

Ultra Lightweight Tracking Device

Transmitter tag
for the *Vespa Velutina*

EE3L11: Bachelor Graduation Project Electrical
Engineering

Cem Çetiner
Yunus Emre Döngel



Ultra Lightweight Tracking Device

Transmitter tag
for the Vespa Velutina

by

Cem Çetiner
Yunus Emre Döngel

Student Name	Student Number
Cem Çetiner	5250471
Yunus Emre Döngel	4850629

Supervisor:	Tomas Manzaneque Garcia
Technical Instructor:	Jeroen Bastemeijer
Project Proposer:	Henk Mezger
Project Duration:	04/2024 - 06/2024
Faculty:	Faculty of EEMCS, Delft

Abstract

The *Vespa velutina*, an invasive hornet species originating from Southeast Asia, has significantly impacted biodiversity in Western Europe, particularly threatening local insect populations and beekeeping industries. This thesis presents the design and development of an ultra-lightweight tracking device to locate and eradicate *Vespa velutina* nests, thereby mitigating their ecological and economic impact.

The project was divided into three subgroups focusing on different subsystems of the project. The primary objective was to create a tracking system that is lightweight, cost-effective, and capable of transmitting a stable signal over a well known distance.

The transmitter design utilized a Surface Acoustic Wave (SAW) resonator-based oscillation circuit operating at a frequency of 433.92 MHz, chosen for its frequency stability and efficiency. The MS412FE battery is discussed to power the system, selected for its low weight and adequate discharge current. The Atmel ATTiny9 was implemented to modulate the signal using ON-OFF Keying, ensuring minimal power consumption and weight.

Extensive simulations and testing were conducted to validate the design, ensuring the desired performance metrics. The final tracking device weighs less than 250 mg, operates within a license-free frequency band, and has a signal range meeting the 500 meters requirement in open field conditions.

The results demonstrate the feasibility and effectiveness of the designed tracking device in locating *Vespa velutina* nests. This system can be a solution for environmental agencies and beekeepers to keep the *Vespa velutina* population under control, preventing any further damage to the biodiversity.

Preface

The invasive species *Vespa velutina*, commonly known as the Asian hornet, has rapidly spread across Western Europe, posing a significant threat to local biodiversity. To prevent further damage and possible collapse of the ecosystem a methodology which exists out of trackers is utilized, helping to locate the *Vespa velutina* nests and eradicate them. The subject of this thesis is the design and validation of an ultra-lightweight tracking device to help locate and eradicate *Vespa velutina* nests

This project existing out of three subgroups was led and supervised by Tomas Manzaneque Garcia with the technical assistance of Jeroen Bastemeijer. We would like to express our sincere gratitude to these gentlemen, who enlightened us with constructive feedback and motivating humour. Last but not least, we want to thank our friends and families for supporting us through the past years of our studies.

*Cem Çetiner
Yunus Emre Döngel
Delft, June 2024*

Contents

Abstract	i
Preface	ii
1 Introduction	1
1.1 Vespa velutina and Problem Definition	1
1.2 Thesis synopsis	3
1.2.1 State of the art analysis	3
1.2.2 Problems with the current designs	3
1.3 Goal of This Thesis	4
1.4 Structure of Thesis	4
2 Program of Requirements	5
2.1 Entire System Requirements	5
2.2 Transmitter Subgroup Requirements	5
3 System Design Path	7
3.1 Powering the System	7
3.1.1 Solution to Possible Shortcomings	8
3.2 Operating Frequency	8
3.3 Possible Transmitter Designs	9
3.3.1 LC Tank Circuit	9
3.3.2 Crystal Oscillator Circuit	10
3.3.3 SAW Resonator-based Oscillation Circuit	12
3.4 Design Choice	13
3.4.1 Design implementation	15
4 Transmitter Design	16
4.1 SAW Resonator	16
4.1.1 SAW Resonator Selection	17
4.2 SAW Resonator-based Transmitter Circuit Design A	18
4.2.1 Input Data and Modulation with Microcontroller	18
4.2.2 Oscillation and Frequency Determination	19
4.2.3 Transistor Amplification	19
4.2.4 Biasing Network	19
4.2.5 Frequency Stabilization and Load Matching Network	19
4.2.6 Power Supply Decoupling	19
4.2.7 Filtering and Stability	19
4.2.8 Final Output Stage	19
4.2.9 Component Value Selection	20
4.2.10 Antenna Impedance Matching	20
4.2.11 Transistor Selection	20
4.3 PCB Design for Design A	21
4.4 SAW Resonator-based Transmitter Circuit Design B	21
5 Micro-controller Design	22
5.1 Microcontroller	22
5.2 Key Considerations in Microcontroller Selection	22
5.2.1 Weight	22
5.2.2 Power Consumption	22
5.2.3 Size	23

5.2.4	Operating Voltage	23
5.2.5	Programming and Development	23
5.3	Reasons for Choosing OOK	23
5.4	Comparison with Other Modulation Techniques	23
5.4.1	Amplitude Modulation (AM)	23
5.4.2	Phase Shift Keying (PSK)	23
5.5	Micro-controller Design and Programming	24
5.5.1	OOK Implementation	24
5.5.2	Gold codes	24
5.5.3	Power down implementation	24
6	Simulation	25
6.1	LTSpice Simulation	25
6.1.1	Design A Simulation	25
7	Testing and Measurements	27
7.1	Building and Testing the Transmitter	27
7.2	Continuous Signal	28
7.3	OOK Modulated Signal	28
7.4	Gold Code Implemented Signal	29
7.5	Signal Strength	31
7.6	Design B	31
7.7	Results Summary	32
8	Discussion, Conclusion and Future work	33
8.1	Discussion	33
8.2	Conclusion	35
8.3	Future Work	35
A	Microcontroller code	36
A.1	The code for testing the transmitters ON OFF keying ability with turning it on for 30 ms, twice every second	36
A.2	Code implementing the chosen Gold code sequence	37
B	Weight budget	39
C	LTSpice Simulations and Results	40
C.1	SAW Resonator Simulation & Results	40
C.2	Design A Simulation & Results	41
D	Microcontroller Specifications	42
D.1		42
D.2		43
D.3		44
E	Price Budget	45
F	Receiver Results	46
F.1	Continuous Signal Results	46
F.2	OOK Modulated Signal Results	47
F.3	Gold Code Implementation Results	48
F.4	Signal Strength	49
G	SAW Resonator-based Design B	51
G.0.1	Power Supply	51
G.0.2	Oscillation Generation and Modulation	52
G.0.3	Amplification and Feedback	52
G.0.4	Biasing and Stability	52
G.0.5	Impedance Matching and Signal Coupling	52
H	Prototype Zoomed in Visualization	53

1

Introduction

This chapter delves into explaining the hornet species *Vespa velutina* that posed different problems in Europe, leading to searches for solutions to resolve the issues. After this the goal of the entire project will be defined which seeks a solution to some of the problems introduced by this species. Also currently existing solutions will be briefly introduced. The different subgroup divisions for this thesis will be explained. Finally, the structure of the thesis will be described.

1.1. *Vespa velutina* and Problem Definition

Vespa velutina, known as the yellow-legged hornet, is a hornet originating from the Southeast Asia which has invaded Europe to become a problematic invasive species. The first sighting of the *Vespa velutina* in the European continent was in Lot-et-Garonne, France, in 2004. It is believed that the hornet species was introduced by a cargo ship transporting a single queen from China. Genetic studies indicate that these hornets likely came from the Zhejiang and Jiangsu provinces in China [1]. As the *Vespa velutina* travelled to expand in other countries, it was first sighted in the Netherlands in Dreischor, Zeeland [2]. By 2017, the species spread to several spots in the Netherlands.

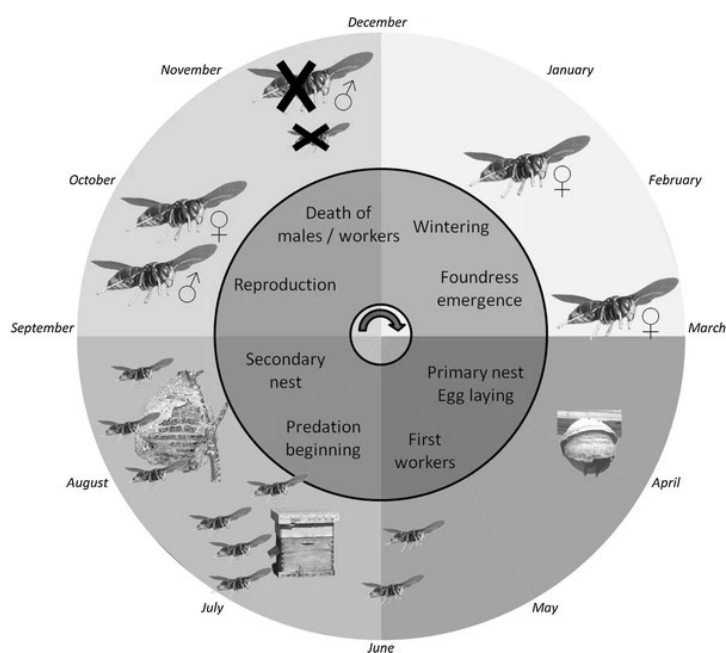


Figure 1.1: Life cycle of *Vespa velutina* in France. The crosses on males and workers in December stand for their death (only gynes survive winter) (© INRA, K. Monceau and D. Thiéry)

in figure 1.2. Then the search area is gradually narrowed down by placing bait traps such as food points. However, this method is very time consuming often taking upto several days to locate the nest and requires many individuals involved being labour intensive. The tracking method is much preferred compared to the baited food traps as it minimizes harm to non-target species.

1.2. Thesis synopsis

The main aim of the project is to design a tracking system that facilitates the location finding of the *Vespa velutina* nests in order to destroy them and regulate the spread of the species to reduce the ecological and economical problems it is posing. This must be accomplished under given certain requirements with a system design that outperforms existing designs. First a transmitter must transmit a signal that can be captured by a receiver antenna. Once the signal is received, further signal processing must be executed in order to locate the nest. The system is divided into three sub categories 1.3, the transmitter circuit, antenna design and receiver circuit in which the subgroups are created accordingly. The transmitter subgroup is entitled to design a transmitter circuit that can transmit a stable frequency operating for far distances. The antenna subgroup is responsible for designing the appropriate transmit and receiver antennas. The receiver subgroup handles the signal processing of the incoming signal utilizing software defined radio direction finding to locate the nest.

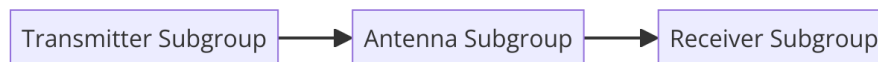


Figure 1.3: Overview of the project configuration

1.2.1. State of the art analysis

There exists two solutions both being miniature tracking devices. These are transmitter devices that are attached on the hornet that transmit a signal at a specific frequency. The two devices are namely PicoPic Ag190 by Lotek [7] and LowlandTag [8]. Both of the trackers transmit a 150MHz signal.

LowlandTag transmitter is currently made to be as cheap as possible, a simple PWM (Pulse Width Modulation) signal is used. With a period of 1s and 6ms pulse duration (10 % Duty cycle) is implemented [8], this refrains the transmitter of any unnecessary intricacies that go along with building the hardware that is needed to transmit more complicated signals.

The Ag190 implements OOK (On-Off Keying) modulation. OOK modulation works similar to PWM signal that the LowlandTag uses however they use a signature ASK signal to make sure they are receiving the correct signal [7].

1.2.2. Problems with the current designs

Lowland design

The LowlandTag is not water tight by itself. It has been proposed by the manufacturer that it can be made water tight by coating it in liquid rubber, however this does lead to a weight increase. Furthermore it can only operate at one frequency of 149.9 MHz and the maximum range of it is about 300 m [8]. The LowlandTag is available at a price of about 100 euros.

Lotek design

The Lotek transmitters are heavier than the LowlandTag. The lightest one starting at 220 mg [7] is significantly heavier than the LowlandTag which is between 160 mg and 180 mg. Furthermore, the battery is not replaceable or rechargeable, which leads them unusable after one usage. The lotek PicoPic tags are available at a price of about 300 euros.

1.3. Goal of This Thesis

The goal of this thesis is to design a ultra light-weight transmitter circuit that will be attached on the hornets facilitating the tracking for nest finding. The aim of the subgroup follows to generate a design that overcomes the problems with the existing transmitter devices. This includes presenting a tracking device that is cheaper, lighter, license free for usage and smarter microcontroller implementation for being more energy efficient and transmitting a distinguishable signal. These goals creating an improved transmitter circuit must be achieved fulfilling the program of requirements mentioned in chapter 2.

1.4. Structure of Thesis

The structure of the thesis is as follows. In chapter 2 the program of requirements are provided as guideline measures for the entire project. In chapter3 research about possible designs and implementation techniques are given, followed by the design choice. In Chapter 4 the transmitter designs are introduced, working principles and component selections are explained in detail. In Chapter 5 the microcontroller design is explored by delving into On-Off Keying Modulation, Gold Codes and Idle mode implementation. In Chapter 6 the LTSpice Simulation of the transmitter design are displayed. Chapter 7 gives the results of testing and measurements. Finally, Chapter 8 provide a conclusion and possible future work about the thesis.

2

Program of Requirements

This chapter states the program of requirements for the entire system and the transmitter subgroup to be fulfilled. These requirements serve as a roadmap and specify features that must be integrated and accomplished.

2.1. Entire System Requirements

These requirements hold for the entire system which have been discussed and provided by the project proposer.

1. **Weight:** The system must weigh less than 250 mg.
2. **Resistance:** The system should be resistant to humidity and rain.
3. **Size:** The system's dimensions should be approximately 11x5x2 mm, matching the size of a hornet abdomen.
4. **Frequency:** The system must operate on a license-free/legal frequency in the Netherlands.
5. **Battery:** The battery should be chargeable or replaceable.
6. **Battery Life:** The battery should last for at least 3 hours of operation.
7. **Signal Range:** The detectable signal range should be at least 500 meters in open field conditions.
8. **Cost:** The system should cost less than 25 euros.
9. **Antenna Material:** The antenna should be made from materials that are not chewable.
10. **Operating Conditions:** The system should function in an urban environment.
11. **Receiver:** The receiver should be portable and capable of approximate direction finding.

2.2. Transmitter Subgroup Requirements

1. The transmitter must be ultra-lightweight to be effectively attached to a hornet. The total weight should be kept under 250 mg to ensure it does not hinder the hornet's natural movement.
2. The transmitter must operate on a license-free/legal frequency in the Netherlands.
3. The battery should be chargeable or replaceable.
4. The battery life should last for at least 3 hours of continuous operation to ensure adequate tracking duration .
5. The detectable signal range should be at least 500 meters in open field conditions to ensure effective tracking .
6. The total cost of the transmitter system should be less than 25 euros, making it economically viable for widespread use .

7. The transmitter should use effective modulation to encode the data, ensuring a distinguishable signal with minimal interference .
8. The transmitter circuit should include necessary amplification stages to ensure that the output signal meets required power levels while maintaining efficiency .
9. A matching network and filtering circuit should be implemented before the transmitting antenna to maximize transmitted power and filter out unwanted harmonics from the output signal .
10. The system's dimensions should be approximately 11x5x2 mm, matching the size of a hornet's abdomen .
11. The transmitter should be resistant to humidity and rain to ensure functionality in various environmental conditions .

3

System Design Path

This chapter provides insight to the research necessary for executing the appropriate design choices for the battery, operating frequency, transmitter design and indices with explanation the pursued design choices.

3.1. Powering the System

Choosing the right battery is a critical step in designing the transmitter circuit, as it significantly impacts the overall weight, available power and the design of the components that can operate at the required power levels. During the design process several options were taken into account like coin cell batteries [9] [10], hearing aid batteries, small size SEIKO battery, supercapacitors and small solar panels. The best options when optimized for weight can be seen in table 3.1. In this table it can be seen that the only option which fulfills the weight requirements are the small size SEIKO battery and supercapacitor. Although the latter one looks good in terms of weight the shortcoming in delivering charge for an extended period of time makes it impossible to use. A design powered by a small solar panel sounds futuristic and groundbreaking but is not feasible due to the fact that the tracker is mounted in ventral position to the Vespa Velutina. The only feasible option is the SEIKO battery which will be discussed in detail in this section.

In selecting the appropriate battery, a balance was sought between discharge current capability and weight in the same product family. The MS412FE battery was chosen because it offers a discharge current of 0.10 mA while weighing only 70 mg[11]. Although the MS518SE battery provides a higher discharge current of 0.15 mA, it weighs 130 mg. The 50% increase in discharge current did not justify the 85% increase in weight, making the MS412FE the more efficient choice for this application.

SEIKO MS412FE is a Manganese Silicon Lithium type rechargeable battery [11] optimized for low current consumption in a physical stable environment. Its mainly used as watch battery or to maintain power for the memory or clock functions in various types of electronic equipment such as personal mobile devices, video cameras etc. and as the main power source for small portable equipment. This aligns them for the objective of this project.

Power source	Weight (in mg)	Operating Voltage (in V)	Maximum Continuous Discharge Current (in mA)	Nominal Capacity (in mAh)
Duracell CR 2450 button cell battery	800	3	3	620
Duracell CR 2032 button cell battery	314	3	6	245
Duracell PR70/10 Hearing aid battery	300	1.4	5	95
TDK BCS1714B6 solar cell	40	2.6 (at 3000 Lux)	0.145 (at 3000 Lux)	x
Supercapacitor RSCSK2043R3D01004T	520	3.3	x	200000 uF
SEIKO MS412FE watch battery	70	3	0.1	1

Table 3.1: Comparison of the different power sources in terms of the limiting specifications a) Duracell's CR 2450 is the button cell battery with the highest energy density b) Lightest widely available button cell battery c) Lightest hearing aid battery d) Solar cell optimized for weight and surface area e) SMD Supercapacitor widely available and optimized in weight f) The actual used battery

Type	Nominal Voltage (V)	Charge Voltage (Standard Charge Voltage)*6 (V)	Nominal Capacity (mAh)*1	Internal Impedance (Ω)*2	Standard Charge/Discharge Current (mA)	Maximum Discharge Current (Continuous) (mA)*3	Cycle Life (Time)*4		Size (mm)		Weight (g)
							100%*5 D.O.D. (Depth of Discharge)	20%*5 D.O.D. (Depth of Discharge)	Diameter	Height	
MS414GE	3	2.8 to 3.3 (3.1)	2.0	100	0.010	0.05	50	500	4.8	1.4	0.08
MS412FE	3	2.8 to 3.3 (3.1)	1.0	100	0.010	0.10	100	1000	4.8	1.2	0.07
MS518SE	3	2.8 to 3.3 (3.1)	3.4	60	0.010	0.15	100	1000	5.8	1.8	0.13
MS614SE	3	2.8 to 3.3 (3.1)	3.4	80	0.015	0.25	100	1000	6.8	1.4	0.17
MS621FE	3	2.8 to 3.3 (3.1)	5.5	80	0.015	0.25	100	1000	6.8	2.1	0.23
MS920SE	3	2.8 to 3.3 (3.1)	11.0	35	0.050	0.80	100	1000	9.5	2.1	0.47

Figure 3.1: MS Battery Specifications

The battery utilizes silicon oxide as the anode and a lithium manganese composite oxide as the cathode. This composition provides several advantages, including a long cycle life (around 100 charge cycles), wide operating temperature range and stable performance even under overdischarge (D.O.D 100%) conditions. The latter one is of importance seen the deploy and forget nature of the device.

