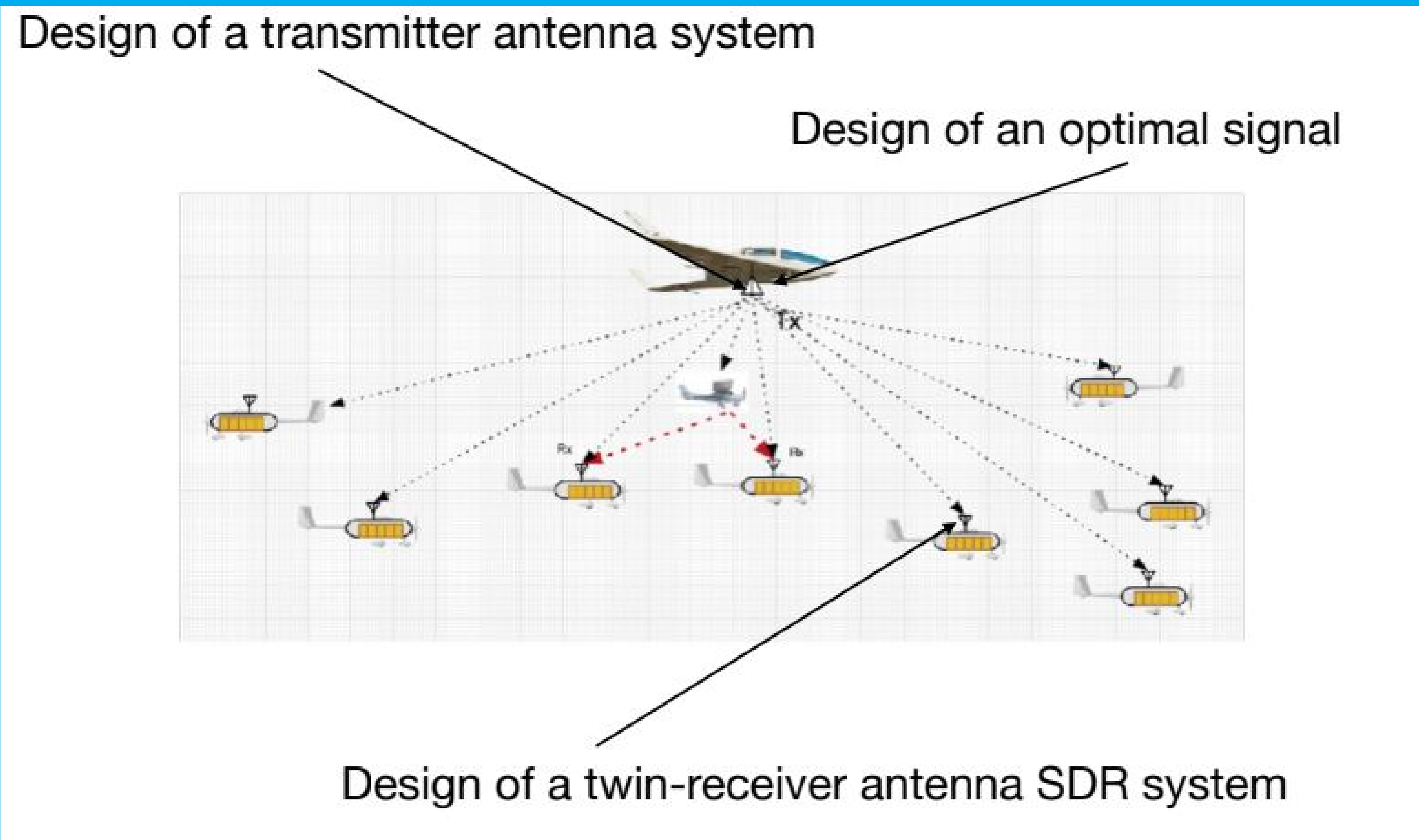
Bachelor Graduation Thesis

Bi-Static Sense and Avoid System for Drones (BiSAD) – The transmitter



TUDelft

Bachelor Graduation Thesis

Bi-Static Sense and Avoid System for Drones (BiSAD)–The transmitter

by

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Preface

This thesis has been written as part of the Bachelor Graduation Project at the TUDelft. The project that is covered in this thesis was created by the companies Selfly NL and Wings for Aid in collaboration with the TUDelft. The project covers designing a bi-static radar system that can be used for drone flying purposes as a 'sense and avoid' system.

