Transmission and reception of an ultra-low power signal

Location Tracking of Vespa Velutina

EE3L11: Bachelor Graduation Project Electrical Engineering

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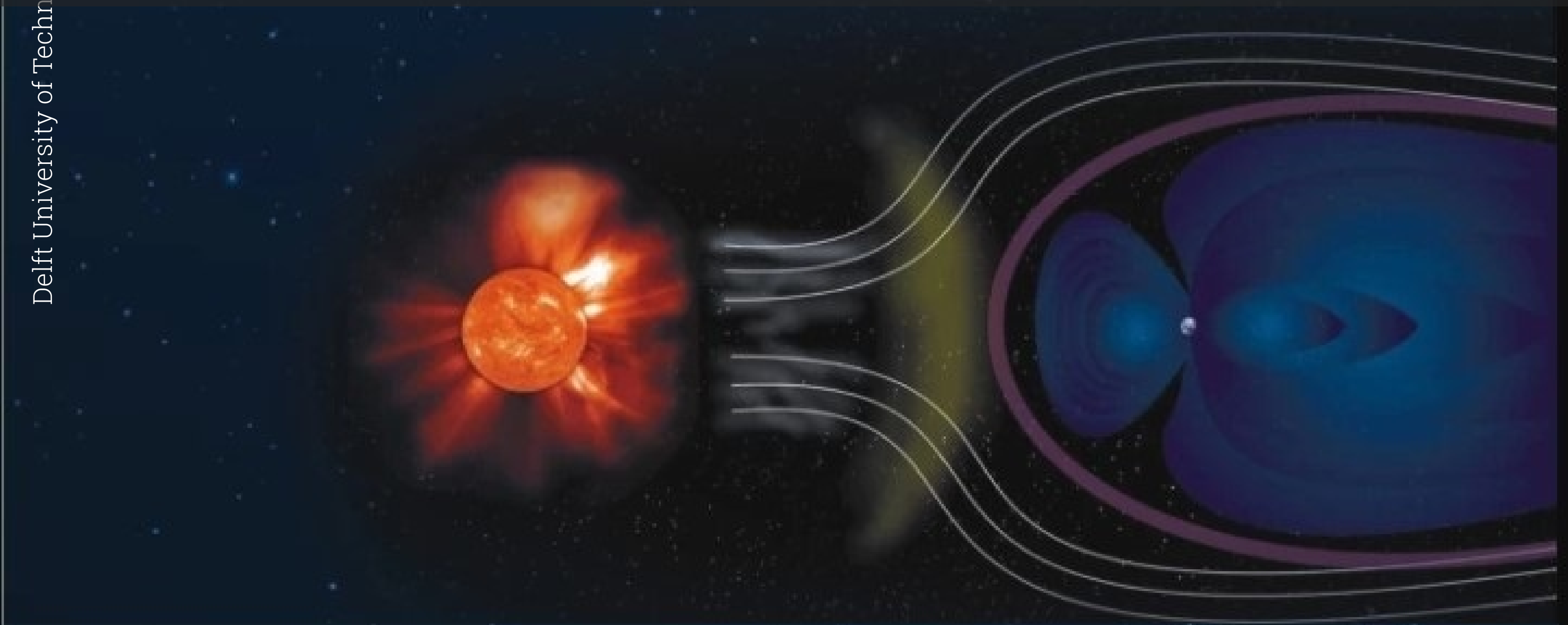

TU Delft

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by

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Project Duration:	04/2024 - 06/2024
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Preface

Designing a tracking system for the species of Vespa velutina, an invasive species that has taken over western Europe. The project was subdivided into 3 groups: transmitter design, transmission and reception design, and localization of the tracker. This project was led and supervised by Tomas Manzaneque Garcia for the client Henk Mezger. We would like to thank TU Delft for their support in this project, including providing working space, equipment and the many professors who have helped consult us during the designing process. Special thank you to our supervisor for continuous support and guidance throughout the entire project.

Emmad Hassan
Sofya Mikhaylitskaya
Delft, July 2024

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1
Introduction

Brought to Europe all the way in 2004 [1], the Asian Hornet (Vespa Velutina) has been an invasive threat ever since. Due to their aggressive temperament, the insect threatens the native wildlife with its ever-increasing population. Beekeepers are one of many who aim to combat this beast in an effort to protect their livestock, which involves tracking down and destroying their nests. To avoid population growth, nest finding must be fast and efficient before new queens can be produced. This is where electrical trackers come in - while manual trackers are labour intensive, electrical trackers can identify the nest's precise location. To achieve that, a tracker is placed on a worker hornet that then returns to its nest. Following the 2018 study [2] the hornets can carry only around 80 [%] of their own weight, which comes to at most 250 [mg]. With this weight, comes the strict limitation of transmission power. Furthermore, hornets are known to fly on average up to 500 [m] away from their nests, setting the transmission range.
This report is concerned with the design of efficient power transmission and reception between the transmitter and receiver. This means designing the signal (frequency and modulation), antennas (transmitter and receiver), and the receiver amplifier to make up for the signal's limited power. Pre-existing trackers, namely Lotek and Lowland, use 150 [MHz] frequencies with 16 [cm] monopole antennas for transmission, causing a lot of concern for efficiency. Additionally, the 150 [MHz] band isn't legally licence-free, making the use of these trackers restrictive. This is why this research aims to create a better hornet tracking device. Since the bigger aim of the project is to facilitate the finding of the Vespa Velutina's nests, the project also includes a receiver algorithm design with an automatic direction finding feature. While this is not a part of this report's subgroup's research, it does influence the receiver antenna design and further limits antenna gain, which must be compensated for with the amplifier.
To handle the project, three subgroups were devised. The other two subgroups being the transmitter circuit subgroup, in charge of designing and building the transmitter PCB and the frequency oscillator; and the the receiver algorithm subgroup, in charge of the automatic direction finding software on the receiver side. While their research will not be discussed in-depth in this report, it is important to understand that the three subgroups are heavily interlinked, and certain design aspects were chosen due to or for the sake of another subgroup. In such a case, this will be briefly mentioned.

Problem definition

As the tracking of the Vespa velutina is currently done using traditional methods such as manually following the hornet to its nest, these methods are notoriously inefficient and require a lot of prior expertise. Therefore, to address this problem a tracker made to be mounted on the hornet was designed, with its main concerns being weight, power, and size: Total transmitter weight must not exceed 250 [mg], causing tiny battery size and a need for a very simple lightweight antenna. The

battery is only able to supply µAmps of current, thereby only creating a small transmitted signal. Antenna gain is to remain small, since without knowing where the receiver is, the transmitter must be omnidirectional. Finally, since the hornet interacts with the environment the antenna is not to exceed certain dimensions, as it would impede the hornet.
Since the transmitted signal is of very low power, its range of reception is extremely small. Therefore, to address this issue a receiver system will be designed to not just extend the range but also to improve the quality of the signal such that it is better able to localise the hornet.

State of the art analysis

There aren't a lot of extremely lightweight transmitters on the market due to their specialised nature. However, this project was inspired by Lotek and Lowland trackers, studying the latter to attempt to make further improvements.
Regarding the receiver, there currently exists several receiver systems that are able to receive an AM modulated signals. However, their two main problems are the following: they are too expensive for the client and they are specific enough for the operating frequency. The designs currently being sold are made for wide band reception, however in this thesis a specialised design will be made for the legal operating frequency transmission and reception.

Thesis synopsis

Before proceeding further, it is highly crucial to mention the thesis synopsis, this allows both the designer and the reader to be clear on what will be further discussed.
First, the signal itself, namely its carrier frequency and modulation must be designed. This is because these characteristics will have severe consequences on the signal's path loss and ability to be picked up by the receiver.
It is important to mention that the transmitter itself, that is designed to be mounted on the hornet, will not be designed in this thesis. Rather, the power transmission system including the antenna and impedance matching circuit will be designed.
Similarly, for the receiver part, the tools for a successful reception of the transmitted signal in a long range will be designed, namely the antennas and the amplifier. However, finding the actual location of the hornet in real-life lies outside the scope of this report. This is instead the responsibility of the receiver software subgroup, which will use the designed receiver system and the received signal to perform further signal processing to eventually find the location of the hornet.

Structure of the thesis

First, the requirements are covered in Chapter 2. Then, the structure of the thesis will follow a similar routing to that of the signal itself: first the properties of the transmitted signal will be designed, referring to the frequency and modulation selection in Chapter 3. After the transmitted signal has been generated it will be transmitted, this will be discussed in Chapter 4, where the possible different methods for the transmission will be delved upon. After designing the appropriate transmission system for the signal has formulated, it will be simulated. If the simulation indeed satisfies the system requirements, the transmission system will be built and tested.
Regarding the receiver system, it will be first carefully described starting in Chapter 5, after designing the system requirements from the properties of the transmitted signal. The receiver antenna will be first discussed as it is what the signal first encounters. The different possible methods of reception, both in according to the different software algorithms will also be carefully discussed. After selecting the receiver antenna, a simulation will be made, if the simulation satisfies the system requirements it will be built and tested. Consequently, a receiver amplifier will also be designed in Chapter 6 to further enhance signal reception.
After each system has been designed and tested, a conclusion and discussion will be mentioned in Chapter 7, to mention any errors or improvements that could have been made in addition to the possible future works.

2
System requirements

2.1. Full System Requirements

To ensure the system works, requirements must be set. These define the end-goal and limitations of the project, and are shared among the thee subgroups. These requirements are as stated below:

Physical Requirements	**Electrical Requirements**	**Auxiliary Requirements**
Weight: $<$ 250 mg	Frequency: License-free/legal in NL	Costs: $<$ 25 euros
Resistant to humidity and rain	Battery: Chargeable/replaceable	Antenna material: Not chewable
Size: $\sim$11x5x2 mm (abdomen size)	Battery life: $\geq$ 3 hours	Operating conditions: Urban environment
	Detectable signal range: $\geq$ 500 meters (open field)	Receiver: Portable, direction approximation

2.2. Subgroup system requirements

Furthermore, to ensure the proper functioning of this subgroup's submodule (being the antenna and system frequency selection), even more indepth requirements must be set for each design element, listed below:

2.2.1. Frequency requirements

1. Carrier frequency should be licence-free if feasible, as defined within the Netherlands [3].
2. Producible by transmitter circuit.
3. Can achieve 500 [m] radius range.

2.2.2. Transmitter system requirements

1. Transmitter antenna should have omnidirectional radiation pattern.
2. Antenna should not impede the flying or walking capabilities of the carrier hornet.
3. Antenna should be able to withstand hornets trying to chew through it.
4. Antenna weight should not exceed 15 [mg].
5. Antenna length should not exceed 15 [cm].
6. Matching network should achieve $|\Gamma| \leq 0.2$.

7. Transmitted power should be maximised.
8. Polarisation should match that of the receiver antenna.

2.2.3. Receiver system requirements

Functional requirements

1. The detectable signal range needs to be at least 500 [m] both in open field and industrial area conditions to ensure effective tracking.
2. The gain of the receiver antenna needs to be higher than 3 [dB].
3. The input impedance of the antenna needs to be 50 [Ω].
4. VSWR of the receiver antenna should be less than 2.
5. The receiver antenna needs to be capable of working with direction finding algorithm.
6. The receiver antennas' directivity should have a major horizontal component.
7. Receiver antennas need to have have matching polarisation with the transmitter antenna.
8. Amplifier gain needs to be 20-25 [dB].
9. The gain of the amplifier at 433.9 [MHz] needs to be constant.
10. The amplifier needs to have a low Noise Figure (< 4 [dB]).
11. A biasing solution needs be design to ensure circuit operation.
12. Both input and output impedance must be 50 [Ω] for maximum power transfer.
13. The amplifier needs to have sufficient safety measures such as ESD protection.

Non-functional requirement

1. Receiver antenna need have maximum height of 1.5 [m].
2. Receiver antenna should be portable.
3. The amplifier needs to have minimal passive and active components.
4. Receiver amplifier should be compact and portable.
5. The receiver antenna should not cost more than 8 [€] to build.
6. Amplifier needs to cost less than 10 [€].

3 Frequency and Modulation Selection

3.1. Introduction

Carrier frequency is one of the most crucial design choices of the entire system, since it defines the oscillator, the receiver spacing, and the transmitted range. Most importantly, it's important to establish what is feasible, and what path loss factors play a role in determining sufficient range and efficiency. Furthermore, since bandwidth is a limited resource, there is also a question of legality. This chapter of the report goes over the design choices for the carrier frequency, as well as its modulation scheme.

Previously used

Previously designed trackers, namely Lowland and Lotek, have used about 150 [MHz] as their carrier frequency. As such it will be included in the analysis in this chapter for comparison.

3.2. Legality

First criteria to look at was legality, since one of the system requirements is for the product to be licence free unless unfeasible. This is an important requirement, as it improves the accessibility of the product: the end users, intended to be hobbyist beekeepers, will not need to pay or wait to obtain a licence. It also acts as a limiting factor, not only in terms of available frequency bands but also for other signal attributes (max power, duty cycle, channel width) as dictated by the dutch law [3].
Before looking into restrictions, the transmitter must be classified. As a tracker, the device is identified as a Radio Intended for Identification Applications (RFID) device. And at 500 [m] open-field range, the device is identified as a Short Range Device (SRD). The restrictions for both are described in Article 2, Annex 11, sub-categories 1 (Non-specific SRD) and 13 (RFID). Most desirable bands from these tables are described in Table 3.1. The duty cycle is defined over a period of one hour (3600 [s]).

Note that the frequencies in Table 3.1 can be split into three main groups: 169 [MHz], 433 [MHz], and 868 [MHz]. Some of the choices are so close-by because despite being close in frequency, they have different restrictions and as such desirable traits. Thus, for simplicity these three main values will be used to analyse the different characteristics of the frequency bands until the final selection, after which a more specific bandwidth will be mentioned.
Further note that the considered frequencies are all under 1 [GHz]. This is because attenuation increases with frequency as will be discussed in Section 3.4, which is highly undesirable.

Frequency [MHz]	ERP Power [mW]	Duty cycle [%]	Channel width [MHz]	Modulation
169.400 - 169.475	500	1	0.050	OOK
169.5875 - 169.8125	10	0.1	0.225	OOK
433.050 - 434.790	1	None	1.74	Any
434.040 - 434.790	10	None	0.025	Any
869.400 – 869.650	500	10	0.250	OOK
865.6 – 867.6	2000	None	0.200	Any

Table 3.1: The legal restrictions as stated for Non-specified SRD (above rows, article 2, annex 11, sub-category 1) and RFID (last row; article 2, annex 11, sub-category 13) [3].

3.3. Wavelength

Wavelength λ is important, because it influences antenna design - optimal antennas are often a multiple of $\lambda/4$ in length. Shorter antennas are much less efficient, and longer ones produce directivity lobes [4]. This will be further explored in Section 4.3.2 of Chapter 4. Furthermore, wavelength also will determine the placement of the receiver antennas. For the receiver algorithm to work, two antennas must be placed $\lambda/2$ distance apart from each other. Thus, λ mustn't be too big so that it's unfittable on the end-user's backpack. Table 3.2 showcases the different frequencies' wavelengths, assuming speed of light c = $3 * 10^8$ ($\lambda = c/f$).

Frequency [MHz]	150	169	433	868
Wavelength λ [cm]	200.0	177.5	69.28	34.56
$\lambda/2$ [cm]	100.0	88.76	34.64	17.28
$\lambda/4$ [cm]	50	44.38	17.32	8.64

Table 3.2: Different frequencies' wavelengths and commonly used wavelength fractions

There is a clear advantage towards higher frequencies - the higher the frequency, the shorter the wavelength, the smaller the antenna must be, and the closer the receiver antennas can be placed. When speaking of hornets, which tend to be about 2 [cm] long [1], a 8.64 [cm] antenna is much more manageable than a 50 [cm] one.

3.4. Path losses

Based on transmitter circuit research, the chosen battery can output only up to 450 [µW]. Furthermore, most of this power is kept within circuit, so the antenna will likely only receive at most 10 [%] of power, about 45 [µW] = -43.47 [dB]. With such a small input power, path loss will be a major issue in achieving the required 500 [m] range, even in open-field. Which is why it must be carefully considered.

Attenuation

Unfortunately, higher frequencies have one major disadvantage: they attenuate much faster than lower frequencies, as demonstrated by the Friis' Equation 3.1 in linear form [5].

$$P_{rx} = P_{tx} G_{tx} G_{rx} \frac{\lambda^2}{(4\pi R)^2} G_a G_r G_p \qquad [W] \tag{3.1}$$

Where: P_{rx} is received power, P_{tx} is transmitted power, G_{tx} and G_{rx} are transmitter and receiver antenna gains, R is rx-tx distance, and G_a, G_r, and G_p are atmospheric gasses gain, rain gain, and polarisation gain respectively. The latter three are at most 1, since they describe losses.

$(4\pi R)^2/\lambda^2$ describes the free space attenuation loss L_{free}. Since $L_{free} \propto 1/\lambda^2$, higher frequencies suffer exponentially larger losses, limiting the achievable range. Table 3.3 demonstrates these free space losses for R = 500 [m]. This is a clear advantage of lower frequencies.

Frequency [MHz]	Losses magnitude [dB]	Losses magnitude [MW]
150	69.94	9.87
169	70.98	12.53
433	79.15	82.24
867	85.18	329.73

Table 3.3: Free space losses for different frequencies at R = 500 [m]

Atmospheric gasses attenuation is negligible below 1 [GHz] [6], and the device will not be used in rainy weather, as hornets don't fly in such conditions. Therefore, both G_a and $G_r \simeq$ 1.
Polarisation losses are a much bigger concern, since a vertical antenna will receive none of a horizontally polarised signal. Therefore, both transmitter and receiver must be designed with the same polarisation in mind to ensure $G_p \simeq 1$ [5].

Multipath and absorption

Despite higher attenuation, higher frequencies do have the advantage of multipath - higher frequencies tend to bounce off medium interfaces, whereas lower frequencies tend to get absorbed or penetrate [7]. Because the hornets are located in urban and rural areas, filled with buildings and foliage, this is an important advantage. For lower frequencies, it is irrelevant that the signal gets less attenuated if it cannot even reach the receiver. In client's previous experience, the 150 [MHz] signal had a tendency to work poorly in dense areas, only serving up to about 30 [m] range. However, this is also a double edged sword. The receiver subgroup's direction finding algorithm depends on a single signal transmission path. Too many alternatives will throw the software off. Furthermore, this is a very difficult topic to research: frequency absorption and reflection is very material dependent, making overall path prediction very difficult. At best, current research only provides possible models for path loss in both urban and rural environments [8] [9].
Another heavily contested property is the ability of a given frequency to penetrate materials. Some sources indicate that higher frequencies are better at penetration [10], however there are others in disagreement [11]. In the end it's too unclear to assign a benefit to either high or low frequencies.

Signal interference

Interference is another big concern - since the desired bandwidths are licence free, it also means they will be popular. For example 433 [MHz] is often used by remotes [12], while 169 [MHz] is used as a building sensor making it less crowded [13]. This may cause issues, as frequency signals tend to be messed up by the presence of other same-frequency signals nearby [14]. Fortunately, since the hornet is likely to move fast, it's less likely to stay in the overlap zone. Thus, this type of interference is not considered a major concern.
As for manmade interference levels, there was no study on interference above 50.5 [MHz] in the Netherlands [15] and no sufficient equipment was found at the university to conduct personal experiments. Therefore, considerations for this criteria are limited and must be verified experimentally via prototype testing.

3.5. Oscillator capabilities

Despite all of the above considerations playing a role, the most crucial is whether a given frequency can even be generated. This topic is further discussed in the transmitter circuit subgroup report, but in the end it was determined 169 and 433 [MHz] were both feasible to generate. Given the amount of resources available to the 433 [MHz] frequency oscillators and other advantages such as receiver antenna spacing and better antenna efficiency, it was chosen as the final frequency. More specifically, 433.92 [MHz] was chosen as central frequency.

3.6. Frequency selection: Conclusion

In the end, 433.92 [MHz] was selected. That is a wavelength λ of 69.14 [cm] and a free-space attenuation of 79.17 [dB]. Given that the antenna will at most receive 45 [µW] = -43.47 [dB] and that the SNR should be at least 10 [dB] to ensure the signal is properly read, the receiver should have sensitivity of at least -132.64 [dB] = 54.45 * 10^{-15} [W] not accounting for antenna gains. 433.92 [MHz] allows for reasonable receiver antenna spacing and approximate antenna size of 34.57 [cm], and introduces multipath while not relying on it. Additionally, since it's a popular band, a lot of transreceivers are available, making testing accessible. Legally speaking, this band falls into the 433.050 - 434.790 band, allowing for no duty cycle restrictions and a bandwidth of 1.5 [MHz] total.

3.7. Modulation

Having selected the carrier frequency, it's also important to look into modulation. Legally speaking, there are no restrictions. However design-wise, there is plenty to consider - the transmitter should be lightweight, and as such the modulation circuit should be simple. The transmitter has limited battery, and so the signal should not be power consuming. The available power at 500 [m] is low, so the signal should be easy to pick up. In the end, On-Off-Keying (OOK) was the best choice. It is a digital amplitude modulation technique that represents '1/0' with a simple 'signal/no signal present' scheme as seen in Figure 3.1. It is by far the simplest to implement, it is capable of encoding a binary code, and it saves battery since for '0'es the oscillator is switched off. Encoding a code is beneficial since having a recognisable code improves the reception of the signal [16]. This is further covered in the report of the receiver subgroup.

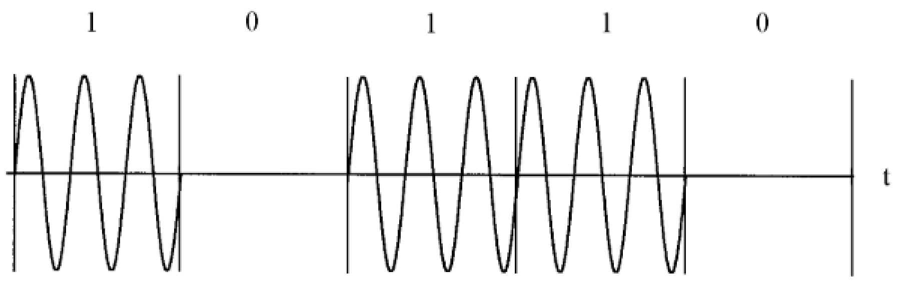


Figure 3.1: An example of OOK modulation [16]

4

Transmitter antenna design

4.1. Introduction

This chapter of the report focuses on the transmitter antenna and its matching L-network. Since this antenna will be connected to the transmitter that as per requirements in Section 2.1 should not weigh more than 250 [mg], it will be subject to many limitations. Not only should the antenna be lightweight (15 [mg] max) and omnidirectional to allow tracking from any direction, it must also be no longer than 15 [cm] in any given direction, and sturdy as set by the client. This is because hornets fly in vegetation-dense environments and the antenna is likely to get stuck in foliage. This will agitate the hornet that will try to chew the antenna off. As such, the antenna should be able to withstand hornet bite force and not catch onto things in the environment. Finally, since the transmitter battery only delivers 450 [µW] worth of power, and only approximately 10 [$\%$] of that will actually reach the antenna at best, the reflection coefficient should be no higher than 0.2.
Keeping this in mind, the following chapter will explain the entire design process, strating from basic background theory to motivatate choices, to the various design explorations, to the final choice simulation and finally testing.

