the circuit and received with the definitive photovoltaic receiver.

The distance between the receiver and the emitter was then increased, until it had reached $41.4\ m$. There was no noticeable drop in the signal intensity at $41.4\ m$, and the SNR and sound quality were unchanged.

During this test, however, people walking have shown the importance of a constant line-of-sight while transmitting any information, due to light not being diffracted by relatively big obstacles.

The distance between the receiver and the emitter was then increased to $70.2\ m$, distance at which there was still no noticeable drop in the signal intensity, SNR, or sound quality.

However, due to the low level of collimation of this laser diode, the illuminated area at $70.2\ m$ had a diameter of around $15\ cm$, which means the light intensity was under $0.3\ Wm^{-2}$, which demonstrates the importance of high-quality LASER diodes with an elevated level of collimation.

This test demonstrates that LASER diodes or any focussed/collimated light sources can be used at relatively long distances, because of the relatively low signal attenuation.

For convenience of access, a video of this test was made and uploaded to YouTube at: https://youtu.be/WjydHmNeUyg

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3.4.3 Pictures

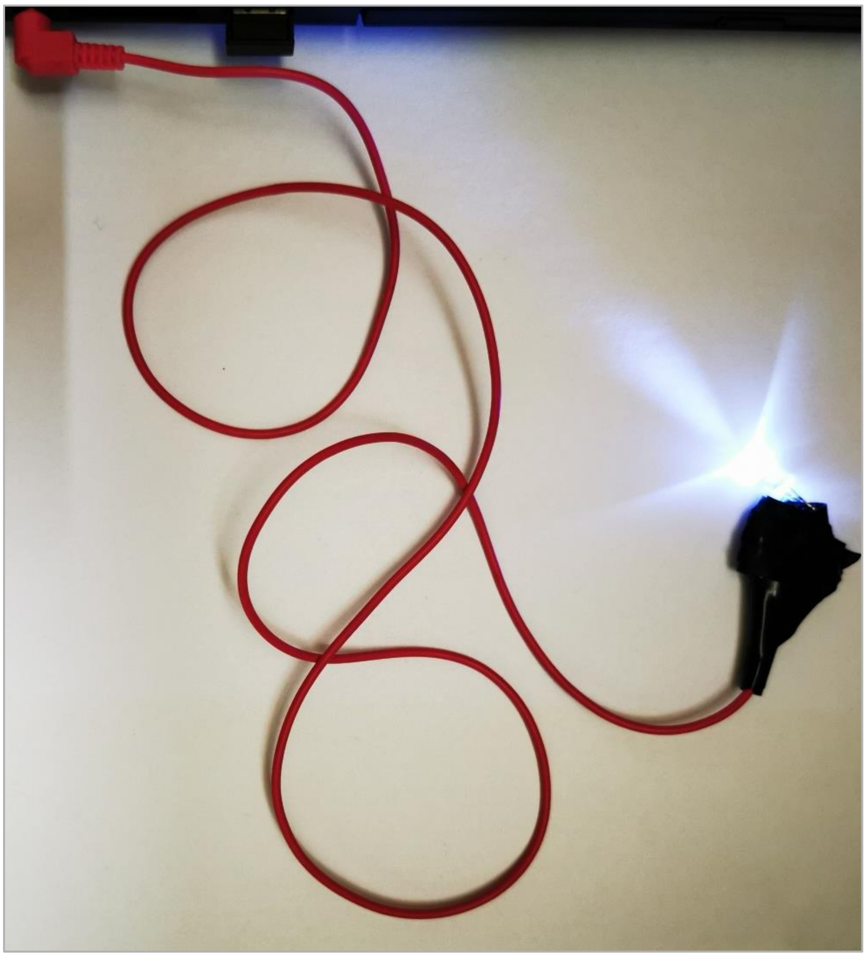

Figure 14: Original "Mk. 1" Prototype, as seen in first video.