3.1.1. Solution to Possible Shortcomings

If more power is needed or if additional applications requiring higher power are implemented in the circuit, using two MS412FE batteries in parallel is the optimal solution. Although this approach increases the weight, it remains preferable to selecting the MS518SE. Using two MS412FE batteries would double the weight to 140 mg, but it also doubles the discharge current, providing a more balanced and efficient power supply for the circuit.

3.2. Operating Frequency

The Operating Frequency of the circuit is extremely important as it determines the circuit design. One of the requirements for the product is that it must be license free therefore the frequency must be selected accordingly. The frequency choices below 1GHz that are license free will be considered which can be grouped into three generalized categories of $\approx 169\text{MHz}$, $\approx 433\text{MHz}$ and $\approx 866\text{MHz}$. Higher frequencies experience greater attenuation due to increased free-space path loss, material absorption, atmospheric absorption, and multi-path effects. These losses at high frequencies are highly significant as the circuit has very low and limited power. Moreover, lower frequencies can penetrate through materials more effectively which is a desired feature for the transmitter in subject [12]. Therefore, lower frequencies

are considered in the transmitter circuit application due to the transmission range, available power, penetration and attenuation.

Utilizing these license free frequency bands the restrictions while using these bands must be considered [13]. The restrictions depend on the type of transmitter that is being utilized which is determined based on the classification the transmitter falls under. The transmission range by the requirements is to minimally transmit at a distance of 500 meters. At this range the transmitter is classified as Short Range Device (SRD)[14] an a Radio Intended for Identification (RFID)[14]. Below in tables 3.2 and 3.3 are shown the frequency bands with the most feasible and desirable restrictions for these two classes of transmitters.

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	10	10	1.74	OOK
434.040 - 434.790	10	None	0.025	Any
869.400 – 869.650	500	10	0.250	OOK

Table 3.2: The legal restrictions as stated for Non-specified SRD [15]

Frequency /MHz	ERP Power /mW	Duty cycle /%	Channel width /MHz	Modulation
865.6 – 867.6	2000	None	0.200	Any

Table 3.3: The legal restrictions as stated for RFID [15]

These potential bands are analyzed alongside the available types of transmitter circuits that can operate at specified frequencies. A choice will be made based on the evaluation of trade-offs.

3.3. Possible Transmitter Designs

There are several possible design methods and ideas for lightweight transmitters. Below each possible transmitter design/idea is explained in detail together with working principles and shortcomings.

3.3.1. LC Tank Circuit

LC Tank circuit is a widely used in transmitter designs serving for frequency selection and signal modulation purposes. The two components being inductor (L) and capacitor (C) are connected in parallel or series in order to form a resonant or tank circuit. This configuration is essential for generating oscillations at a specific frequency, determined by the inductance and capacitance values of the components involved [16].

The key parameter in such a circuit is resonance as the circuit oscillates at its natural resonant frequency. This resonant frequency is denoted as f_o and can be calculated using the formula 3.1 [17]:

$$f_o = \frac{1}{2\pi\sqrt{LC}} \quad (3.1)$$

Sinusoidal waveform is created at this resonant frequency as energy continuously transfers between the inductor and the capacitor which sets the characteristic of such a circuit transmitting a frequency signal at a specific frequency [18].

In transmitter applications LC Tank circuit usually generates the carrier frequency, namely the frequency which will be modulated with the information signal to be sent. On top of this the LC Tank circuit can act as a filter where the unwanted frequencies are filtered out of the transmitted signal [18]. Additionally, the circuit can be designed to match the impedance of the transmitter to the antenna, optimizing power

transfer and minimizing signal reflections.

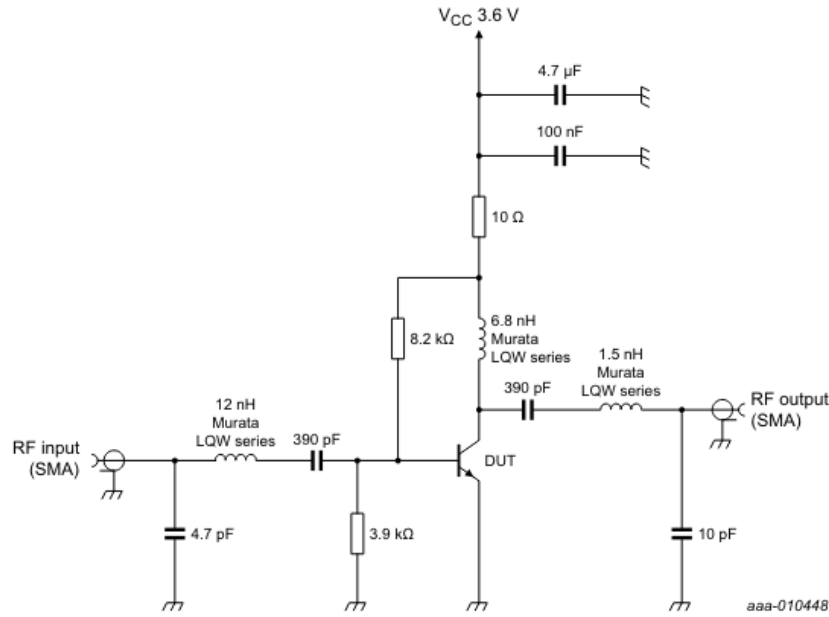


Figure 3.2: LC Tank Circuit 433MHz implementation [19]

Even though LC Tank circuit have useful advantages, it also has several shortcomings to it. The primary issue is that the frequency stability is not guaranteed in LC Tank circuits. The resonant frequency of the circuit can change due to factors such as temperature changes, component aging, and other environmental factors, making it less stable compared to alternatives like quartz crystal oscillators. This instability can affect the performance and reliability of the transmitter.

Another drawback is the quality factor, or Q factor, which indicates the sharpness of the resonance. The Q factor depends on the quality of the inductor and capacitor used, when the Q factor is lower the frequency response can be broader which might result in less selective/efficient frequency tuning [18]. This means very precise components must be used which can be very costly and further usually there always exists component variations due to manufacturing tolerances.

3.3.2. Crystal Oscillator Circuit

A crystal oscillator circuit is an electronic circuit, that utilizes the mechanical resonance of a vibrating crystal of piezoelectric material to create an electrical signal with a very precise frequency. The basic principle behind a crystal oscillator is that when a voltage is applied to a crystal, it vibrates at a specific frequency determined by its size, shape, and material properties. This vibration creates an electrical signal with a precise frequency, which can be used as a reference for timing various operations in electronic circuits [17].

The crystal oscillator does not only provide stable frequency but also a good selectivity as it has a very high quality factor typically somewhere between 10k-20k [18].

Crystal Oscillators work in the principle of inverse-piezoelectric and is made up of piezoelectric material. When an external voltage is applied to a material this induces a mechanical deformation, if an oscillating signal is applied this means that the material starts vibrating at the same frequency as the applied voltage which is the inverse piezoelectric effect. When the material is "forced" to vibrate at a

certain frequency, then the material can generate an AC signal of the same frequency. Rochelle Salt, Tourmaline and Quartz are some examples of naturally occurring crystals that carry the piezoelectric property. These crystals have their own features in terms of piezoelectric activity and strength, such as Rochelle Salt has the highest piezoelectric activity among these crystals meaning it will generate the highest vibration output however it is very weak and breaks easily [20]. While on the other hand the Tourmaline has the least piezoelectric activity but it is strongest among the given crystals [20]. The Quartz accommodates the common ground between the other two crystals having in-between properties, as it is inexpensive and easily available, it is the most preferred crystal.

The crystal oscillator circuit can be implemented using the MICRF114 [21] by Microchip and a micro-controller. The circuit below represents the schematic for the utilization of such an RF transmitter IC working to reach an 433.92MHz frequency multiplying the crystal oscillator frequency.

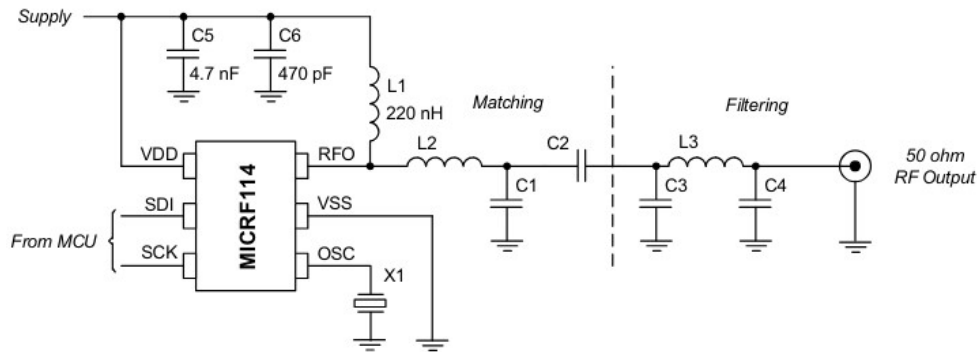


Figure 3.3: Schematic of Transmitter Circuit Utilizing MICRF114 [21]

The MICRF114 contains a Phase-Locked Loop (PLL) synthesizer which is used to generate a stable and precise RF signal. This is the most simplest PLL form of achieving such a purpose. The simple PLL operation provides the possibility to be a low-power wireless transmitter and it is fully responsible of frequency accuracy and stability.

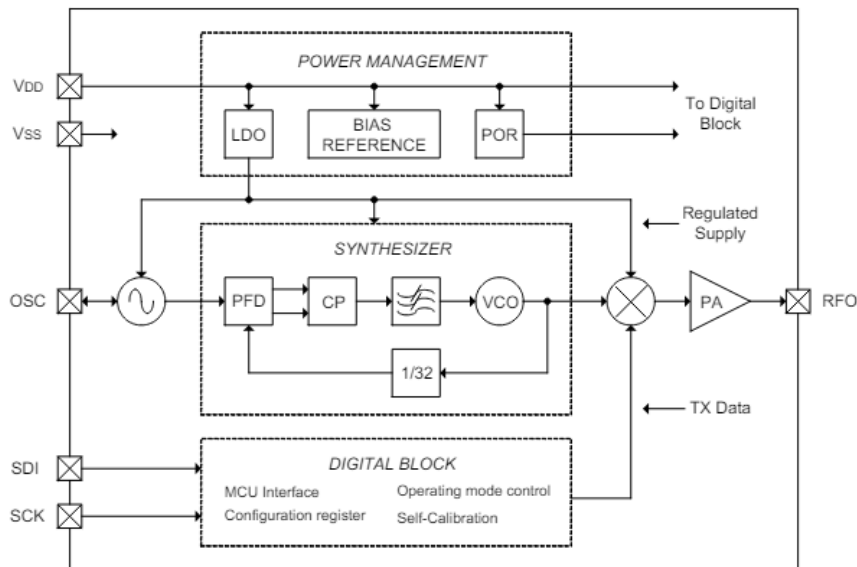


Figure 3.4: PLL Synthesizer Schematic [21]

The PLL synthesizer 3.4 consists of several integral parts: a Voltage-Controlled Oscillator (VCO), a Phase Detector (PD), a Low Pass Filter (LPF), and a Frequency Divider, all working together to lock the output frequency to a stable reference. The reference oscillator in the MICRF114 uses a crystal connected to the OSC pin, providing a stable reference frequency. For example, a 13.56 MHz crystal sets the reference for achieving a 433.92 MHz transmit frequency, as the PLL multiplies this frequency to reach the desired RF output.

After VCO's output has been adjusted to match the reference frequency, the Phase Detector compares the phase of the VCO's output with the reference oscillator's phase. The phase difference indicates how much the VCO's phase is off and it generates an error signal proportional to this deviation. This error signal is smoothed by the Low Pass Filter to produce a control voltage. This control voltage adjust the VCO's frequency to keep it aligned with the reference frequency, namely ensures it is 'locked' to the reference frequency. This entire process keeps the VCO frequency stabilized.

In the MICRF114, the VCO operates directly at the transmit frequency, which optimizes power usage by eliminating the need for additional frequency multipliers. The frequency range for this PLL Synthesizer is from 285MHz to 445MHz which means there is no flexibility in terms of the operation frequency and the 433MHz choice must be made. The advantage of MICRF114 is that it is programmable which makes it easy to adjust the output frequency without making major hardware changes.

The shortcomings to such a circuit configuration is that the MICRF114 needs a minimal of 18mA current in order to operate. Such a current surpasses the power limitations as the battery is able to only provide a 0.1mA maximal discharge current. Furthermore, the circuit requires crystals that resonate at a specific frequency, which necessitates the use of specially cut crystals. These custom crystals can be costly and have long lead times to order.

3.3.3. SAW Resonator-based Oscillation Circuit

Surface Acoustic Wave (SAW) resonator-based oscillation circuits provide the feature to create stable and precise oscillating signals. The SAW Resonator is the component that sets the circuit frequency and the signal is further amplified, matched and filtered.

A SAW resonator comprises a piezoelectric substrate, commonly made of materials such as quartz, lithium niobate, or lithium tantalate. Acoustic waves propagate on the surface of the substrate from which the resonator is constructed. Interdigitated transducers (IDTs), which are metallic comb-like structures, are fabricated on the substrate. These IDTs play a crucial role in converting electrical signals into surface acoustic waves and vice versa [22]. The IDTs can be considered in two different classes as input IDT and output IDT. The input IDT transforms the incoming electrical signal into a surface acoustic wave. The output IDT on the other hand converts the acoustic wave into an electrical signal [22].

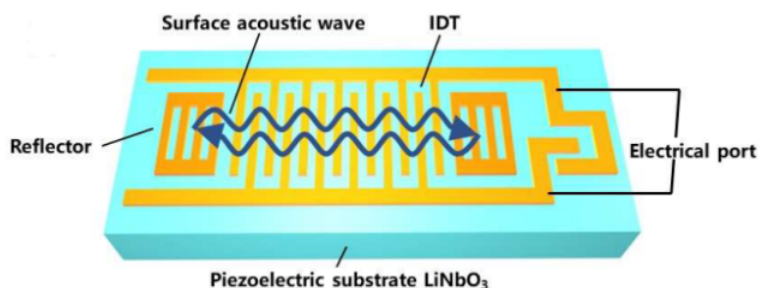


Figure 3.5: Diagram of single port SAW resonator [23]

For SAW resonator-based oscillation circuit to start operating there must exist a initial condition such

as an generation of an initial signal, circuit noise or small excitation signal. Once this initial condition is set, the initial signal is amplified which provides the necessary gain to sustain oscillations. This amplified initial signal is received by the input IDT where it is converted into a surface acoustic wave due to the piezoelectric effect. The generated wave propagates along the surface of the substrate at the resonant frequency which is determined by the LC characteristics. This wave undergoes constructive interference which significantly strengthens the wave [22].

The output IDT detects the resonant acoustic wave and converts it back into an electrical signal. This signal is sent back to the amplifier through a feedback network, creating a loop that strengthens the oscillations at the resonant frequency of the SAW resonator. The feedback network is important because it contains phase-shifting components that make sure the signal is in the correct phase when it returns to the amplifier, which is essential for maintaining continuous oscillations.

As mentioned previously the SAW Resonator determines the frequency oscillations in such a circuit. This frequency is influenced by the physical properties of the piezoelectric material and the geometric design of the IDTs.

The SAW resonator-based oscillator circuits have many advantages in terms of transmitter circuit applications. As a stable frequency is needed the use of piezoelectric materials such as quartz, lithium niobate, and lithium tantalate ensures minimal frequency drift over time and with temperature variations. Just like the crystal oscillators, SAW Resonator have a high Q-factor which enables signal generation within very narrow bandwidths. Additionally, SAW resonators have a very compact size meaning that they are perfectly suitable for miniature circuit applications such as surface mount technology. Also complimenting to the size SAW resonator-based circuits typically exhibit low phase noise, ensuring signal integrity in communication systems.

These circuits also have certain drawbacks such as custom resonators being costly as they require custom cutting and specific material properties and long lead times for delivery due to specification. SAW resonators usually handle lower power levels compared to other resonators and they might not be functioning properly in high power applications, however, this is not a big constraint for the ultra lightweight transmitter application as it falls under the low level power specifications [24].

3.4. Design Choice

In this section the design choice is explained and further detailed design specifications are discussed in the next chapter.

Firstly, the MS412FE battery was chosen as it offers the best discharge current at 0.1mA at a low weight of 70mg. The further design must consider the power availability from the battery to be able to generate a stable signal at a specified frequency that does not drain the battery have a lifetime less than 3 hours.

Operating frequency selection is the key aspect in understanding the feasibility of possible circuit designs and the components needed for generating such a frequency. Considering the three generalized categories of $\approx 169\text{MHz}$, $\approx 433\text{MHz}$ and $\approx 866\text{MHz}$ mentioned in 3.2, the 433.05-434.79MHz 3.2 range is chosen to be further pursued in the transmitter design. This frequency range falls within the license-free band for Short-Range Devices (SRD), eliminating the need for a license and adhering to regulatory guidelines. The legal restrictions for the 433.050 - 434.790 MHz band allow for an effective radiated power (ERP) of 10 mW with a duty cycle limit of 10% and a channel width of 1.74 MHz, utilizing On-Off Keying (OOK) modulation. These parameters align well with the transmitter's design requirements, ensuring compliance with regulatory standards while providing sufficient power and bandwidth for reliable operation.

The 433.05-434.79MHz range has the most surface mount technology components available operat-

ing at this frequency range which makes a significant support ground for designing the circuit with less restrictions from possible component choices. Previous designs used an operating frequency around $\approx 150\text{MHz}$ with an OOK modulation however, this frequency band is not license free therefore it was not considered. Moreover, the 169MHz category was not chosen due to the difficulty in design possibilities resulting from very restricted component availability operating at this frequency. Additionally, 433.050-434.790MHz frequency band experiences lower attenuation compared to higher frequency bands such as 869.400-869.650MHz or 865.6-867.6MHz and have higher penetration properties, ensuring sufficient signal strength for the short-range transmission requirements.

Once the operating frequency band is chosen, the possible circuit designs were explored to find the better fitting design under mentioned conditions in order to achieve a stable and efficient transmission system. Among the options considered were LC tank circuits, crystal oscillator circuits, and SAW resonator-based circuits.

LC tank circuits, which are a good fit for the purposes of frequency selection and modulation, were ultimately ruled out due to their inherent limitations in frequency stability. The frequency instability in these circuits usually are derived from temperature variations and component tolerances, however, these are considered under good battery conditions. It is almost a given that there will be shifts in transmitted frequency as the voltage of the utilized battery will decrease by time and such a voltage deviation will significantly effect the operation of the circuit transmitting at another unwanted frequency.

Crystal oscillator circuits offer high stability but require crystals specifically cut for the desired frequency (especially for the 433.050-433.790MHz band it is expensive and challenging to obtain crystals with a matching resonant frequency), leading to potential cost and lead time constraints. Furthermore, the circuit considered using a RF transmitter IC, MICRF114, exceeds the power limitations of the battery as it can operate at a minimal current of 18mA while the battery can only provide 0.1mA.

After careful consideration, the decision is taken to pursue with an SAW resonator-based circuit that operates at the 433.050-433.790MHz frequency band as it has advantages over alternative methods such as LC tank circuits and crystal oscillators. SAW resonators offer exceptional frequency stability and the high Q-factor of SAW resonators ensures narrow bandwidths and precise signal generation, minimizing the risk of interference and enhancing overall performance. Furthermore, the frequency band of 433.050-433.790MHz is the most optimized choice in terms of regulations, penetration and attenuation. This band might have higher interference a many remote devices operate in this band, however, the SAW resonator implementation significantly reduces the problem by generating stable oscillations at a very specific frequency.