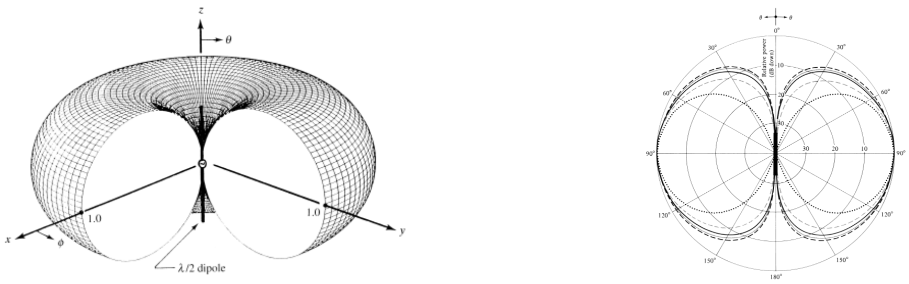
4.2. Background theory

Before jumping into unique shapes, it's important to understand the underlying workings of antennas and their key parameters to make an informed choice. For this project, the main two parameters are the antenna length l and input impedance Z_{in}. A lot of the discussed theory comes from the book Antenna Theory by Constantine A. Balanis [4]. So unless cited otherwise, it can be assumed the information and illustrations in this chapter originate from this book.

Omnidirectional radiation pattern

Antenna radiation patterns depend on the distribution of current along the dimensions of the antenna. This makes wire antennas' length l proportional to desired frequency's wavelength λ. A more thorough explanation is located in Appendix A.1.1.
An omnidirectional radiation pattern is one that closely approximates an isotropic radiation pattern either in full or half plane. An isotropic antenna is a hypothetical antenna radiating in all directions equally in a 3D space with an antenna gain of 1. Unfortunately, an isotropic antenna is not a realisable design, and instead can only be approximated. An antenna is said to be omnidirectional if its maximal gain is $\simeq 1$ and it is single-lobed. For example, a $\lambda/2$ dipole can be said to be omnidirectional, with a maximal broadside gain of $G_A \simeq 1.643$ and a single lobed "donut-shaped" radiation pattern, as shown in Subfigure 4.1a. Because the pattern is simply circular looking at the xy-plane, oftentimes omnidirectional radiation patterns are also described in the 2D zy- or zx-plane where the pattern is more interesting like in Subfigure 4.1b, called the cutplane radiation

pattern.



(a) 3D example of an omnidirectional dipole radiation pattern **(b)** The 2D zy-plane cutplane of the omnidirectional dipole radiation pattern

Figure 4.1: Dipole geometry and radiation pattern, with z being the antenna axis

Since the transmitter antenna should be omnidirectional, lobes are undesirable (lobes explained in Appendix A.1.1). Luckily, lobes appear only if the antenna is "electrically big" enough (aka, big proportionally to the desired frequency's wavelength), which only occurs for $l \geq 1.25\lambda$. With the chosen 433.92 [MHz], $\lambda/4$ = 17.28 [cm], which is already longer than the allowed 15 [cm] as stated in Section 2.2. In the $l < 1.25\lambda$ case, the radiation pattern is similar to that of 1/2 wavelength antenna, but will suffer inefficiency due to small R_r (see next Section). So for wire designs, 15 [cm] should be used to reduce losses. Unfortunately, inefficiency is hard to theoretically calculate, so during designing, general design guidelines will be used, and a numerical value will be reached via simulation in Section 4.4.

Antenna impedance

To explain this inefficiency, it's important to understand antenna impedance Z_A. Antenna impedance is complex as described by Equation 4.1. The real part R_A consists of the radiation resistance R_r, which represents the actual power radiated in the far-field, and the load resistance R_L, which represents the conductor losses of the antenna. The imaginary part X_A represents losses due to energy stored in the antenna's near-fields - this energy never travels far from the antenna, and thus is not part of the transmission. If X_A is not impedance matched, it can cause severe losses.

$$Z_A = R_A + jX_A \tag{4.1}$$

$$R_A = R_r + R_L \tag{4.2}$$

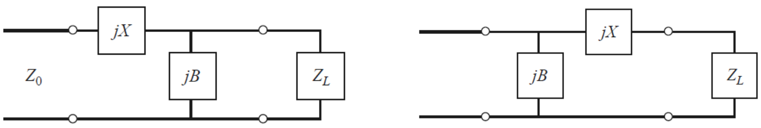
While X_A can be corrected for, R_L is a constant loss and can be a major issue if R_r is proportionally small. Caused by conductor imperfections, it's why electrically small antennas (aka those proportionally small than the desired wavelength) are poor radiators as they have small R_r. For this project, it has been estimated that R_L = 6.40 [Ω], which is non-negligible. The steps taken to arrive to this approximation are located in Appendix A.2.1.

Impedance matching

Another very important aspect of design is impedance matching. Antenna's impedance depends on its dimensions. But then this impedance must also be matched to the rest of the circuit. This is crucial due to transmission line theory - unless the antenna matches the characteristic impedance Z_0, characterised by the ratio of voltage and current that can travel together in the same direction, the power that arrives to the antenna will be reflected back. The bigger the impedance mismatch, the more power is reflected and the less efficient the antenna is, as described by Equation 4.3 denoting the reflection coefficient $\Gamma \in [-1, 1]$. Ideally, $\Gamma = 0$ [5] [17].

$$\Gamma = \frac{Z_A - Z_0}{Z_A + Z_0} \tag{4.3}$$

To rectify this, an impedance matching circuit is used. For this project's purposes, an L-network suffices as it is simple, light, and serves a single central frequency. L-network is made up of two elements - an inductor L and a capacitor C, to be able to match both R_A and X_A to Z_0. Typically, Z_0 = 50 [Ω]. This value is widely used in testing equipment, and as such is a good choice to ensure the design can also be tested with ease. An L-network has 2 possible layouts demonstrated in Figure 4.2, depending on whether R_A is bigger or smaller than Z_0 [17]. The design of this circuit will be further discussed in Section 4.4, once Z_A is determined.



(a) L-network topology if $R_A > Z_0$ **(b)** L-network topology if $R_A < Z_0$

Figure 4.2: The possible L-network structures based on R_A relative size to Z_0 [17]

X and B in Figure 4.2 stand for the impedances that need to be added to match Z_A to Z_0. The equations necessary for calculating these values can be found in Appendix A.2.2. $X > 0$ implies an inductor and $X < 0$ implies a capacitor. For B, the reverse applies. Note that since the transmission line now 'sees' not only Z_A but also the L-network, together they form what's called the equivalent input impedance Z_{in}, which now replaces Z_A in Equation 4.3.
Despite the L-network being part of the transmitter circuit design, it is very important to mention in this report as well, as the values for the inductor and capacitor are directly derived from antenna design.

Radiation efficiency

Another important quantity is radiation efficiency η, which describes the fraction of inputted power P_{in} that gets used for transmission P_{rad}. In impedance-matched conditions, $X_{in} = 0$, so η can be described solely through R_r and R_L as per Equation 4.4. Ideally, η = 1 [5].

$$\eta = \frac{P_{rad}}{P_{in}} = \frac{R_r}{R_r + R_L} \tag{4.4}$$

4.3. Antenna design

With the basic theory covered, it is now possible to design the antenna itself.

4.3.1. Wire and material design

Given that most considered designs are wire designs, they share certain characteristics like wire diameter and material. For this project, 0.1 [mm] was selected as the diameter and titanium was selected as the material. The full explanation of these choices are found in Appendices A.2.3 and A.2.4 respectively.

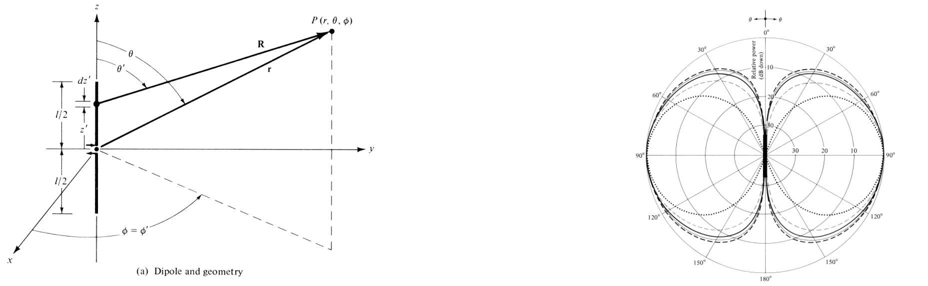
4.3.2. Shape design

The shape of the antenna is crucial - it determines radiation pattern and antenna impedance. Different shapes achieve different effects. This Section of the report will aim to briefly cover all considered choices and why they were rejected / chosen in the end. The main criteria are length, weight, radiation pattern, radiation efficiency, polarisation, hornet comfort, environmental interaction, antenna impedance, and general feasibility.
As stated in Section 2.2, weight limit is 15 [mg], length limit is 15 [cm] in any given direction,

radiation pattern must be omnidirectional, polarisation must match that of the receiver, and the antenna should not get easily stuck in the environment. Radiation efficiency should be as large as possible.
It's also important to note that the hornet's position relative to the antenna cannot be ignored during designing. Typically, trackers are put on the lower abdomen of hornets. Having contacted a professional hornet exterminator through our client, this is typically done by tying the transmitter to the hornet's thorax by a thread, and then allowing the PCB to hang down from the hornet's body. Therefore, the PCB is located right below the hornet's body. This must be taken into account when designing the antenna to ensure it does not get in the hornet's way.

Symmetrical (center-fed) dipole

Symmetrical dipole antennas are perhaps the most well-known wire antennas. They consist of two wires of length $l/2$, going into opposite directions with a central feeding point as illustrated by Figure 4.3a. Ideally, $l = \lambda/2$, which for 433.92 [MHz] means $l/2$ = 17.28 [cm]. This is close to the maximum 15 [cm], which is good for radiation efficiency. The total weight of a 30 [cm] titanium wire comes to 10.8 [mg], being below the limit. The impedance of a $\lambda/2$ dipole is about Z_A = 73 + j42.5 [Ω], which can provide radiation efficiency $\eta = 0.919$. Its radiation pattern is omnidirectional, with only two blind spots as illustrated by Figure 4.3b. If positioned vertically, one of the blind spots will face the sky, effectively causing only one blind spot to matter - one right below the hornet. Furthermore, a vertical dipole is linearly polarised, with a 'vertical' E_θ electrical field component, which is a commonly used antenna polarisation.
Despite these great characteristics, the center-fed dipole has one major flaw - if it were to be vertical, its upper wire would have to impede the hornet - if not physically having to pass through it, it would definitely get in the flapping wing-path, making the design unfeasible. A horizontal dipole could be designed, but that would cause two major radiation pattern blindspots that could directly face the receiver. Furthermore - a 0.1 [mm] wire isn't sturdy and would bend under its own weight, further reducing radiation efficiency.



(a) Center-fed dipole geometry **(b)** 2D radiation pattern of a dipole

Figure 4.3: Dipole geometry and radiation pattern, with z being the antenna axis

J-pole

J-pole is a wire antenna consisting of 2 parts: a quarter-wavelength transmission line segment, and a half-wavelength dipole radiating element, giving it its unique shape seen in Figure 4.4. These antennas have practically the same radiation pattern as the center-fed dipole in Subfigure 4.3b. Yet, they have one major advantage: they are end-fed and depending on the feed's position, can have a direct 50 [Ω] match, eliminating the need for an L-network. This means the antenna does not need to be fed in the centre but rather at the quarter-wavelength end, making it out of the hornet's way. The major disadvantage, however, is the length.
J-poles work on transmission line theory, more specifically the quarter-wavelength transmission line's ability to create the opposite impedance on either side of itself. By shorting the side closest to the hornet, it guarantees almost infinite impedance on the side where the dipole begins. Since dipoles naturally have infinite impedance at either end, this makes the second segment behave as one [18]. Therefore, the $\lambda/4 = 17.28$ [cm] length of the first segment is non-negotiable. This

directly clashes with maximal allowed length of 15 [cm]. Even extending the boundary would simply cause a relatively small radiating dipole segment, which would be a poor radiator. As such, this design is unfeasible.

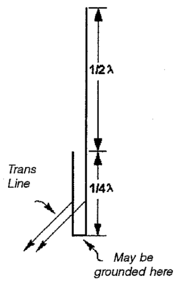


Figure 4.4: The construction of a J-pole

Loop antenna

The loop antenna has a similar radiation pattern to the dipole antenna, except its blind-spots are located at the through-the-hole axis as seen in Figure 4.5 and its linear polarisation component is the 'horizontal' E_ϕ. This causes several issues - first, to avoid the blind spots the loop must be set up horizontally, for which it needs to be sturdy enough. An optimal loop has circumference $C \simeq \lambda$. For 433.92 [MHz] that is a diameter d of 22.05 [cm]. Since only 15 [cm] is allowed in either direction, either the loop must be centered around the hornet, or reduced to diameter of 15 [cm], with a circumference of 47.12 [cm], reducing efficiency. Finally, the most crucial flaw is the most simple - loops are prone to catching on things. Since the hornet is likely to sit in vegetation and rough terrain, most likely the loop will cause constant struggle for the hornet and the antenna will likely break. Therefore, this design is also unfeasible.

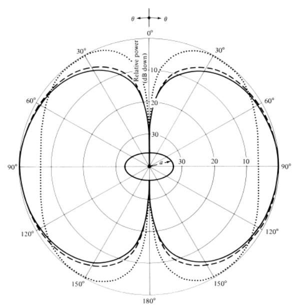
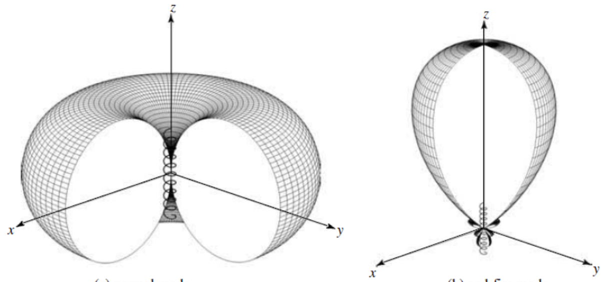


Figure 4.5: 2D loop radiation pattern

Helix antenna

Helix antennas are interesting because they are compact and have both E_θ and E_ϕ polarisation components. That is because they can be said to consist of both dipoles and loops. Furthermore, helix antennas have several modes, two of which is normal (omnidirectional) mode and end-fire (directed) mode as illustrated in Figure 4.6. Since the transmitter antenna should be omnidirectional, normal mode is of bigger interest. To achieve normal mode, the dipole and loop elements of the helix must be electrically small. For the dipoles, that means a length $S \leq \lambda/10 = 6.9$ [cm], and for loops it means a circumference $C \leq \lambda/10$, which gives diameter $d \leq 2.2$ [cm]. While feasible, as previously discussed in Section 4.2, electrically small antennas are poor radiators because they have relatively small R_r. Furthermore, having two separate polarisation components means splitting up the available power between the two, decreasing range for either. Because of this, it was determined it was best to keep polarisation linear to maximise reception as long as the receiver antenna is held right. Finally, as with the loop antenna, there is concern of the helix antenna catching on the vegetation-dense environment.

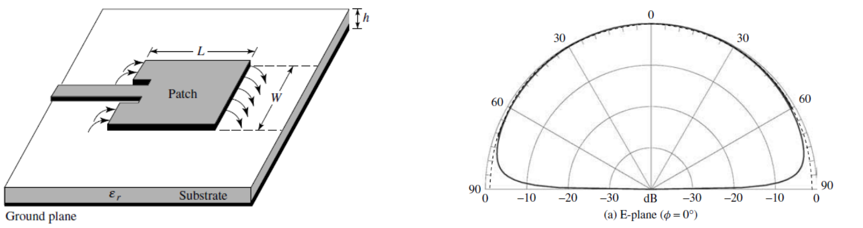


(a) normal mode (b) end-fire mode

Figure 4.6: 3D helix radiation pattern

Patch antenna

Patch, or microstrip antennas come in varios shapes - rectangular, circular, etc. In all cases the main construction is made of two conducting plates between which a dielectric substrate is placed as shown in Subfigure 4.7a. Patch antennas have an interesting radiation pattern, being omnidirectional is only half-plane as seen in Subfigure 4.7b. This may act as an advantage - concentrating power in a direction humans are likely to be at - below the nest. However, this may also have the disadvantage if the loaded hornet flies low and thus is untrackable.
The main disadvantage of this antenna, however, is weight - unlike wire antennas, patch antennas require conductive plates, and a further substrate to be placed between the two. An effective 433 [MHz] rectangular patch appears to have 30.5x30.5x2 [cm] dimensions [19]. Assuming titanium, the ground plate alone with no height would weigh 4.28 [kg/cm] - obviously far too heavy. Searching appropriate dielectric substrate and packaging would also complicate the process. Thus, this design was rejected.



(a) Rectangular patch antenna geometry **(b)** 2D rectangular patch radiation pattern

Figure 4.7: Rectangular patch antenna geometry and radiation pattern

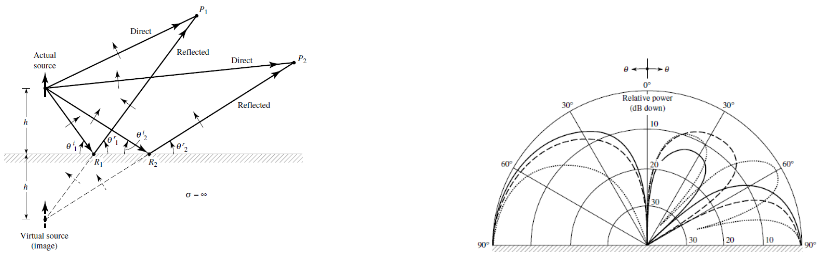
Integrated antenna

Integrated antennas for 433.92 [MHz] can be bought as relatively small SMD components. However, they are very inefficient due to their tiny size and are too heavy. For example, this 293mg antenna with 0.79 [dB] gain [20]. To compare, a half-wave dipole has a maximal broadside gain of 2.156 [dB]. Therefore, they are unsuitable for our project.

Monopole

A monopole is essentially a half-dipole. Its ideal length is about quarter-wavelength (17.28 [cm] for 433.92 [MHz]), and its impedance is Z_A = 36.5 + j21.25 [Ω], half of that of a dipole. Unfortunately that slightly reduces efficiency η to 0.851. A monopole compensates for a missing half via image theory - monopoles are placed orthogonally to a reflective ground, that via reflection complete the monopole's half-plane radiation pattern, doubling gain as if a second equal element was present under the ground. A monopole is light, at only 5.4 [mg] for 15 [cm], short, and does not directly

impede the hornet if left to hang upside-down. This makes it vertically oriented, avoiding major radiation pattern blind spots and reliance on wire sturdiness.
Despite this, its major issue is reliance on ground - an ideal ground is a perfect reflector and infinite. In this project's case, that is not at all the case - the hornet is small, non-reflective, and the second end of the antenna is connected to the PCB's ground, which is also relatively small. Therefore, a true monopole is unfeasible for this transmitter, and the monopole will instead behave as a asymmetrical dipole. Given how feasible it is to attach a single 15 [cm] wire to the PCB otherwise, this became the chosen design.



(a) Vertical monopole image theory

(b) 2D monopole radiation patterns. Multilobed patterns reflect electrically longer monopoles.

Figure 4.8: Monopole geopmetry and radiation pattern

4.3.3. Final design - Asymmetrical dipole

Previously, a centre-fed dipole antenna was explored. An asymmetrical dipole is one that instead has "hands" unequal in width, and typically also in length. As a dipole, its optimal length is closer to $\lambda/2$ than $\lambda/4$, which unfortunately reduces the efficacy of the design, being only 15 [cm] compared to wanted 34.57 [cm]. Additionally, given how unbalanced the lengths of the wires will be (about 11 [mm] for PCB ground and 15 [cm] for the 'monopole'), the dipole is essentially end-fed, increasing Z_A (see Appendix A.1.1). Both studies found on asymmetric dipoles show lopsided radiation patterns [21] [22], also seen in Figure 4.9. Since the asymmetric dipole behaviour would be hard to predict theoretically, instead the next Section 4.4 covers the simulations done to obtain efficiency η and antenna impedance Z_A to further design the matching L-network.

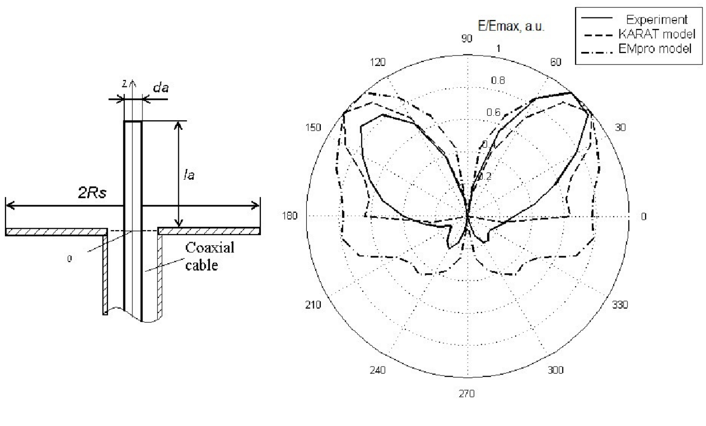


Figure 4.9: Asymmetric dipole geometry and radiation pattern [22]

4.4. Simulation

4.4.1. Introduction

Having discussed theoretical shape design, next step is simulation. Antenna impedance and radiation efficiency are hard to theoretically calculate, especially in conditions as volatile as being

attached to a small insect with one of the dipole 'hands' being a PCB ground. Therefore, an EM field solver Ansys HFSS was used to make a simple model for these estimations. Z_A is crucial for the design, as for an asymmetric dipole it's much larger than 50 [Ω], causing a reflection coefficient of $|\Gamma| \simeq 1$. This has disastrous consequences for antenna efficiency unless an L-network is designed. And to design an L-network, Z_A must be known.
Ansys HFSS allows the user to build a 3D model out of various shapes and materials, establish the point of excitation (in this case, a lump port), and then collect data for a frequency sweep. Upon this, the simulation produces various graphs as function of frequency, most importantly the reflection coefficient $|\Gamma|$, denoted as parameter S(1,1), the real and imaginary antenna impedance, and finally the 2D and 3D graphs of the radiation pattern for the selected operational frequency [23].