We would like to express our gratitude to Dr Faruk Uysal as our main supervisor in creating our design of this system. He has always helped us overcome many design obstacles, that we would not be able to clear without his help. The same goes for Dr Ozan Dogan, he is an expert in this field and came with good feedback on how to improve our system in the final stages.

We would also like to thank Jerome and Ronald for bringing the project to the table and having interesting discussions with us and showing us other points of view on the project from the consumer side.

Finally we would like to thank our project peers; Ossama El Boustani, Mohammed Abo Alainein, Sander Renger and Job van der Kleij. As they have been a great support in creating the system and have been great peers to work with.

Abstract

Wings for Aid is a company which develops an airborne aid-delivery system in emergency-struck areas and wants to use the radar system of Selfly to make an autonomously flying system. The goal of this project is to optimise the current ground-based radar system of Selfly for this application. This is done through the design of a Bi-static radar system, which can be mounted on, and used for drones to detect and avoid other obstacles in the airspace.
This thesis describes the design process and results of a sub-system of the Bi-static Sense and Avoid System for Drones (BiSAD). This a Bi-static radar system, consisting of three sub-systems that together form the base of the radar system. There will be one transmitter drone and several smaller receiver drones which are designed. Also, an optimal waveform is created for this purpose.
The report gives a proof of concept and will focus on a proof of concept for the transmitter chain as well as highlight some total system design choices and results.

Contents

1
Introduction

The companies Selfly NL and Wings for Aid have been trying to develop a solution for the bad accessibility for disaster sites, for example natural disasters often disrupt ground traffic. The solution they have come up with is to use automated drones without human steering to deliver helping supplies to these disaster sites a lot quicker on sites where ground traffic is not possible.

The drones in this scenario have to be equipped with radars to detect and avoid other flying drones but also other obstacles that could hinder their delivery of supplies [1]. The first experiment that the companies tried was to develop a mono-static radar for each drone to sense other drones and also other objects in the airspace. Yet this experiment was not deemed satisfactory because of the physical weight and dimensions that cross the limitations that the radar has on the drones. That is why the companies wanted to look for another solution, which became our project: the Bi-static radar.

Radar is a principle where a transmitter system transmits electromagnetic waves and a receiver system consequently receives these waves. The transmitter and receiver antenna can be the same antenna, but also different antennas at some distance from each other. The travelling waves can bounce off other targets as well. These reflected waves can also be received by the receiver system and when processed, the location of these targets can be determined. The determination of the location of the targets is done through time difference of arrival accompanied by the angle of arrival, these components give us the information necessary to determine the position of the target. The bi-static radar is a radar where the transmitter and receiver systems are separated by a considerable distance and the target range is equal to, or smaller than the range between the transmitter and receiver antenna of the radar, and there could be multiple receivers. This is in contrary to the mono-static radar which has the transmitter and receiver on the same object [2]. In the drones application for this project this means that there will be a 'mother-ship' drone which transmits the signal to a wide range below her and a lot of 'child' drones which will receive the signal and also possible reflections of the signal to determine other objects in the airspace. A visual representation is given in Figure 1.1. In a more technical view, a diagram can be viewed in Figure 1.2. This thesis will contain our design sequence of this bi-static radar system.