Moreover, SAW resonators are compact and lightweight, making them highly suitable for the ultra-lightweight transmitter application without sacrificing any loss from performance. Additionally, SAW resonators exhibit low phase noise, ensuring signal integrity and reducing the likelihood of signal degradation over time. The table 3.4 below exhibits a summary for the design choices.

Design Aspect	Choice/Details	Reasoning
Battery	MS412FE	Offers best discharge current at 3V with a low weight of 70mg.
Frequency Bands Considered	169MHz, 433MHz, 866MHz	433.05-434.79MHz chosen due to free license advantage for SRD, more components available at this range, lower attenuation, and higher penetration properties in urban areas. This band allows for 10mW ERP with 10% duty cycle and 1.74MHz channel width using OOK modulation.
LC Tank Circuits	Not pursued	Frequency instability due to temperature variations and component tolerances. Voltage deviations from battery also affect frequency stability.
Crystal Oscillator Circuits	Not pursued	High stability but expensive and challenging to obtain crystals for the specific frequency band. RF transmitter IC (MICRF114) exceeds battery power limitations.
SAW Resonator-Based Circuits	Chosen	Good frequency stability, high Q-factor, narrow bandwidths, precise signal generation, compact, lightweight, low phase noise, optimal for regulations and performance.

Table 3.4: Design Choice Summary

3.4.1. Design implementation

For the chosen circuit type, an SAW resonator will be utilized in order to create stable and precise frequency oscillations. This signal created by the resonator will be utilized to generate a stable carrier signal which will then be modulated using On-Off Keying (OOK) to encode the transmitted information. A micro-controller will be incorporated in order to modulate the signal with specified OOK parameters.

The circuit will include necessary amplification stages to ensure that the output signal meets the required power levels while maintaining efficiency. Further, a matching network and filtering circuit will be implemented before the transmitting antenna in order to maximize transmitted power and filter unwanted harmonics from the output signal.

By choosing the 433.050 - 434.790 MHz frequency band and implementing a SAW resonator-based oscillation circuit, the transmitter design achieves a balance between regulatory compliance, performance, and power efficiency.

4

Transmitter Design

In this section transmitter Design A and its alternative Design B are presented with detailed explanation of their working principles and design choices such as component choices and values are discussed. Firstly, the SAW resonator, the most important component of the circuit, and its working principles are exhibited. Following that the implementation of such a resonator in Design A and Design B are explored.

4.1. SAW Resonator

To understand the dynamics of the transmitter circuit, some background information about Surface Acoustic Wave (SAW) resonator operation is essential. Some of the information from the section 3.3.3 is revised and a more detailed explanation is provided.

The piezoelectric effect is the sole basis for the SAW resonator operation which allows for the conversion between electrical signals and mechanical waves (namely surface acoustic waves) using a piezoelectric material such as quartz, lithium niobate or lithium tantalate. When a voltage is applied to one of these piezoelectric materials, mechanical deformations are induced which result in the generation of surface acoustic waves. On the contrary, when mechanical stress is applied to these materials, it generates an electric charge creating the electrical and mechanical transformation domain for the SAW resonators.

A crucial component for the operation of the SAW resonators to exploit the characteristics of piezoelectric materials is the interdigital transducers (IDTs). These consist of interleaved metallic electrodes deposited on the surface of the piezoelectric substrate. The IDTs have two types serving for different purposes, namely input and output IDTs. The input IDT transforms the electrical signal into a surface acoustic wave while conversely the output IDT converts the acoustic wave into an electrical signal. When a voltage is applied to the IDTs, it creates alternating electric fields that induce mechanical deformations in the piezoelectric substrate, generating surface acoustic waves. The created waves propagate on the surface of the piezoelectric substrate.

A single port SAW resonator will be used for the transmitter circuit application as it serves the purpose for frequency stability with its simplicity. In a single port SAW resonator a single pair of IDTs acts as both the transmitter and receiver of acoustic waves. There exists reflectors in the edges of the IDTs where the generated surface acoustic waves are reflected back and forth. This process results in creation of standing wave patterns at different resonant frequencies where constructive interference occurs. This resonance condition significantly enhances the signal at the desired frequency, providing high frequency stability and selectivity.

The equivalent circuit of SAW resonator is a good way to visualize and model the performance of the component. The equivalent circuit is constructed from motional inductance (L_1), motional capacitance (C_1), motional resistance (R_1), and parallel capacitance (C_0) as shown in the figure 4.1. Combination of these elements contribute in determining the resonance frequency and the quality factor of the resonator. The quality factor is a measure of the resonator's efficiency in terms of energy loss, with a higher Q indicating lower energy loss and higher frequency stability.

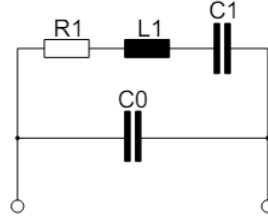


Figure 4.1: Equivalent Circuit of an SAW resonator [25]

4.1.1. SAW Resonator Selection

There are several single port SAW resonators available which have the same working principles and operate within the desired frequency band. The key metrics considered in choosing the resonator are the size and reliability of the component.

Two single port SAW Resonators were considered namely R900 [25] and E45 [26]. For the transmitter application operating in the 433.050-433.790MHz band the R900 resonator, operating at a nominal frequency of 433.92 MHz, was ultimately chosen due to its superior temperature and environmental resistance, which are critical for the application of tracking hornets in varying outdoor conditions. This resonator was selected for its reliable performance, simplicity, 3x3mm extremely small size and suitability for the chosen operating frequency range. Also, the R900 SAW resonator is packaged in a robust ceramic case with gold-plated terminals, ensuring durability and reliable electrical connections. Below the specification comparison between the R900 and E45 resonators are exhibited.

Specification	R900 Resonator [25]	E45 Resonator [26]
Frequency	433.92 MHz	433.92 MHz
Package	Ceramic package DCC6C	Ceramic, dimensions 1.8 * 1.4 mm
Weight	0.037 g	Not specified
Operating Temperature Range	-40°C to +125°C	-40°C to +85°C
Storage Temperature Range	-40°C to +125°C	-40°C to +85°C
DC Voltage	12V	±30V
Center Frequency	433.845 - 433.995 MHz	433.82 - 434.02 MHz
Insertion Loss	1.4 - 1.9 dB	1.6 - 2 dB
Unloaded Quality Factor (QU)	8300 - 12000	9510
Loaded Quality Factor (QL)	Not specified	1600
Frequency Aging	±50 ppm	±10 ppm/year
Motional Capacitance (C1)	1.685 fF	1.908 fF
Motional Inductance (L1)	79.82 μH	70.591 μH
Motional Resistance (R1)	18 - 26 Ω	20.23 - 25 Ω
Shunt Capacitance (C0)	2.3 pF	1.8 - 2.2 pF
Temperature Coefficient of Frequency	-0.032 ppm/K ²	-0.016 ppm/°C ²
Turnover Temperature	20°C - 50°C	20°C - 35°C

Table 4.1: Comparison of Specifications of R900 and E45 Resonators

Two factors contributing to the reliability of the component are the aging of the center frequency and the temperature coefficient together with the turnover temperature. The aging of the center frequency of this resonator is at ± 50 ppm per year, meaning that the center frequency might drift ± 21.696 kHz. This makes the new center frequency after a year in the range 433.898304 - 433.941696 MHz which means the resonator in the circuit must be replaced with a new one every year. However, for the use case of the transmitter circuit attached to the hornets, such a frequency drift has no impact, as the operational lifetime of the transmitters spans only a few uses.

The frequency stability in varying temperature conditions are critical for the reliable performance of the resonator. The R900 SAW Resonator has a temperature coefficient of frequency (TC_f) of -0.032 ppm/K² and a turnover temperature (T_0) between 20°C and 50°C. Where T_0 is the temperature range within which the frequency variation due to temperature changes is minimized and TC_f is a measure of how the frequency of the device changes with temperature (a negative value indicates a decrease in frequency in case of increase in temperature). These parameters ensure minimal frequency variation with temperature changes.

On the other hand, the E45 resonator, while also operating at the same nominal frequency, has a narrower operating temperature range of -40°C to $+85^\circ\text{C}$. Although the E45 offers slightly better aging characteristics, with an aging rate of ± 10 ppm/year compared to the R900's ± 50 ppm/year, this factor is less critical for the short-term use of the transmitters attached to hornets. The R900 ability to operate reliably under a broader range of environmental conditions is a more valuable and desired feature rather than long term frequency stability for the hornet tracking devices.

4.2. SAW Resonator-based Transmitter Circuit Design A

This section explores the details of the working principles of the Design A, its component values, design choices. Design A utilizes the selected R900 SAW Resonator implementing it in a transmitting circuit consisting of matching network and filtering which performs OOK modulation via a microcontroller. First a model working with a $50\ \Omega$ load is presented and the further matching circuits with the antenna are discussed.

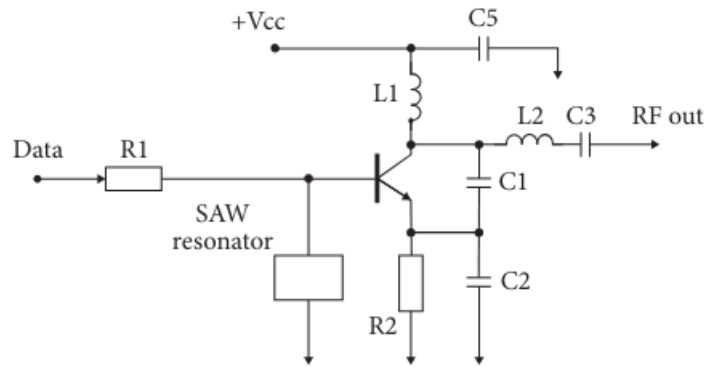


Figure 4.2: Design A Schematic [27]

4.2.1. Input Data and Modulation with Microcontroller

The microcontroller sends the data signal by using OOK modulation. This is done via sending a digital signal that is 'high' or 'low' in order to encode the transmitted data. When the microcontroller send a 'high' signal the carrier signal generated by the SAW Resonator is amplified by the transistor as it is in forward bias. Conversely, when a 'low' signal is sent the transistor is in cut off, and no carrier signal is transmitted. By turning the carrier wave on and off in this way, the microcontroller can encode the data into the RF signal. This modulated signal can then be transmitted to a receiver, which decodes the on and off states back into the original data. This data signal generated by the microcontroller is

introduced to the circuit via resistor R1. Resistor R1 is essential for impedance matching and current limiting. It protects the subsequent stages of the circuit from potential damage due to excessive current.

4.2.2. Oscillation and Frequency Determination

The carrier frequency generated by the SAW Resonator is at 433.92MHz exploiting the piezoelectric effect of the material. As previously explained, an electric field deforming the material causes mechanical vibrations from which oscillating electric field at 433.92MHz is obtained. This is the core of the circuit setting the circuit operation frequency.

4.2.3. Transistor Amplification

After the SAW Resonator, the signal is fed to the Bipolar Junction Transistor (BJT) for amplification. In the transmitter circuit, BJT is placed such that the base-emitter junction acts as a forward-biased diode, while the collector-emitter junction acts as a controlled current path. A tiny input current flowing in from the base results in the creation of the path between collector and emitter which allows a much larger current to flow from collector to emitter. This amplifies the incoming oscillations from the SAW resonator creating a stronger signal with a power level suitable for transmission.

4.2.4. Biasing Network

Resistor R2 forms part of the biasing network, establishing the correct operating point for the transistor. The biasing from the R2 by controlling the current flow into the transistor ensures that the transistor operates in the active region where it can amplify the incoming signal without distorting it. Variations in temperature can affect the transistor's behaviour. For instance, if the temperature rises that might cause the current through the transistor to increase. R2 in this case provides a support such that the voltage and the current is stabilized so that the transistor operates consistently which also brings stability to the entire circuit.

4.2.5. Frequency Stabilization and Load Matching Network

Inductor L1 plays a very important role in frequency stabilization. It works alongside the SAW resonator, C1 and C2 to maintain the oscillation at the precise frequency of 433.92 MHz. This is important for ensuring that the transmitter remains on the correct frequency even with variations in temperature or power supply. Additionally, L1, in combination with capacitor C5, forms part of the load matching network. This helps in optimizing power transfer from the transistor to the antenna. The values of L1 and C5 are chosen to match the output impedance, maximizing power transfer.

4.2.6. Power Supply Decoupling

Just like the inductor L1 the capacitor serves a dual purpose in this circuit. The other purpose of this capacitor is to function as a supply decoupling capacitor. This means it helps to filter out noise and stabilize the voltage supply to the circuit. The noise is filtered out in order to prevent it affecting the sensitive RF components and the stabilization ensures to provide a stable DC voltage to the active components in the circuit.

4.2.7. Filtering and Stability

Capacitors C1 and C2, alongside resistor R2 and inductor L1, serve to stabilize the circuit and filter out unwanted noise. C1 can be visualized as a bypass path for high frequency signals like unwanted noise. It directs unwanted noise away from important parts of the circuit such as power supply in order to prevent interference and instability. C2 helps maintain a steady voltage at the transistor's emitter. This act of stabilization improves the overall linearity and performance of the transistor which results in the amplified signals being clear and accurate.

4.2.8. Final Output Stage

To have a clear signal at the output the inductor L2 and the capacitor C3 further process the output RF signal by executing fine-tuning of the signal. They work together to form a resonant circuit that filters out unwanted frequencies where only the desired 433.92MHz signal is transmitted and the capacitor C3 blocks DC components only allowing the AC signal to reach the antenna.

4.2.9. Component Value Selection

Before matching network with the antenna impedance, a design with components matching the $50\ \Omega$ load is employed in order to deploy testing. The capacitors must be within the pF range and the inductors at the nH range for the circuit to operate. Rather than the values of the components, the ratios in the feedback loop are more important to comply with the system dynamics such as applying the Barkhausen criterion.

Component	Value	Unit
R1	4.7	k Ω
R2	100	Ω
C1	3	pF
C2	7	pF
C3	470	pF
C5	470	pF
L1	27	nH
L2	68	nH

Table 4.2: Component Values

4.2.10. Antenna Impedance Matching

The matching and filtering network for the final RF signal output depends on the type of antenna utilized. There are two main configurations namely LC1 and LC2 displayed in the figure 4.3. The inductor and capacitor values can be adjust accordingly for the chosen antenna. The antennas length is chosen to be 15cm and different simulations are done in order to understand the best fitting antenna length and diameter. For the final transmitter design, the 13cm-1mm (simulation size) copper antenna with an impedance of $17.66 - j1095$ is selected by the subgroup C2.

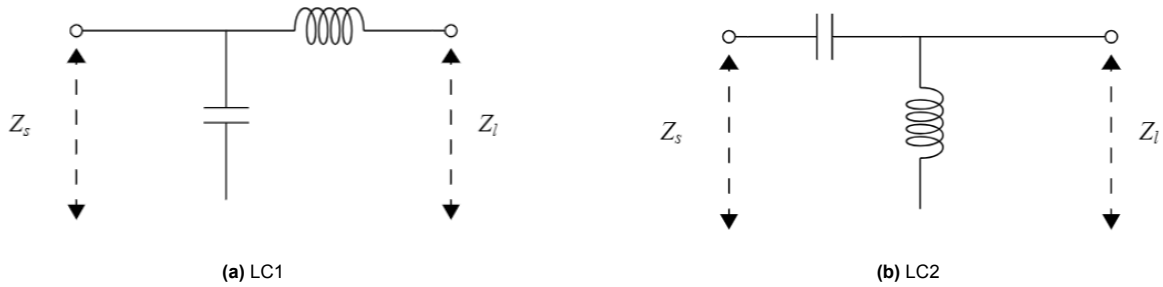


Figure 4.3: Two configurations for antenna impedance matching

Antenna Simulation Dimensions	Impedance	LC1		LC2	
		Inductor	Capacitor	Inductor	Capacitor
13cm-2mm copper	$17.66 - j1095$	410.4 nH	9.927 pF	252.0 nH	0.1991 pF

Table 4.3: Antenna Impedance and Matching Components [15]

4.2.11. Transistor Selection

For ensuring optimal performance of the design a transistor is selected such that gain, noise figure, and stability are ensured at operating ranges. For this design two transistors were considered namely the BFU530A [28] and the BFP640 [29]. Both transistors will be analyzed leading to a selection that best fits the needs.

The BFU530A is an NPN RF transistor designed for high-speed, low-noise applications. This transistor is a good choice for small signal applications. While the BFP640 is also an NPN RF transistor that

has low noise figure and high gain. Below is a table for visualizing the relevant characteristics of both transistors.

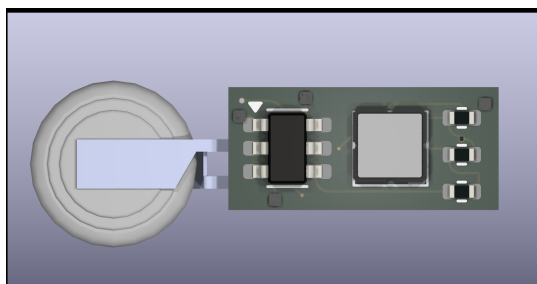
Parameter	BFU530A [28]	BFP640 [29]
Low Noise Figure (NFmin)	0.6 dB at 900 MHz	0.9 dB at 2 GHz
Maximum Stable Gain	18 dB at 900 MHz	20 dB at 2 GHz
Transition Frequency (fT)	11 GHz	45 GHz
Collector-Base Voltage (VCB)	24 V	20 V
Collector-Emitter Voltage (VCE)	12 V	12 V
Collector Current (IC)	10-40 mA	20-70 mA

Table 4.4: Comparison of BFU530A and BFP640 Transistors

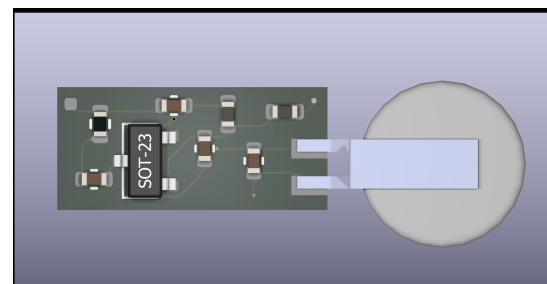
Both of the transistors offer a low noise figure which is suitable for the desired application. The BFP640 offers a better maximum stable gain with a 20dB at 2GHz while the BFU530A provides 18dB at 900MHz, however, the operation frequency is 4339.92MHz meaning the characteristic of BFU530A better matches the circuit application. Both transistors cover the operation specifics in terms of transition frequency, voltage and current ratings (collector current, collector-base voltage, collector-emitter voltage), however, the characteristics of BFP640 exceeds the requirements of the current design making these characteristics an over specification. Both of the transistors meet the operation requirements of the circuit with a low noise figure. Despite this, BFU530A is selected for the circuit as BFP640 has several over specifications that are not needed and the stable gain of the BFU530A is more suitable for the operation frequency.

4.3. PCB Design for Design A

Design A was worked out as a PCB design so the transmitter could be fabricated. To do this KiCad was used which is an open source board design software. Since the available space for the circuit is limited (5mm x 11mm), it was opted to use 0.1 mm traces for lowering the total weight and occupied space. Due to the fact that the circuit operates at a very low current this is not a problem. The final design will be fabricated as a flex PCB to further reduce the weight, this is a widely known and used technology whose only setback is that thin traces can break when bended so it is recommended to not twist it.