4.4.2. 3D model

Starting off with the model, there are five main elements - the hornet, the PCB, the PCB's ground, the monopole antenna, and the gap at the monopole's base which acts as the excitation point. Figure 4.10 demonstrates how the model looks from top angle, while Table 4.1 Demonstrates the different elements' dimensions. The limitations of this model are discussed in Appendix A.3.1. Appendix A.3.2 further explains the effects of modifying various dimension parameters, illustrating their importance and how tolerant the model is to inaccuracy.

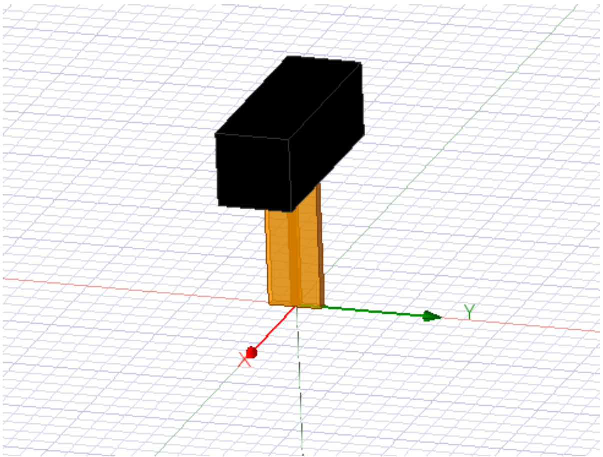


Figure 4.10: Ansys 3D model of a hornet with a transmitter hanging off its thorax

Element	Colour	Material	Shape	Dimensions [mm^3]
Hornet	Black	Water	Box	20x7x7
PCB	Orange	Polyimide	Box	0.75x0.75x13
PCB GND	Brown	Copper	Box	1x5x12.875
Monopole	Grey	Titanium	Cylinder	r=0.05, l=150
Gap	Clear	Vacuum	Cylinder	r=0.05, l=1

Table 4.1: Simulation elements and their respective make and dimensions. Box elements are described in XxYxZ format

4.4.3. Simulation results

Radiation pattern and antenna impedance

For a 15 [cm] antenna, a maximum radiation gain of -0.1824 [dB] = 0.9589 and an impedance of 17.66 - j1095.0 [Ω] are obtained. The radiation pattern is seen in Figure 4.11, which as expected is an omnidirectional pattern of the dipole antenna. Interestingly, it is not lopsided to the below half-plane as the radiation pattern in Figure 4.9. Likely, the PBC GND is close enough to the monopole in width, so instead the antenna acts as an off-centre fed dipole, which simply has a dipole's radiation pattern. Unfortunately, maximal gain is below 1, which indicates losses, but it is not so much lower to indicate total inefficiency. R_r is only 17.66 [Ω], which given R_L = 6.40 [Ω] provides radiation efficiency $\eta = 0.638$, explaining such low gain.

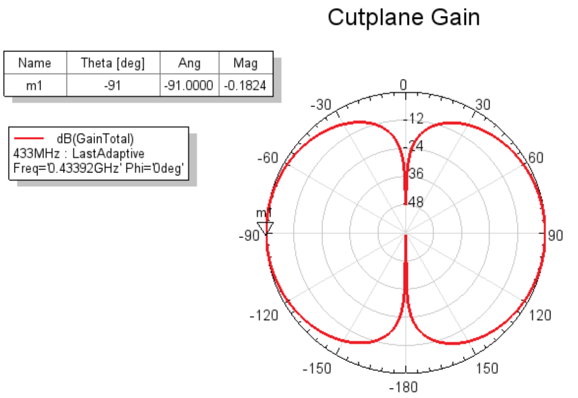


Figure 4.11: Simulated 2D cutplane radiation pattern

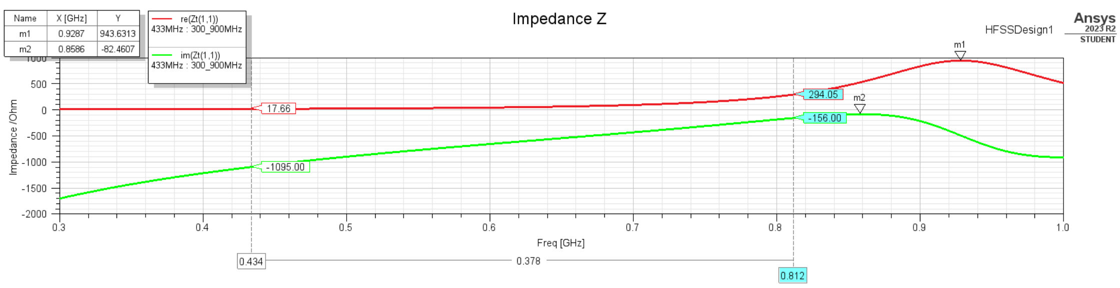


Figure 4.12: Graph of simulated impedances across 300-1000MHz range

Reflection coefficient without impedance match

Figure 4.13 demonstrates Γ. Lowest at 812 [MHz] with -2.903 [dB] = 0.513, it is only -0.013 [dB] = 0.9970 at the desired frequency of 433.92 [MHz]. Clearly then, with no L-network, most power will be unnecessarily wasted. Looking at the impedance sweep in Figure 4.12, 812 [MHz] aligns with 294.05 - j156.0 [Ω] impedance - a much better X_A and R_r ratio than 17.66 - j1095.0 [Ω].

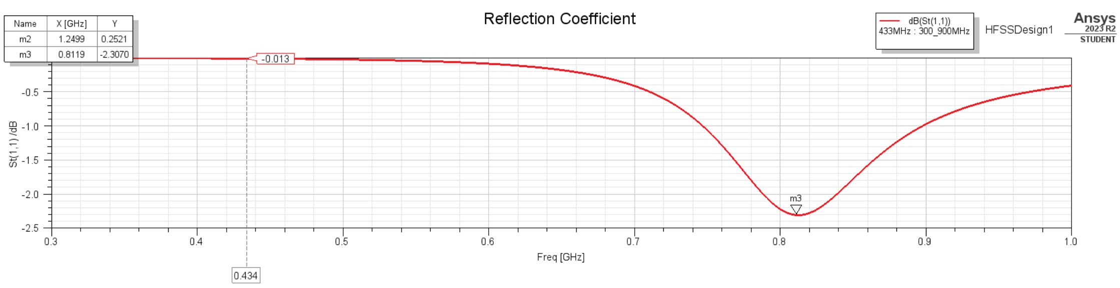


Figure 4.13: Simulated reflection coefficient graph with no impedance matching

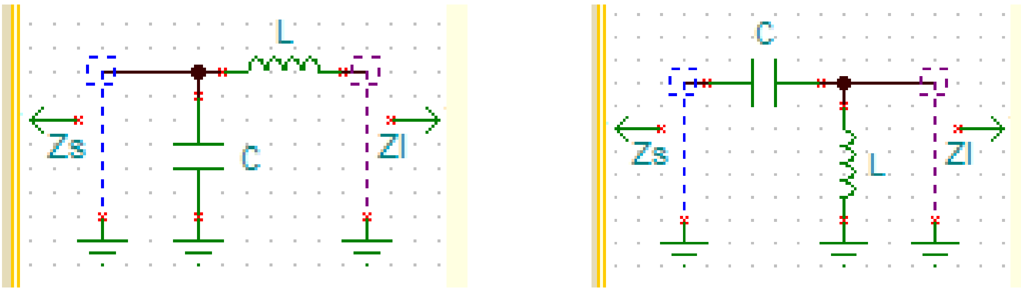
Reflection coefficient with impedance match

On the contrary, with a post processing impedance match equalling that of 433.92 [MHz]'s impedance, the reflection coefficient becomes -62.89 [dB] = 0.514E-6 as seen in Figure 4.14, a much better result. Notice that impedance matching affects the entire graph. Although it may appear that 892 [MHz] reflection coefficient was significantly reduced, in reality its value became -2.3944 [dB] = 0.576, only a minor change. This demonstrates that having impedance matching is a major benefit across a spectrum of frequencies, even if the best results are felt only around the 433.92 [MHz] mark. Aiming for $|\Gamma| \leq 0.2$ as per requirements in Section 2.2 gives a band of up to 705 [MHz].

Figure 4.14: Simulated reflection coefficient graph with impedance matching for 433.92 [MHz]

4.4.4. L-network values

Finally, using the simulated impedance, an L-network can be constructed. To match 17.66 - j1095.0 [Ω], two possible L-network topology solutions are available as demonstrated in Figure 4.15 with the corresponding values described in Table 4.2. Topology 1 refers to that illustrated in Figure 4.15a, and the latter refers to the topology in figure 4.15b. These values were further passed onto subgroup 1 for their PCB design.



(a) First L-network topology

(b) Second L-network topology

Figure 4.15: Possible L-network topologies [24]

	Calculated values	E-12 standard values
Topology 1	410.4 nH / 9.927 pF	390 nH / 10 pF
Topology 2	252.0 nH / 0.1991 pF	270 nH / 0.18 pF

Table 4.2: The calculated L/C values for the impedance matching network

4.5. Testing

4.5.1. Introduction

Having simulated the transmitter system, the next step is testing to verify results. Ideally, since all the elements of the transmitter are small and thus prone to tiny changes, the antenna should be tested already integrated with the PCB, with and without the matching L-network. Unfortunately, by the time the antenna was ready for testing the transmitter PCB was not. Therefore, the testing has focused on proof of concept for impedance matching as opposed to the efficacy of the simulated L-network design. Furthermore, the material used for this testing is brass wire, as the purchased titanium wire wasn't straight enough. Given this is a proof of concept test, this isn't influential.

4.5.2. Method

All of the impedance testing has been done with the help of a Vector Network Analyser (VNA).

1. Calibrate equipment for 200-300 [MHz] range to ensure internal imperfections and attached wires do not influence readings.
2. Solder a 15 [cm] antenna onto the RF PCB SMA connector. Connect it to Port 1 of VNA.
3. Test for reflection coefficient (S(1,1)), and for real and reactive impedance.
4. Design an L-network based on the impedance values measured in step 3.
5. Repeat steps 2-3 for two RF PCB SMA connectors now also containing an L-network each. First one should have the 330 [nH] /10 [pF] network designed via simulation in Section 4.4, and the second a 33 [nH] / 2.5 [pF] network designed in step 4.

4.5.3. Results

Table 4.3 showcases the results of the experiment. As can be seen below, The 330 [nH] /10 [pF] L-network is completely unsuited for the testing conditions. In fact, it has performed worse than no network conditions, with a higher reflection coefficient of Γ = 0.909 as opposed to Γ = 0.790. What is interesting to observe, however, is that the network has managed to completely change the impedance from 64.42 -j144.82 [Ω] to 2.99 - j14.31 [Ω], showing promise in the technique, but also highlighting the dangers of a mis-designed network.
The 33 [nH] / 2.5 [pF] network on the other hand has worked with excellent results: Γ has fallen all the way to 0.042 as opposed to 0.790, with an impedance of almost 50 [Ω] as desired: 51.62 - j4.15 [Ω]. Given that this network has been designed specifically for this antenna setup, it by extension showcases great promise in using an L-network in reducing transmission power losses as long as it fits the design.

	Linear S(1,1)	Linear SWR	Impedance
No matching	0.790	8.96	64.42 - j144.82
330 nH / 10 pF match	0.909	21.17	2.99 - j14.31
33 nH / 2.5 pF match	0.042	1.09	51.62 - j4.15

Table 4.3: Transmitter antenna VNA testing results

4.6. Conclusion

To conclude, the transmitter antenna has been designed as a monopole acting as an asymmetrical dipole. Unfortunately, due to the many requirements restricting the design, this antenna is not very effective at power transmission, primarily due to a non-negligible R_L compared to R_r. Even in best conditions, radiation efficiency η is approximately 0.638. Many of the designs that could potentially improve this are unfeasible. Nevertheless, with careful consideration these setbacks can be reduced - by pushing the antenna to be as long as possible, R_r can be increased. And by carefully designing the L-network, power reflection should not pose any major concerns.

5 Receiver antenna design

5.1. Introduction

As previously discussed, the transmitted signal is of an ultra-low power, of around 45 [μW]. This has a major repercussions in terms of its reception, specifically its range. In order to meet the detection range requirement of 500 [m], it is paramount to build a receiver system that is able to detect even the smallest signal. Furthermore, since the signal has to be found even in industrial area where there is extensive interference, this must also be accounted for during the design. Additionally, the receiver system has to be portable given the use case of the entire system, therefore the design has to be minimal yet highly efficient and robust.

The entire receiver system will be composed of the following elements shown in Figure 5.1. This chapter will delve into the design of the receiver antenna section, the possible implementations for each case, discussing the possible pros and cons for each implementations, then making a model for the designed antenna and then finally testing the antenna and its workings in real-life.

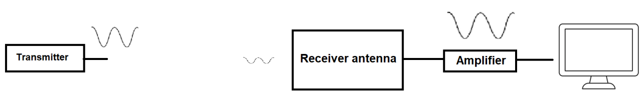


Figure 5.1: Receiver system (not to scale)

The research and the design choices made regarding the receiver amplifier will be explained further in Chapter 6 as the antenna design choices are independent of the design choices made for the amplifier, the antenna needs to meet its requirements 2.2.3.

5.2. Antenna design

In the context of this project and the use case of the transmitter, the direction from which the received signal is entirely unknown. As the hornet can fly in any direction and at any amplitude, it is not possible to predict its location or direction. As mentioned earlier, the receiver antenna needs to integrate with the receiver group responsible for finding the location of the tracker. Their main goal is to build an algorithm that find the exact location of the tracker using an omnidirectional antenna, however, in the case this algorithm is not feasible or non-functional, an additional directional will also be designed. This system, although will not be able to work with the algorithm is a good substitution. Therefore, in the design of the receiver antenna, both an omnidirectional and directional antenna will be designed to address all possible points of failure.

5.2.1. Antenna requirements

The requirements of the receiver antenna taken from 2.2.3 are as follows.

1. The detectable signal range needs to be at least 500 meters both in open field and industrial area conditions to ensure effective tracking .
2. The gain of the receiver antenna needs to be higher than 3 [dB].
3. The input impedance of the antenna needs to be 50 [Ω].
4. VSWR of the receiver antenna should be less than 2.
5. The receiver antenna needs to be capable of working with direction finding algorithm
6. The receiver antennas' directivity should have a major horizontal component.

5.2.2. Design process

After the design and calculations for the particular type of antenna has been made, a simulation (using 4NEC2 [25]) will be performed. If the simulation meets the requirements of the system and works as designed, the antenna will be built and tested. These tests involve making sure that the antenna works as expected, afterwards if any improvements are necessary the changes to the design will be made and again tested in the software. Any discrepancies with the antenna and its working compared to the simulation will also be mentioned and further discussed.

Below are the possible antenna solutions that were explored are mentioned and discussed. It will first begin with finding and designing an omnidirectional antenna and then a directional antenna.

5.3. Omnidirectional antennas

As mentioned above, one of the possible implementations to find the direction of the transmitter is through using an omnidirectional antenna. An omnidirectional antenna is an antenna that has a non-directional pattern (circular pattern) in a given plane with a directional pattern in any orthogonal plane as shown in Figure 5.3a. The issue of finding a low power transmitted signal can be resolved given that they can have a high gain in the horizontal place and low noise. It is important to mention the defenition of gain in this case, the usage of the word high gain is made after comparing the difference in gain in the horizontal plane axis compared to the vertical plane [26]. Examples of omnidirectional antennas are discone and collinear antennas, these will be further discussed below.

5.3.1. Collinear Antennas

The collinear antenna is based on the simplest type of antenna, the dipole antenna. However, a single dipole antenna has limited directionality and relatively low gain. To address this issue, multiple dipole antennas can be vertically stacked, effectively multiplying the gain of each individual antenna and resulting in a greater overall gain.

A working concept of the collinear antenna can be seen in Figure 5.2 with an example shown in Figure 5.3b. This figure showcases a collinear antenna with 3 elements, each equally spaced between each other. Each radiating point is a short dipole wherein the received signal is fed onto, however due to being connected the leftmost dipole feeds into the center dipole, which then feeds into the rightmost dipole, ultimately connecting to the rest of the receiver system.These radiating dipoles combine their radiation intensities, resulting in higher performance and increased gain.

The gain of a collinear antenna increases with the number of dipole elements stacked vertically. Each additional dipole contributes to a higher overall gain by concentrating the radiation pattern

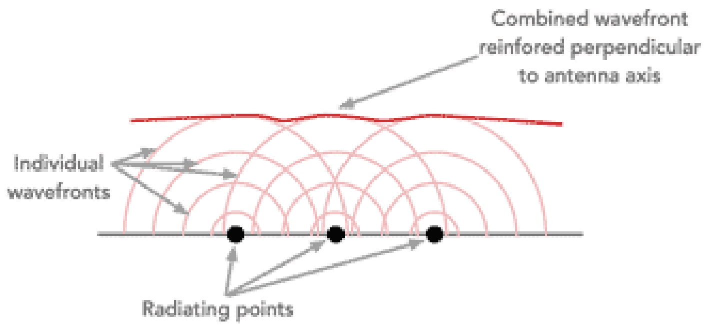
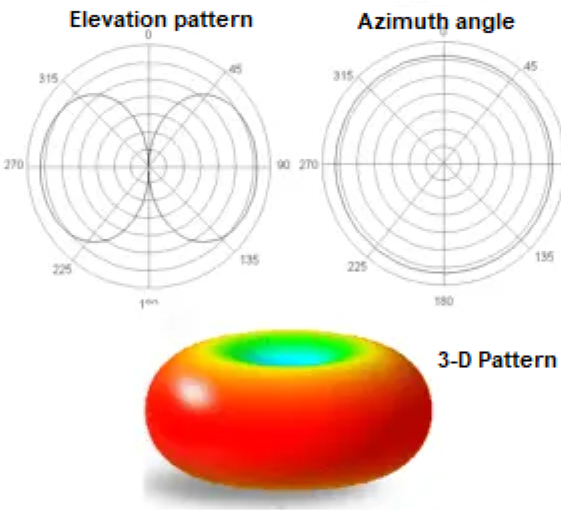
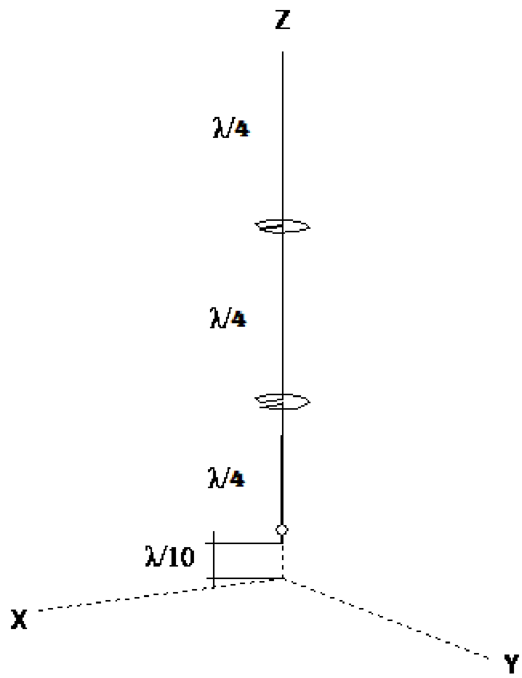


Figure 5.2: Collinear antenna theory



(a) Omnidirectional antenna



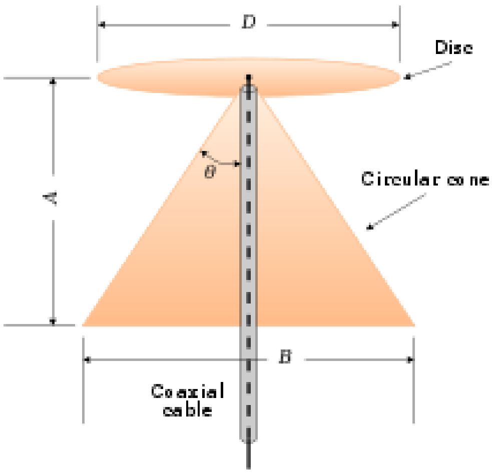
(b) 2 element collinear antenna

Figure 5.3: Collinear antenna

more effectively. For example, a basic dipole antenna typically has a gain of about 2.15 [dBi]. When three dipoles are stacked to form a collinear antenna, the gain increases significantly. A collinear antenna with three dipoles can achieve a gain of approximately 5 to 6 [dBi], depending on the design and spacing between the elements. This increase in gain enhances the antenna's ability to transmit and receive signals over greater distances with improved performance.This high-gain and high performance makes it a perfect candidate for working outdoors and in use case of this project.

5.3.2. Discone antennas

A discone antenna is a type of circular antenna, an example is shown in Figure 5.4a it is made using a disc and a cone (hence the name discone) which is mainly used to monitor a wide band of frequencies, however, for a specialised frequency it is capable of having a gain in the horizontal plane. It's arranged so that the cone sits underneath the disc as shown in Figure 5.4b. There's an insulator between the cone and disc, which is essential for the antenna to function properly.



(a) Discone (circular) antenna

(b) Example discone antenna

Figure 5.4: Discone antennas

Radiation Pattern

The radiation pattern of discone antennas, as illustrated in the Figure 5.5 from a PhD thesis at TU Delft, exhibits distinct characteristics in both the horizontal and vertical planes. In the horizontal plane (the left graph of Figure 5.5), the radiation pattern is omnidirectional, indicating that the antenna radiates energy uniformly in all directions around the antenna, resulting in consistent signal strength at all azimuth angles.

In the vertical plane (the right graph of Figure 5.5), the radiation pattern forms a doughnut shape, with the strongest radiation occurring perpendicular to the axis of the antenna (broadside direction). The pattern shows minimal radiation along the axis (end-fire direction), typical of a discone antenna's vertical radiation pattern. This combination of omnidirectional horizontal radiation and doughnut-shaped vertical radiation makes discone antennas suitable for applications requiring broad horizontal coverage however, for this use case of this project it does not satisfy the requirements unlike the collinear antenna.

Drawbacks

When compared to the collinear antenna it has several drawbacks, these will be explored below. **Bandwidth:** Collinear antennas typically have a narrower bandwidth compared to discone antennas. This characteristic is usually a huge disadvantage for wideband coverage, however, since the receiver is only interested in the 433.9 [MHz] band, it is can be quite beneficial for the design as it gets rid of the redundant noise and interference from other frequencies.