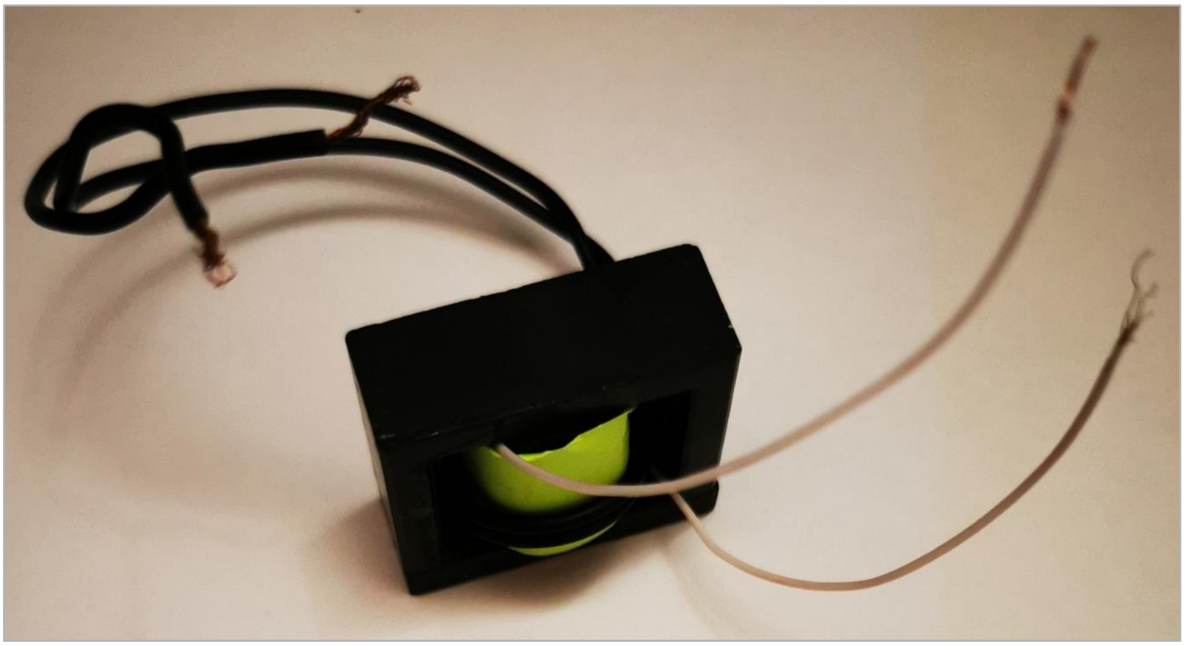

Figure 15: Transformer used in original Mk. 2 Design

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Figure 16: Definitive Photovoltaic Receiver

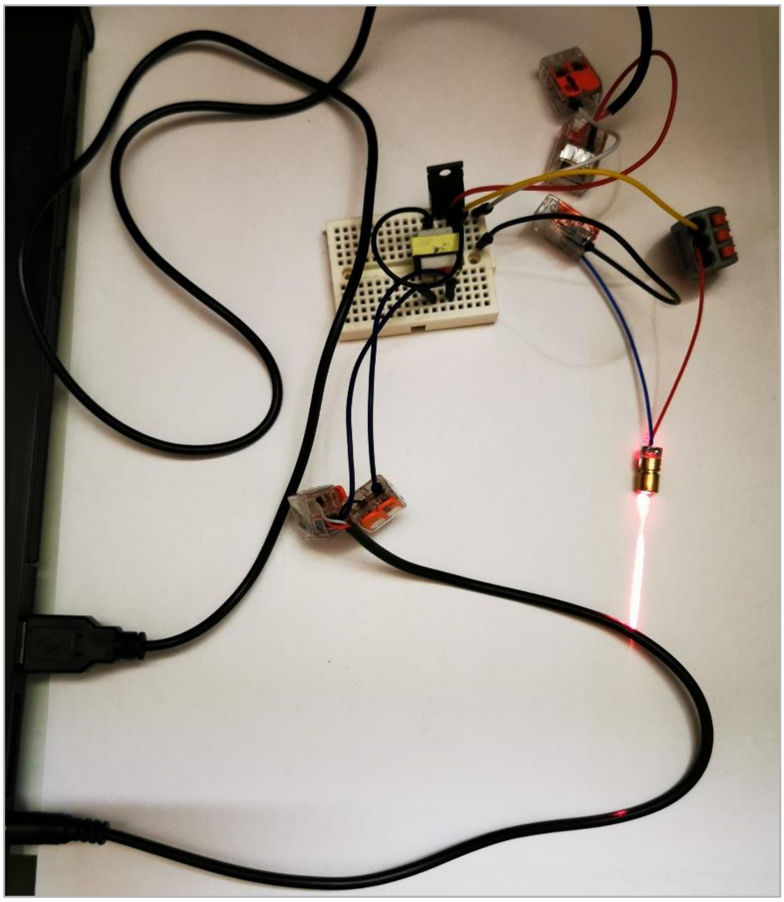

Figure 17: Definitive components for Mk. 2

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Figure 18: Loudspeaker used for testing (JBL GO)

Figure 19: Multimeters used for testing (Elro M940 & Chauvin Arnoux F11)

3.5 Conclusion of Chapter Three

Fabricating an analogue wireless optical transmitter was the key to understanding how to communicate by analogue wireless optical audio transmission. Understanding the wave properties described in Chapter One and understanding its applications mentioned in Chapter Two was critical to the fabrication of such a device.