(a) Front view of the transmitter PCB



(b) Back view of the transmitter PCB

Figure 4.4: Front and Back views of the transmitter PCB

4.4. SAW Resonator-based Transmitter Circuit Design B

An alternative Design B is generated for the same operating purposes and requirements. This design holds as a back-up option which was inspired by a widely known radio amateur design. The working principles and details of this design is discussed in Appendix H.

5

Micro-controller Design

A microcontroller will be implemented in the system to drive the transistor. This microcontroller is integrated for modulation encoding data onto the carrier signal and managing power efficiency to prolong battery life. This chapter details the selection, design, modulation technique, programming of the microcontroller, gold code and idle mode implementation used in the Vespa velutina transmitter.

5.1. Microcontroller

The microcontroller selection is key in meeting the program of requirements in terms of size, power consumption, and functionality for the system 2. For the appropriate microcontroller two options were considered namely the Atmel ATtiny9 and the NXP MC9RS08KA1CSC. Below is a detailed comparison highlighting why the ATtiny9 was ultimately chosen.

5.2. Key Considerations in Microcontroller Selection

Requirement	Atmel ATtiny9 [30]	NXP MC9RS08KA1CSC [31]
Weight	16.6 mg	74.15 mg
Supply Current at 3V	0.04 mA (128 kHz)	0.9 mA (1 MHz)
Program Memory	1 kB	1 kB
RAM	32 B	63 B
Architecture	AVR 8-bit RISC	ARM 8-bit RISC
Programming Language	C++ (using Arduino IDE)	Assembly or C++ (using CodeWarrior)
Package Size	6-pin SOIC	8-pin TSSOP
Operating Voltage	1.8V - 5.5V	2.7V - 5.5V
Power-down Mode Current	0.1 μ A	1 μ A

Table 5.1: Comparison of Microcontrollers

5.2.1. Weight

The ATtiny9 weighs 16.6 mg while the MC9RS08KA1CSC weighs 74.15 mg. This significant difference in weight makes the ATtiny9 much more advantageous as it complements the projects weight requirements and does not hinder the hornets natural movements due being lighter.

5.2.2. Power Consumption

The ATtiny9 has a much lower supply current of 0.04 mA as in Figure D.1 compared to the 0.9 mA of the MC9RS08KA1CSC [31]. For prolonging the battery life the low power consumption is desired as it complements the 3 hours of battery life requirement. Additionally, the idle mode of the ATtiny9

consumes only 0.1 mA (at 1MHz as seen in Figure D.2), the exact data at 256 kHz was not found but it is known that the current consumption scales down with the frequency. This future helps the battery life to be longer as less power is utilized during idle periods.

5.2.3. Size

The ATtiny9 is equipped with an 6-pin SOIC package while the MC9RS08KA1CSC comes with 8-pin TSSOP package. The lower amount of pins contributes to the overall compactness of the transmitter design, making it a more suitable selection for size requirements.

5.2.4. Operating Voltage

The operating range of ATtiny9 is 1.8-5.5V [30] which is much wider than the 2.7-5.5V of MC9RS08KA1CSC [31]. The wider range is preferred as it provides the flexibility and stability for operation even though there is a decrease in the battery voltage over time.

5.2.5. Programming and Development

The programming of ATtiny9 can be executed by the Arduino IDE which is user friendly and open source. On the contrary, the MC9RS08KA1CSC requires the use of CodeWarrior, which may not be as accessible or easy to use for rapid development and prototyping. Given the project limited time the ATtiny9's programming simplicity using accessible Arduino ecosystem makes it the preferred choice to be able to develop it quickly.

5.3. Reasons for Choosing OOK

On-Off Keying (OOK) modulation is utilized to encode the data onto the carrier signal. This technique is chosen due its low power consumption and simplicity not requiring high amounts of memory on the microcontroller. In OOK, the presence of a carrier wave represents a binary '1' and its absence represents a binary '0'. The ATtiny9 is programmed to generate this modulated signal by toggling the carrier wave on and off according to the input data which will be transfered into the BJT. This simplicity reduces the overall complexity of the transmitter design while keeping the cost lower as well. The signal is transmitted using power only on the 'on' periods which minimizes power usage, increasing battery life. The selected SAW Resonator and BJT are well suited for the OOK application at the 256kHz data rate. Other modulation techniques might require additional components or complex circuit connections increasing weight and power consumption. The ATtiny9's lower current draw is more suitable for the chosen battery together with its AVR architecture making it much easier to troubleshoot during development as it is supported by many libraries.

5.4. Comparison with Other Modulation Techniques

5.4.1. Amplitude Modulation (AM)

AM modulation requires a complex modulation compared to OOK involving additional circuitry in order to modulate the amplitude of the carrier wave according to the input signal. The carrier wave is continuously transmitted meaning that the power consumption is continuous even though when there is no data to send, making it a less desired choice. While AM provides better signal strength and fidelity, the extra circuitry introduces extra weight and complexity as well as extra power consumption which makes it less preferred.

5.4.2. Phase Shift Keying (PSK)

PSK encodes the data onto the carrier wave by modulating the phase of the carrier wave which requires precise control and complex algorithms occupying loads of memory to modulate the signal accurately. Just like the AM modulation, PSK implements continuous transmission which results in higher power consumption. PSK is very robust against noise and suitable for high data rates, however, the features do not provide a significant advantage to compensate for implementing such complex design and high power consumption for the projects requirements.

5.5. Micro-controller Design and Programming

5.5.1. OOK Implementation

The microcontroller implements the OOK by transmitting a Gold code sequence together with a sleep mode implemented to save power. From a specific transmit pin the predefined Gold code is transmitted and when there is no signal sent the microcontroller enters in sleep mode for power conservation until it is woken up by an external signal.

The microcontroller code enables the operation mentioned above by several working principles. The frequency of the microcontroller is set to 256kHz as this allows the period for the Gold code to be transmitted. The PB1 pin is assigned as the **TRANSMIT_PIN** which is the output pin sending the Gold code while PB2 is assigned as the **WAKEUP_PIN**, a pin with an internal pull-up resistor serving as an input pin to detect an external signal in order to wake up the microcontroller from sleep (exit sleep mode). The function **enterSleep()** is utilized for power conservation to enter and exit sleep mode using interrupts. For the **WAKEUP_PIN** pin change interrupts are enabled so that when there is a change of state in this pin it will trigger an interrupt and exit sleep mode. **ISR(PCINT0_vect)** is the interrupt service routine that is executed when a change is detected. Further the **setup** function initializes the pins by setting **TRANSMIT_PIN** as output, **WAKEUP_PIN** as input with a pull-up resistor, and enables pin change interrupts on **WAKEUP_PIN**. Moreover, to transmit the Gold code the function **loop** is utilized. The Gold code is stored in an array called **goldCodeSequence** and this sequence is transmitted bit by bit using the **transmitBit** function. For each bit in the predefined sequence the **transmitBit** function sets the **TRANSMIT_PIN** high or low depending whether the bit is a '1' or '0' where each bit is held for 10 milliseconds. Once the entire sequence is transmitted, to allow time between transmissions a wait period is implemented by making the microcontroller wait for 3 seconds. This means that every 3 seconds a signal is transmitted.

5.5.2. Gold codes

In communication systems, multiple signals might share the same channel such as in satellite communications and cellular networks. Gold codes [32] help differentiate these signals. Each transmitter uses a unique sequence to "mark" its signal. This helps the receiver to extract the desired signal while minimizing interference from others. The important properties of gold codes are periodicity, balance and low cross-correlation. Low cross-correlation means that different gold codes should have minimal overlap when compared allowing clear signal distinction. To insure a robust transmission the number of 1's and 0's should be roughly equal, so they are balanced. While the simple concept of gold codes makes distinction of signals easier in multi-path scenarios, this simplicity has a drawback in performance. The bandwidth is not utilized very efficient and data has transfer speed limitations, nevertheless this method works good enough in the current transmitter application where simplicity is priority. The Gold code chosen for transmission is '1110011101011001001001110010010' which makes the transmitted signal distinguishable facilitating the reception of the signal during the signal processing stage.

5.5.3. Power down implementation

During the design process the stand-by power usage of the transmitter was taken into account. A design with a switch would add weight which is out of question. Due to this a power down mode is implemented with the script. The ATTiny9 has the capability to shut itself down minimizing the current consumption, this is called the power down mode. According to the datasheet [30] the typical current consumption then is 4.5 μ A with the watchdog timer enabled and a supply voltage of 3 V. The design is made such that at the side of the PCB, contacts leading to the pins are available which when shorted with for example a paperclip creates the needed signal to power off the microcontroller, preserving battery life when the tracker is stored.

6

Simulation

Initial to the physical construction of the circuits, in order to identify potential issues and to have a general idea if the design works LTSpice simulations were deployed. This chapter provides an overview of the simulation process together with the discussion of the outcomes and shortcomings encountered during the simulations.

6.1. LTSpice Simulation

Prior to the entire circuit simulations, first solely the SAW Resonator equivalent circuit [25] simulation is generated to have a correctly operating circuit at the desired frequency. The simulation is implemented with the parasitics, namely simulating with introducing an initial condition of 3V to the SAW Resonator for a kick-start purpose. The simulated equivalent circuit is displayed in the Appendix C. The frequency response of the resonator verified the correct operation by exhibiting a gain of 0.5dB in between 426MHz and 436MHz. Once a trusted simulation of the resonator is obtained, it was further continued to simulate the designs A and B.

6.1.1. Design A Simulation

In this section firstly the simulation with the selected component values together with the SAW Resonator is implemented. The circuit is set so that it transmits a continuous signal, therefore, both the operating voltage and the SAW Resonator are driven with a DC voltage of 3V. Further parasitics are implemented with an initial condition of 1mV to recreate physical environment. To understand the time domain behaviour of the transmitted signal, a transient analysis is performed for a period of 3 μ s with a time step of 1ns.

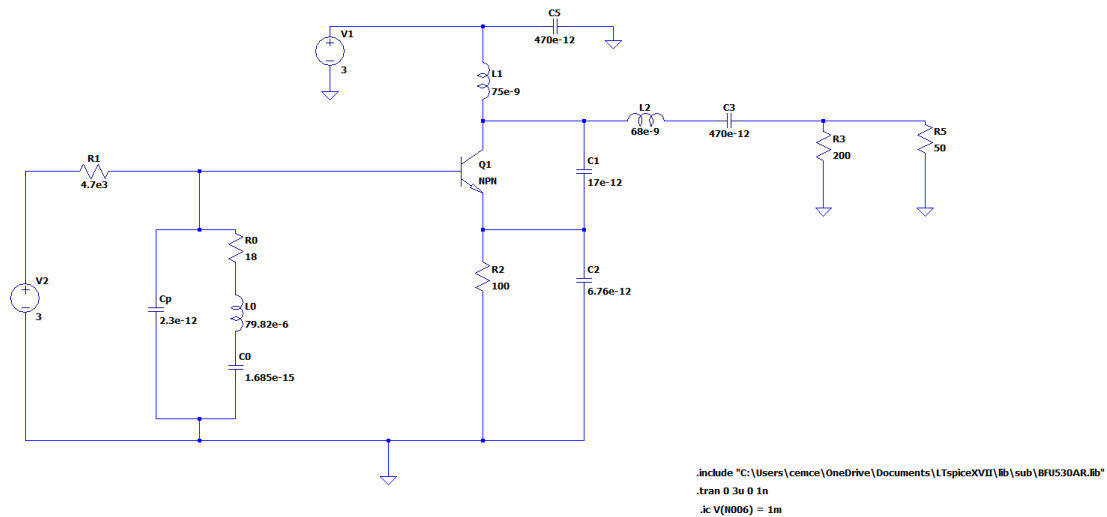


Figure 6.1: Design A Simulation

The configuration of the simulated circuit is displayed in figure C.3. The output on the 50ohm load resistor resulted in a RF signal of 821.6MHz which was not the desired operating frequency. Even though the transistor was created manually based on the library imported from the manufacturer's LTSpice model for the transistor, it is suspected that the imported library was corrupt, showcasing a transistor that does not operate in the desired frequency range. Further replacing the transistor with an ideal NPN transistor was pursued keeping the rest of the circuit the same. This resulted in an output signal of 620 MHz. To get the desired operating frequency the components values were further adjusted, keeping in mind that the ratio of the component values (namely C1 and C2) which stabilize the oscillations to comply with the Barkhausen Stability Criterion. These values were selected such that C1 is in the range of 5-10pF and C2 is in the range of 10-15pF. However, this methodology resulted in frequencies similar to 620 MHz, therefore, the component values were fine-tuned to achieve the desired operating frequency. Noticeably, the ratio of the components in the feedback loop were inversely related compared to the intended design.

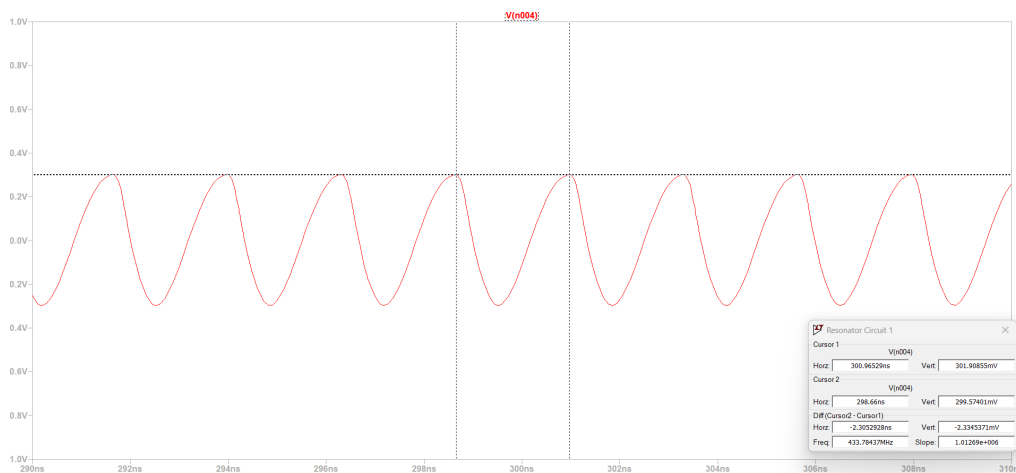


Figure 6.2: Design A Simulation Results

The operating simulation suggested that the output must be oscillating at 433.7MHz at an amplitude of 300mV with adjusted component values. The component values suggested by the simulation were considered inconvenient as they are very specific to decimals and not widely used, therefore, difficult to reach. It is concluded that the simulation is unable to take real life parasitics into account.

7

Testing and Measurements

After accomplishing the design measures the circuits are physically built and tested. This chapter delves into the building process of the transmitters, the test performed, the measurements resulting from the executed tests and reflection on these results.

7.1. Building and Testing the Transmitter

Building the transmitter for Design A the LTSpice simulation is disregarded as the results suggested unreliable component values and relations. The initial design values were further pursued. In order to facilitate the prototyping, SMD 0805 components were utilized. For the actual product a smaller SMD size of 0402 is recommended (to meet the size and weight requirements) implementing the PCB design provided in section 4.3.

The circuit is built on top of a copper board, serving as a ground plate. The SMD components were soldered in Manhattan style, as the designs' configuration as displayed in figure H.1 in Appendix H. Due to the fact that the selected SEIKO batteries not arriving on time the circuit was powered by an analog lab power supply of 3V. During this process it was seen that the circuit draws a current of 12 mA at its peak and having the strongest measured transmission power. The lowest received power was when the supply was limited at a current of 0.8 mA, which suggests that at a current draw below 0.8mA there was no signal transmitted. This current draw was not the expected 0.1 mA value, which was an essential design requirement. It is believed that this phenomena occurs due to the fact that the circuit is not completely matched with the output impedance which will be further discussed in the next chapter.

Therefore, a DURACELL CR2032 coin-cell battery operating at 3V with a discharge current of 6mA was used to appropriately power the circuit in order to be able to check whether the transmitter design works even though the power requirements were not met. The circuit implemented a 15cm long copper antenna with a diameter of 1mm. Prototype was built with a matching and filtering circuit for a 50ohm load, as the component value calculations for the matching and filtering circuit were supplied with a delay from the subgroup C2 (values were provided after the component orders were placed).

Once the prototype was constructed, connection to the coin-cell battery was established to start transmitting. To retrieve the signal an antenna is connected to the RTL SDR dongle which is inserted into the PC via a USB port [33]. The software SDRsharp by AIRSPY is utilized to capture and analyze the received signal integrating features such as SNR and signal gain. Performing the tests, three conditions were considered, initially receiving the signal in a near field approximately 1 meter away from the transmitter and secondly a far field at a distance of 100 meters in urban area, lastly at a distance of 500 meters in open field. The urban area in the experiments were chosen to be the EEMCS building of TU Delft while the open field is the Mekelweg in TU Delft campus. First, a continuous signal is transmitted to confirm and ensure the transmitting frequency of the circuit. Further, a simple periodic OOK mod-

ulation code was loaded to the microcontroller to analyze a modulated signal. Finally, the Gold code sequence was loaded to the microcontroller to test the quality of distinguishability.

7.2. Continuous Signal

The transmission of the continuous signal allowed to determine the operating frequency of the prototype. The figure 7.1 exhibits that the operating frequency is 433.982MHz.

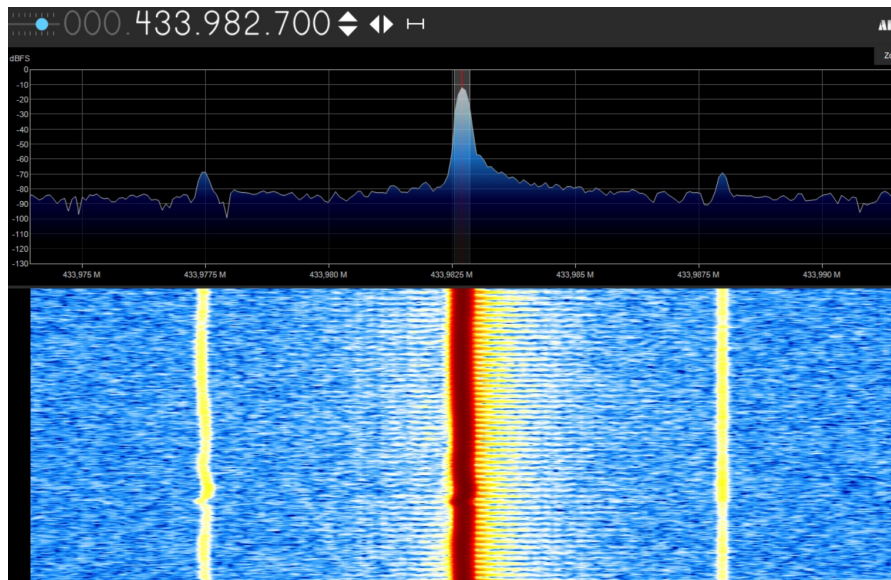


Figure 7.1: Continuous Transmission in Near Field

This outputs a difference of 62kHz compared to the expected operational frequency of 433.92MHz. The reason for such a frequency drift might be due to the temperature change within the transistor. Further details can be visualized in Appendix F for the continuous signal received at 100 meters which exhibited the same frequency at a lower SNR.