Gain and Radiation Pattern: Collinear antennas offer higher gain compared to discone antennas due to the vertical stacking of elements, which enhances the horizontal radiation pattern. This can be explicitly observed using Figure 5.5 where the gain in the horizontal plane is shown to maximally be 2.13 [dB]. The increased in the case of the collinear antenna results in better signal reception at greater distances and improves the signal-to-noise ratio, which is critical for clear AM signal reception. Discone antennas, while providing omnidirectional coverage, do not offer the same level of gain and thus may perform less effectively in scenarios requiring long-range reception.

Impedance Matching: Collinear antennas are designed to match standard impedance values (typically 50 ohms), making them compatible with most transmission lines and receivers without requiring additional impedance matching components. Discone antennas also offer good

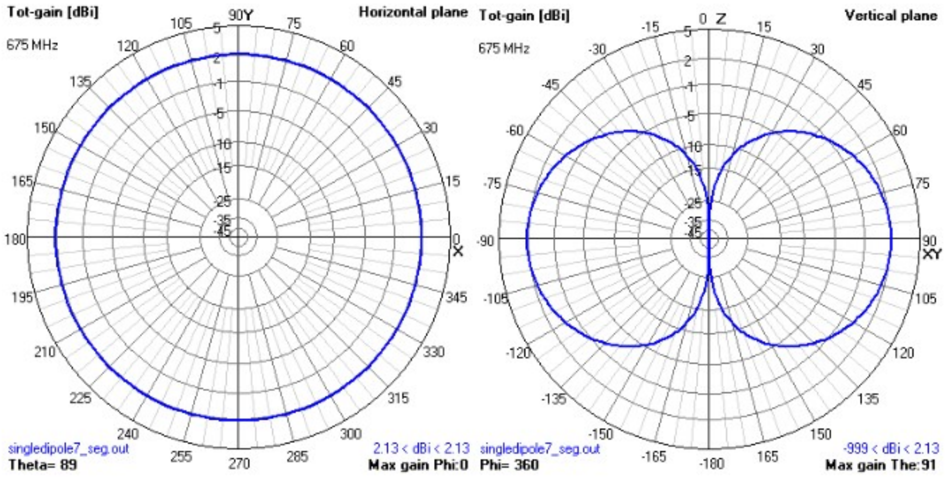


Figure 5.5: Radiation pattern of discone antenna [27]

impedance matching over a wide frequency range, but the design complexity can vary, and achieving optimal performance may require careful tuning.

Conclusion

In summary, while discone antennas offer broad bandwidth and consistent impedance across a wide range of frequencies, collinear antennas provide distinct advantages in terms of meeting the antenna requirements 2.2.3. The higher gain, improved signal-to-noise ratio, focused horizontal radiation pattern, and simplicity of integration make collinear antennas a superior choice for this application. These attributes ensure better performance in terms of signal clarity and detection range, making collinear antennas the preferred option. In the following sections, the simulation of the design of the collinear antenna will be further discussed and looked upon.

5.3.3. Design

To meet the high gain requirement of the antenna, it is very important to make the right choice in terms of number of elements. The gain of a collinear antenna is logarithmically proportional to the its number of elements [28].

Therefore, the best solution would be add as many elements as possible to achieve the highest possible gain. However, to make the antennas portable a trade-off in terms of the gain and the total can be performed. Some rough calculations were performed in Table 5.1, the calculations take into account the spacing designed for maximum gain.

# elements	Spacing [m]	Gain [dB]	Total height [m]	Normalized gain [dB]
2	0.89λ	3.2	1.403	2.28
3	0.9λ	5.1	2.038	2.50
4	0.93λ	6.4	2.73	2.34
6	0.97λ	8.5	3.52	2.41

Table 5.1: Normalized gain collinear antenna

As shown, the largest possible normalized gain is for 3 element collinear antenna, where for a total height of 2.0 [m] with 3 elements it is possible to get a total gain of 5.1 [dBi], therefore it was chosen to design the antenna with 3 elements. Additionally, this type of antenna would meet the requirement that the maximum antenna height is 1.5 [m].

Although the design of the collinear antennas could relatively simple by designing each dipole of

$\frac{1}{4}\lambda$ as shown in Figure 5.3b, an impact on radiation pattern for the use case of the receiver should be taken into account. In order words, smarter designs should be explored and discussed.

Instead of the using the $\frac{1}{4}\lambda$ dipoles, other designs can include a $\frac{1}{2}\lambda$ or a $\frac{3}{4}\lambda$ spacing between each dipole. As shown in Figure 5.6, the higher the spacing between the antenna elements, the higher the gain, which is at its max at around 0.9λ [m] spacing between each of the radiating short-dipoles.

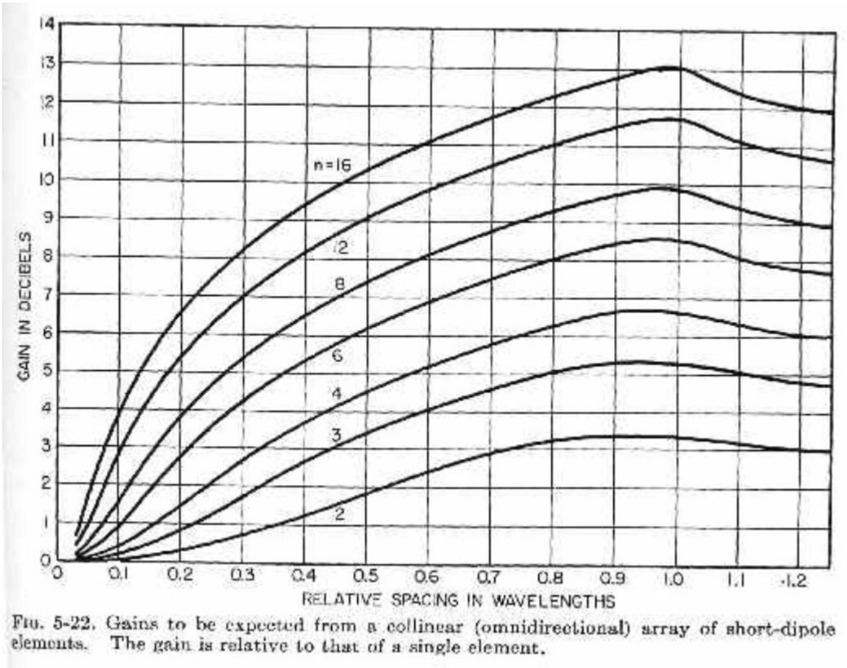


Figure 5.6: Gain vs Spacing between elements [29]

However, according to [30] the addition of the last wire for the last element is redundant. Removing the final wire has insignificant consequences on the gain but reduces the total height of the antenna thereby making it is very portable. Additionally, the dipole spacing s in Figure 5.7 between should not be too long as otherwise there would be too many parasitic noise.

Therefore, taking this into account the final antenna design was made which is shown in Figure 5.7. This antenna meets all the requirements showcased in 5.2.1 with a gain of around 5 [dB], omnidirectional properties in the horizontal plane and being portable.

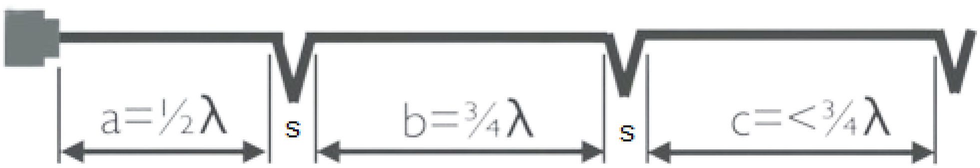


Figure 5.7: Collinear antenna calculations

Radials

In the design of a 3-element collinear antenna, achieving proper impedance matching is a critical challenge. Impedance mismatches can result in significant power losses, reducing the efficiency and performance of the antenna. Ideally, the impedance of the antenna should be around 50 [Ω] to ensure optimal power transfer to the transmission line. Without adequate matching, the antenna might suffer from poor radiation efficiency and increased signal reflection.

To address this issue, the inclusion of radials is an effective solution [31]. Radials help achieve the desired impedance by acting as a counterpoise, thus providing a better impedance match and facilitating a smoother transition of power. Radials also enhance the ground plane, which is essential for the efficient operation of collinear antennas. A robust ground plane stabilizes the radiation pattern and impedance, ensuring consistent performance across the antenna's operating frequency.

Moreover, radials contribute to shaping the radiation pattern, often making it more omnidirectional and reducing undesirable lobes. This results in a more uniform signal distribution, which is particularly beneficial in applications requiring consistent coverage. Additionally, the improved impedance match and stabilized radiation pattern provided by radials can enhance the antenna's gain, potentially surpassing the theoretical 5.1 [dB] gain of a 3-element collinear design. Overall, incorporating radials not only solves the problem of impedance matching but also improves the antenna's efficiency, radiation pattern, and gain, leading to a more effective and reliable antenna system.

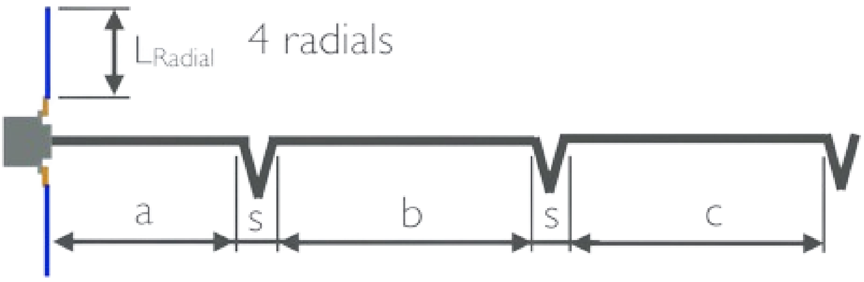


Figure 5.8: Collinear antenna with radials

Simulation

A model of the designed antenna was done using 4NEC-2 [25] to simulate its operation in an industrial area where there is a significant amount of interference. In the model, shown in Figure 5.9 the antenna was made out of copper wire to keep the cost as low as possible.

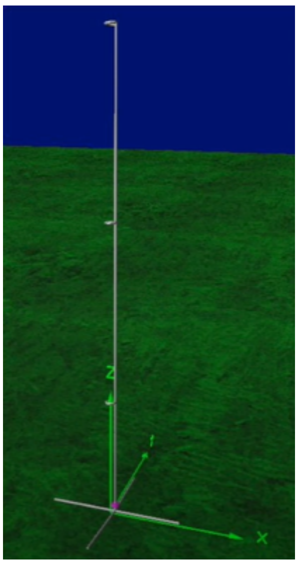
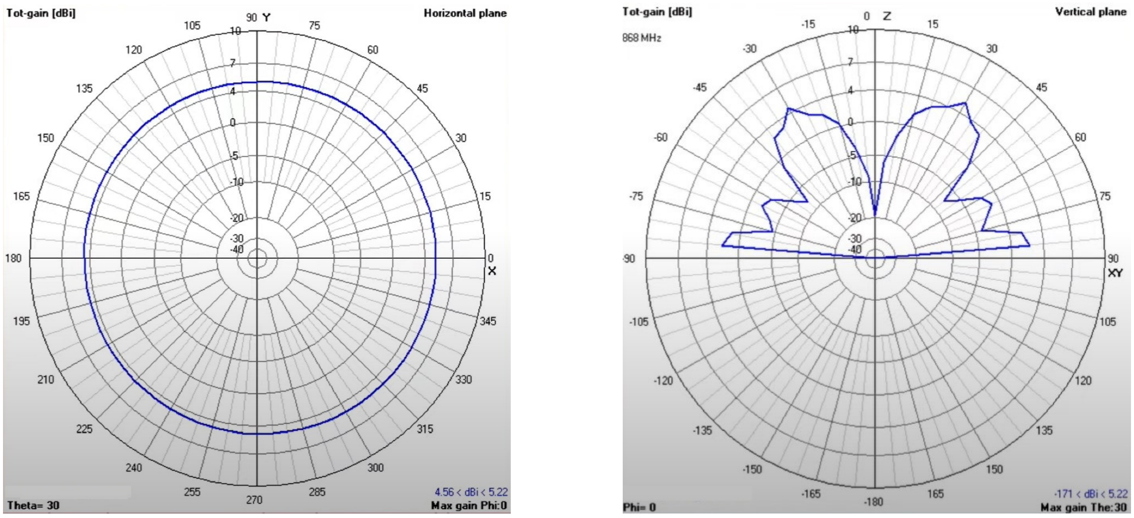


Figure 5.9: Model collinear antenna 4NEC-2

This model, as mentioned above was simulted in an industrial area and yieled the following radiation pattern shown in Figure 5.10. As shown in Figure 5.10a, the antenna displays excellent omnidirectional properties in the horizontal plane, it is capable of receiving all signals in the horizontal plane.

In contrast, the radiation pattern in the vertical plane, illustrated in Figure 5.10b, exhibits multiple lobes with a distinct configuration. The primary lobe is oriented horizontally, with nulls and secondary lobes extending above and below this plane. This formation is characteristic of collinear antennas, where the vertical beamwidth is typically narrow, concentrating the radiated energy along the horizontal axis.

However, at an elevation angle of around 30° there is a gain of 5.22 [dBi], therefore, if the hornet is caught flying higher than the antenna, it is still able to receiver the signal with a gain of 5.22 [dBi]. It is important to clarify the use of the unit [dBi], which is a comparison between the he power output of an antenna in a particular direction to that of an ideal isotropic antenna (a theoretical antenna that radiates equally in all directions). Therefore, the value of 5.22 [dBi] demonstrates that the designed collinear antenna for 433.9 [MHz] with 3 elements is able to satisfy all the antenna requirements mentioned in 5.2.1. In the following section, the assembly and results of real-life tests of the antenna will be discussed.



(a) Horizontal plane

(b) Vertical plane

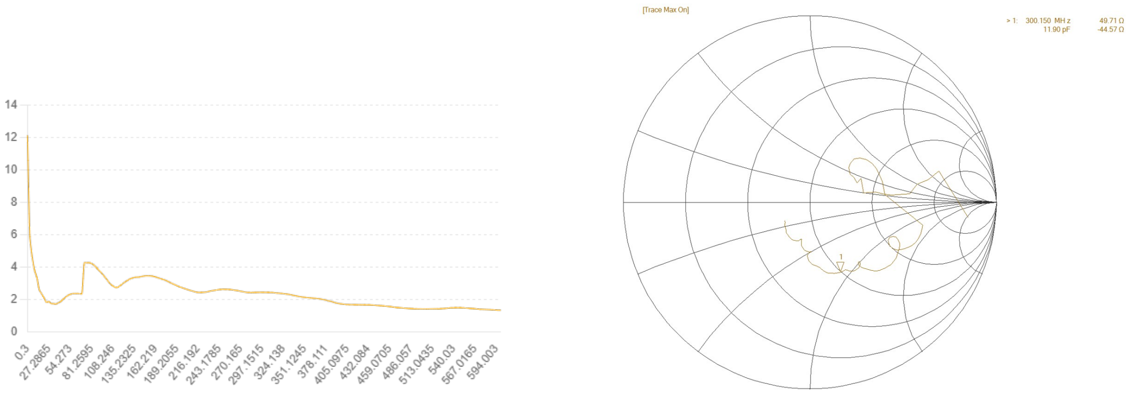
Figure 5.10: Radiation pattern

5.3.4. Results

After successfully designing the antenna, the assembly and testing of the antenna began. Initially, the antenna was tested by itself and without integration with other modules (such as the transmitter) to make sure that its characteristics matched the simulation/model and met all the requirements. This was measured using the VNA using a frequency sweep from 600 [kHz] to 600 [MHz]; the VSWR as shown in Figure 5.11a of the antenna is around 1.66 which successfully meets the requirements of the antenna as it should be less than 2.

A VSWR of 1.66 indicates that the antenna is well-matched to the transmission line and the transmitter, which minimises the reflection of the signal back to the source. This means that most of the power is radiated by the antenna rather than being reflected back, which improves the efficiency of the antenna and ensures better signal quality and range.

The impedance of the antenna is also around 49 [Ω] as shown in Figure 5.11b, which also meets the requirements of the antenna since a difference of 1 [Ω] is negligible. The impedance value being close to the standard 50 [Ω] is beneficial because it ensures maximum power transfer from



(a) VSWR Collinear antenna **(b)** Smith chart and Impedance

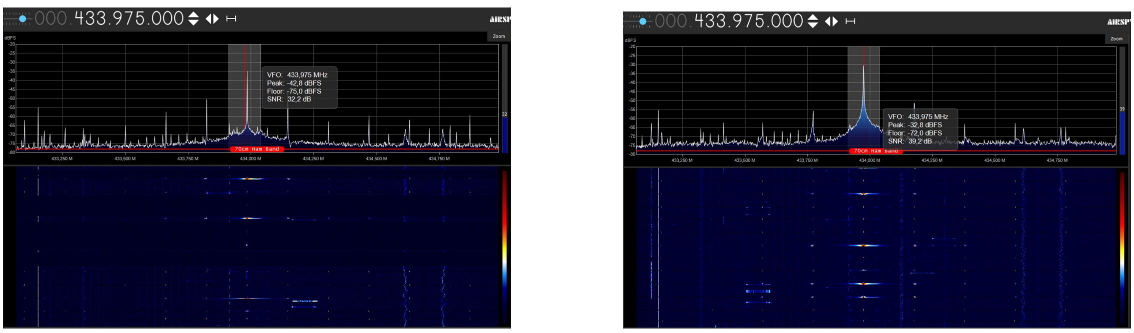
Figure 5.11: Comparison of VSWR and Smith Chart for the Collinear Antenna

the transmitter to the antenna. When the impedance of the antenna matches the impedance of the transmission line and transmitter, it reduces the potential for signal loss and reflections. This impedance matching is critical for maintaining the integrity of the transmitted signal, leading to more effective communication and signal reception.

Overall, achieving a low VSWR and an impedance close to 50 [Ω] indicates that the antenna is well-designed and performs efficiently, which is essential for reliable AM signal reception at 433 [MHz].

Since the antenna roughly meets its requirements, it is time to test with the actual tracker. Regarding the integration with different modules it is important to mention that the 3rd (receiver subgroup) responsible for creating a direction and location finding algorithm did not manage to successfully solve their issues, therefore, all the tests further explained will be performed using a transmitter which transmits an AM signal at 433 [MHz].

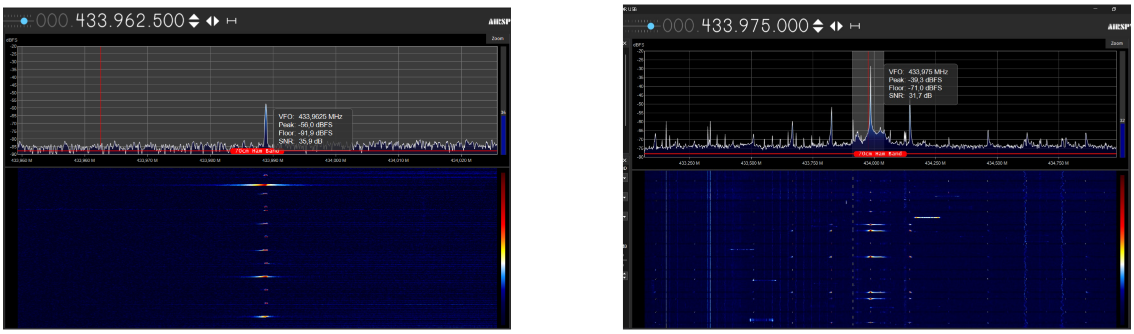
The designed collinear antenna will be tested and compared to the dipole antenna, the most significant things to take into account during these tests is the SNR and the directionality. Initially, the tests were performed 3metres away from the tracker, for the dipole antenna the SNR is around 32.5 [dB] as shown in Figure 5.12a while for the collinear antenna it is around 39 [dB] as shown in Figure 5.12b, this also matches the theoretical expectation and there should be a 5 [dB] gain difference for the collinear antenna compared to the dipole antenna. While this may seem like a complete success, this is not always the case.



(a) Dipole antenna SNR **(b)** Collinear antenna SNR

Figure 5.12: Comparison of SNR for Dipole and Collinear Antennas at 3m from the tracker

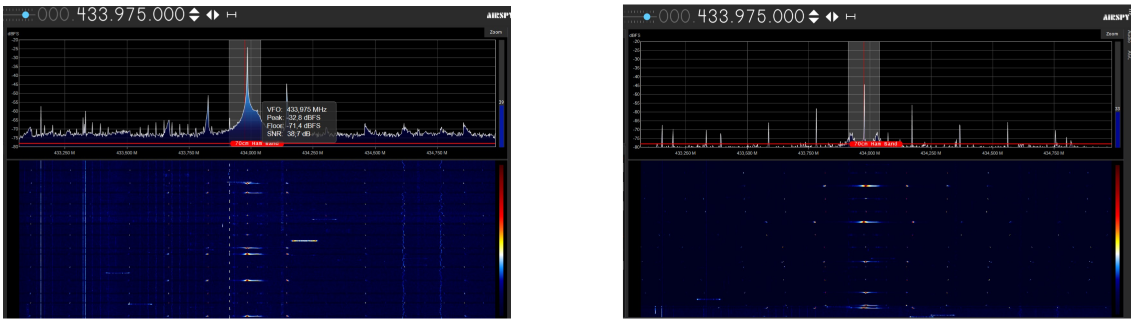
This refers to the performance of the collinear antenna in very long distances. For very long distances, the dipole antenna performs better than the collinear as shown in 5.13b where the SNR was around 32 [dB] compared to the SNR of the dipole which was around 36 [dB] as shown in 5.13a. This is likely due to the fact that the dipole antenna is better suited to pick small signals with its twin software, additionally since the dipole which with the tested were performed is an industrial grade antenna while the collinear antenna is a cheaper solution. Unfortunately an extensive testing on the range was not performed due to time constraints.



(a) Dipole antenna SNR **(b)** Collinear antenna

Figure 5.13: Comparison of SNR for Dipole and Collinear Antennas at 100m from the tracker

However, despite the range being worse than the dipole antenna, the collinear antenna performs better than the dipole antenna in terms of its directivity. The collinear antenna performs much better than the dipole antenna in the vertical plane, when the tracker is more than 1 [m] higher than the dipole antenna in the vertical plane, the SNR is around as shown 5.14a whereas the collinear antenna is calculated to be around 43 [dB] in Figure 5.14b.