By using a solar panel as a receiver and build the simple amplifier-based Mk. 2 circuit, the definitive product of this paper was created.

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4 CONCLUSIONS AND FURTHER RESEARCH

4.1 CONCLUSIONS

4.1.1 Applicability

There can be no doubt that optical wireless communication is a technology that will be used soon. Due to its properties, such as its ease of collimation and thus relatively low power loss, light proves to be an advantageous replacement for radio or microwaves.

4.1.2 Wave behaviour

Wave properties and effects, such as *diffraction*, *refraction*, *interference*, and the *Doppler Effect* are particularly important when building an analogue optical wireless transmitter.

4.1.3 Fabrication

Analogue optical wireless audio transmission is achieved relatively easily, using either modulated LED's or LASER diodes, which makes it an interesting technology for hobbyists or even artists. However, for efficient scientific or public use, *digital* optical wireless communication may be a better alternative. For this to be certain, however, FURTHER RESEARCH is required.

4.2 FURTHER RESEARCH

4.2.1 Radio propagation tests

When the Mk. 1, Mk. 2 and both receivers were successfully built and evaluated, further research about radio was done. For *SDL*[18]'s 2020 *Treasure Hunt* (organised with Kasper van Maasdam), a simple radio emitter was made using a *Raspberry Pi*[19] 1 Model B running *CLI*[20] *Raspbian*[21] with the PiFM software, which was created by Oliver Mattos and Oskar Weigl.

This made it the perfect fit for a radio range and propagation experiment. The operating system used was the CLI version of Raspbian.

This *OS*[22] is relatively lightweight, making it suitable for running *headless*[23] and thus saving valuable resources for radio emission, which is why it was used for this test.

[18] Stedelijk Dalton Lyceum

[19] "The Raspberry Pi is a tiny and affordable computer that you can use to learn programming through fun, practical projects." (Raspberry Pi Foundation, 2021)

[20] Command-Line-Interface

[21] "Raspbian is a free operating system based on Debian optimized for the Raspberry Pi hardware." (A small, dedicated team of developers that are fans of the Raspberry Pi hardware, 2020)

[22] Operating System

[23] Without a monitor, keyboard, or mouse

The PiFM software "*uses the hardware on the raspberry pi that is actually meant to generate spread-spectrum clock signals on the GPIO*[24] *pins to output FM*[25] *Radio energy*." (Mattos & Weigl, 2015)

This software runs smoothly on the *RPI 1B*[26], which is why it was a perfect fit for these experiments.

Video reports of the experiments using this setup, which evaluate radio range and propagation were uploaded to YouTube for convenience of access at: https://youtu.be/u8YnelKJhyw.

In the video, was first made a simple emitter, which was evaluated (with the default starwars.wav file) at short-range, to assess whether it worked at all. Once it was determined the emission system worked correctly, a hint audio file from the *Treasure Hunt* was used in a loop, to demonstrate the PiFM software's ability to modulate FM frequencies (95.1 MHz).

Subsequently, the radio emitter was placed in the middle of the ground level of SDL, after which was listened to the emitting frequency with a radio receiver at varying distances, until the transmitted signal was unrecognisable. At ground level (without obstructions) a maximum detectable distance of 50 m was achieved, however, on the second floor, a distance of 14 m was enough to render the signal unrecognisable due to an extremely low SNR.

However, during the tests, at specific places within the emitter's range, interference was caused by external emitters, causing an unrecognisable alternating noise. Additionally, sometimes, the emitter would quite randomly start emitting on all frequencies, most likely due to *radio harmonics*.

With the results of this experiment was confirmed the sections above, which compare light and radio propagation.

However, even with those results, analogue optical wireless audio transmission is not practical, which means that further research is needed to make is useable on a greater scale.

4.2.2 Recommendations for further research

The author may suggest the use of CC[27] drivers when using LASER diodes in opposition to pulsing drivers, to increase the SNR when using the Mk. 2 transmission circuit. May also be suggested the use of mirrors to increase the testable communication range of optical wireless communicators.

Even though it is more complex, *digital optical wireless communication* is much more applicable to modern technology due to its use of binary to communicate. Additionally, using digital communication instead of analogue permits the use of ECC[28] to further reduce the BEP and thus significantly increase the SNR.