7.3. OOK Modulated Signal

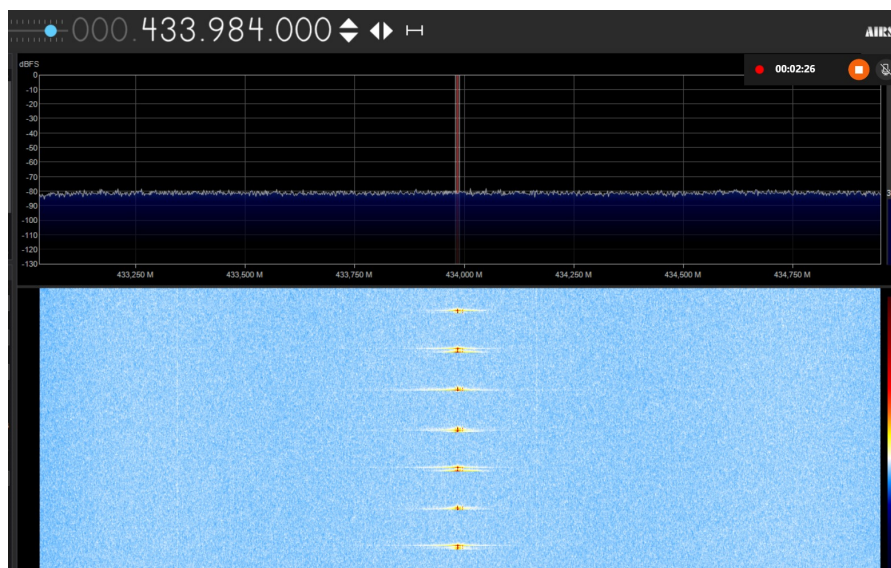


Figure 7.2: Transmission with OOK Modulation in Near Field

A simple OOK modulation was implemented on the microcontroller operating at 256kHz. Such a system facilitated understanding if a modulated signal can be retrieved while keeping the operating frequency stable. The microcontroller enabled two high signals (transmission) every second lasting for 30 milliseconds. The following signal was detected displayed in figure 7.2 in which the operating frequency remained the same while a signal was detected every second ensuring a correct performance. Further, the signal received at a distance of 100 meters demonstrated in Appendix F showed exactly the same behaviour as the near field.

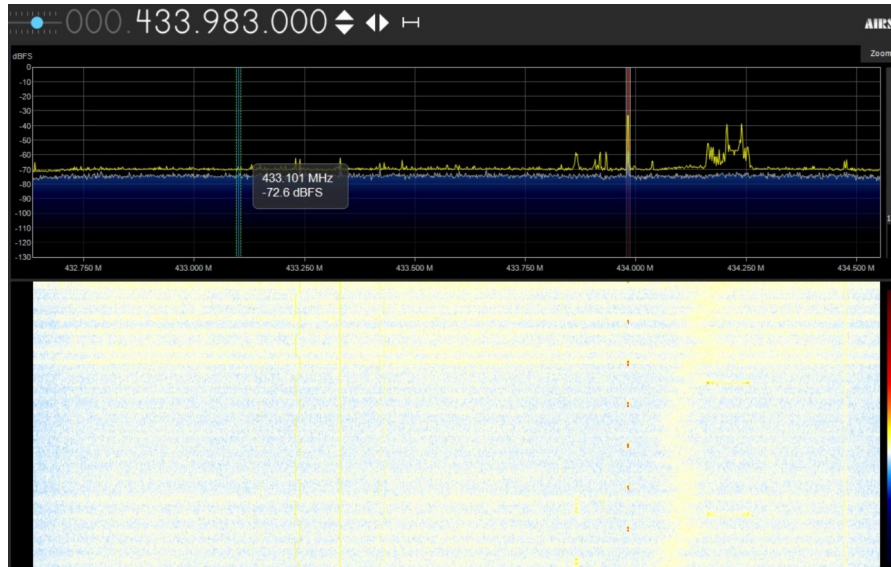


Figure 7.3: Transmission with OOK Modulation at 500 meter

The test deployed at a distance of 500 meters in open field yielded a detectable signal at this range displayed in figure 7.3.

7.4. Gold Code Implemented Signal

After implementing a OOK modulated signal, a unique signal encoded with a Gold code sequence was loaded onto the microcontroller. This Gold code sequence increases the distinguishability of the signal by transmitting in a certain predefined pattern. The utilized Gold code for this test was the previously explained '1110011101011001001001110010010'. This sequence is sent every three seconds where each bit takes 20 milliseconds.

The figure F.3 exhibits the Gold code transmitted signal in a near field. The received signal was operating at a frequency of 433.992MHz exhibiting a 10kHz frequency drift from the previously recorded results. The received signal conveyed a sequence transmitted appearing every three seconds however, the sequence signal was distorted having a wide spectrum.

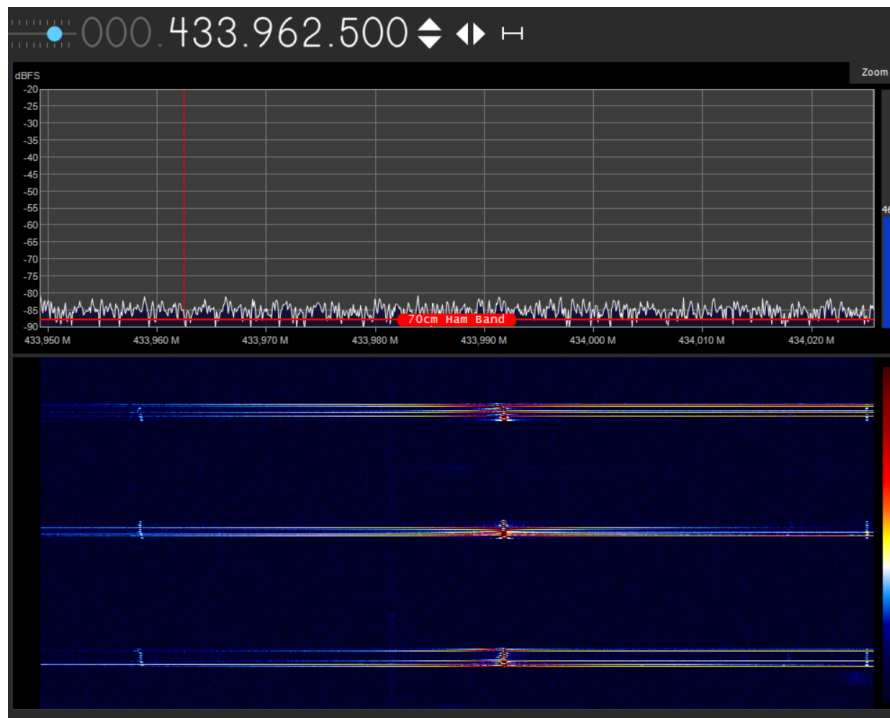


Figure 7.4: Transmission using Gold Code Sequence in Near Field

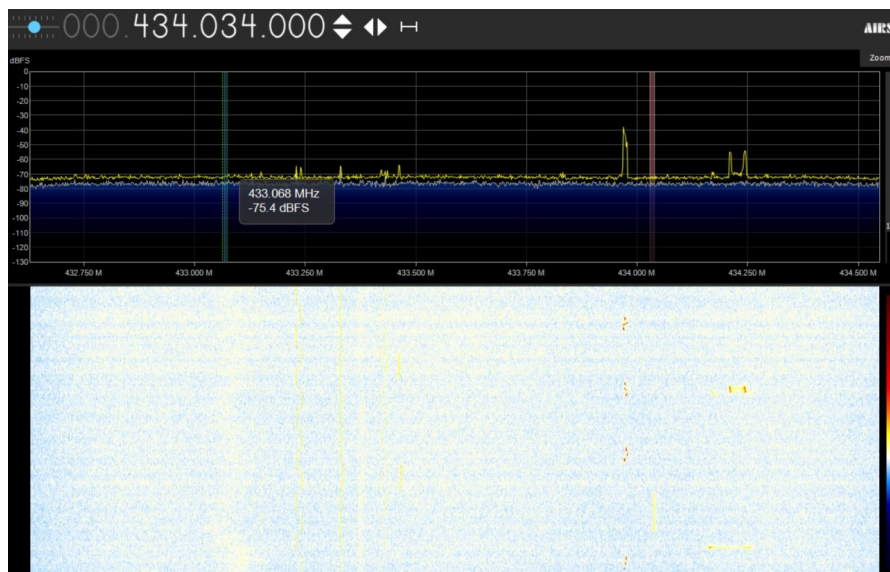


Figure 7.5: Transmission using Gold Code Sequence in 500 meters

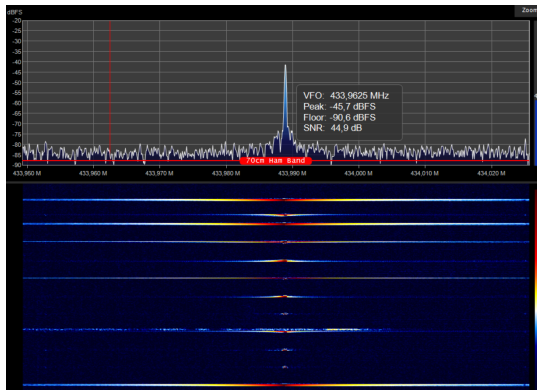
The measurements from a distance of 500 meters shown in figure 7.5 resulted in a detected Gold code signal. Unlike the widely spread signal in near field, the open field 500 meters tests resulted in a sharply transmitted signal. The reason behind such results is due to harmonics generated as the transmitter is very closely located to the antenna in near field experiments.

7.5. Signal Strength

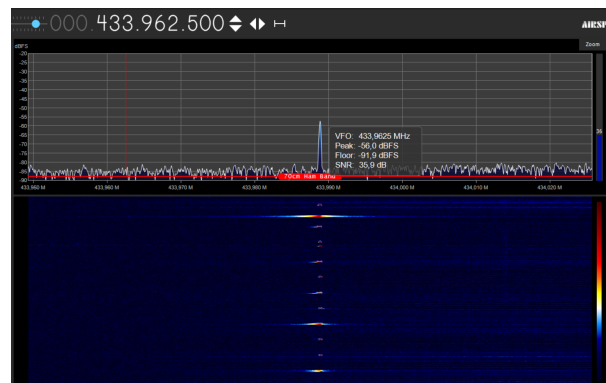
To understand if the signal has sufficient SNR(signal to noise ratio) the signal strength is measured. Initially the reference SNR is measured at a distance of 1 meter and the the quality of the signal is inspected at 100 meters and 500 meters comparing the SNRs. Signal strength measurements in the near field and 100 meter urban area were executed with an receiving antenna RF gain for 15.7dB where the approximate floor noise was -91dBFS. While the measurements executed in open field at 500 meters included an adjustment to the receiving antenna RF gain by increasing it to 28dB to be able to capture the incoming signal and a floor noise of approximately -75dBFS.

Measurements for the OOK modulated version were completed only considering the near field and the urban area for creating a clear understanding of the SNR values, before measuring the Gold code sequence at a distance of 500 meters. The reference SNR is 44.9dB F.4 showing a significantly high signal quality. The measurements in urban area at a distance of 100 meters demonstrate an SNR of 35.9dB F.5. The signal strength remains high as the SNR is remarkably higher than the required minimal SNR of 10dB. However, this slight decrease in the SNR can be justified with increasing noise levels due to increased distance, attenuation of the signal and interference from other signals as the measurement was done in the EEMCS building.

Furthermore, in the open field at 500 meters the OOK modulated signal and the Gold code sequence signal strengths were measured. As the previously displayed figures 7.3 & 7.5 indicate, these measurements yielded an SNR of 43dB for the OOK modulated signal and an SNR of 37dB for the transmission using the Gold code sequence. As these SNR values were significantly above the minimal limit of 10dB, it was concluded that both OOK modulated signal and Gold code sequence signal were successfully transmitted with sufficient signal strength.



(a) Signal Strength in Near Field



(b) Signal Strength in Urban Area at 100 meters

Figure 7.6: Signal Strength in different scenarios

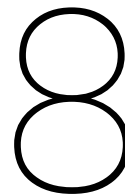
7.6. Design B

Alternatively, Design B was physically constructed with similarities to Design A, with the utilization of a copper ground plane and SMD components. Nonetheless, the chosen inductors, valued at 35nH and 150nH; were wound by hand around a winding ground, with 3mm diameter, using copper wire with a diameter of 0.3mm. The matching and filtering circuit remained the same. The remainder of the circuit incorporated two capacitors, each valued at 36pF. Finally, the output signal is transmitted via the same copper antenna with a length of 15cm and a diameter of 1mm. When connected to the power supply, the circuit did not draw any current, leading to the conclusion that the circuit was not viable. Even though theoretically the circuit must operate correctly, it is suspected that the chosen capacitor values were not optimal, resulting in a non oscillating SAW resonator.

7.7. Results Summary

Measurement	Scenario	Frequency	Signal Type	SNR (dB)	Notes
Continuous Signal	Near Field (1 meter)	433.982 MHz	Continuous	N/A	Frequency drift of 62 kHz
Continuous Signal	Urban Area (100 meters)	433.982 MHz	Continuous	N/A	Lower SNR compared to near field
OOK Modulated Signal	Near Field (1 meter)	433.982 MHz	OOK Modulated	44.9	Stable operating frequency, correct performance
OOK Modulated Signal	Urban Area (100 meters)	433.982 MHz	OOK Modulated	35.9	SNR decreased due to increased distance and noise
OOK Modulated Signal	Open Field (500 meters)	433.982 MHz	OOK Modulated	43	Detectable signal, high SNR
Gold Code Implemented Signal	Near Field (1 meter)	433.992 MHz	Gold Code Sequence	N/A	Frequency drift of 10 kHz, distorted signal
Gold Code Implemented Signal	Open Field (500 meters)	433.992 MHz	Gold Code Sequence	37	Sharp signal, SNR significantly above minimal limit
Signal Strength	Near Field (1 meter)	N/A	OOK Modulated & Gold Code	44.9	Reference SNR
Signal Strength	Urban Area (100 meters)	N/A	OOK Modulated	35.9	High signal quality, SNR > 10 dB
Signal Strength	Open Field (500 meters)	N/A	OOK Modulated & Gold Code	43 (OOK), 37 (Gold Code)	SNR > 10 dB for both signals
Design B	-	-	-	-	Circuit not viable, suspected suboptimal capacitor values

Table 7.1: Summary of Test and Measurement Results



Discussion, Conclusion and Future work

8.1. Discussion

The primary objective of this thesis was to develop an ultra-lightweight tracking device for the invasive species *Vespa velutina* focusing on improving existing designs. The results obtained from the different phases of the project such as design, simulation, physical testing provided comprehensive insights into the system's performance, strengths and limitations.

The transmitter design followed a use of SAW resonator-based circuit regarding the advantages of frequency stability and a high Q-factor. The modulation for transmission was chosen to employ an OOK modulation implementing a Gold code for its simplicity and low power consumption adding a feature to become more distinguishable. The selected ATTiny9 microcontroller effectively managed power consumption and processing capabilities for signal modulation. The coded script when compiled gives a size of 900 Bytes which is in the specifications of the ATTiny9. The decision to pursue with the R900 SAW resonator operating at 433.92MHz was essentially due to its superiority in temperature and environmental resistance which are key for outdoor applications. The circuit design incorporated the SAW resonator to generate a stable carrier signal, which was then modulated using OOK by the microcontroller. The choice of components, including the BFU530A transistor, was aimed at achieving optimal signal amplification and stability. During the component selection procedure not only the component values were considered, but also their self-inductance as this measure could potentially interfere with the operation of the tracker.

Furthermore, simulations were conducted via LTSpice prior to the physical construction of the circuit in order to gain insight about the working principles of the design. Several mismatching and disappearances were observed between the simulations and real life conditions, especially in terms of achieving the desired operating frequency. Fine-tuning of stability circuit, incorporating an inductor and two capacitors, was conducted in order to achieve the desired operating frequency. This resulted with selection of component values specific to two decimals being almost non-applicable under real life conditions. This was attributed to the limitations of the simulation software in accounting for real-world parasitic elements and the precise behavior of components under varying conditions even though initial conditions were applied in the simulation.

Pursuing the construction of the chosen design, the prototype was build as a Manhattan style circuit. This is a frequently used method when prototyping an RF-circuit or by radio-amateurs at home. With this particular method the connecting wire distance between the wires should be minimal, with the hands-on experience we gained during our studies this was done in our best capability. Still some traces could

be shorter, reducing overall unwanted parasitic inductance in the traces preventing losses, increasing efficiency and providing a more stable frequency.

Once the transmitter's construction was completed, the performance of the transmitter was evaluated through various tests. These tests included a current draw test, continuous signal transmission, OOK modulated signal transmission, Gold code sequence signal transmission. The signal transmission tests were conducted under different conditions, namely near field, urban area, open field, to assess the transmitter's robustness and signal strength.

Initially the current draw of the circuit was examined. This test yielded the information that the circuit required a minimal of 0.8mA current in order to transmit a signal. The current draw at a 0.1mA remains, however, it is not enough to power the antenna for transmission. The reason for this might lie in the inefficiencies such as not using an exact matched circuit with the antenna impedance (50 Ω load matching was implemented), connections longer than needed adding parasitic inductance and capacitance in an already sensitive circuit and the connections made of iron instead of a better conductor such as copper. The components used were standard SMD components (complying with the operating frequency) which were not of the highest possible quality implying the deficiencies might be recovered by utilizing more robust components.

The continuous signal tests allowed to identify the operating frequency at 433.982 MHz which showed a frequency drift of 62kHz from the SAW resonator's resonant frequency. This drift is occurring likely due to the heat up of the transistor inducing temperature changes affecting its operation.

Moreover, the OOK modulated signal tests provided confirmation for the stable operating frequency of the transmitted signal while detectable signals were generated at different distances. The near field tests yielded an SNR of 44.9 dB, while the urban area tests showed an SNR of 35.9 dB. In open field conditions, the transmitter successfully transmitted a detectable signal up to 500 meters with an SNR of 43 dB, indicating robust performance.

For better distinguishability of the signal the Gold code sequence was implemented and tested for detection. The near field tests showed a frequency drift of 10 kHz, resulting in a distorted signal. The wide spread spectrum in the signal diminished in open field conditions as this was due to harmonics created caused by the near placement of the transmitter and the receiving antenna in the near field. Further, according to findings the frequency drifting phenomena is related with the fall and rise time of the signal when the microcontroller's operating frequency is set to 256 kHz at 3 V. Although the operating frequency is capable of handling this signal, the combination of it with the voltage is influencing the Gold sequence generation. Another fact was the retrieval of the sequence, the RTL-SDR module did not have enough resolution to retrieve it at the modulated signal of 31 bits each 10 ms long. This would be able with the more advanced reading out capabilities of subgroup C3 which had some unfortunate hold-backs leading to the inability of processing received signals. Even though there was a frequency drift in the signal, it demonstrated a sharp and detectable signal with an SNR of 37dB suggesting an effective implementation, especially in less noisy environments.

All measurements receiving the signal were completed utilizing a simple dipole antenna, not fully optimized for 433.92 MHz and an RTL-SDR setup. This possibly influenced the efficiency of the system. The use of an optimized antenna with a high directivity (such as a Yagi Uda antenna) would increase the range and power efficiency, which is a widely used method in other tracker designs.