(a) Dipole antenna SNR **(b)** Collinear antenna

Figure 5.14: Comparison of SNR for Dipole and Collinear Antennas at 2m horizontal, 1m higher than the tracker

As shown above, the omnidirectional (collinear) antenna designed and built successfully meets all the requirements despite several issues and non-ideal behaviour. However, several improvements could be made such as the fact that the antenna is not rigid and tilts to one side, this could allow for several parasitics to influence the received signal. One solution to this is to add a cover to the antenna, for this antenna this means adding a non-conducting glass rod starting from the bottom until the top of the antenna.

Due to time constraints and the fact that the omnidirectional antenna was able to meet the antenna requirements 5.2.1. Therefore, despite the fact that a directional antenna was successfully designed, modelled and simulated, it was chosen not to build the respective antenna. The design of the antenna can be found in the Appendix B.

5.4. Conclusion

In the design of the receiver antenna an omnidirectional antenna was designed. This design met all the requirements of the system. After this antenna was built it has a similar behaviour behaviour to that of its simulation, however, the impact of range on the amplifier was huge. Despite the fact that it performed better than a simple dipole it has some flaws. In conclusion, the receiver antenna satisfied the system requirements but several improvements could be made to further improve its behaviour.

6 Receiver Amplifier

6.1. Introduction

As discussed in Chapter 5, the transmitted power is -13 [dBm], which is of extreme low nature. To provide another perspective, the noise in the environment is around the -7 [dBm] (-37 [dB]) making is highly challenging to find the transmitted AM signal from the transmitter. The solution for this issue to use an amplifier which amplifies any weak signals at the 433.9 [MHz] frequency band, this section will delve into the design of this amplifier, its design, simulation and final results of the actual amplifier.

Before proceeding further with the design of the amplifier, it is important to make some top level estimations of the received signal. This takes into account the worst and the base case scenario to make the entire receiver system highly robust.

6.1.1. Characteristics of the system

- Transmitted signal power: -13 [dBm]
- Free space loss: -80 [dB]
- Frequency : 433.9 [MHz]
- Noise level (surrounding) max: -37 [dB] = -7 [dBm]

The transmitted signal power was converted into [dB], regarding the attenuation Friis Equation was used as explained in 3.3. The noise level refers to the general noise found in the environment, or any system noise that does not correspond to a useful signal transmitted by any source. It was found out through performing several tests in the different environments in an industrial areas.

6.1.2. System requirements

As previously mentioned, the transmitted signal lies around 10 [dB] lower than the noise level of the environment. In addition to this, the noise generated by the amplifier needs to be taken into account, this has a maximum value of 4 [dB], an estimation made in [32]. Taking all noise sources into account a 20 [dB] gain of the amplifier is sufficient as otherwise the design and component cost would become too high, additionally a very high gain could be unstable.

While a high gain is essential for the overall system's functionality, it is even more critical for this gain to remain constant at 433 [MHz]. If the gain is unstable and fluctuates, the localisation algorithm could misinterpret it as a false reading or as a signal from a different source. Therefore, it is of utmost importance to design an amplifier with stable gain at 433 [MHz]. Taking into account these requirements a list of functional requirements for the system was generated:

1. Amplifier gain : 20-25 [dB]
2. Stable gain at 433.9 [MHz]
3. Low Noise Figure (< 4 [dB])
4. Biasing solution to ensure circuit operation
5. Input and output impedance of 50 [Ω]
6. Minimal passive and active components
7. Sufficient safety measures such as ESD protection
8. Cheapest possible implementation (of high quality)

Although some of the requirements mentioned above have been explained, others will be further defined later on, these include the definition of ”stable” and ”high quality”.

6.2. Design

The design of the amplifier will follow a bottom-up approach. This process begins with identifying the best amplification method, selecting between Bipolar Junction Transistors (BJTs), specifically NPN transistors, and Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs). The benefits and drawbacks of each will be evaluated. After selecting the most suitable amplification method, different amplifier classes will be discussed. Sequentially,an amplifier circuit will be constructed and tested to ensure it meets the specified requirements. Once the core amplifier circuit is successfully designed, the appropriate biasing solution for the chosen type of transistor will be thoroughly explored and optimised to ensure stability and performance.

6.2.1. Transistor

A table was compiled to discuss the differences between BJTs and MOSFETs, highlighting their main differences, their benefits and drawbacks.

Feature	**BJT (Bipolar Junction Transistor)**	**MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor)**
Control Method	Current-controlled device	Voltage-controlled device
Input Impedance	Low input impedance	High input impedance
Output Impedance	Low output impedance	Medium output impedance
Power Consumption	Higher power consumption	Lower power consumption
Noise Performance	Generally lower noise at lower frequencies	Improved noise performance with advanced designs
Temperature Coefficient	Negative temperature coefficient	Positive temperature coefficient
Robustness	More robust, less sensitive to static	Sensitive to static, requires careful handling

Table 6.1: Comparison of BJTs and MOSFETs for High-Frequency RF Amplifier Design

Taking into account the comparative study conducted in Table 6.1, BJTS are a better implementation for a High frequency (such as 433.9 [MHz]) operation.

In designing Low Noise Amplifiers (LNAs), the choice between NPN Bipolar Junction Transistors (BJTs) and MOSFETs involves several considerations. NPN BJTs are often favoured due to their low noise figure at low to moderate frequencies, which is crucial for minimising noise in RF amplification. They offer high gain and excellent linearity, ensuring that weak signals are amplified without significant distortion. Additionally, BJTs exhibit good high-frequency performance and robustness, making them less susceptible to static damage and more reliable in various environmental conditions.

NPN BJTs are thus preferred in LNAs where low noise and high gain are critical, whereas MOSFETs are chosen for their efficiency and high-frequency performance. This comparative understanding helps in selecting the appropriate transistor type based on specific design requirements. Therefore, in the design of this amplifier, NPN transistors will be favoured to using MOSFETs.

6.2.2. Amplifier classes

In designing an RF amplifier with the specified requirements, understanding the different amplifier classes is essential. Each class has unique characteristics that influence linearity, efficiency, noise performance, and power consumption. Here is a comparison of the main amplifier classes in relation to the given requirements discussed in 6.1.2:

Amplifier Classes

Class A amplifiers conduct for the entire cycle of the input signal (360 degrees), providing high linearity and low noise, which is beneficial for sensitive applications. However, they are inefficient (around 25-30 [%]) due to continuous conduction, leading to high power dissipation. While Class A amplifiers offer stable gain and low noise figure, their low efficiency makes them less suitable for applications requiring energy conservation. [33]

Class B amplifiers conduct for half of the input signal cycle (180 degrees). They are more efficient than Class A (about 50 [%]) but suffer from crossover distortion at the zero-crossing point of the signal, impacting linearity and noise performance. This class is not ideal for applications demanding high linearity and low noise.

Class AB amplifiers conduct for more than half but less than the full cycle of the input signal. They offer a compromise between the linearity of Class A and the efficiency of Class B, with efficiencies around 50-60 [%]. Class AB amplifiers significantly reduce crossover distortion, providing good linearity and low noise. This balance makes them suitable for RF amplification where low distortion and reasonable efficiency are required.

Class C amplifiers conduct for less than half of the input signal cycle. They offer high efficiency (up to 80 [%]) but at the cost of poor linearity and significant distortion. Class C amplifiers are typically used in RF applications where signal purity is less critical and the signal can be filtered later, such as in RF transmitters.

Class D and E (Switching amplifiers) operate with the transistor either fully on or off, achieving very high efficiency (up to 90 [%] or more). However, they have poor linearity and high noise, making them unsuitable for analog RF amplification.

Conclusion

Given the requirements for the RF amplifier 6.1.2, including an amplifier gain of 20-25 [dB], stable gain at 433.9 [MHz], low noise figure ($<$ 4 [dB]), adequate biasing solution, 50 [Ω] input and output impedance, minimal passive and active components, and cost-effectiveness, the most suitable amplifier class is **Class A**.

Class A amplifiers provide a good balance between necessary linearity and efficiency, making them ideal for the current use case. They offer:

- **Stable gain** suitable for maintaining consistent amplification at 433.9 [MHz].
- **High linearity** Class A amplifiers are known for their excellent linearity because the transistor operates in the active region for the entire input signal cycle, this ensures that the signal's integrity is maintained.
- **Low noise figure**, typically lower than 4 [dB], meeting the noise requirement.

- **Efficiency** Although the efficiency of Class A amplifiers is low, its impact on the use case of this amplifier is not significant since the trade off with the stable gain remedies the low efficiency.
- **Impedance matching** that can be designed to match the 50 [Ω] input and output impedance.

This makes Class A amplifiers commonly used in RF amplification due to their balanced performance characteristics, ensuring that the requirements for gain stability, low noise, and efficiency without excessive complexity or cost are met.

6.2.3. Class A amplifiers

Class A amplifiers are widely recognized for their high linearity and low distortion, making them ideal for applications where signal fidelity is paramount. It is designed to produce a large output voltage swing from a relatively small input signal voltage of only a few [mV] and are used mainly as “small signal amplifiers”. These amplifiers are designed to conduct for the entire 360 degrees of the input signal cycle, ensuring that the output closely follows the input waveform. This continuous operation results in a highly linear amplification process, minimizing harmonic distortion and preserving the integrity of the signal.

The typical layout of a Class A amplifier, as shown in Figure 6.3, includes a single active device, such as a Bipolar Junction Transistor (BJT), biased in such a way that it remains in the active region throughout the entire signal cycle. Key components of a Class A amplifier circuit include the active device (transistor) responsible for the actual signal amplification, a biasing network composed of resistors R_1 and R_2 which set the operating point of the transistor ensuring it remains in the active region, coupling capacitors C_1 that block DC components while allowing AC signals to pass, and a load resistor R_L connected to the collector of the transistor to help develop the amplified signal across it. Additionally, the emitter resistor R_E and bypass capacitor C_E stabilize the bias point and improve the amplifier’s linearity by providing local feedback.

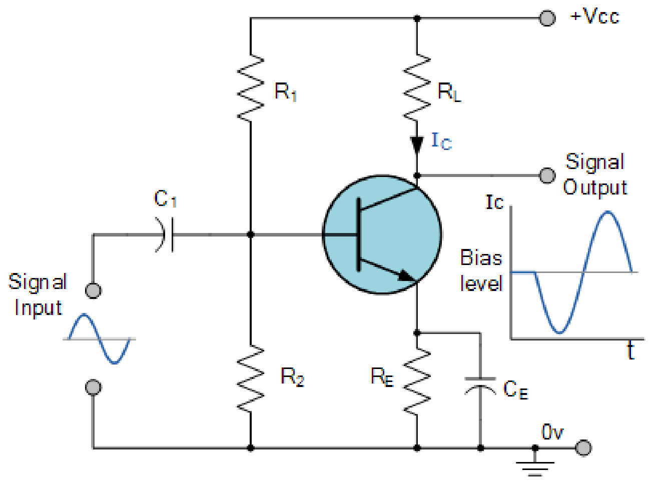


Figure 6.1: Basic class A amplifier circuit

Class A amplifiers are known for their excellent linearity, making them suitable for high-fidelity audio and RF applications where low distortion is critical. The continuous conduction ensures minimal crossover distortion, a common issue in other amplifier classes such as Class B and AB. Additionally, the continuous operation of the active device in Class A amplifiers results in a low noise figure, essential for applications of this amplifier. However, one of the primary drawbacks of Class A amplifiers is their poor efficiency, typically around 25-30 [%]. The transistor is always conducting, resulting in continuous power dissipation as heat, necessitating the use of substantial heatsinking to manage thermal dissipation.

Despite their low efficiency and thermal management challenges, the performance characteristics of Class A amplifiers make them invaluable in high-precision audio and RF applications. By carefully designing the biasing network and ensuring proper thermal management, Class A amplifiers can deliver exceptional performance in these demanding applications. In the following sections, the BJT will be selected using the amplifier requirements 6.1.2, sequentially, the biasing circuit for the transistor for the circuit in Figure 6.3 will be designed.

6.2.4. NPN Transistor Selection

After having selected an amplifier class and the type of transistor for the use of this project, which is an NPN transistor. This section will dive into the various NPN transistor available on the market, their suitability for this project and drawbacks. The primary focus is on achieving a high gain and low noise figure while maintaining stability and linearity.

When designing a receiver amplifier for operation at 433 [MHz], it is crucial to select an NPN transistor that offers low noise, high gain, and robust performance. The BFU520 transistor was selected for this purpose, and it is compared with other suitable transistors: BFP640ESD, BFU530A, and BFP420. This comparison focuses on their performance at 433 [MHz].

BFU520 by NXP Semiconductors

The BFU520 is optimized for high-frequency, low-noise applications, making it ideal for RF amplifiers. At 433 [MHz], it delivers a low noise figure of approximately 0.5 [dB] and a high gain of around 25 [dB], ensuring efficient low noise amplification. Its characteristics make it particularly suitable for ISM band applications and RF mixers.

BFP640ESD by Infineon Technologies

The BFP640ESD is a silicon germanium carbon (SiGe:C) NPN transistor known for its robust performance and high ESD protection. It offers a noise figure of 0.65 [dB] at 1.5 [GHz] and a gain of 26.5 [dB] at the same frequency. At 433 [MHz], it is expected to perform with a low noise figure and high gain, making it suitable for mobile, satellite, and multimedia applications within the 433 [MHz] ISM band.

BFU530A by NXP Semiconductors

The BFU530A provides a noise figure of 0.6 [dB] at 900 [MHz] and a maximum stable gain of 18 [dB] at the same frequency. For 433 [MHz] applications, it offers similar low noise performance with slightly higher gain. This transistor is versatile for various RF designs, including broadband amplifiers and low noise amplifiers for ISM band applications.

BFP420 by Infineon Technologies

The BFP420 offers a noise figure of 1.1 [dB] at 1.8 [GHz] and a gain of 21 [dB] at the same frequency. At 433 [MHz], its performance includes a lower noise figure and higher gain, making it a viable option for RF applications. It is suitable for wireless communication receivers, active mixers, and oscillators in RF front-end systems.

Detailed Comparison at 433 [MHz]

Conclusion

For the 433 [MHz] receiver amplifier design, the BFU520 transistor by NXP Semiconductors is a highly suitable choice due to its very low noise figure (0.5 [dB]) and high gain (25 [dB]). These characteristics make it ideal for low noise amplification, ensuring the integrity of weak signals at 433 [MHz].

Other transistors also offer competitive performance:

- **BFP640ESD**: Provides robust performance with high ESD protection and a noise figure around 0.6 [dB], making it suitable for mobile and satellite applications.

Feature	BFU520 (NXP)	BFP640ESD (Infineon)	BFU530A (NXP)	BFP420 (Infineon)
Noise Figure	0.5 dB	0.6 dB	0.5 dB	0.9 dB
Gain	25 dB	25 dB	22 dB	20 dB
Frequency Range	Up to 2 GHz	Up to 3.5 GHz	Up to 2 GHz	Up to 10 GHz
ESD Protection	Standard	High (2 kV HBM)	Standard	Standard
Applications	ISM Band, RF Mixers	Mobile, Satellite	ISM Band, Broadband	Wireless Comm, Mixers
Robustness	Good	Excellent	Good	Good
Power Consumption	Low	Low	Low	Low

Table 6.2: Detailed comparison of NPN transistors at 433 [MHz]

- **BFU530A**: Offers a low noise figure of about 0.5 [dB] and is versatile for various RF designs, including ISM band applications.
- **BFP420**: Suitable for high-frequency applications with a noise figure around 0.9 [dB] at 433 [MHz], making it a reliable choice for wireless communication receivers and mixers.

In summary, the BFU520 ensures that the receiver amplifier meets stringent requirements for low noise and high gain at 433 [MHz], making it an optimal choice for RF systems operating in this frequency band. Therefore, moving further on from now, all design and discussions will incorporate the BFU520 series in Class A amplifier fashion.

6.2.5. Biasing solution: BFU520

In the design of a Class A amplifier, the implementation of an effective biasing circuit is crucial. The biasing circuit establishes the operating point, or Q-point, of the transistor, ensuring it remains in the active region throughout the entire signal cycle. This is essential for achieving linear amplification, minimizing distortion, and maintaining signal fidelity. For the BFU520 transistor, which is a high-frequency, low-noise NPN transistor, an appropriate biasing solution is necessary to harness its optimal performance in RF applications at 433 [MHz].

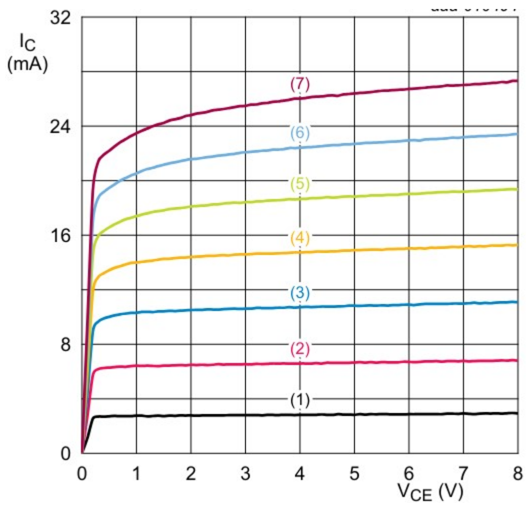


Figure 6.2: Transistor operation

Biasing Solutions for BFU520

The BFU520 transistor requires a well-designed biasing circuit for efficient Class A amplifier operation. The figure below (Figure 6.3) shows a Class A amplifier with a voltage divider bias. This section explains the circuit, discusses planned testing with the BFU520, and explores other potential biasing methods.

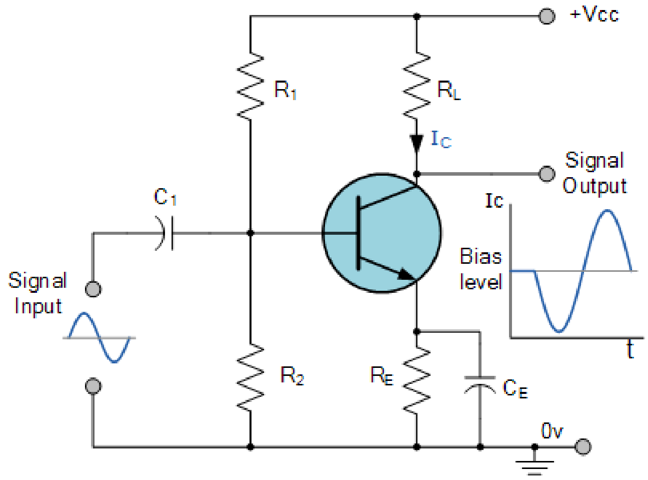


Figure 6.3: Basic class A amplifier circuit

Explanation of the Biasing Circuit in Figure 6.3

The biasing circuit shown in Figure 6.3 is a classic example of a voltage divider bias configuration. This method is favored for its ability to provide a stable and reliable operating point for the transistor.

Voltage Divider Network: The resistors R_1 and R_2 form a voltage divider that sets the base voltage (V_B) of the transistor. This network ensures that the base voltage remains stable despite variations in the transistor's current gain (β).

$$V_B = \frac{R_2}{R_1 + R_2} V_{CC} \tag{1}$$

Emitter Resistor and Bypass Capacitor: The emitter resistor (R_E) provides negative feedback, which enhances the stability and linearity of the amplifier. The bypass capacitor (C_E) is used to bypass the AC signal around the emitter resistor, maintaining the amplifier's gain for AC signals.

$$I_E = \frac{V_B - V_{BE}}{R_E} \tag{2}$$

Collector Resistor: The collector resistor (R_C) helps set the desired collector voltage (V_C), ensuring the transistor operates in the active region.

$$V_C = V_{CC} - I_C R_C \tag{3}$$

This biasing configuration offers simplicity and effectiveness in maintaining a stable operating point, which is crucial for achieving linear amplification with minimal distortion.

Testing the BFU520 Transistor in This Configuration

The BFU520 transistor will be tested in the biasing configuration depicted in Figure 7.1. The BFU520, known for its high frequency and low noise characteristics, is well-suited for this Class A amplifier design. The stability provided by the voltage divider bias will help harness the optimal performance of the BFU520, ensuring consistent gain and minimal distortion.

The testing process will involve measuring the amplifier's gain, linearity, and noise performance at the target frequency of 433 [MHz]. By using this configuration, the suitability of the BFU520 for RF applications will be verified, and design parameters will be refined to achieve the best possible performance.

Optimising the Biasing Resistors

To achieve the desired base voltage (V_B) of 1.2 [V], the voltage divider formed by resistors $R1$ and $R2$ was adjusted. The voltage divider equation is given by:

$$V_B = V_{CC} \cdot \frac{R_2}{R_1 + R_2}$$

Given a supply voltage $V_{CC} = 5$ [V] and the desired base voltage $V_B = 1.2$ [V], the resistor ratio should satisfy:

$$\frac{R_2}{R_1 + R_2} = \frac{1.2}{5} = 0.24$$

Using relatively large resistors to ensure that the transistor operates in the active region, and using standard resistors values it was chosen to have $R_1 = 8.2$ [Ω] and $R_2 = 3.3$ [$k\Omega$]

Updated Circuit, Simulation, and Testing

A basic LTSpice model was built to test this biasing circuit. The updated circuit, incorporating these new resistor values, resulted in a base voltage of approximately 425 [mV] shown in Figure 6.5a. While the gain achieved was around 20 [dB] shown in Figure 6.5b, the base voltage is unreliable and indicates improper biasing. The simulation results highlighted this inconsistency, indicating that the current biasing configuration is not optimal, necessitating the investigation of alternative biasing methods to achieve a more stable and accurate operating point.

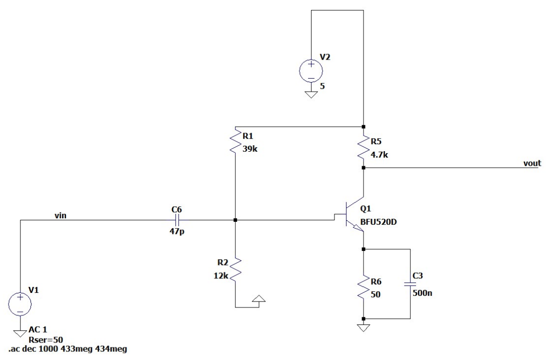
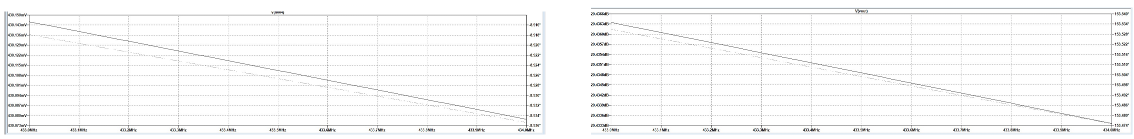


Figure 6.4: Updated Class A amplifier circuit with corrected biasing resistors



(a) Base voltage **(b)** Gain

Figure 6.5: Voltage divider biasing

Alternative Biasing Methods

Alternative biasing solutions were explored in Appendix C, however, it was shown that the best biasing solution is still the solution implemented above using both a voltage divider circuit and a collector resistor. Therefore, when proceeding further the circuit showcased in Figure 6.4 will be used and further improved.