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[24] General Purpose Input/Output
[25] Frequency Modulation
[26] Raspberry Pi 1 Model B
[27] Constant Current
[28] Error Correction Code

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5 BIBLIOGRAPHY

A small, dedicated team of developers that are fans of the Raspberry Pi hardware. (2020). *Welcome to Raspbian*. Retrieved September 14, 2021, from Raspbian: https://www.raspbian.org/

Arnon, S. (2003, January 15). *Effects of atmospheric turbulence and building sway on optical.* Retrieved August 26, 2021, from Satellite and Wireless Communication Laboratory, Department of Electrical and Computer Engineering, Ben-Gurion University of the Negev: https://web.archive.org/web/20040406122259id_/http://www.ee.bgu.ac.il:80/~shlomi/publication/21.pdf

Ashish. (2019, November 22). *What Is The Law Of Reflection?* Retrieved September 22, 2021, from https://www.scienceabc.com/wp-content/uploads/2018/11/A-diagrammatic-representation-of-the-law-of-reflection-768x462.jpg

Bouwens, R., Groot, P. d., Kranendonk, W., Lune, J. v., Prop - Berg, C. v., Riswick, J. v., & Westra, J. (2013). *Binas* (Zesde ed.). Groningen, The Netherlands: Noordhoff Uitgevers.

Dimitrios. (n.d.). The Doppler effect explained by comparing a static and a moving sound source. *Adobe Stock*. Retrieved September 22, 2021, from https://stock.adobe.com/nl/images/the-doppler-effect-explained-by-comparing-a-static-and-a-moving-sound-source/388859337

Encyclopædia Britannica, Inc. (2021). *Longitudinal and Transverse waves*. Retrieved September 22, 2021, from https://cdn.britannica.com/08/62908-004-6E7798B5.jpg

Hosch, W. L., Gregersen, E., & Grinchenko, V. (2016, December 22). *Wave physics.* Retrieved May 27, 2021, from Encyclopaedia Britannica: https://www.britannica.com/science/wave-physics

Hosch, W., Hero, A. O., & Gregersen, E. (2014, March 21). *Telecommunications media.* Retrieved May 27, 2021, from Encyclopaedia Britannica: https://www.britannica.com/topic/telecommunications-media

Mattos, O., & Weigl, O. (2015, March 11). *Turning the Raspberry Pi Into an FM Transmitter*. Retrieved September 14, 2021, from Imperial College Robotics Society: http://www.icrobotics.co.uk/wiki/index.php/Turning_the_Raspberry_Pi_Into_an_FM_Transmitter

pureLiFi. (2021). *LiFi Technology*. Retrieved August 27, 2021, from pureLiFi: https://purelifi.com/lifi-technology/

Purves, D., Augustine, G., & Fitzpatrick, D. (2001). *The Audible Spectrum*. Retrieved September 15, 2021, from National Center for Biotechnology Information: https://www.ncbi.nlm.nih.gov/books/NBK10924/

Raspberry Pi Foundation. (2021). *Teach, Learn, and Make with Raspberry Pi*. Retrieved September 10, 2021, from Raspberry Pi Foundation: https://www.raspberrypi.org/

All illustrations in this document were made by Evan Pacini (inspired by cited sources).

Science Ready. (2021). *Diffraction of Light*. Retrieved September 22, 2021, from https://cdn.shopify.com/s/files/1/0093/2298/7617/files/Screen_Shot_2019-06-24_at_4.38.14_PM.png

Sonneveld, W., Bouwens, R., Doorschot, P., Reisen, J. v., & Vennix, A. (2014). *Overal Natuurkunde 5 VWO* (Vierde ed.). Groningen, The Netherlands: Noordhoff Uitgevers.

Szyk, B. (2021, July 13). *Snell's Law Calculator*. Retrieved September 22, 2021, from https://uploads-cdn.omnicalculator.com/images/snells-law2.png

Tom, Rob, Routley, S., & David. (2017, October 4). *Why do radio waves spread out while higher frequency waves travel in beams?* Retrieved August 25, 2021, from Physics at StackExchange: https://physics.stackexchange.com/questions/361055/why-do-radio-waves-spread-out-while-higher-frequency-waves-travel-in-beams

VideoSurveillance.com LLC. (2021). *Frame Rate*. Retrieved Spetember 15, 2021, from Video Surveillance.com: https://www.videosurveillance.com/tech/frame-rate.asp

Wood, L. (2011, March 21). *The Clock Is Ticking for Encryption*. Retrieved October 4, 2021, from Computerworld: https://www.computerworld.com/article/2550008/the-clock-is-ticking-for-encryption.html

All illustrations in this document were made by Evan Pacini (inspired by cited sources).