Despite the encountered challenges, a partially effective system satisfying the majority of the program of requirements is accomplished. The weight requirement of 250 mg was satisfied as the entire PCB designed circuit ideally must weigh 170.68 mg (displayed in Appendix B) according to the calculations executed utilizing the component data sheet information. This suggests that the encountered current

draw problem could possibly be resolved utilizing the room for a heavier battery providing higher current. The transmitter's size requirement is satisfied dimensions being 11x5x2mm as all the components were chosen accordingly and the PCB was designed to comply with the abdomen of the hornets. The cost requirement of 25 euros was accomplished with a total cost of 5.149 euros (price tags and calculation indicated in Appendix E), this was calculated for bulk production of 100 transmitter with prices accordingly mouser.com and farnell.com. This suggests that the cost gap of approximately 20 euros could be utilized to purchase higher quality components. The frequency requirement was satisfied as this design implements the usage of a frequency band of 433.05-434.790MHz with a SAW resonator operating at 433.92MHz and a tested prototype operating in the range 433.982-433.992MHz which still falls into the legal license free band. The chosen battery is a replaceable and rechargeable battery, for further improvements a charging circuit can be added to the circuit. Battery life requirement was not met due to the fact that the circuit could not power the tracker at a current of 0.1 mA, therefore, the battery life specification could not be tested. Highlighted in the tests performed the operating conditions and signal range requirements were met successfully transmitting a detectable signal with a effective signal strength in urban environments at a minimal distance of 500 meters. The components, especially the SAW Resonator, were chosen to operate under varying environmental conditions, with the help of durable components and a room for possible added weight of 80mg, to make the transmitter resistant to humidity and rain it is covered with transparent nail polish. Further, the system implemented a OOK modulation using a Gold code sequence spotlighting distinguishability which was combined with an amplifying circuit and a matching & filtering circuit.

8.2. Conclusion

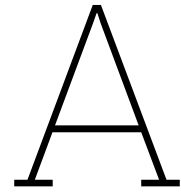
This thesis successfully developed an ultra-lightweight tracking device for locating *Vespa velutina* nests. The designed transmitter met the weight requirement with a 170.68 mg and demonstrated a stable frequency operation at 433.992MHz implementing a SAW resonator and OOK modulation with Gold code. The transmitter was able to achieve a signal range of 500 meters with an SNR of 43dB. The total cost was well within the budget with a 5.149 euros per transmitter. However, issues with powering the system and frequency shift with the Gold code sequence remain. Future work will focus on battery optimization, component quality improvement, signal retrieval enhancement, antenna and charging circuit.

8.3. Future Work

Several areas have been identified in the current prototype for future improvement and exploration.

- **Battery Optimization:** the current draw issue can be resolved by exploring alternative batteries or enhancing the existing power system.
- **Component Quality:** higher quality components can be used as the cost budget allows it, particularly for SMD capacitors and inductors in order to improve overall circuit efficiency and performance.
- **Signal Retrieval:** the utilized RTL-SDR module can be enhanced to receive 433.92MHz or a custom receiver can be utilized to accurately retrieve the Gold code sequence.
- **Antenna:** Experiment with optimized antenna designs, such as a Yagi Uda antenna, to increase range and power efficiency which will improve signal strength and quality in various environments. Additionally, a prototype must be built incorporating the matching and filtering circuit for the specific antenna utilized.
- **Charging Circuit:** a charging circuit can be implemented for extra features enhancing the utility.

By addressing these areas, the tracking device can be further improved to provide a more reliable, efficient, and practical solution for controlling the *Vespa velutina* population mitigating its ecological impact in Europe.



Microcontroller code

A.1. The code for testing the transmitters ON OFF keying ability with turning it on for 30 ms, twice every second

```
// Bachelor Aftstudeerproject TU Delft EWI
// Gold code implementation script for the ATtiny9
// Yunus Emre Döngel and Cem Çetiner

#define F_CPU 256000UL // Define the clock frequency as 256 kHz
#include <avr/io.h>
#include <avr/interrupt.h>
#include <avr/sleep.h>
#include <util/delay.h>

#define TRANSMIT_PIN PB1 // Define the pin connected to the transmitter

void setup() {
    // Set the transmit pin as output
    DDRB |= (1 << TRANSMIT_PIN);
}

void loop() {
    // Transmit first high signal (30 ms)
    PORTB |= (1 << TRANSMIT_PIN); // Set pin high
    _delay_ms(30); // Wait for 30 milliseconds
    PORTB &= ~(1 << TRANSMIT_PIN); // Set pin low

    // Wait for the time before the next high signal
    _delay_ms(470); // Wait for 470 milliseconds

    // Transmit second high signal (30 ms)
    PORTB |= (1 << TRANSMIT_PIN); // Set pin high
    _delay_ms(30); // Wait for 30 milliseconds
    PORTB &= ~(1 << TRANSMIT_PIN); // Set pin low

    // Wait until the end of the second to transmit the next set of signals
    _delay_ms(470); // Wait for 470 milliseconds
}
```

A.2. Code implementing the chosen Gold code sequence

```
// Bachelor Aftstudeerproject TU Delft EWI
// Gold code implementation script for the ATtiny9
// Yunus Emre Döngel and Cem Çetiner

#define F_CPU 256000UL // Define the clock frequency as 256 kHz
#include <avr/io.h>
#include <avr/interrupt.h>
#include <avr/sleep.h>
#include <util/delay.h>

#define TRANSMIT_PIN PB1 // Define the pin connected to the transmitter
#define WAKEUP_PIN PB2 // Define the pin used to wake up the microcontroller

// Define the Gold code sequence
const uint8_t goldCodeSequence[] = {1, 1, 1, 0, 0, 1, 1, 1, 0, 1, 0, 1, 1, 0, 0, 1, 0, 0, 1, 0, 0, 1};
const uint8_t sequenceLength = sizeof(goldCodeSequence) / sizeof(goldCodeSequence[0]);

void transmitBit(uint8_t bit) {
    if (bit) {
        PORTB |= (1 << TRANSMIT_PIN); // Set pin high
    } else {
        PORTB &= ~(1 << TRANSMIT_PIN); // Set pin low
    }
    _delay_ms(10); // 10 ms duration for each bit
}

void enterSleep() {
    // Set sleep mode to Power Down
    set_sleep_mode(SLEEP_MODE_PWR_DOWN);
    cli(); // Disable interrupts
    sleep_enable(); // Enable sleep mode

    // Ensure the WAKEUP_PIN interrupt is enabled
    GIMSK |= (1 << PCIE); // Enable Pin Change Interrupt
    PCMSK |= (1 << WAKEUP_PIN); // Enable interrupt on WAKEUP_PIN

    sei(); // Enable interrupts
    sleep_cpu(); // Put the microcontroller to sleep

    // The program will continue from here after waking up
    sleep_disable(); // Disable sleep mode
}

ISR(PCINT0_vect) {
    // Interrupt service routine for pin change interrupt
    // This will wake up the microcontroller from sleep
}

void setup() {
    // Set the transmit pin as output
    DDRB |= (1 << TRANSMIT_PIN);

    // Set the WAKEUP_PIN as input with pull-up resistor enabled
    DDRB &= ~(1 << WAKEUP_PIN);
}
```

```
PORTB |= (1 << WAKEUP_PIN);

// Enable pin change interrupt
GIMSK |= (1 << PCIE); // Enable Pin Change Interrupt
PCMSK |= (1 << WAKEUP_PIN); // Enable interrupt on WAKEUP_PIN

sei(); // Enable global interrupts
}

void loop() {
    for (uint8_t i = 0; i < sequenceLength; i++) {
        transmitBit(goldCodeSequence[i]);
    }

    // Wait for 3 seconds before repeating the sequence
    _delay_ms(3000);

    // Enter sleep mode after transmitting the sequence
    enterSleep();
}
```

B

Weight budget

Component name	Weight in milligrams
Atmel ATtiny9	16.6
Qualcomm R900 Resonator	37
BFU530AR RF Transistor	7.53
SEIKO MS412FE battery	70
SMD Capacitors (4x)	6
SMD Resistor (3x)	1.95
SMD Inductor (2x)	3.6
Flex PCB	28
Total	170.68

Table B.1: Design A weight budget

C

LTSpice Simulations and Results

C.1. SAW Resonator Simulation & Results

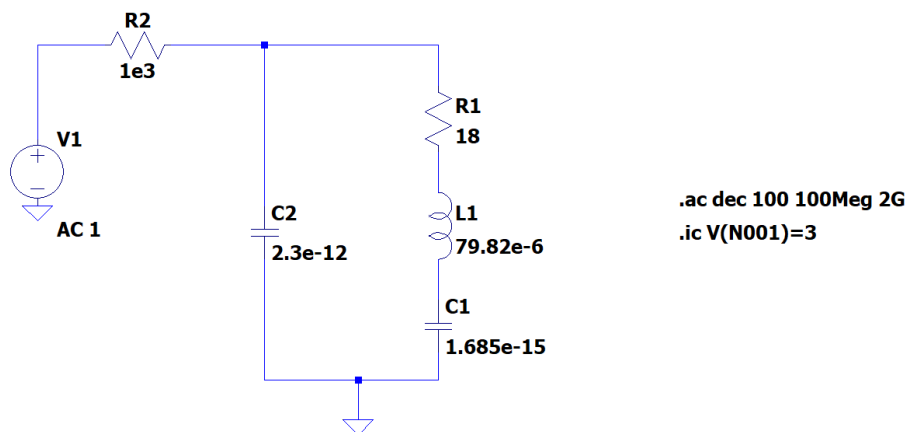


Figure C.1: SAW Resonator Equivalent Circuit Simulation

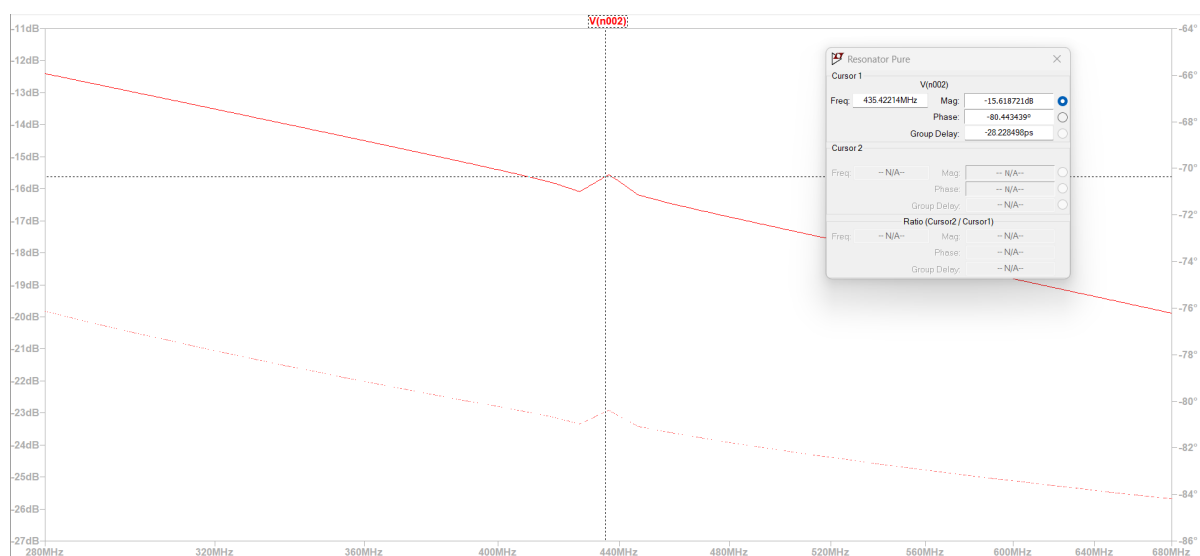


Figure C.2: Frequency Response of the SAW Resonator

C.2. Design A Simulation & Results

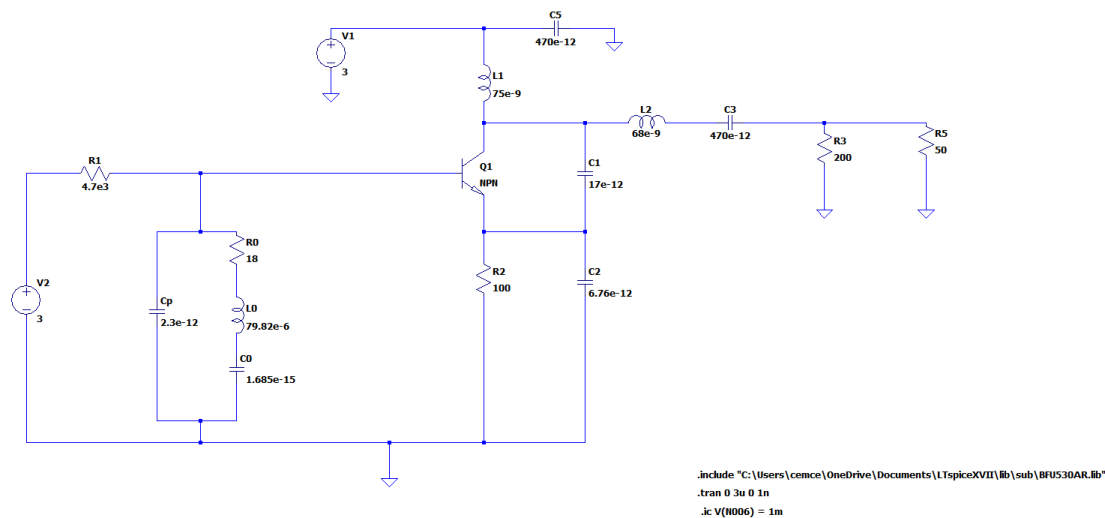


Figure C.3: Design A Simulation

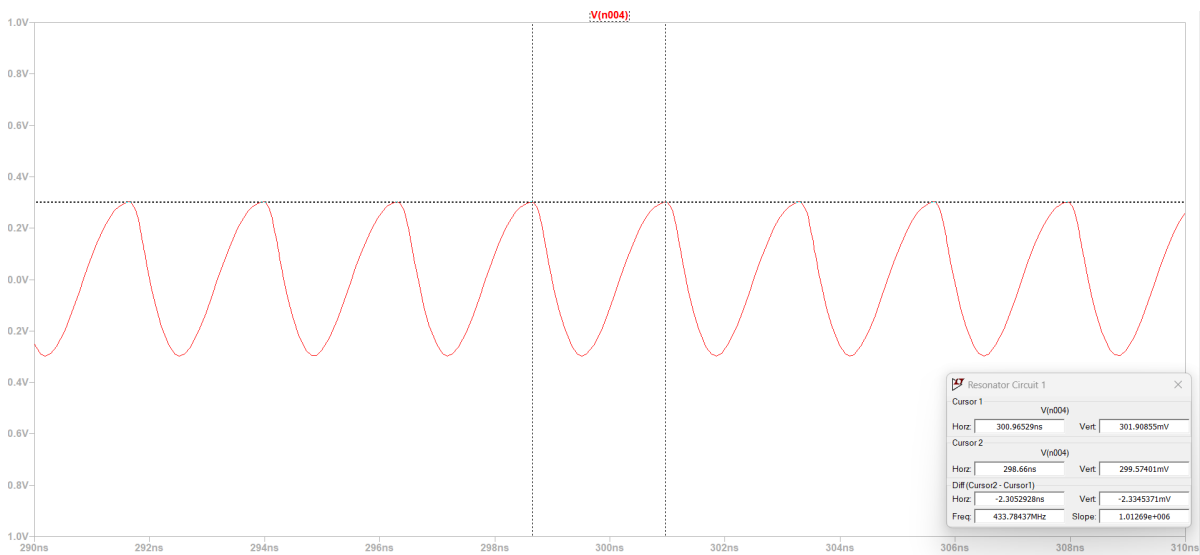


Figure C.4: Design A Simulation Results

D

Microcontroller Specifications

The following graphs were used to make decisions when designing, all extracted from the datasheet [30].

D.1.

Figure 2-3. Active Supply Current vs. V_{CC} (Internal Oscillator, 128 kHz)

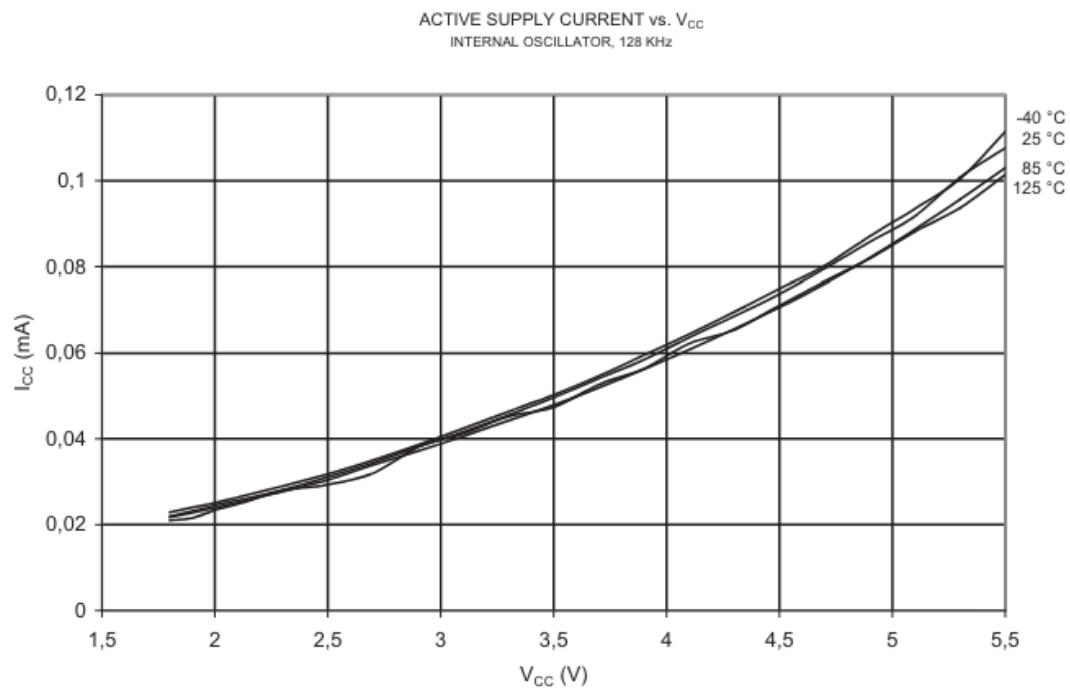


Figure D.1: Current consumption at 128 MHz

D.2.