1.1. Thesis structure

This thesis will be structured as follows: In Chapter 2, the requirements for the whole system and for the transmitter sub-system will be given. Chapter 3 will consist of some design choices concerning the system as a whole. Chapter 4 will elaborate on some necessary general theory for the design and verification of the design. Chapter 5, will go deeper into the design of the transmitter chain. In Chapter 6, a selection of real components for the transmitter chain will be discussed and component choices are made. Chapter 7 shows the resulting transmitting system as well as the total system and Chapter 8 concludes on and discusses these results along with some points of improvement for future work. The Appendix will include a list of hardware data sheets and some Matlab code created and used in the project.

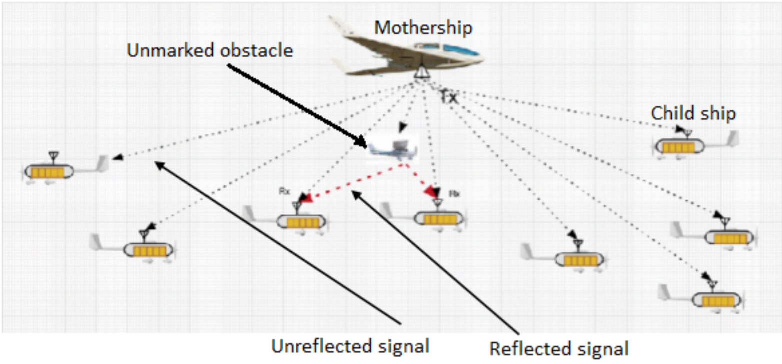


Figure 1.1: Visualisation of the bi-static radar in combination with drones.

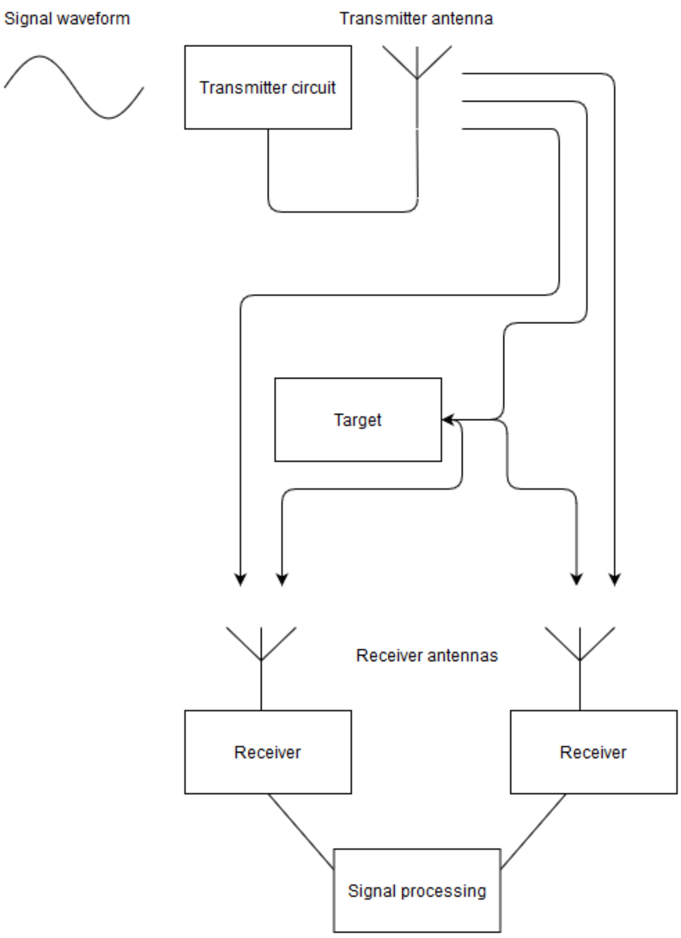


Figure 1.2: Diagram of the bi-static radar

2
Program of Requirements

2.1. General Requirements

The Bi-Static Sense and Avoid System for Drones (BiSAD) includes a transmitter and receiver chain, and radar waveform or signal design. BiSAD is not merely composed of the three mentioned parts, the entire system includes a compunction link between drones and the mother-ship and software that implements localisation of the drones and the targets detected by the bi-static radar. The scope of the project is limited to the design of the transmitter and receiver chain and the radar waveform. The general requirements address these three parts of the Bi-Static Sense and Avoid System for Drones.