Low Pass filter and Impedance matching circuit

After having decided the biasing solution, it is paramount to build a low pass filter to get rid of the redundant frequencies and all dc values. Additional an impedance matching circuit will be designed to maximise the power transfer and stability of the amplifier it cab found in the Appendix C.1.

6.2.6. Design Conclusion

In conclusion, the entire amplifier has been designed. It includes selecting the best transistor, determining the amplifier class of choice, designing its biasing circuits, a low pass filter at the output and finally designing an impedance matching circuit. For each particular component the system requirements 6.1.2 were taken into account. The final circuit shown in Figure 6.6.

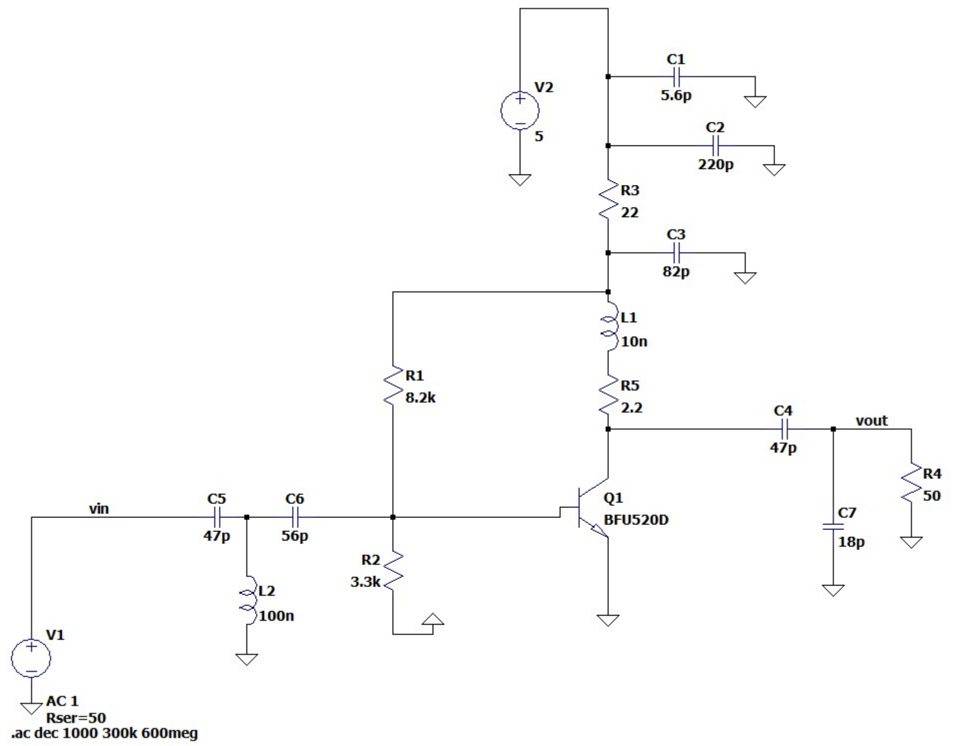


Figure 6.6: Final amplifier circuit

This modelled amplifier circuit meets all the system requirements mentioned in 6.1.2. Therefore, the circuit was built and tested in the following sections.

6.3. Assembly and results

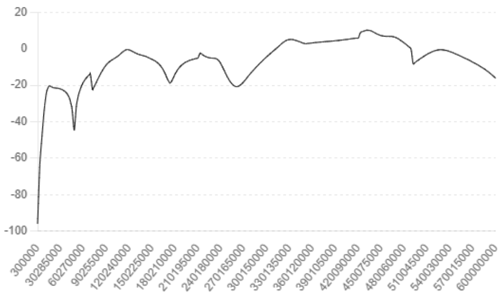
While simulations provide valuable insights, building and testing the actual amplifier circuit is essential to validate these predictions. Physical construction allows for the assessment of real-world factors like parasitic capacitance and noise sources not fully accounted for in simulations. Measuring the noise figure helps determine the amplifier's added noise, crucial for high-fidelity applications. Testing the physical circuit also verifies impedance matching, gain, and other performance metrics, ensuring the final design meets specifications.

Initially, the amplifier will be built using through-hole components due to their ease of handling and soldering, facilitating rapid prototyping and troubleshooting. Although SMD components offer advantages such as smaller size and better high-frequency performance, transitioning to SMD will be considered after successful testing of the through-hole prototype.

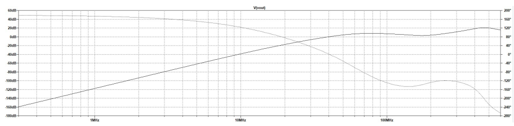
The amplifier was assembled on a soldering board, with inductors made using 29 AWG wire. Due to lab equipment limitations, the actual inductance measured was around 0.05 [μH] instead of the intended 100 [nH].

6.3.1. Results

When using a soldering board to build the circuit as shown in Figure C.5, the circuit did not seem to be working as expected. Despite the layout being rigorously checked for any short circuit or other errors the main problem did not seem to be apparent, the output gain was around 3 [dB]. Therefore, instead another route was taken by using a copper board to use as a large common ground plane as shown in Figure C.6, this is able to provide more stability to a system considering high frequency operation.



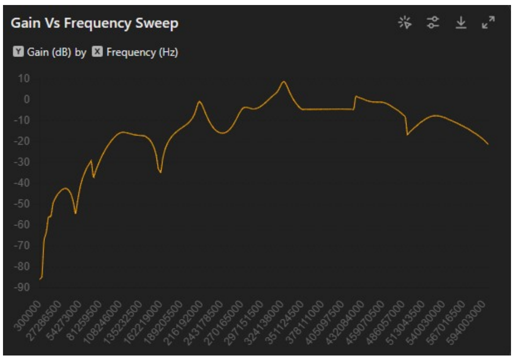
(a) Real gain curve



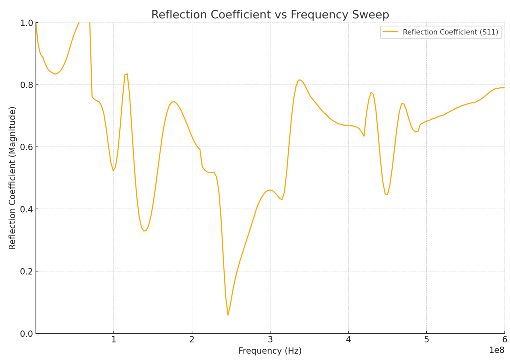
(b) Theoretical gain curve

Figure 6.7: Comparison of real and theoretical gain curves

Using the copper plate a large common ground plane did have an impact on the outcome of the circuit. However, the gain of the amplifier as checked using a VNA with a frequency sweep from 300 [kHz] to 600 [MHz] shown in Figure 6.7a did not match the simulated gain shown in Figure 6.7b which is 20 [dB] but the gain at 433 [MHz] came out to be around 11 [dB]. There were a lot of speculations made regarding the reason why the gain of the amplifier did not match the simulated gain. The first possible cause of failure was the biasing circuit, the base voltage of the transistor was measured and it did not come out to be 1.2 [V]. However, after running the analysis of the reflection coefficient for the input signal it was clear why the circuit behaved the way it did.



(a) Gain with amplifier off



(b) Reflection coefficient

Figure 6.8: Circuit malfunction

As shown in Figure 6.8b the reflection coefficient of the circuit is shown to be around 0.7, this can also be seen when the amplifier is off as shown in Figure 6.7a. The main possible reasons why this could be the case is due to the poor matching circuit and the quality of the components. Although in theory the impedance was matched to be 50 [Ω], this was not the case in reality as shown to be around 10 [Ω] input and 45 [Ω] output impedance. The main cause of this impedance is the quality of components, since operating in high frequencies the capacitor and inductor might create a resonance frequency that does not match that of the circuit. For instance, real capacitors have parasitic inductance and resistance. At high frequencies, the inductive reactance ($2\pi fL$ of the parasitic inductance can become significant, causing the capacitor to resonate at certain frequencies, leading to unexpected impedance peaks. In addition to this, as previously mentioned in the assembly section the exact inductance of the inductor is unknown due to the measurement equipment. The poor quality of both creates a high resonance frequencies causing significant reflection and since amplifiers are made to operate at a linear gain, however these oscillations can cause the amplifier to destabilise which significantly reduces its performance.

Despite the fact that the standing wave ratio of the circuit as shown in Figure 6.9 is less than 2 and is around 1.92, it is much higher for other frequencies, as high as 16 for frequencies around 150 [MHz]. This fluctuation in SWR has a significant impact on the voltage across the amplifier thereby causing malfunction and the final gain to be less than expected.

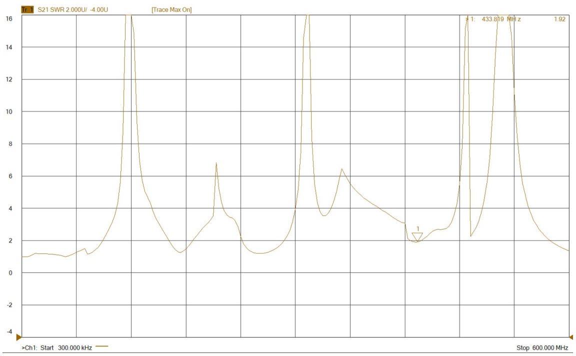


Figure 6.9: SWR of the amplifier

The best possible solution to this would be to use high RF components and to use variable capacitors such that in the case that there is an impedance mismatch fine tuning can be performed and the final gain can be as expected.

6.4. Conclusion

Although the design for the amplifier was robust and satisfied all the system requirements, the addition of low quality components was not taken into account. The theoretical gain of the amplifier was to be around 20 [dB] however when built it was around 11 [dB] due to the high reflection coefficient which caused the amplifier to destabilise thereby reducing the final gain.

7
Discussion and future work

Despite all of the progress done in the previous 6 weeks, there is still a lot that could and should be done in the future. The biggest issue by far was the time-constraint - given how consequential the transmitter weight limit is, all of the subgroups depended on each other for progress. For the transmitter antenna, a lot of options were unavailable and had to be weeded out, which took a lot of time. This further clashed with the ordering of necessary components and equipment that would take time to arrive. Since the transmitter subgroup flexPCB prototype was not yet ready, it was impossible to do tests that could accurately verify the L-network design. Similarly, the receiver system also heavily suffered due to time constraints, and despite the extensive designing and testing performed, the receiver amplifier came short. Additionally, the receiver subgroup had several issues with their direction finding algorithm. Consequently, the receiver system could not be integrated with all three subgroups and an entire system test could not be performed. Additional testing time would be highly beneficial for this project.

7.1. Frequency design

Frequency design suffered greatly from both time constraints and unavailability of data. Since the entire project depended on the choice, it had to be decided quickly. At the same time due to the conflicting sources on path loss frequency characteristics, it was hard to make a concrete choice. Finally, the heavy dependency on the transmitter circuit subgroup limited the choice.
For the future, due to how uncertain path loss is, it would be beneficial to first run in-field tests with different frequencies over a range of different outdoor environments to select the best one. These environments would include urban, rural and open-field, with the transmitter approached from various angles with various obstacles or lack thereof placed in the way.

7.2. Transmitter system

Transmitter antenna suffered time constraints on its theoretical design. For example, there are countless materials that were not considered: glass fibres, nitinol, and many more. Consultancy with a materials expert is heavily suggested. Expansion on shape design is also recommended - despite the best of efforts, the antenna still has significant losses. 0.1 [mm] diameter causes a very high R_L, so if feasible weight-wise, it may be of interest to thicken the wire. Other options, like zigzag antennas should have also been explored, but unfortunately were suggested too late. The simulation can be improved too - outside of model inaccuracies, it also only considers the free-space case, when the hornet is airborne. Keep in mind that the radiation pattern will change as the hornet is surrounded by vegetation or sitting within its nest. Large objects like trees are likely to act as imperfect ground, causing reflection. In the future, at least a simple model of a hornet sitting on its nest should be simulated and compared to the airborne scenario to make sure

the tracker is still efficient.
Most importantly, the antenna should have been tested for the transmission range requirement, which unfortunately there was not enough time nor was the transmitter circuit ready in time for this. A signal strength test would also collect data on the efficacy of the L-network, which could be further fine-tuned if necessary.
Another suggestion is to take the transmitter into an altogether new direction - with the relatively short range, using a reflector instead of a transmitter circuit would remove the need for such a strict power limit. If feasible in an urban environment, this has the potential to be an alternative with less losses, even if path loss is doubled.

7.3. Receiver system

Similar to the transmitter system, the entire receiver system suffered heavily due to time constraints. Despite successfully building the receiver antenna, more time could have been used to test the antenna with the tracker itself to measure its range in different environments.
Regarding the receiver antenna, additional integration designs could have been made using both omnidirectional and the Yagi (directional) antenna. Such a system would first find the transmitter in the surrounding and then find its direction relative to the subject. Another extension that could be made to the omnidirectional antenna is regarding its noise figure. By adding a glass or a non-conductive cover on the antenna the noise figure would become much better, on top of this it would also become more portable and less likely to break.
Regarding the receiver amplifier, although the design and simulation suggested that it was robust and fully met all the requirements of the system. This was not the case when it was built in reality as it performed much worse that expected. Initially all the connections in the circuit were checked to make sure that there no short circuit between components but this was not the case. Going back to the simulation was another explored wherein all the parasitic components were added to the model, the resulted simulation was worse than before but did not fully justify the behaviour of the assembled amplifier circuit.
The main reason for the poor performance of the amplifier was due to its poor reflection coefficient. The main cause of this issue was found out to be poor quality of components used in the circuit. The main components that could have been erroneous is the inductor as the lab did not have hardware that was able to measure inductors that were lower than 0.1 [μH], this could have played a major factor. During the assembly this was resolved in roughly calculating the theoretical inductance using the wire diameter, number of turns and radius of the turn but as previously mentioned, there was no method to verify whether this was accurate. The impact of inductors in the circuit was quite substantial, as the collector relies on a high impedance to have a constant gain. In the future, using high quality RF components and variable capacitors will have a huge impact on the final gain and stability of the circuit.

7.4. Integration

Unfortunately, there was not enough time for inter-module integration. For proper testing, at least the antennas must be connected to the transmitter and receiver prototypes respectively, and tested: for the transmitter, received signal strength and range; for the receiver antennas and amplifier, signal amplification and range. Furthermore, the entire system must be tested altogether, even if it cannot meet all the requirements. Such data is invaluable for future corrections of the design.

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A

Transmitter system

A.1. Basic Antenna theory

A.1.1. Antenna radiation patterns

Transmitter antennas are radiating elements – they take AC current fed into them, and since the electrons have nowhere to go, instead they radiate their energy into the surrounding medium. Thus, EM waves are propagated into the atmosphere. The distribution of the current along the wire determines the radiation pattern of the antenna – points of maximum current amplitude correspond to points of maximum radiation gain, and 0 points correspond to 0 gain. These patterns may create major and minor lobes, if the antenna is long enough. Figure A.1 showcases current distribution along dipole antennas. Out of the four, the first three are single lobed, while the last one has three lobes, correlating to the separation by the 0 [A] current points.
Typically, antennas have maximal current at the feeding point and no current at the antenna ends, with the reverse being true for voltage. As such, the impedance tends to be highest at the ends and lowest in the centre. Since AC (sinusoidal) current cycles directly correspond to wavelength, antenna dimensions are also proportional to it.

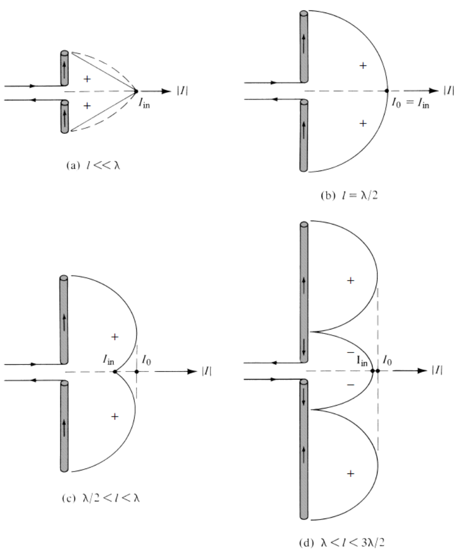


Figure A.1: Different current distributions along a dipole antenna depending on length

A.2. Antenna design

A.2.1. R_L approximation

R_L is caused by conductor imperfections. For a wire antenna of length l, as most considered designs will be, this is expressed via Equations A.1 and A.2, for DC and high frequency conditions respectively.

$$R_{dc} = \frac{l}{\sigma A} \tag{A.1}$$

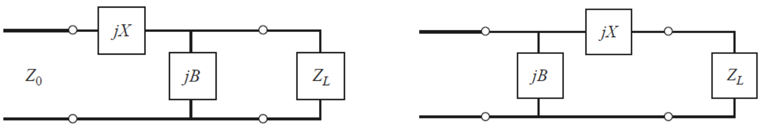
$$R_{hf} = \frac{l}{P}\sqrt{\frac{\omega\mu_0}{2\sigma}} \tag{A.2}$$

In the equations, $\mu_0 = 4\pi * 10^{-7}$ is the magnetic permeability in vacuum and σ is the conductivity of the wire's material. $\omega = 2\pi f$ and r denotes the radius. R_{hf} assumes equal current distribution along the wire, and so must take into account the sinusoidal average factor of 1/2 : $R_L = \frac{1}{2}R_{hf}$. Furthermore, Equation A.2 assumes skin depth $\delta = \sqrt{2/\omega\mu_0\sigma}$ is very small compared to the wire's diameter, thus bounding the effects to the perimeter of the wire $P = 2\pi r$ with radius r.

For this project, titanium is used as material with $\sigma = 2.38$ [MS/m], and the wire diameter is 0.1 [mm]. This gives $R_{hf} = 12.81$ [Ω], which in turn gives R_L = 6.40 [Ω]. In reality, δ = 15.66 [μm] is 15.66% of the 100 [μm] diameter, which is not a small fraction. Because of this, the R_{hf} is likely overestimated as current can travel through a bigger area than just the perimeter.

A.2.2. X and B calculation

X and B for the L-network can be calculated via Equations A.3a and A.3b for the topology in Subfigure A.2a, and otherwise through Equations A.4a and A.4b for the topology in Subfigure A.2b.



(a) L-network topology if $R_A > Z_0$ **(b)** L-network topology if $R_A < Z_0$

Figure A.2: The possible L-network structures based on R_A relative size to Z_0

$$X = \frac{1}{B} + \frac{X_A Z_0}{R_A} - \frac{Z_0}{BR_A} \tag{A.3a}$$

$$B = \frac{X_A \pm \sqrt{R_A/Z_0}\sqrt{R_A^2 + X_A^2 - Z_0 R_A}}{R_A^2 + X_A^2} \tag{A.3b}$$

$$X = \pm\sqrt{R_A(Z_0 - R_A)} - X_A \tag{A.4a}$$

$$B = \pm\frac{\sqrt{(Z_0 - R_A)/R_A}}{Z_0} \tag{A.4b}$$

A.2.3. Wire diameter

Most of the considered antennas will be wire antennas. Therefore, they will share a given wire diameter. The diameter is crucial, as it determines weight as per Equation A.5, and sturdiness of the antenna. Thicker wires will not bend under their own weight as much, but since weight is proportional to diameter squared, the weight grows exponentially. In the end, 0.1 [mm] diameter has been selected.

$$Weight = (\frac{Diameter}{2})^2 \pi * Length * Density \tag{A.5}$$

This choice stems from several factors. Firstly, Lowland transmitter used the same diameter titanium antenna, proving that the hornets cannot chew through it, so long as its made out of titanium at least; Having obtained a sample tracker, the measured diameter averaged at 0.107 [mm]. Secondly, a sample 0.25 [mm] diameter steel wire has proven to be too heavy; At 25.5 [cm] long and measured 0.248 [mm] thick, the wire weighed 81 [mg], far above the 15 [mg] weight limit. Thirdly, a 0.05 [mm] wire has proven to be too weak to either stand up or hold shape - any strain applied to the wire caused it to curl up on itself, making it unworkable for a sturdy antenna design.

A.2.4. Material

Due to the strict weight requirement, the diameter of the antenna wire must be tiny. At the same time, it is a known problem that the Asian Hornet has a bite force powerful enough to chew through a copper wire, as is relayed by the client. Therefore, a stronger material is required. The main parameter to look out for in this case is machinability. Machinability is the ability of a metal to be cut - the higher the parameter, the easier it is to cut, or machine, a metal. Since this is a rather subjective parameter relying on many factors, it is measured in reference to another material. In Table A.1 below, CuZn36Pb3 is taken as 100 [%] machinable. Since copper poses an issue, a suitable material should have lower machinability, aka below 20 [%] [34].

In this report only a limited amount of metals was analysed - namely copper, steel, titanium and brass (CuZn37). This is for two reasons - first is the availability of the materials - steel and brass are commonly spun into wires and are available at the university. Second is the suitability of the material - titanium wire may not be readily available, but due to its low density and high strength it is highly suitable. Many other metals such as colbalt, magnezium, zinc, iron, silver, etc are neither available nor are suitable for the job.

Another three important properties to consider are density, conductivity and price. Density is important since the weight restriction of the transmitter is strict. Since most of the antennas to be explored will be made of wire, Equation A.5 in Appendix A.2.3 can be used to calculate the weight. For other cases, the weight equation will be mentioned. Conductivity is important as it determines antenna's conductive losses R_L as per Equation A.2 in Appendix A.2.1. The price is not as important, but since one of the requirements in Section 2.1 is component price below 25€, it should be briefly considered.

Material	Copper	Brass (CuZn37)	Titanium	Stainless steel
Machinability [%]	20	35	10	12
Density [g/cm^3]	8.9	8.4	4.6	7.85
Electric conductivity [MS/m]	59.6	16.0	2.38	1.45
Price [$/kg]	7.45	-	23.5	6.2
15 [cm] 0.1 [mm] wire weight [mg]	10.49	9.90	5.42	9.25

Table A.1: The properties of considered transmitter antenna materials [34] [35] [36] [37]

As described in Table A.1, brass is not a suitable metal due to its higher machinability than copper. This leaves two choices: titanium and steel. Steel is heavier, more machinable and a worse conductor, but much cheaper. However, at 15 [cm] max, the price of a 0.1mm titanium wire is only 127 * 10^{-6} [$], far below so much as a cent. Finally, only 0.25 [mm] diameter steel wire is available at the university, so in either case the material would have to be ordered from external party. Due to this, titanium was chosen.