Figure 2-6. Idle Supply Current vs. V_{CC} (Internal Oscillator, 1 MHz)

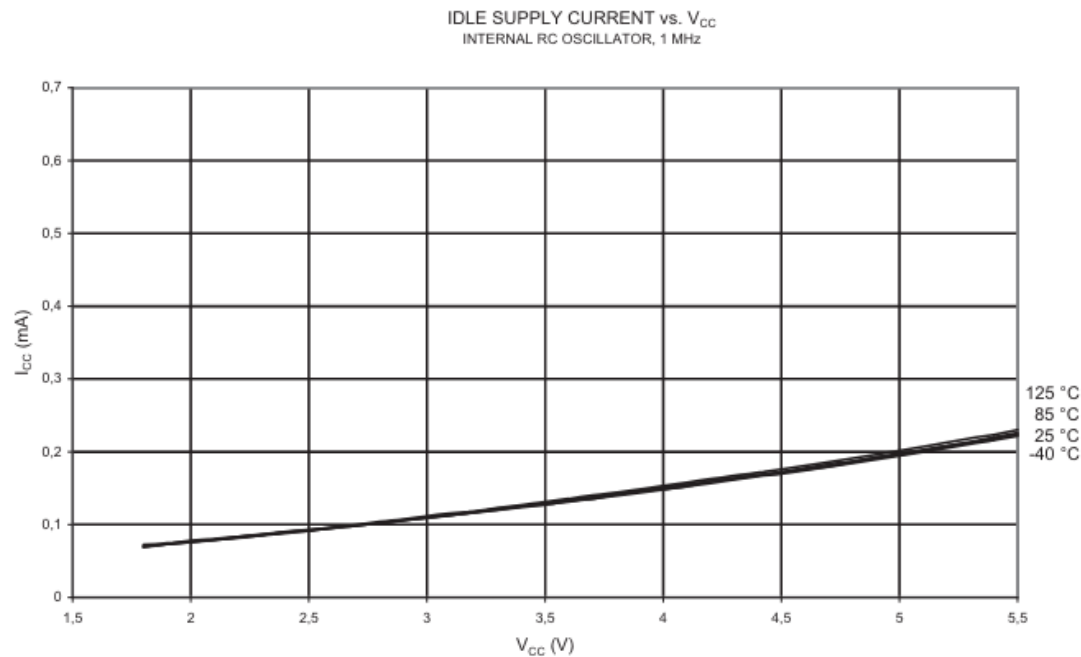


Figure D.2: Idle current vs input voltage when operating at 1MHz

D.3.

Figure 2-8. Power-down Supply Current vs. V_{CC} (Watchdog Timer Enabled)

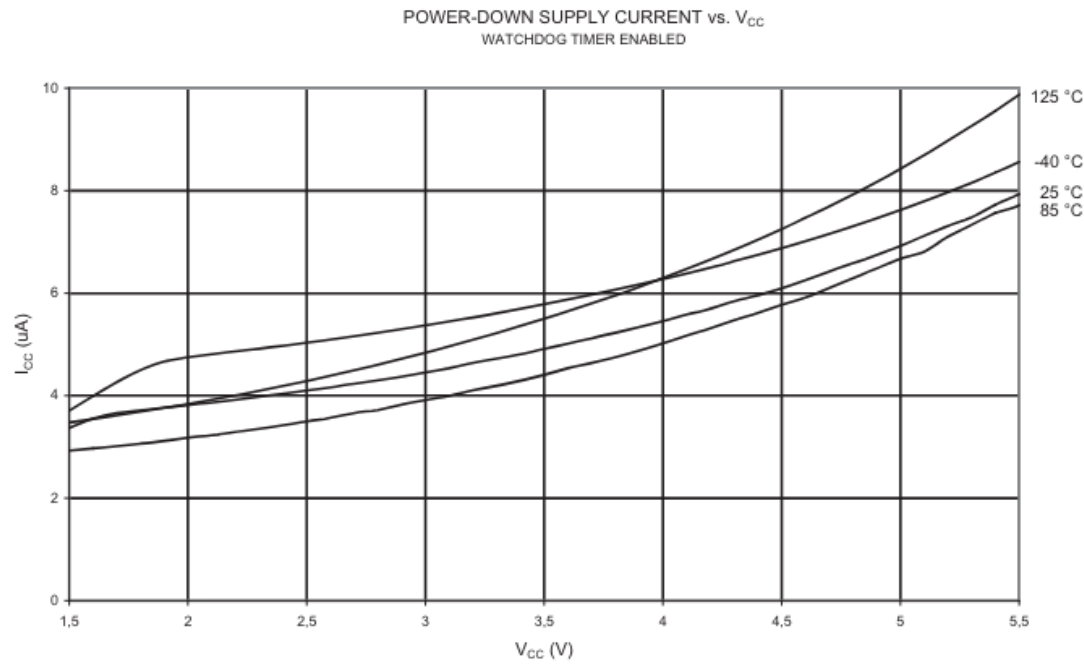


Figure D.3: Current consumption at power down mode

E

Price Budget

Expected cost price of components when bought in to produce in mass (100 transmitters):

Component name	Component price	Amount needed for one transmitter
NXP RF Transmitter BFU530AR	€ 0.343	1
Qualcomm RF360 SAW Resonator B39431R900U410	€ 0.60	1
ATTINY9 microcontroller	€ 0.338	1
4.7 kohms 0402 SMD Resistor	€ 0.294	1
6.8 kohms 0402 SMD Resistor	€ 0.326	1
100 ohm 0402 SMD Resistor	€ 0.004	1
200 ohm 0402 SMD Resistor	€ 0.326	1
27 nH 0402 SMD Inductor	€ 0.072	1
68 nH 0402 SMD Inductor	€ 0.098	1
3pF 0402 SMD Capacitor	€ 0.10	1
7pF 0402 SMD Capacitor	€ 0.10	1
470pF 0402 SMD Capacitor	€ 0.11	2
SEIKO MS412FE	€ 1.86	1
Flex PCB 5 mm x 11mm	€ 0.468	1
Total price of one transmitter	€ 5.149	

Table E.1: Price balance to produce the transmitter in bulk (100 pieces), prices according to mouser.com and farnell.com