2.2. Assumptions

The scope of the project is limited to the design of the transmitter and receiver chain and the radar waveform. To simplify the project and ensure feasibility, especially during the COVID-19 pandemic, it is assumed that the project owner Selfly EDA already has the software packages necessary to implement positioning of the mother-ship and drones using GPS and localising the targets on a Plan position Indicator (PPI) and visualising the targets on a map.

2.3. Mandatory Requirements

The mandatory requirements specify the requirements that ought to be complied with at all times. These are subdivided into two categories, functional requirements and non-functional requirements. The functional requirements describe what the system/product does, and non-functional requirements describe attributes the system/product has got to have.

1. Non-functional Requirements
    - The receiver must have reception of the direct-path from the transmitter up to 50 km.
    - The receiver must have reception of echoes reflected from target within a radius of up to 5 km to the receiver.
    - The position of the reflection must be determined within 300 m accuracy.
    - The system should transmit frequencies which are freely available for use determined by Agentschap Telecom.
    - The transmitter and receiver should be built with commercial of the shelf (COTS) equipment.
    - The transmitter should use at most 3 kW of power.
    - The transmitter should weigh at most 20 kg.
    - The transmitter and receivers should use Software Defined Radio. An SDR is a radio communication device which has the typical RF hardware implemented in software.
2. Functional Requirements
    - The system should detect objects with a bistatic radar target cross section $\sigma \geq 1\text{m}^2$

- The system should determine the Direction of Arrival (DoA).
- The system should determine the distance between receiver and targets.

This project will aim to give a proof of concept for the intended actual system. This means that all of the above requirements are the requirements of the intended system. For this report, the requirements related to ranges are being ignored and a short range proof of concept is given. The feasible ranges with this proof of concept will then be analysed.

2.4. Transmitter Design Requirements

As seen in Section 2.3 there are specific attributes that are directly connected to the transmitter. Some requirements are connected in a non-direct manner and should therefore be translated to a transmitter design requirement. The following requirements can be connected to components of the transmitter:

- The maximum ranges between transmitter and receiver are linked to the Gain (G_t), Power (P_t) and losses (L_t) of the transmitter system.
- The requirements of Agentschap Telecom is connected to the Power and center frequency of the sent signal. It gives us certain ranges at which we can transmit and the maximum of power that we may send.
- The transmitter should be built with commercial of the shelf (COTS) equipment, which means that we can not assume that the best and ideal components can be used. They should be available on the market already.
- Ideally the full transmitter chain should cost around € 20k.

Finally the transmitter should be designed with the following ideals in mind: Low cost, low weight, small volume and power efficient.

2.5. Simulations

Because of the Covid-19 measures, it is not possible to build an actual proof of concept by ourselves. Instead, only simulations can be done. To check the gains, losses and power of the final transmitter circuit, all components will be modeled into Matlab. These can be connected giving the total transmitter system parameters. For the total system, the transmitter chain must be connected with the receiver system and the signal waveform. Together, a simulation of transmitting and receiving in free space is made. This is done in GNU radio, which provides a toolkit for simulating software defined radios and RF hardware. Conclusions will be based on these simulations.

3
System Design Choices

Before the bi-static radar could be designed some things should be determined on the hand of specifications of the system. These specifications are of great importance for the overall design of the system and that is why they are handled outside of the transmitter design. The specifications that are of great importance are the frequency band in which the bi-static radar will send its signal. Thereby, the center frequency of the transmitted signal also concerns the complete system. A third important specification is the bandwidth of the signal, because the system needs to be build around this bandwidth. The final important thing to realize is that our preference may be in a certain bandwidth, but that could make finding a low cost SDR impossible so maybe for both the transmitter and the receiver an up- and down-conversion stage has to be made.