A.3. Simulation

A.3.1. 3D model limitations

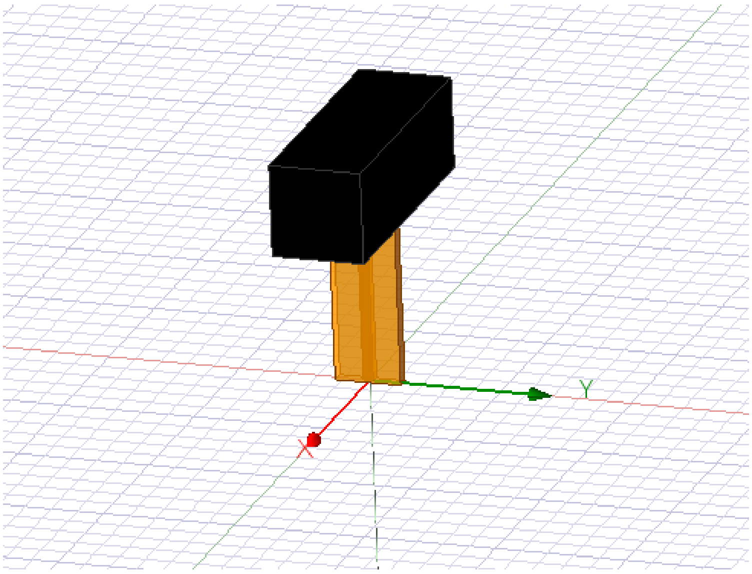


Figure A.3: Ansys 3D model of a hornet with a transmitter hanging off its thorax

Element	Colour	Material	Shape	Dimensions [mm^3]
Hornet	Black	Water	Box	20x7x7
PCB	Orange	Polyimide	Box	0.75x0.75x13
PCB GND	Brown	Copper	Box	1x5x12.875
Monopole	Grey	Titanium	Cylinder	r=0.05, l=150
Gap	Clear	Vacuum	Cylinder	r=0.05, l=1

Table A.2: Simulation elements and their respective make and dimensions. Box elements are described in XxYxZ format

The used Ansys model as shown in Figure A.3 is very simple. In reality, it has a lot of limitations:

- The hornet is of course a much more complicated shape. Furthermore, Ansys' HFSS base library did not contain any biomaterials and therefore water was chosen as the closest replacement material. The dimensions used in Table A.2 were personally measured via dead hornet sample.
- In reality flexPCBs are much thinner than 1 [mm], with only about 0.1 [mm] width. However, since the PCB will also have a lot of SMD components soldered on it, 1 [mm] width was used as a compensation to not simulating those elements on the PCB itself. Flex PCBs are usually made up of materials like polyimide and copper, hence the choice for base 'outer' layer and ground materials [38].
- In reality, ground would be very difficult to estimate, as at the time of building this model transmitter subgroup has not yet built their prototype. The best approximation given was that the ground will likely take up 15-20 [%] of the total PCB area, and since the studied Lowland tracker has its battery closest to the hornet, its length would be almost the entirety of the PCB's height.

- The monopole is pretty realistic, however in real circumstances the wire would bend and have imperfections. Furthermore, in the model the monopole is centered relative to the PCB. In reality, it's likely that the antenna will be placed on the side. Furthermore, in the model the copper is fully encased in the polyimide outer layer. In reality, parts of copper will be on the PCB's surface, connecting SMD components together.
- The gap acts as the excitation point since that's how Ansys simulation works. It was placed right at the base of the monopole, for the lack of better PCB aproximation. The gap is filled with a "lump port" that has a input impedance of 50 [Ω] and can be impedance matched in post-processing to include a matching L-network.

A.3.2. Effect of different elements

Because of how small the transmitter system is, even small changes can have an effect. To study this, as well as how well the L-network will withstand inaccuracies, different parameters were altered from the base 15 [cm] antenna, 1 [mm] PCB, 13 [mm] GND to see the effect on impedance, radiation gain, and the reflection coefficients for both unmatched and matched conditions. Table A.3 outlines these effects. In all cases, the antenna is matched to the base 15 [cm] antenna since the point is to study how much deviation the model can handle, before Γ becomes unacceptable. In all cases of alteration, only one parameter has been changed compared to the base case, which is described in the "Case" column. The first row describes the base case.

Case	Impedance	$\lvert\Gamma\rvert$ unmatched [dB]	$\lvert\Gamma\rvert$ matched [dB]	Cutplane gain [dB]
Antenna length = 15 [cm] PCB thickness = 1 [mm] GND length = 13 [mm]	17.66 - j1095.0	-0.013	-62.89	-0.1824
Antenna length = 20 [cm]	35.75 - j969.77	-0.033	-24.26	0.5997
Antenna length = 10 [cm]	9.35 - j1155.12	-0.006	-31.39	-1.2147
PCB thickness = 2 [mm]	16.79 - j893.55	-0.018	-19.89	-0.0397
GND length = 10 [mm]	17.31 - j1209.07	-0.0103	-26.11	-0.425

Table A.3: The effect of different parameters on the reflection coefficient and impedance, when matched to the base 15 [cm] antenna, 1 [mm] PCB, 13 [mm] ground impedance

As can be seen, antenna length indeed affects radiation efficiency, as the 20 [cm] antenna has the highest cutplane gain of 0.5997 [dB] and η = 0.821, and the 10 [cm] antenna has the lowest cutplane gain of -1.2147 [dB] and η of 0.316. Unfortunately 20 [cm] is unfeasible due to the requirements in Section 2.2. Likewise, shortening the GND has a similar effect, even if to a lesser degree: the cutplane gain reduces to -0.425 [dB] with η = 0.630. It should be noted however, that the ground gets shorter only by 3 [mm], as opposed to 5 [cm].
Despite not seeming particularly important at first, interestingly PCB thickness has the biggest effect on Γ, giving the lowest Γ = -19.89 [dB] = 0.0103 as opposed to the original -62.89 [dB]. In spite of this, all deviations keep well within the desired $\Gamma \leq 0.2$, implying that the design is not susceptible to minor inaccuracies, which is good, as likely the simulation is not a true reflection of reality.
All simulation cases have similarly large Γ without impedance matching, showcasing once again the importance of the L-network.

B

Directional antennas

Since the final goal of the reception of the signal is to find the location, an algorithm was designed to calculate the signal's origin. However, due to complexities in accurately pinpointing the signal using omnidirectional antennas, it was also chosen to look into designing a directional antenna system. Although the direction-finding algorithm would not be able to function with a single directional antenna, the issue of gain could be significantly improved and it would be possible to manually find the directional antenna by measuring the direction from the signal level is at its highest.

A directional antenna is one that radiates its energy more effectively in one (or some) direction than others, providing higher gain and better signal quality from the intended direction while minimising interference from other directions. This focused radiation pattern enhances the ability to receive weak signals over greater distances and improves the signal-to-noise ratio, which is crucial for accurate signal processing and location estimation.

There are several types of directional antennas, each with unique features that make them suitable for specific applications. The antennas discussed below incorporate features that meet the antenna requirements mentioned in Section 5.2.1. By leveraging the advantages of directional antennas, the system can achieve higher accuracy in signal reception, thereby facilitating more reliable location determination despite the inherent challenges.

The two primary types of directional antennas considered in this design are the simple dipole antenna and the Yagi-Uda antenna. Both types are well-suited to different aspects of the design requirements, offering a balance between simplicity, ease of implementation, and high directional gain. By exploring the characteristics and benefits of these antennas, the optimal solution for the signal reception system can be determined, ensuring robust performance in locating the signal source.

B.0.1. Dipole antennas

A dipole antenna is one of the most fundamental and widely utilized types of antennas in radio communication. It consists of two conductive elements, typically metal rods, aligned end-to-end with a small gap between them where the feedline is connected.

Structure and Operation: The dipole antenna's elements are each a quarter wavelength long, resulting in a total length of half the wavelength of the signal it is designed to receive or transmit. For a signal frequency of 433 [MHz], the total length of the dipole antenna would be approximately 34.6 [cm], as the wavelength (λ) is given by the speed of light (c) divided by the frequency (f), $\lambda = c/f$.

When an alternating current (AC) at the target frequency is applied to the feed point—the gap between the elements—it induces an oscillation of electrons within the conductive elements. This oscillatory motion generates an electromagnetic wave that propagates away from the antenna.

Radiation Pattern: The radiation pattern of a dipole antenna is characterized by a doughnut shape, where the strongest radiation is perpendicular to the axis of the antenna. Consequently, the dipole antenna exhibits good radiation in the horizontal plane, with minimal radiation along its vertical axis as shown in Figure B.1.

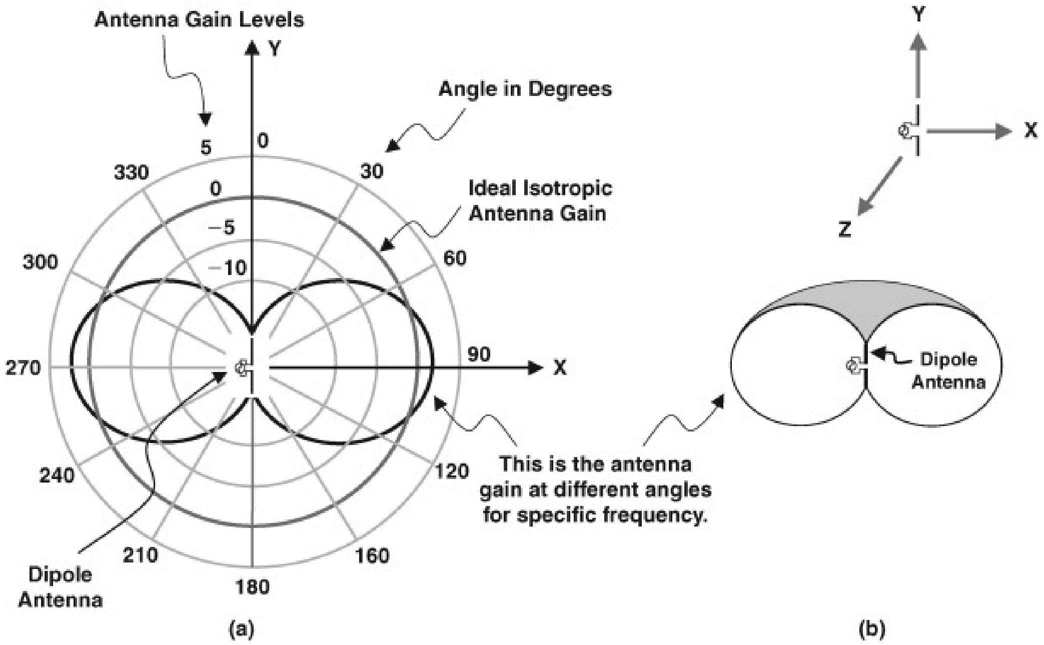


Figure B.1: Radiation pattern: dipole antenna

Impedance: A typical dipole antenna exhibits an impedance of approximately 73 ohms, making it compatible with standard transmission lines and facilitating efficient power transfer.

Figure B.2: Example dipole antenna

Drawbacks

While dipole antennas are popular due to their simplicity and effectiveness, they have certain drawbacks that may limit their application in specific scenarios. One significant limitation is their relatively low gain, typically around 2.15 [dBi]. This low gain may not be sufficient for applications requiring long-range communication or where the signal needs to be amplified to overcome significant transmission losses.

Additionally, the radiation pattern of a dipole antenna is doughnut-shaped, providing omnidirectional coverage in the horizontal plane but lacking strong directionality in the vertical plane. This lack of strong directionality can be a limitation when a focused signal beam is required to enhance reception from a particular direction while rejecting interference from others.

Another challenge with dipole antennas is impedance matching. The typical impedance of a dipole antenna is around 73 ohms. When used with standard 50-ohm transmission lines, additional impedance matching components or techniques are necessary to ensure efficient power transfer and minimize signal reflections. These matching techniques can complicate the antenna design and setup.

Furthermore, to achieve optimal performance, a dipole antenna needs to be installed at a height of at least half the wavelength above the ground. For a 433 [MHz] signal, this corresponds to approximately 34.6 [cm]. In some cases, achieving this height may be impractical, especially in mobile or constrained environments.

Lastly, dipole antennas can be affected by their surrounding environment, including nearby objects and ground effects, which can alter their impedance and radiation pattern. This sensitivity requires careful placement and tuning to maintain optimal performance.

B.0.2. Yagi Antenna

The Yagi-Uda antenna, often referred to simply as a Yagi antenna, offers a solution to some of the limitations associated with dipole antennas by providing higher gain and more focused directionality.

Yagi antennas can achieve substantial gain, typically ranging from 7 to 20 [dBi], depending on the number and configuration of the elements. This high gain, created by creation of multiple dipoles and multiplying their gain makes Yagi antennas suitable for long-range communication and applications requiring strong signal amplification. The Yagi antenna's design incorporates a driven element, a reflector, and one or more directors as shown in Figure B.3. This configuration focuses the radiation pattern in a single direction, enhancing the ability to receive or transmit signals from a specific direction while minimizing interference from other directions.

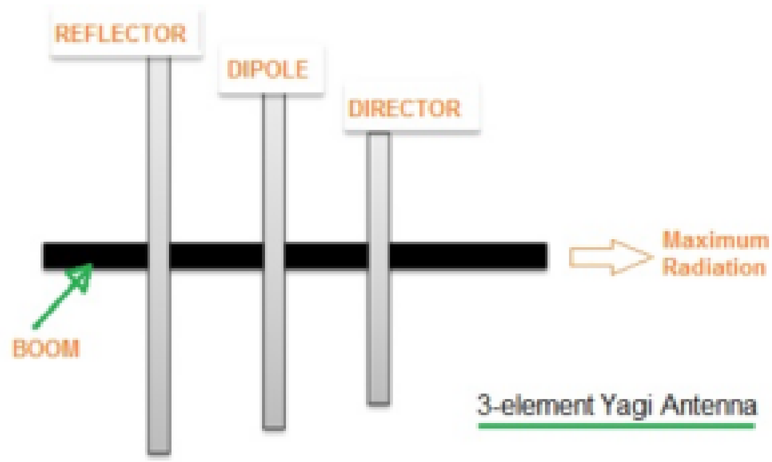
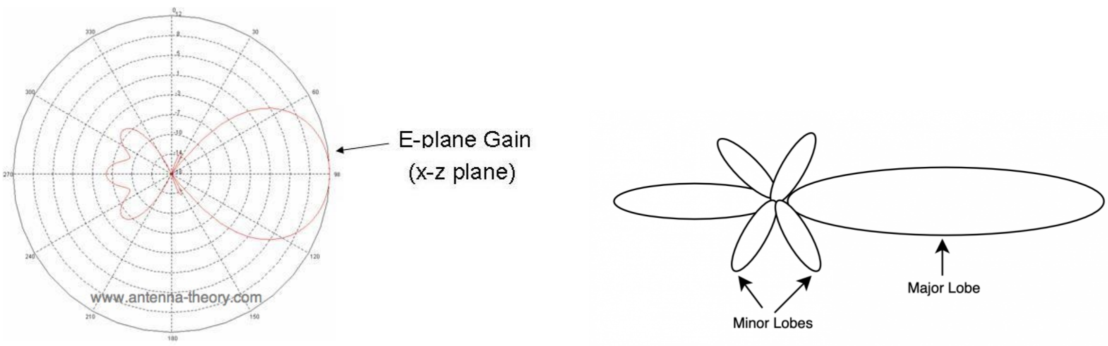


Figure B.3: 3 element Yagi antenna [39]

However, Yagi antennas are more complex and larger compared to dipole antennas. The multiple elements (reflector and directors) add to the size and complexity of the antenna, making it less suitable for portable or space-constrained applications. Additionally, Yagi antennas typically have a narrower bandwidth compared to dipole antennas. This means they are more frequency-specific and may require precise tuning to operate effectively at the desired frequency.

The highly directional nature of Yagi antennas requires precise alignment towards the signal source. This directional alignment can be challenging and may necessitate additional mounting equipment and adjustments. Similar to dipole antennas, Yagi antennas can be affected by their environment. Their performance can be influenced by nearby objects, ground effects, and weather conditions, requiring careful installation and maintenance. Although dipole antennas are relatively simple, easy to design and cheap. They do not offer the highest possible gain that directional antennas can have. One possible solution is to have multiple dipole antennas in one antenna, this type of antenna is known as a Yagi antenna.

Radiation pattern The radiation pattern of the Yagi antenna is highly directive as shown in B.4. In this radiation pattern, the major lobe corresponds to the forward radiated wave and there are many minor lobes at the rear and sideways. The foremost minor lobe is the reverse one that happened by the radiation in the reflector's direction.



(a) Radiation pattern

(b) Main and side lobes

Figure B.4: Radiation pattern Yagi antenna

Due to its highly directive gain in one direction, it is easily able to pick up signals up to 5km away, this makes them a very good candidate for antenna choice in the use case of the receiver system.

Design

It was chosen to go with the smallest Yagi antenna which is a 3 element Yagi antenna. This is due to several reasons. In the case of a 3 element Yagi antenna the gain is around 6-8 [dB] [40] which suffices since, in combination with the receiver amplifier the likelihood in finding the AM signal is very high. Additionally, the act of adding more elements in the antenna has a greater impact on the directivity rather than its gain [40] which as shown above is sufficient. Therefore, proceeding further a 3 element Yagi antenna for the specific band of 433.9 [MHz] will be designed.

Building a cost-effective Yagi-Uda antenna for 433.9 [MHz] involves optimising the design to use readily available materials while maintaining performance. A 3-element Yagi antenna consists of a driven element, a reflector, and a director. Here, we provide detailed design parameters and practical guidelines for constructing this antenna.

Design Specifications

The wavelength (λ) for a 433.9 [MHz] signal is approximately 69.1 [cm]. The dimensions of the elements and their spacing are derived based on this wavelength.

- Driven Element: This is typically a half-wavelength dipole.
- Reflector: Slightly longer than the driven element.
- Director: Slightly shorter than the driven element.

Element Dimensions

Driven Element Length: $L_{\text{driven}} = 0.5 \times \lambda = 34.55$ [cm]
Reflector Length: $L_{\text{reflector}} \approx 0.55 \times \lambda = 38.0$ [cm]
Director Length: $L_{\text{director}} \approx 0.45 \times \lambda = 31.1$ [cm]

Element Spacing

The spacing between elements is crucial for the antenna's performance. According to [40], the distance for each element to the driven element (dipole) has to follow the Figure B.5.

Reflector Spacing: $S_{\text{reflector}} = 0.35 \times \lambda = 24.1$ [cm] behind the driven element
Director Spacing: $S_{\text{director}} = 0.125 \times \lambda = 8.63$ [cm] in front of the driven element

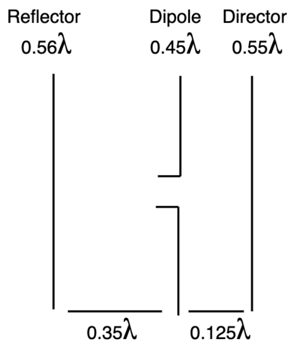


Figure B.5: Distance between elements

A 3-element Yagi antenna generally provides a gain in the range of 6 to 8 [dBi]. This gain is achieved through the constructive interference of the signals radiated by the driven element and the parasitic elements (reflector and director). The reflector increases the forward gain by reflecting energy towards the direction of the director, while the director focuses the energy further, enhancing the antenna's directivity.

The driven element (dipole) itself adds a gain of 2.15 [dBi], the addition of the reflector adds about 4 [dBi] of gain by reflecting the radiated signal forward. The director, positioned in the front of the driven element adds approximately 2 [dBi] of gain by focusing the signal in the forward direction [40].

B.0.3. Modelling and simulation

This antenna was also modelled using the 4NEC2 software. As expected it had a gain of around 8 [dBi] as shown in Figure B.6.

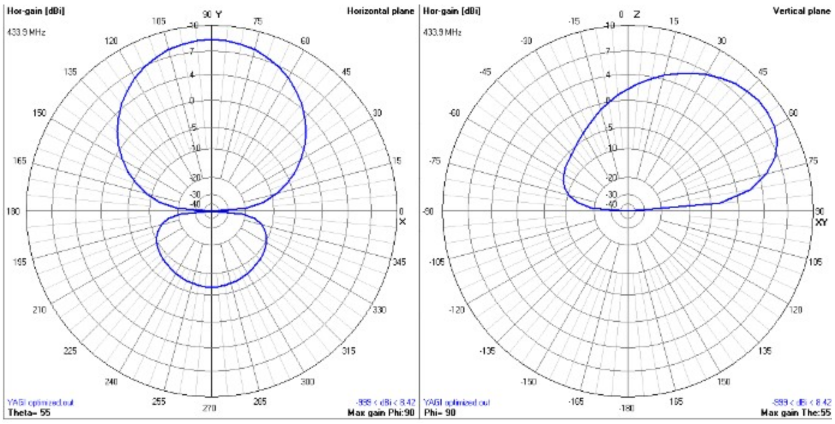


Figure B.6: Horizontal and vertical plane model

B.0.4. Assembly and testing

As mentioned in the results of the omnidirectional antenna 5.3.4, the collinear antennas performs a bit better than the dipole antennas in terms of the directivity in the horizontal and vertical direction. Therefore, it was decided to not build the directional Yagi antenna and instead use the collinear antenna to perform further testing and integration.

C

Alternative biasing methods

This chapter will explore the several other biasing methods that were explored to ensure that the transistors always stays on. While the voltage divider bias method shown in Figure 7.1 is effective, other biasing methods can be considered for further stability and performance enhancements:

Fixed Bias with Emitter Resistor: This method involves connecting a resistor between the base and a fixed voltage source, along with an emitter resistor connected to ground. The emitter resistor provides negative feedback, improving linearity and thermal stability.

$$V_B = I_B R_B + V_{BE} + I_E R_E$$

Collector-to-Base Feedback Bias: In this configuration, a resistor is placed between the collector and base, creating a feedback loop that stabilizes the operating point. This feedback mechanism helps counteract variations in the collector current, providing excellent stability.

Active Biasing with Constant Current Source: This method uses a constant current source in place of the emitter resistor, providing a stable bias current. This approach significantly enhances temperature stability and linearity. This implementation however is not feasible in the case of this project since the current is quite limited by the USB supply.