F

Receiver Results

F.1. Continuous Signal Results

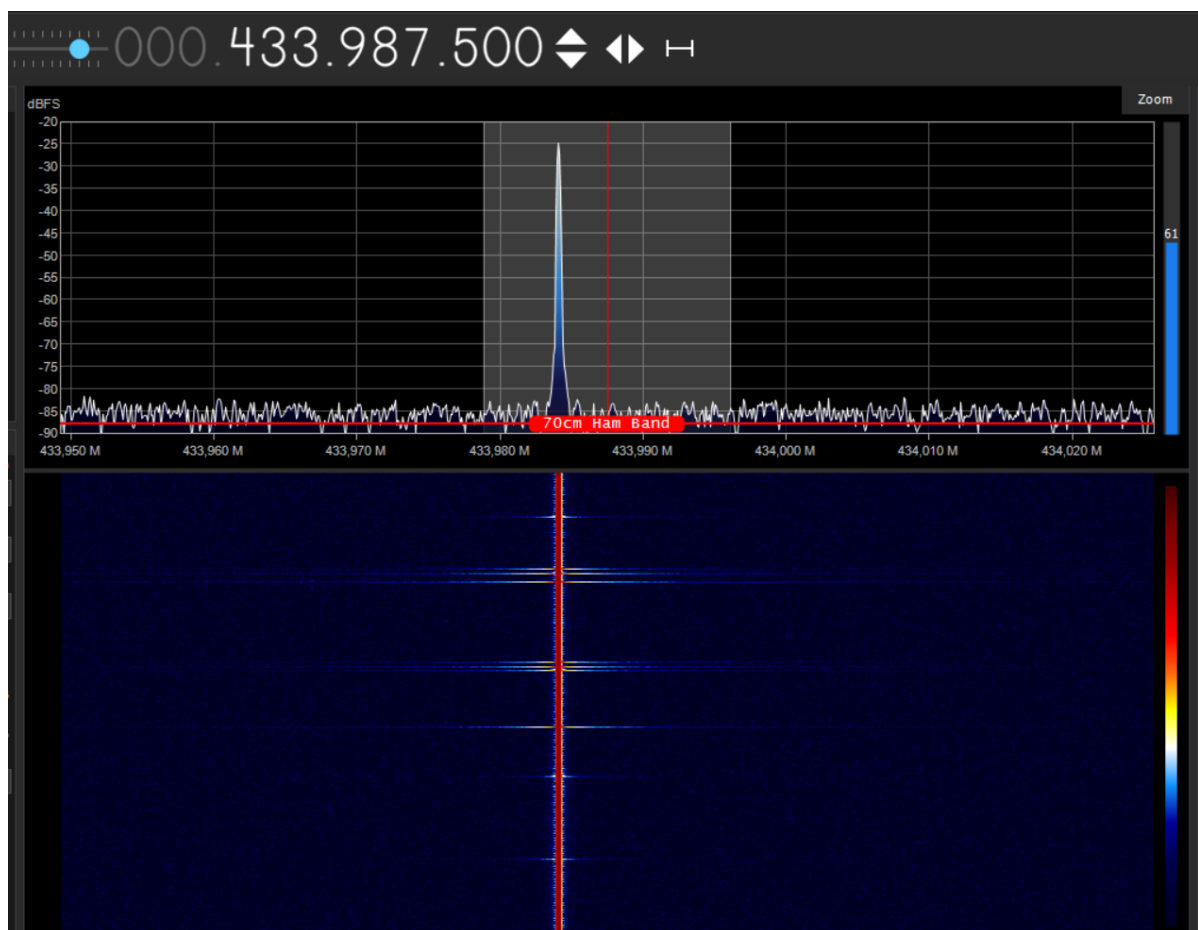


Figure F.1: Continuous Transmission in Urban Area at 100 meters

F.2. OOK Modulated Signal Results

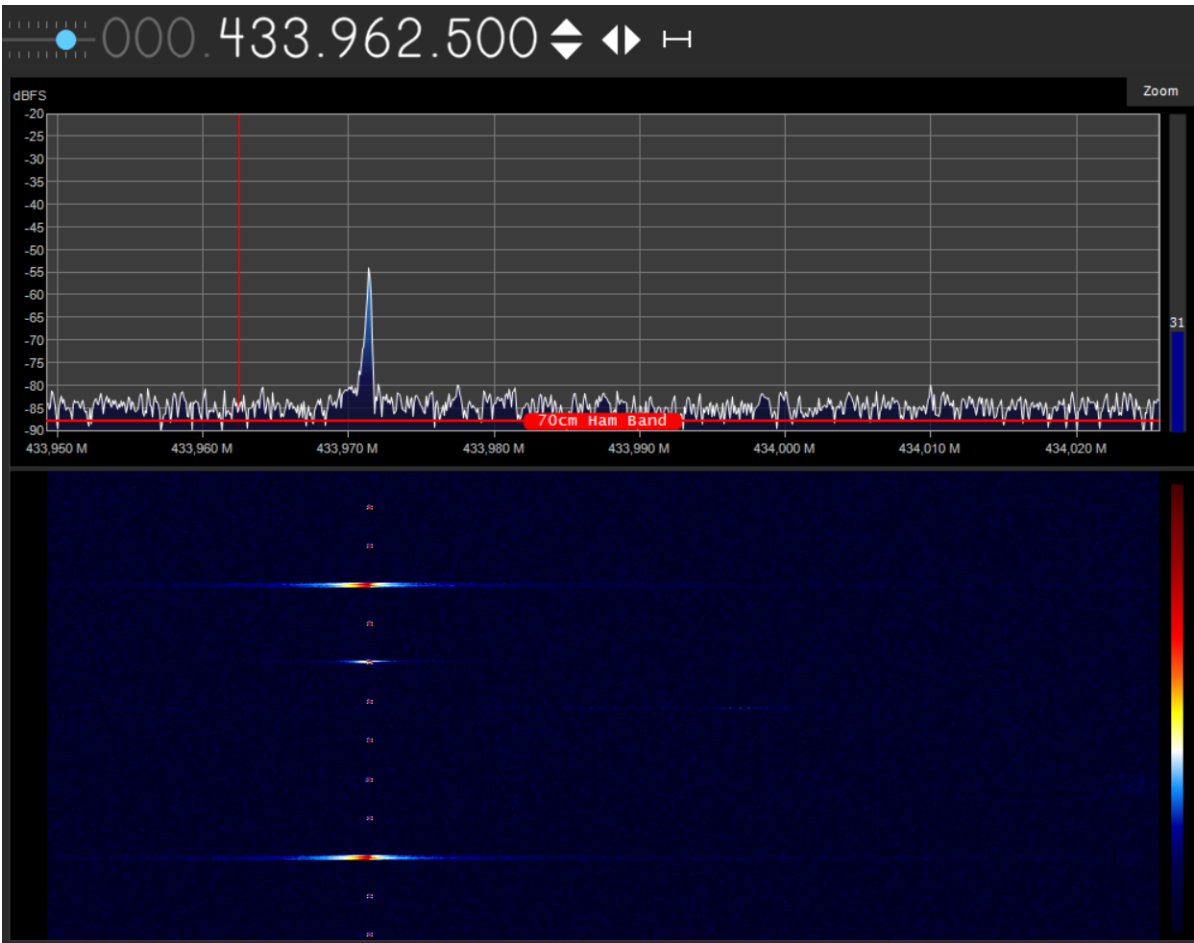


Figure F.2: Transmission with OOK Modulation in Urban Area at 100 meters

F.3. Gold Code Implementation Results

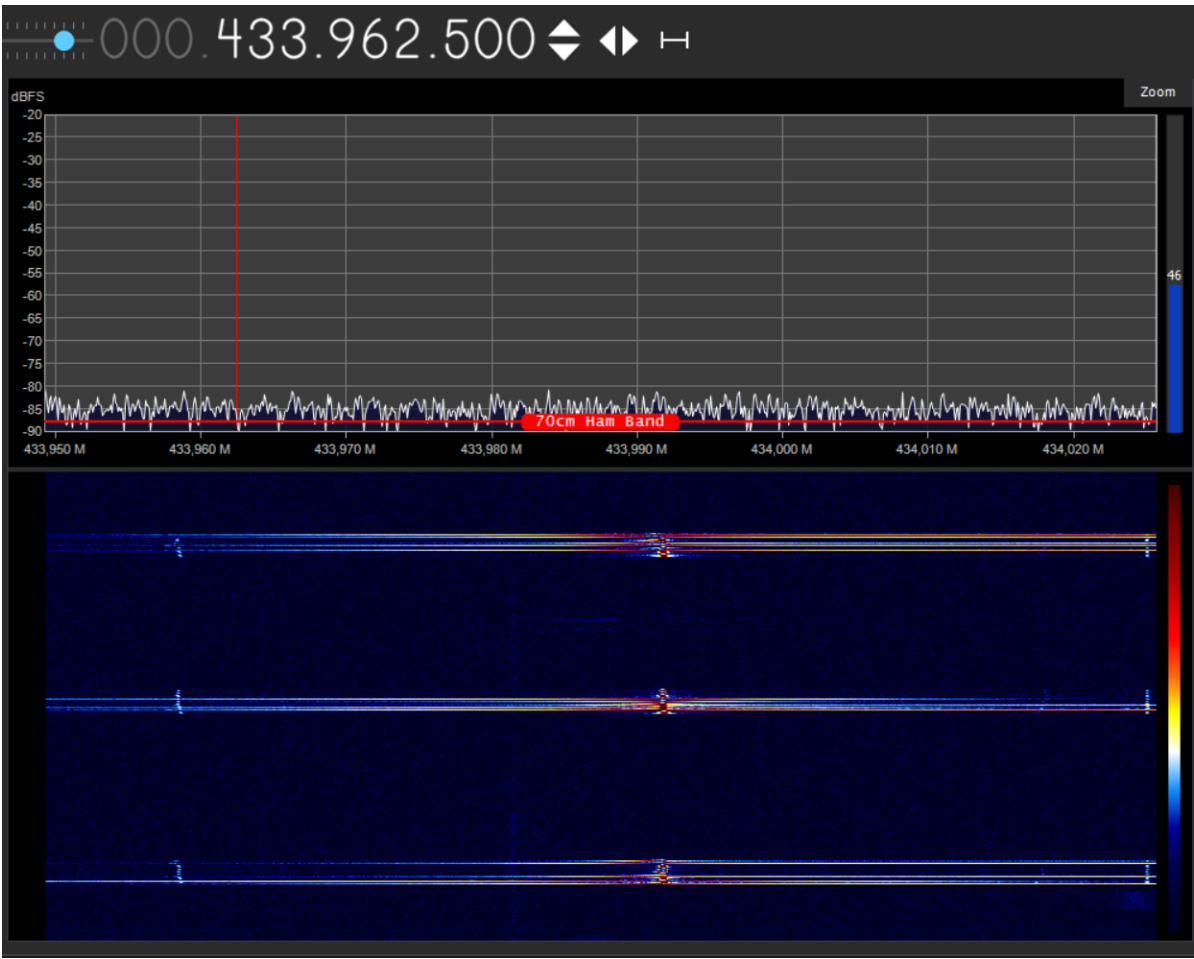


Figure F.3: Transmission using Gold Code Sequence in Near Field

F.4. Signal Strength

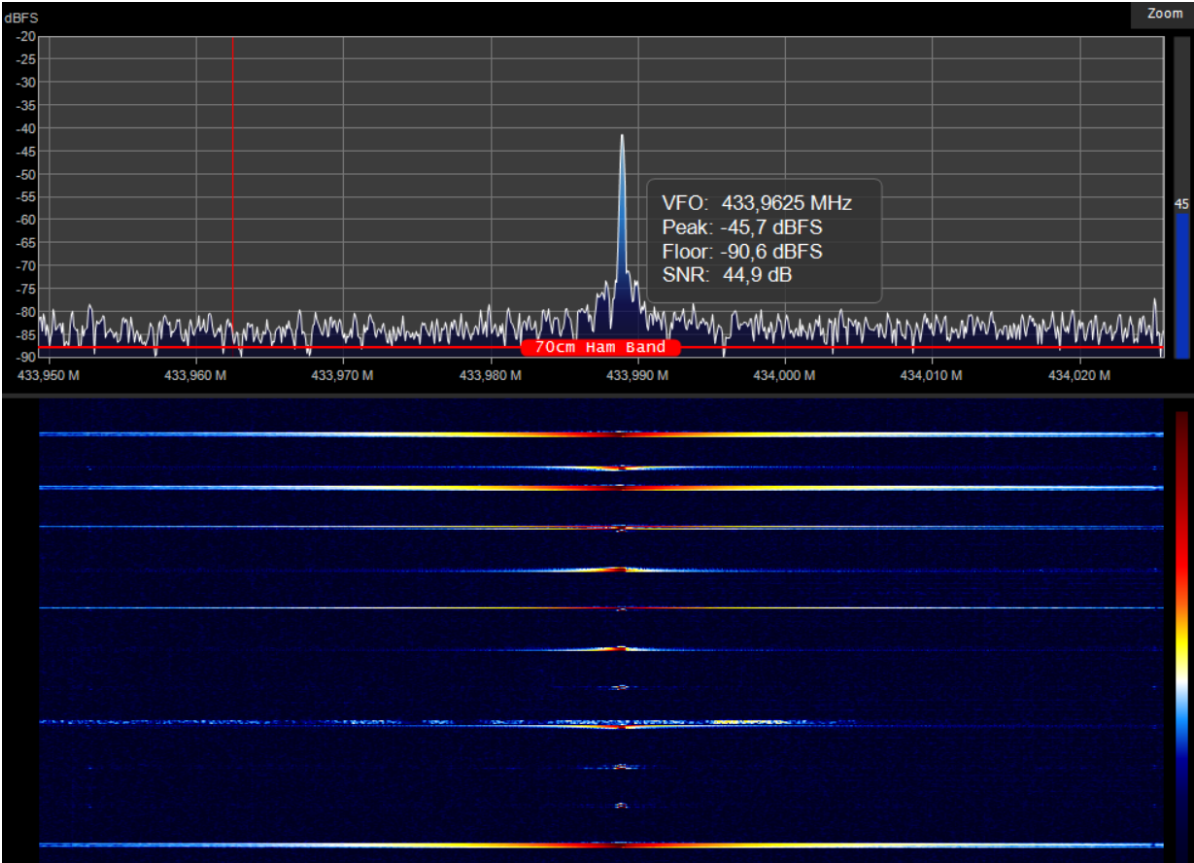


Figure F.4: Signal Strength in Near Field

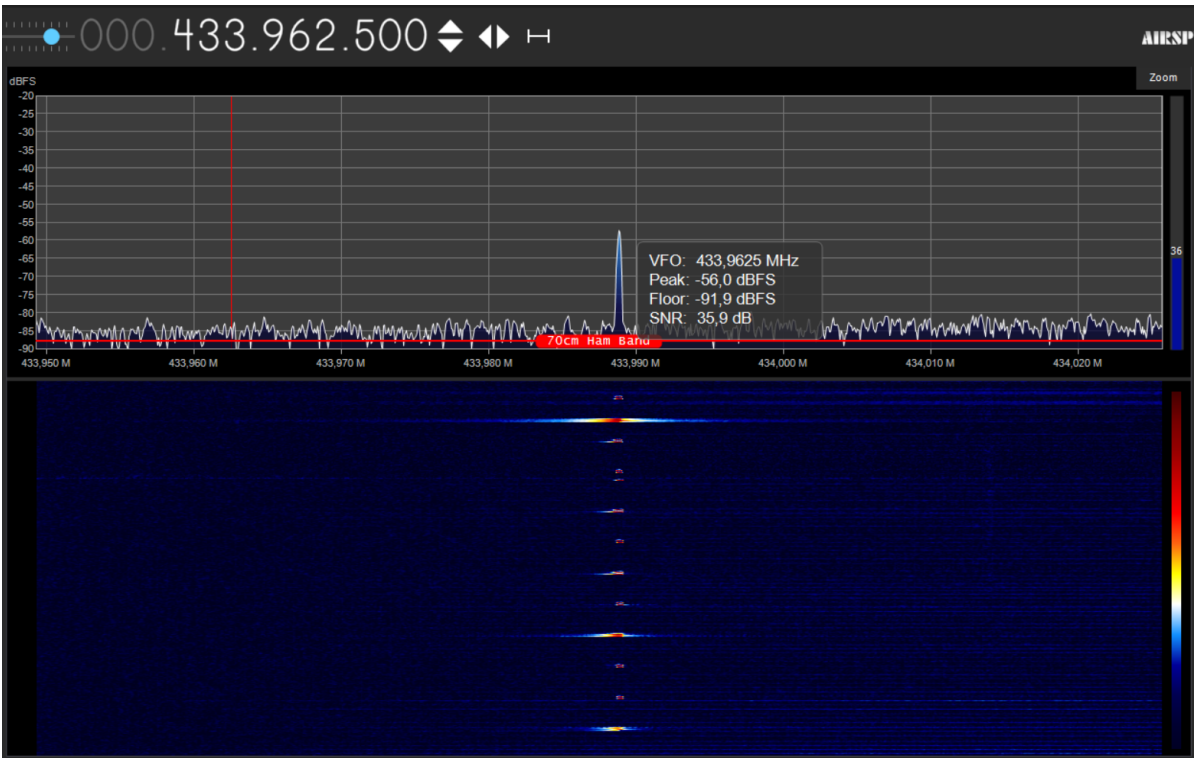


Figure F.5: Signal Strength in Urban Area at 100 meters

G

SAW Resonator-based Design B

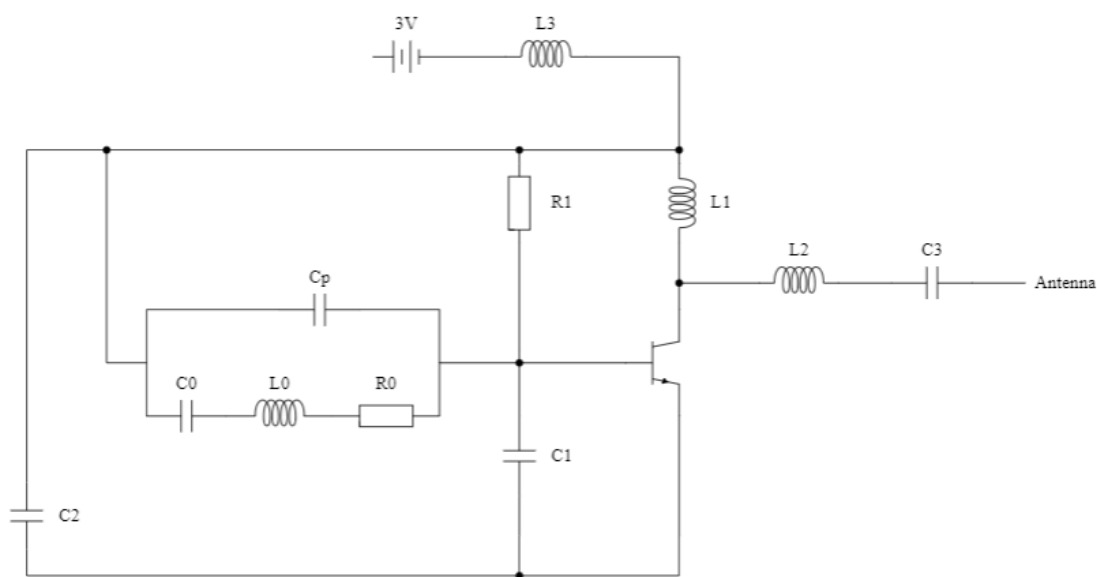


Figure G.1: Design B Schematic

In this appendix the alternative Design B is explained and the differences compared to the Design A are discussed. This design is purposed as a back-up in case the Design A does not function as expected. Most of the working principles of the components and stages are explored in Design A, therefore, these will be briefly revised and the section will focus more on the newly introduced configurations/components. Similarly to Design A, Design B utilizes the same SAW Resonator operating at 433.92MHz. A microcontroller is implemented to employ OOK modulation to encode data to the carrier wave from the SAW resonator. The modulated signal is amplified by a BJT and matching and filtering is performed for a clean and precise output RF signal. While the working principles remain similar, there are significant adjustments to the configuration of the oscillation stabilizer circuit containing the capacitors. The matching and filtering stage is the same as Design A.

G.0.1. Power Supply

When the battery is powering the circuit, unlike Design A, an RF choke is introduced via the inductor L3. It prevents high-frequency signals from feeding back into the power supply essentially decoupling the power supply. This phenomena helps maintaining a stable DC supply and reducing interference.

G.0.2. Oscillation Generation and Modulation

The SAW resonator initiates oscillations at a precise frequency of 433.92 MHz. When power is applied, mechanical waves are set up within the resonator due to the piezoelectric effect that is a characteristic of the utilized material. These mechanical waves are then converted back into electrical signals at the desired frequency. This is deployed by the equivalent LC circuit constructed by the components C_0 , L_0 , R_0 and C_p . A microcontroller connected to the base of the transistor via the resistor R_1 is utilized for digital data transmission which has the same working principles discussed in section 4.2.1. This microcontroller provides a binary on-off pattern encoding digital data into the RF signal by OOK.

G.0.3. Amplification and Feedback

The BJT chosen in section 4.2.11 for Design A is implemented into Design B as well. This transistor amplifies the incoming signal from the base in order to make transmission possible at desired power level for the antenna. The feedback network, involving the inductor L_1 and the capacitor C_1 , ensures a portion of the output signal is fed back to the transistor's input in order to sustain oscillations in which they provide the necessary inductive reactance and phase shift required for maintaining oscillations and compensating for losses. The inductor L_1 is used for aligning the feedback signal with the input signal by providing appropriate phase shift. The capacitor C_1 is used to provide a low-impedance path to ground for high-frequency signals. By doing so the AC signals are bypassed to the ground while a steady DC operating point is ensured.

G.0.4. Biasing and Stability

The resistor R_1 also serves as a biasing resistor for the transistor for it to operate in the active region feeding it the appropriate current which ensures correct amplification of the signal.

The capacitor C_2 acts as a decoupling capacitor for the power supply. It filters out noise and fluctuations at high frequencies that may be present in the power supply. By doing so a cleaner and stable voltage is supplied to the circuit.

G.0.5. Impedance Matching and Signal Coupling

The amplified signal is matched to the antenna impedance and filter through the components L_2 and C_3 maximizing power transfer and minimizing losses while transmitting a precise filtered frequency. This circuit remains the same as Design A with the chosen parameters in section 4.2.10.

H

Prototype Zoomed in Visualization

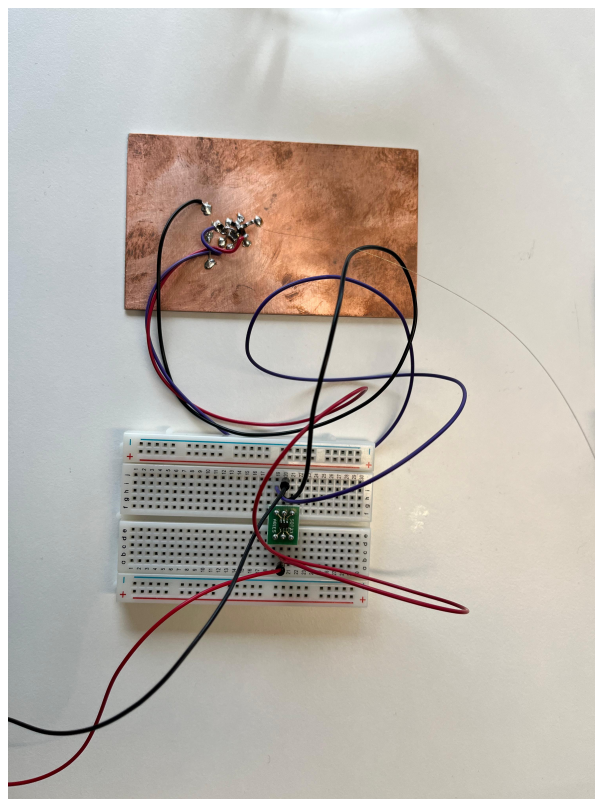


Figure H.1: Design A Prototype for Testing and Measurements



Figure H.2: Design A Prototype Circuit Zoomed in

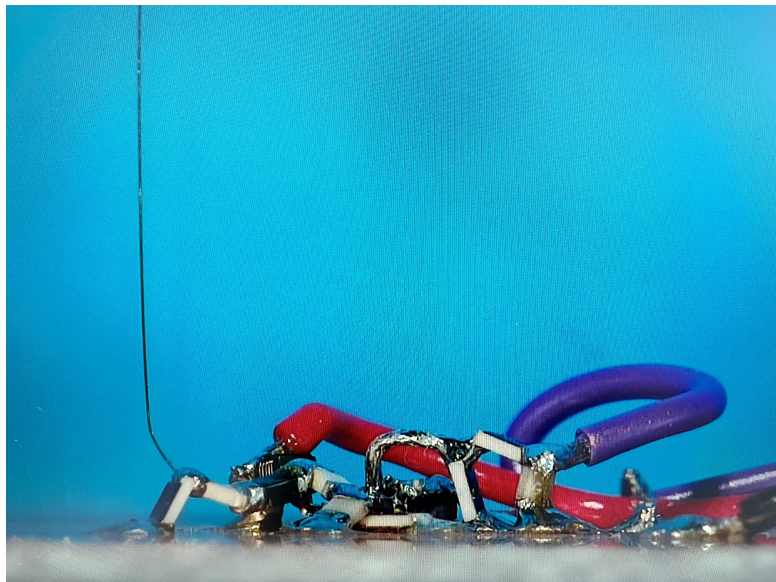


Figure H.3: Design A Prototype Circuit Zoomed in

Bibliography

- [1] S. K, M. S, C. C, *et al.*, “Molecular identification of asian hornet vespa velutina nigrithorax prey from larval gut contents: A promising method to study the diet of an invasive pest,” *Animals*, vol. 13, no. 3, p. 511, 2023. DOI: [10.3390/ani13030511](https://doi.org/10.3390/ani13030511). [Online]. Available: <https://www.mdpi.com/2076-2615/13/3/511>.
- [2] C. Herrera and J. F. Ferragut *et al.*, “Invasion genetics of the yellow-legged hornet vespa velutina in the westernmost mediterranean archipelago,” *Journal of Pest Science*, vol. 97, no. 3, pp. 645–656, 2024. DOI: [10.1007/s10340-023-01680-y](https://doi.org/10.1007/s10340-023-01680-y). [Online]. Available: <https://doi.org/10.1007/s10340-023-01680-y>.
- [3] S. Liou, C. Bergamino, and M. Porporato, “The invasive hornet vespa velutina: Distribution, impacts and management options,” *CABI Reviews*, vol. 2022, no. 17, pp. 1–30, 2022. DOI: [10.1079/cabireviews202217030](https://doi.org/10.1079/cabireviews202217030). [Online]. Available: <https://www.researchgate.net/publication/364412648>.
- [4] K. Tan, S. E. Radloff, J. J. Li, *et al.*, “Bee-hawking by the wasp, vespa velutina, on the honeybees apis cerana and a. mellifera,” *Naturwissenschaften*, vol. 94, no. 6, pp. 469–472, 2007. DOI: [10.1007/s00114-006-0210-2](https://doi.org/10.1007/s00114-006-0210-2). [Online]. Available: <https://doi.org/10.1007/s00114-006-0210-2>.
- [5] F. Requier, Q. Rome, G. Chiron, *et al.*, “Predation of the invasive asian hornet affects foraging activity and survival probability of honey bees in western europe,” *Journal of Pest Science*, vol. 92, no. 2, pp. 567–578, 2019. DOI: [10.1007/s10340-018-1063-0](https://doi.org/10.1007/s10340-018-1063-0). [Online]. Available: <https://doi.org/10.1007/s10340-018-1063-0>.
- [6] C. Vidal, “The asian wasp vespa velutina nigrithorax: Entomological and allergological characteristics,” *Clinical and Experimental Allergy*, vol. 52, no. 4, pp. 489–498, Apr. 2022, Epub 2021 Dec 2. DOI: [10.1111/cea.14063](https://doi.org/10.1111/cea.14063).
- [7] Lotek, *Vhf-avian-tags-for-smaller-species-spec-sheet*. [Online]. Available: <https://www.lotek.com/products/vhf-avian-tags-for-smaller-species/>.
- [8] L. Electronics, *Lowlandtag manual en₂*. [Online]. Available: <https://lowland-electronics.be/>.
- [9] Duracell, *Cr2450ch lithium/manganese dioxide battery datasheet*, https://www.duracell.com/wp-content/uploads/2021/06/CR2450CH_620mAh.pdf, 2020.
- [10] Duracell, *Cr2032ch lithium/manganese dioxide battery datasheet*, https://www.duracell.com/wp-content/uploads/2021/06/CR2032CH_245mAh-CS.pdf, 2020.
- [11] SEIKO, *Ms lithium rechargeable battery datasheet*, <https://www.sii.co.jp/en/me/datasheets/ms-rechargeable/ms412fe-5/>, 2011.
- [12] I. F. Akyildiz and J. M. Jornet, “Electromagnetic wireless nanosensor networks,” *Nano Communication Networks*, vol. 1, no. 1, pp. 3–19, 2010, ISSN: 1878-7789. DOI: <https://doi.org/10.1016/j.nancom.2010.04.001>. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S1878778910000050>.
- [13] European Telecommunications Standards Institute, *Electromagnetic compatibility and Radio spectrum Matters (ERM); Short Range Devices (SRD) operating in the frequency range 25 MHz to 1,000 MHz; Part 1: Technical characteristics and methods of measurement*, ETSI EN 300 220-1 V3.1.1, 2017. [Online]. Available: https://www.etsi.org/deliver/etsi_en/302200_302299/30220801/01.01.02_40/en_30220801v010102o.pdf.
- [14] D. M. Dobkin, *The RF in RFID: UHF RFID in Practice*. Newnes, 2012, pp. 80–155.
- [15] E. H. S. Mikhaylitskaya, “Transmission and reception of an ultra-low power signal,” 2024, Course Information: Bachelor graduation project.

- [16] W. H. P. Horowitz, *The art of electronics*, 3th ed. Cambridge, TAS, Australia: Cambridge University Press, 2015.
- [17] B. Razavi, *RF Microelectronics*. Prentice Hall, 2012, pp. 497–511.
- [18] T. H. Lee, *The Design of CMOS Radio-Frequency Integrated Circuits*. Cambridge University Press, 2004, pp. 86–104, 484–524.
- [19] N. Semiconductors, *Bfu530a npn wideband silicon rf transistor datasheet*, <https://www.nxp.com/docs/en/data-sheet/BFU530A.pdf>, 2014.
- [20] S. N. Songkhla and T. Nakamoto, “Overview of quartz crystal microbalance behavior analysis and measurement,” *Chemosensors*, vol. 9, no. 12, p. 350, 2021. DOI: [10.3390/chemosensors9120350](https://doi.org/10.3390/chemosensors9120350). [Online]. Available: <https://doi.org/10.3390/chemosensors9120350>.
- [21] M. T. Inc., *Micrf114 low-power integrated sub-ghz wireless rf transmitter*, <https://www.microchip.com>, 2015.
- [22] C. Campbell, *Surface Acoustic Wave Devices for Mobile and Wireless Communications*. Academic Press, 1998.
- [23] MDPI, *Special issue “nanomaterials for energy storage and conversion”*, <https://www.mdpi.com/2079-4991/12/12/2109>, 2022.
- [24] K. Lakin, “Thin film resonator technology,” *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 52, no. 5, pp. 707–716, 2005. DOI: [10.1109/TUFFC.2005.1503959](https://doi.org/10.1109/TUFFC.2005.1503959).
- [25] E. AG, *Saw components r900 433.92 mhz resonator datasheet*, <https://www.mouser.com/datasheet/2/400/B39431R900U410-1151610.pdf>, 2004.
- [26] NEDI, *Saw resonator 433.92 mhz e45 datasheet*, <http://www.sc-tech.cn/E45.pdf>, 2018.
- [27] N. Daldal, M. Nour, and K. Polat, “The methods toward improving communication performance in transparent radio frequency signals,” *Mathematical Problems in Engineering*, vol. 2020, pp. 1–8, 2020. DOI: [10.1155/2020/7175864](https://doi.org/10.1155/2020/7175864). [Online]. Available: <https://doi.org/10.1155/2020/7175864>.
- [28] N. Semiconductors, *BFU530A NPN Wideband Silicon RF Transistor*, <https://www.nxp.com/docs/en/data-sheet/BFU530A.pdf>, Accessed: 2024-06-10, Jan. 2014.
- [29] I. Technologies, *BFP640 Silicon RF Transistor*, https://www.infineon.com/dgdl/Infineon-BFP640-DS-v01_00-EN.pdf, Accessed: 2024-06-10, Jun. 2024.
- [30] Atmel, *Atmel 8-bit AVR Microcontroller with 512/1024 Bytes In-System Programmable Flash*, https://ww1.microchip.com/downloads/en/DeviceDoc/8127_125.pdf, Accessed: 2024-05-15, Nov. 2011.
- [31] NXP, *RS08 Microcontrollers: SC9RS08KA1*, <https://nl.mouser.com/datasheet/2/302/SC9RS08KA2-3139600.pdf>, Accessed: 2024-05-16, Sep. 2009.
- [32] R. Gold, “Optimal binary sequences for spread spectrum multiplexing (corresp.),” *IEEE Transactions on Information Theory*, vol. 13, no. 4, pp. 619–621, 1967. DOI: [10.1109/TIT.1967.1054048](https://doi.org/10.1109/TIT.1967.1054048).
- [33] N. de Klerk; Y. Kroeze, “Receiver of the hornet tracking device,” 2024, Course Information: Bachelor graduation project.