3.1. Frequency band

The choice of frequency band is the first obstacle to tackle when trying to design a radar. There are requirements from the Agentschap Telecom in which frequencies you can send out signals and the thereby necessary licenses needed to send in these bandwidths. Taken into account the open frequencies and the licenses that TUDelft has in its repository we narrowed the choice of possible frequency bands to the S-band and the X-band. The S-band contains the frequencies between 2-4 GHz and the X-band contains the frequencies between 8-12 GHz. The frequency difference translates to the S-band having a larger wavelength than the X-band. Because of the smaller wavelength in the X-band the radars in this frequency range have a better range resolution than radars in the S-band. [3] Range resolution means the ability of the radar to make a good distinction between targets in very close range or bearing, which would increase the accuracy of the system. The S-band radars do have a better resistance against weather influence and a larger maximum range than the X-band radars because of the longer wavelength. The final thing to worry about when choosing frequency bands is related to the spacing on the receiver drones. The receiver group wants to have multiple antennas on the receiver drones which are spaced half a wavelength away from each other. X-band frequencies are roughly four times higher than S-band frequencies, meaning that the wavelength for X-band is roughly four times smaller than for S-band. This is the main reason why in the end the choice was made to make our radar system in the X-band. The receiver system has to use two antennas in vertical orientation even though they already have a small space to work with.

3.2. Center Frequency

Since the center frequency is an important parameter in the complete system, all the design components had a say in which frequency it should become. The center frequency is determined by the input in connection with the antenna of the transmitter. In the Component Discussion Section 6.10 the antennas are elaborated on. Two different antennas are discussed and because of the difference in antennas the center frequency has been chosen as either 9.7 GHz for the slotted waveguide antenna and 9.4 GHz for the patch array antenna. This frequency has to be accounted for when choosing the receiver antenna and has been done so accordingly.

3.3. Waveform Transmission

The waveform that will be used is designed by the Signal Design sub-group of the project. The result of this design is an LFM waveform, this waveform is not transmitted continuously but with pulses. The pulse width is 0.2 µs. The pulse repetition interval time is 1 ms. This is something to account for when choosing a platform because the rotational speed of the platform must take this into account.

3.4. Bandwidth of the signal

The bandwidth of the signal is one of the most important parameters of the signal, because no component of any design may interfere with the bandwidth of the signal or the signal could become heavily distorted. Since the signal was designed by the Signal Design group, with a say from the other groups of course, the bandwidth was chosen to be 20 MHz, also because this was the maximum that the chosen SDR could handle, this will be discussed later on. The bandwidth was also chosen to be this value because it gave a good trade-off between accuracy, performance and distortion. The bandwidth of the signal has a heavy impact on the choice of filters and the power amplification, since the bandwidth of both components should not interfere with the bandwidth of the signal.

3.5. Up- and down-conversion

Since the chosen frequency band was the X-band, we had to find an SDR that was in an acceptable price range in the X-band. Unfortunately we were not able to find a sufficiently good SDR within the price range and therefore had to settle with the following consequence, an up- and down-conversion of the signal. This means that the SDR could be chosen in a lower frequency band which gave more results within the price range for the desired performance specifications. This however meant that the signal generated by the SDR was not in the desired frequency that the signal was supposed to be sent it in. Therefore at the transmitter side, an up-conversion stage had to be implemented and at the receiver side a down-conversion stage had to be implemented. This was however not a drastic hard impact on the overall design because the up- and down-conversion could be done with a frequency mixer and with the SDR having multiple inputs and outputs, the local oscillator signal for the mixer could be formed by one of the remaining SDR ports. More on this later.

4

Radar Mathematics

4.1. Radar Equation

[2] [4] To see whether our transmitter design is valid and can reach the requirements there are some equations that can help us calculate if our system will reach the requirements. For this we have the following illustration. Figure 4.1 shows the bi-static radar system. L, Rr, Rt are the distances between the mother-ship, receiver and target. β is the bi-static angle and θ_r is the Angle Of Arrival (AOA) of the target relative to the receiver antenna.