In summary, the biasing circuit depicted in Figure 7.1 is a reliable and effective method for ensuring stable operation of the BFU520 transistor in a Class A amplifier. By testing this configuration and considering alternative biasing methods, optimal performance for RF applications at 433 [MHz] can be achieved.

$$V_B = V_C - I_B R_B$$

Emitter Degeneration

Emitter degeneration involves placing a resistor (R_E) in the emitter leg of a transistor amplifier. This technique introduces negative feedback, which stabilizes the operating point and enhances the linearity of the amplifier. The emitter resistor improves thermal stability and reduces distortion, making the amplifier less sensitive to variations in transistor parameters and temperature changes. The voltage gain of the amplifier is controlled and reduced by the value of the emitter resistor, allowing for predictable and manageable gain settings.

$$V_E = I_E R_E$$

The base-emitter voltage (V_{BE}) is given by:

$$V_{BE} = V_B - V_E$$

As the collector current (I_C) increases, the emitter current (I_E) also increases, causing a larger voltage drop across R_E. This increased voltage drop reduces V_{BE}, which in turn reduces I_C, creating a feedback loop that helps stabilize the transistor's operating point.

Emitter degeneration offers several advantages over other biasing methods, such as fixed bias with emitter resistor and collector-to-base feedback bias. Unlike fixed bias with emitter resistor, emitter degeneration provides superior stability against variations in transistor parameters and temperature changes. The negative feedback mechanism inherent in emitter degeneration adjusts the operating point dynamically, maintaining consistent performance.

In comparison to collector-to-base feedback bias, emitter degeneration offers enhanced linearity. The feedback mechanism in collector-to-base feedback can introduce unwanted phase shifts at high frequencies, affecting linearity. Emitter degeneration maintains a more linear response, which is crucial for high-frequency operations.

Additionally, the thermal stability provided by emitter degeneration is more robust than other methods. As temperature increases, the emitter current rises, but the increased voltage drop across R_E reduces V_{BE}, counteracting the rise in current. This self-regulating mechanism is less pronounced in other biasing methods.

The biasing circuit implemented in the provided schematic uses a combination of voltage divider biasing and emitter degeneration to establish a stable operating point for the BFU520D transistor.

Voltage Divider Network (R1 and R2): Resistors $R1$ and $R2$ form a voltage divider that sets the base voltage (V_B) of the transistor. This network ensures that the base voltage remains stable despite variations in transistor parameters and power supply fluctuations.

$$V_B = V_{CC} \cdot \frac{R2}{R1 + R2}$$

Given: - $V_{CC} = 5[V]$ - $R1 = 8.2[k\Omega]$ - $R2 = 3.3[k\Omega]$

$$V_B = 5[V] \cdot \frac{3.3[k\Omega]}{8.2[k\Omega] + 3.3[k\Omega]} = 5[V] \cdot \frac{3.3[k\Omega]}{11.5[k\Omega]} \approx 1.43[V]$$

Emitter Resistor (R5): The emitter resistor $R5$ provides negative feedback, stabilizing the operating point and enhancing linearity. The emitter voltage (V_E) can be calculated as:

$$V_E = V_B - V_{BE}$$

Assuming $V_{BE} \approx 0.7[V]$:

$$V_E = 1.43[V] - 0.7[V] = 0.73[V]$$

The emitter current (I_E) is then:

$$I_E = \frac{V_E}{R_E}$$

Given $R_E = 2.2[\Omega]$:

$$I_E = \frac{0.73[V]}{2.2[\Omega]} \approx 0.332[A]$$

The voltage divider network sets the base voltage, while the emitter resistor provides negative feedback to stabilize the operating point. The calculations confirm that the biasing circuit is designed to maintain a stable and linear operation, essential for RF applications.

A circuit that incorporates both Emitter degeneration and the previously working voltage divider biasing was simulated in LTSpice. The results however, were not promising, it showed that the addition of the emitter degeneration had a negative effect on the output gain. Therefore, the best method is indeed the use of a voltage divider is the best viable biasing solution for the circuit.

C.1. Low Pass Fitler and Impedance matching

The Low Pass Fitler and the corresponding impedance matching circuit will be further explored below.

C.1.1. Low Pass Filter

As discussed in 6.2.4, the selected NPN transistor has quite a wide range of operation and amplifies all signals between 0-2 [GHz]. Therefore, The output stage of the circuit should incorporate a low-pass filter (LPF) designed to remove DC components and attenuate unwanted high-frequency signals, ensuring a clean and stable output. A

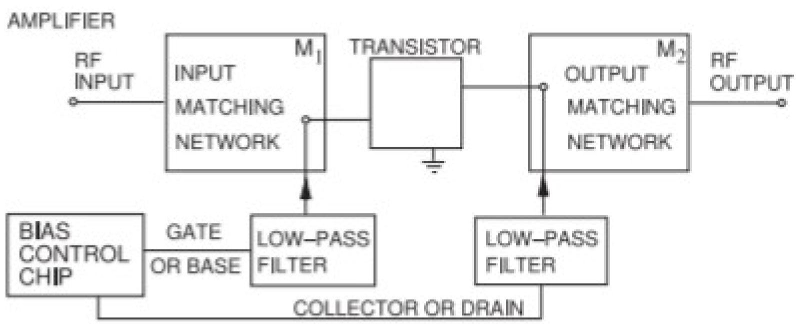


Figure C.1: Amplifier with LPF

Various types of LPFs can be implemented, each with its advantages and disadvantages depending on the application requirements.

A single-pole RC filter is the simplest form of low-pass filter, using a single resistor (R) and capacitor (C) to create a basic RC network. The cutoff frequency of this filter is determined by the values of R and C, following the relation $f_c = \frac{1}{2\pi RC}$. The primary advantages of this type of filter include its simplicity, cost-effectiveness, and ease of implementation with minimal components. However, it provides a gentle roll-off rate of 20 [dB/decade].

Higher-order RC filters, which use multiple RC stages, can achieve steeper roll-off rates. A second-order RC filter uses two RC networks in series, providing a roll-off rate of 40 [dB/decade]. While these filters offer sharper frequency cutoffs, they also increase the circuit's complexity, component count, and potentially the physical size.

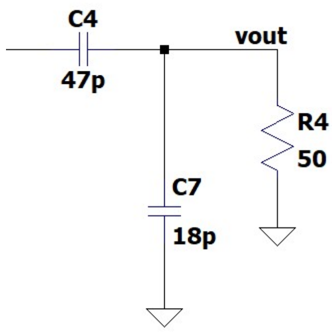


Figure C.2: Output Low Pass Filter

LC filters utilize inductors (L) and capacitors (C) to create resonant circuits that offer sharp cutoff frequencies. These filters are advantageous due to their low insertion loss and steep roll-off rates, making them suitable for high-frequency applications. However designing such a heavy and expensive system does not meet the portability and cost requirements of this design, therefore, further research needs to be conducted.

Active filters employ operational amplifiers (op-amps) along with resistors and capacitors to achieve desired filter characteristics. These filters allow for precise control over gain and cutoff frequency and offer adjustable characteristics, including amplification. Despite these benefits, active filters require a power supply, increasing power consumption and complexity, making them less ideal for low-power applications.

A single-pole RC low-pass filter can be implemented at the output stage using 2 capacitors and the load resistor itself. This design was chosen for several reasons. Firstly, the single-pole RC filter is straightforward to implement, requiring only minimal components. This simplicity translates to lower cost and reduced design complexity, making it suitable for a wide range of applications. Secondly, for the specified application, the single-pole RC filter provides sufficient attenuation of high-frequency noise and DC components. While higher-order filters offer sharper roll-offs, the gentle 20 [dB/decade] roll-off of the single-pole RC filter is adequate for ensuring a clean output signal in this context.

Moreover, the use of just two capacitors and one resistor results in a compact filter design. This is particularly advantageous in space-constrained applications where physical size and component footprint are critical considerations. Additionally, the RC filter can be easily integrated into the existing circuit without requiring additional power supplies or complex design adjustments, supporting efficient design and testing processes.

In conclusion, the single-pole RC low-pass filter implemented in this circuit provides an optimal balance between simplicity, performance, and cost. While alternative filter designs like higher-order RC, LC, and active filters offer certain advantages, the chosen implementation is superior for the given application due to its ease of implementation, sufficient performance, compactness, and cost-effectiveness. This makes it an ideal choice for achieving the desired filtering objectives without introducing unnecessary complexity.

Therefore, a simple RC low pass filter taking into regard the output impedance of 50 [Ω] was designed as shown in Figure C.2.

C.1.2. Impedance matching

Impedance matching is a fundamental aspect of circuit design, particularly in high-frequency applications such as RF circuits. Proper impedance matching ensures maximum power transfer between different stages of the circuit and minimizes signal reflections, which can degrade performance. In the context of the provided circuit, impedance matching is necessary to ensure that the signal is transferred efficiently from the source through the amplification stages to the output, maintaining signal integrity and strength.

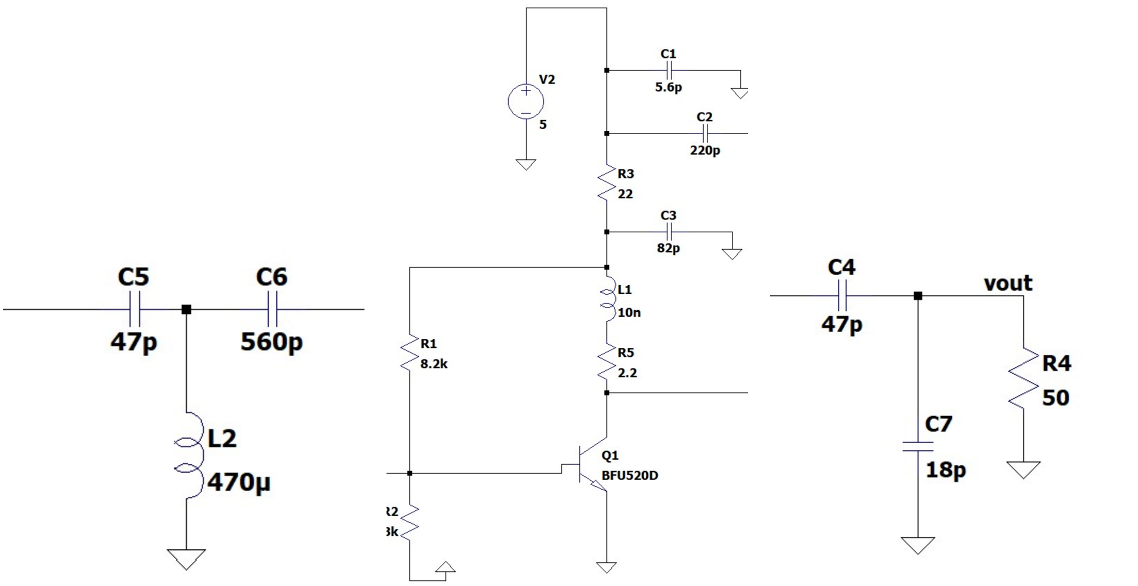
Necessity of Impedance Matching

Impedance matching is essential for several reasons. Firstly, it ensures maximal power transfer between the source, transmission line, and load. When the source impedance matches the load impedance, the power delivered to the load is maximized, which is crucial for efficient circuit operation. Secondly, impedance matching minimizes signal reflections, which can cause standing waves and signal loss. This is particularly critical in high-frequency circuits, where even small impedance mismatches can significantly impact performance. Lastly, impedance matching improves signal quality by preserving the fidelity of the amplified signal and minimizing distortions.

In this circuit, the impedance is matched to 50 ohms because the coaxial cable used for signal transmission has a characteristic impedance of 50 ohms. Matching the circuit impedance to the cable's impedance ensures that the maximum power is transferred with minimal reflections, maintaining signal integrity over the transmission line.

Implementation of Impedance Matching

In the provided circuit, several strategies have been employed to achieve impedance matching:



(a) Input matching circuit **(b)** Amplification matching circuit **(c)** Output matching circit

Figure C.3: Matching circuit

Input Stage Matching

Impedance matching at the input stage is crucial to ensure that the maximum amount of the input signal is transferred into the circuit with minimal reflection. This is especially important to prevent loss of signal strength and to maintain signal integrity from the very beginning of the signal path.

As shown in Figure C.3a the input signal from the source V_1 is coupled through capacitors C_5 (47 [pF]) and C_6 (560 [pF]), forming a capacitive network that assists in matching the input source impedance to the subsequent stage. Inductor L_2 (470 [µH]) acts as a high inductance coil to block high-frequency noise, stabilizing the input impedance and contributing to effective impedance matching.

Amplification Stage Matching

At the amplification stage, impedance matching is necessary to ensure that the transistor operates efficiently, with maximum power transfer between the preceding and subsequent circuit elements. This is critical for achieving the desired amplification while maintaining signal integrity and minimizing losses.

As shown in Figure C.3b the transistor Q_1 (BFU520D) is biased using resistors R_1 (8.2 [kΩ]), R_2 (3.3 [kΩ]), and R_5 (2.2 [Ω]), setting the appropriate operating point for the transistor and ensuring that its input and output impedances are matched to the surrounding circuit elements. Inductor L_1 (10 [nH]) provides frequency-dependent feedback, aiding in impedance matching by ensuring that the transistor operates efficiently within the desired frequency range.

Output Stage Matching

Impedance matching at the output stage is vital to ensure that the amplified signal is transferred to the load or next stage with minimal reflection and maximal power efficiency. This stage must effectively interface with the transmission line or load to maintain the signal's strength and integrity.

As shown in Figure C.3c the low-pass filter at the output stage consists of C_4 (47 [pF]), C_7 (18 [pF]), and R_4 (50 [Ω]). This filter not only removes unwanted frequencies but also contributes to impedance matching at the output. Resistor R_4 provides a load that matches the characteristic impedance of the transmission line or the next stage in the signal path, ensuring minimal reflections and optimal power transfer.

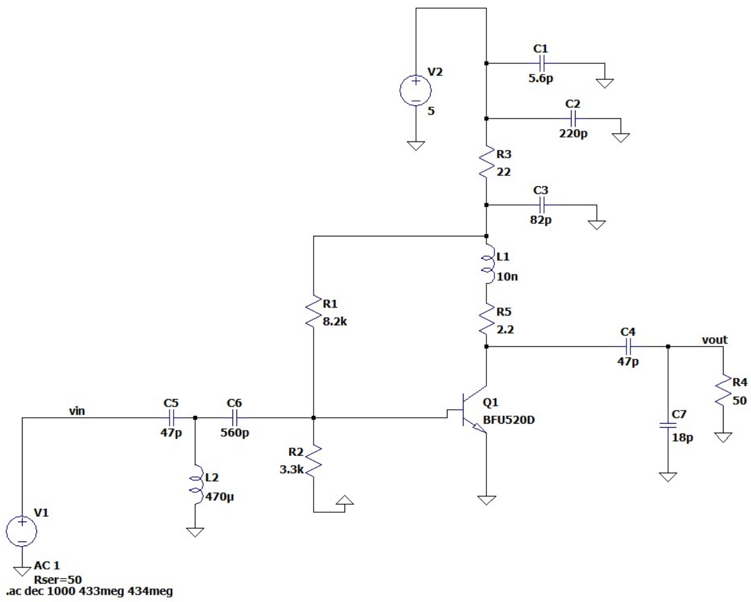


Figure C.4: Impedance matching complete

C.1.3. Superior Implementation

The impedance matching strategy employed in this circuit design is particularly effective for several reasons. The use of a combination of resistors, capacitors, and inductors provides a straightforward yet highly effective means of achieving impedance matching without adding unnecessary complexity to the circuit. The selected component values are carefully chosen to match impedances across a wide frequency range, ensuring that the circuit performs well in its intended application. By addressing impedance matching at the input, amplification, and output stages, the design ensures consistent and reliable performance throughout the entire signal path, minimising losses and preserving signal integrity.

It is also crucial to mention that the addition of the impedance matching required the changing of the resistor in the biasing solution. Despite the ratio being the same, the resistors had a smaller value to make sure that the input impedance remains 50 [Ω] for maximum power transfer.

In conclusion, the impedance matching strategies implemented in this circuit are essential for maximising power transfer, minimising signal reflections, and maintaining high signal quality. The chosen implementation strikes a balance between simplicity and effectiveness, making it a superior choice for the intended high-frequency application. This approach ensures that the circuit operates efficiently and reliably, providing a robust solution for high-frequency signal processing.

C.2. Assembly

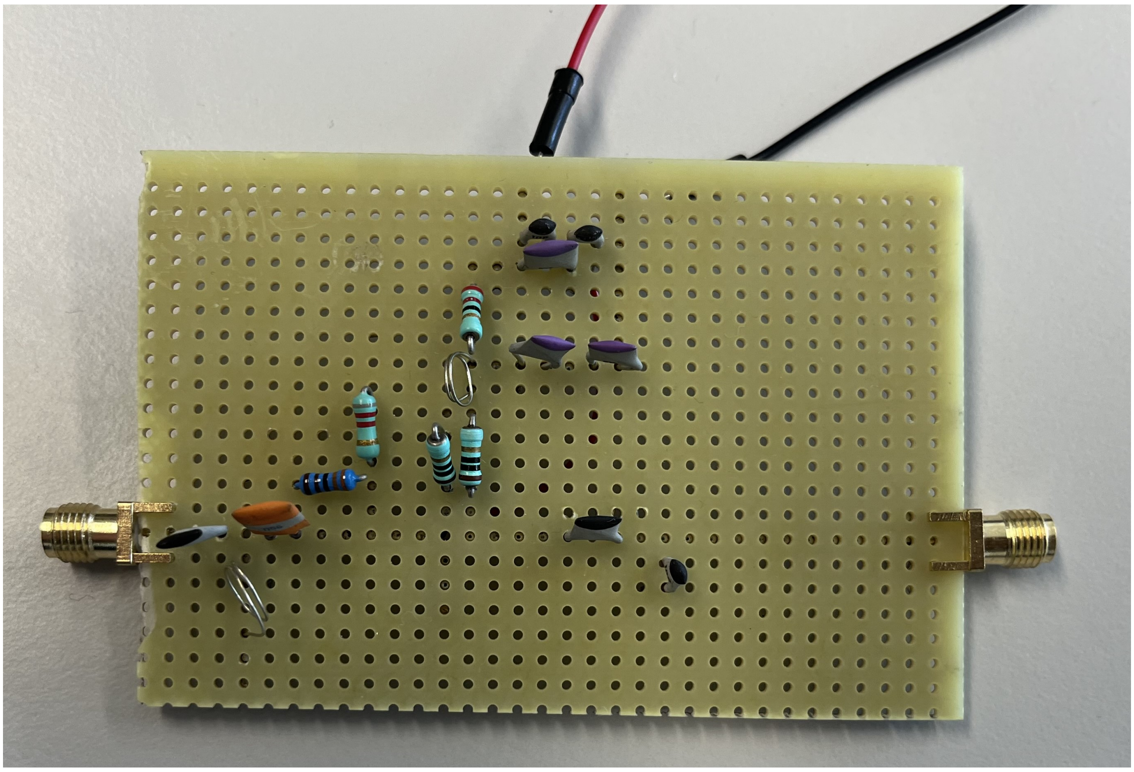


Figure C.5: Soldering board build

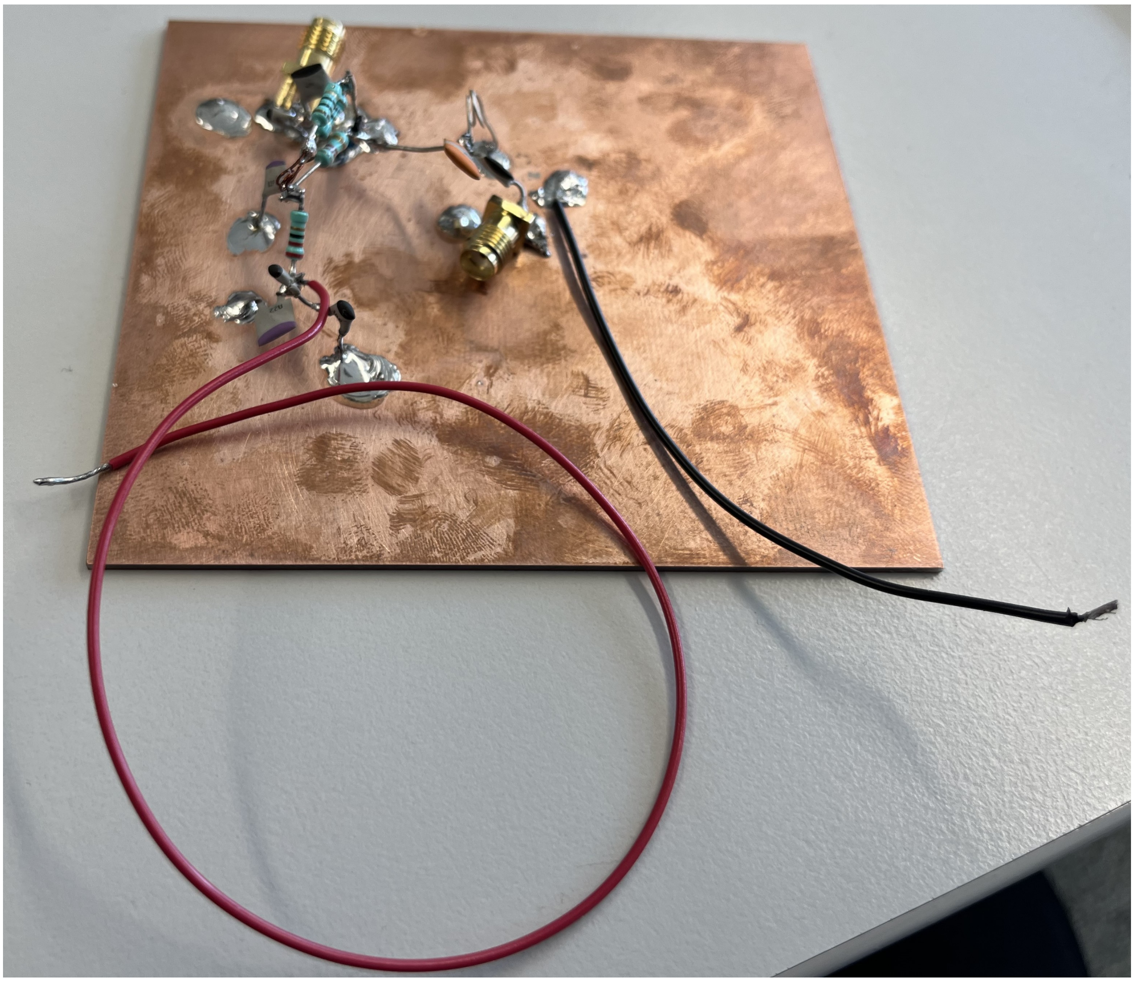


Figure C.6: Copper plate build