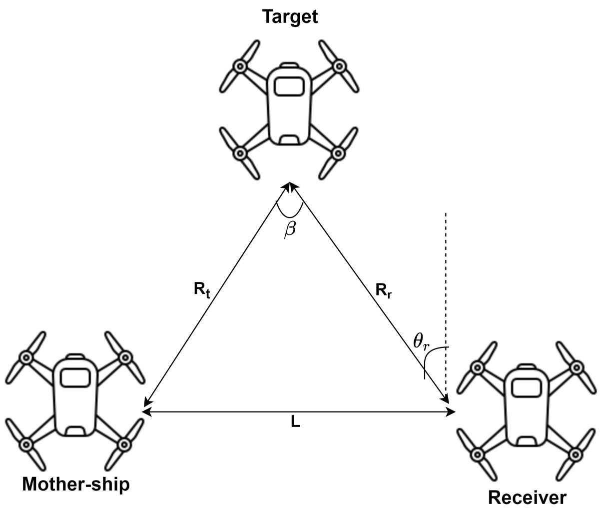


Figure 4.1: Bi-static radar configuration.

The received power due to the direct line of sight pulse can be written according to Friis equation [2] [4] [5] as:

$$P_{rd} = P_t G_t G_r L_s \left(\frac{\lambda}{4\pi L}\right)^2 \qquad \text{(W)} \tag{4.1}$$

- P_t is the transmitter power (W) (before the antenna)
- G_t is the gain of the transmitter antenna(W)
- G_r is the gain of the receiver antenna(W)
- L_s are the losses of the system (W)
- λ the wavelength of the signal (m)
- L the baseline between the transmitter and the receiver (m)

The received power due to the reflected pulses from the target is given by the radar equation as [2][4]:

$$P_r = \frac{P_t G_t G_r L_s \lambda^2 \sigma_t}{(4\pi)^3 R_t^2 R_r^2} \qquad \text{(W)} \tag{4.2}$$

- R_t the range between the transmitter and the target (m)
- R_r the range between the receiver and the target (m)
- σ_t the radar cross section (m^2)
- Other variables are previously declared

G_p is the processing gain due to pulse compression and matched filtering. G_p is given as:

$$G_p = B\tau \tag{4.3}$$

Where B is the bandwidth of the waveform and τ is the pulse duration. L_s accounts for the system losses in both transmitter and receiver chains. Note that $L_s < 1$.
P_t is the peak transmit power at the output of the antenna without losses. The peak power is related to the average power as:

$$P_{avg} = P_t \frac{\tau}{PRI} \qquad \text{(W)} \tag{4.4}$$

Where PRI is the pulse repetition interval of the radar waveform.
The detection process is based on the echo from a single pulse. We can detect a target as long as the received power P_r is above a certain threshold of the noise power P_n at the receiver. The noise power is given by:

$$P_n = k_b T_0 B F \tag{4.5}$$

Where k_b is Boltzmann's constant, $k_b = 1.38 \times 10^{-23} J.K^{-1}$. $T_0 = 290K$ is the ambient temperature. B is the receiver bandwidth. F is the noise factor ($F > 1$).The noise figure NF is the noise factor but given in dB $NF = 10log(F)$. The noise figure/factor must account for all noise added in the receiver chain (SDR, PA, BPF, etc).
We can write the radar equation given in Equation 4.2 in terms of signal to noise ratio $SNR = P_r/P_n$. This results into:

$$SNR = \frac{P_t G_t G_r L_s \lambda^2 \sigma_t}{(4\pi)^3 R_t^2 R_r^2 k_b T_0 B F} G_p \tag{4.6}$$

For a minimum SNR we can define a maximum detectable range product and rewrite Equation 4.7 as:

$$(R_t R_r)_{max} = \left(\frac{P_t G_t G_r L_s \lambda^2 \sigma_t}{(4\pi)^3 k_b T_0 B F (SNR)_{min}} G_p \right)^{\frac{1}{2}} \tag{4.7}$$

4.2. Ovals of Cassini

[2][4] A Cassini Oval is defined as a curve such that for any point on the curve the product of two distances to two fixed points is constant. Applying this to the geometry shown in Figure 4.1, we can construct curves as a function of SNR where $R_t \times R_r$ is constant for a fixed length L. In polar form, a Cassini oval equation is given as:

$$r^4 - 2a^2 r^2 cos(2\theta) = b^4 - a^4 \tag{4.8}$$

Equation 4.6 can be rewritten as:

$$R_t^2 R_r^2 = \frac{P_t G_t G_r G_p L_s \lambda^2 \sigma_t}{(4\pi)^3 k_b T_0 B F} \frac{1}{SNR} \tag{4.9}$$

If we consider the first fraction to be constant K, we can plot the $R_t^2 R_r^2$ as a function of SNR:

$$R_t^2 R_r^2 = \frac{K}{SNR} \tag{4.10}$$

By writing R_t and R_r in polar form, we conclude that the SNR contours are defined by ovals of Cassini with:

$$a = \frac{L}{2}$$
$$b = \left(\frac{K}{SNR}\right)^{\frac{1}{4}} \tag{4.11}$$

4.3. Link budget

[5] In the Radar Range Equation and Ovals of Cassini equation the parameters; transmit power P_t, G_t and L_s are directly involved with the transmitter design. In our design these three parameters need to be optimised. The antenna gain can directly be used from the data sheet of the chosen antenna, yet the power is a product of the complete transmitter chain behind the antenna. To calculate this power it is good to make a link budget of the transmitter chain.

A link budget accounts for all gains and losses of power in the system that the communication signal experiences. A simple link budget can be seen below where P_i is the input power of the chain:

$$P_t = P_i + \sum Gains - \sum Losses \tag{4.12}$$

While doing a link budget analysis, it is also possible to analyse the noise of the whole system. This can be done by looking at the noise factor F, the noise figure NF and the signal to noise ratio SNR. It is desirable to have an as high as possible SNR as this means that the signal is clearer and thus easier to distinguish. To calculate this for the system and look at the contribution of every component, the noise factor or noise figure, which is just the noise factor in dB as stated earlier, can be used. The noise factor is a measure of the deterioration of the SNR and is defined as follows:

$$F = \frac{SNR_{in}}{SNR_{out}} \tag{4.13}$$

Given the noise factor each individual component, the noise factor of the cascaded system can then be calculated using Friis formula for noise. For most active components the noise figure is given. For passive components the noise figure equals the attenuation, insertion loss, or conversion loss of the component. It is possible to convert the noise factor immediately in dB giving the noise figure as is shown in Equation 4.14.

$$NF_{total} = 10\log_{10}(F_1 + \sum_{i=2}^{M} \frac{F_i - 1}{\prod_{j=1}^{i-1} G_j}) \tag{4.14}$$

Here F_i is the noise factor of the i'th component and G_i the gain in W of the ith component. The result will be the total noise factor in dB. When looking at the whole system including the receiver system and signal path to the receiver, the most noise induced will be during the free space propagation of the signal. Other than the little noise the components introduce, there will not be much noise in the transmitter chain itself. This is why noise analysis will not be one of the primary objectives for the transmitter chain analysis. The primary goal of the transmitter is to amplify the signal as much as possible, not to reduce the noise.

4.4. Frequency harmonics and intermodulation

[5][6] A signal can be described by a sinusoidal wave with a certain amplitude, frequency and phase as $Asin(\omega t + \phi)$. Because the designed circuit has different components, of which some are nonlinear, the output signal from these components can exhibit some undesired behaviour. If a single signal enters a nonlinear component, higher harmonics could appear at the output. This means the output signal has different, higher frequency components other than the desired frequency. The output can be related to the input through a Taylor series of the input, $v_{in} = A_0 sin(2\pi f_0 t + \phi_0)$, giving

$$v_{out} = K_0 + K_1 v_{in} + K_2 v_{in}^2 + K_3 v_{in}^3 + ... \tag{4.15}$$

The higher order sines can be rewritten giving sines with frequency components of f_0, $2f_0$, $3f_0$, ... = nf_0, with n positive integer values.

If there are multiple input signals with different frequencies, a nonlinear device can create new frequencies by modulating the two input signals. The Taylor series thus gives not only multiples of the two input signal frequencies f_1 and f_2, but also sums and differences of f_1 and f_2 resulting in

$$f_{out} = n * f_1 + m * f_2 \tag{4.16}$$

Where n and m are integers and can be positive or negative, but the resulting f_{out} can not be negative. The produced frequencies can be ordered by intermodulation, which is the sum of the absolute values of the coefficients. So for 3rd order intermodulation, the frequencies are given by filling in n = ± 1 and m± 2, but also n = ± 2 and m = ± 1 in Equation 4.16.

5
Chain Analysis

5.1. Simple transmitter

A very simple transmitter chain could consist of the following components: A signal generator, a power amplifier, a filter and then the antenna. An illustration is given in Figure 5.1.

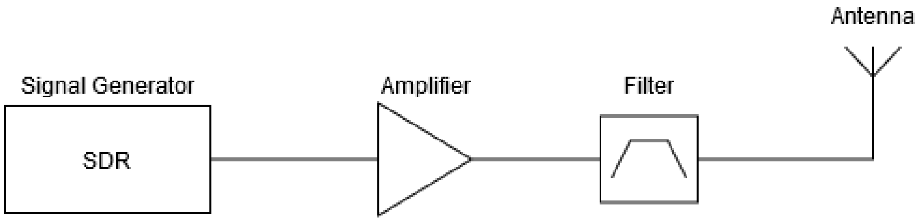


Figure 5.1: Simple transmitter design.

The problem with this design is that in our case it is not possible to design it in just such a simple manner, because our antenna will be on a rotating platform to send the signal in all 360 ° direction. Some solutions for this rotating platform are either a rotary waveguide or a slipring. The location of this rotary part will also determine whether the amplification or filtering has to be done with components connected by coax or waveguide.

5.2. Antenna

For the antenna a high, directional gain is desired. The antenna will be rotating to be able to transmit a signal all around the transmitter drone. For the location calculations of the receiver systems, it is best to have a narrow horizontal beam and a broad vertical beam. A narrow horizontal, from now on called azimuth beamwidth, will ensure that the receivers do not get a signal for an extended period of time. This gives a better performance, because the bigger the azimuth beamwidth, the longer the receiver is receiving a signal which makes it harder to calculate where the transmitted signal is exactly coming from. On the other hand, the vertical beamwidth, from now on the elevation beamwidth, is desired to be larger. This way, drones have more space in how high they can fly.

Also, antennas always have a certain antenna pattern, meaning they don't just transmit in one given direction, but in a range where there is a main lobe of gain and multiple smaller side lobes next to the main. Because the antenna is being rotated all the time during operation, the side lobes could be received as well if these are too high. Because of this, it is desirable to have low side lobes. If the antenna pattern, or at least the maximum side lobe level is known, the effects can be simulated to check whether they will interfere or not.

5.3. Coax versus Waveguide

[7] [8] The various components of the transmitter chain need to be connected by means of transmission lines. Transmission lines are devices, which are able to guide electromagnetic waves. Two very popular types of transmission lines are coaxial cables and rectangular waveguides. Waveguides have a lot less attenuation in

its transmission lines, when compared to coaxial cables. Waveguides however, are also very expensive and hard to implement in small spaces, because of their innate sizes that can not be altered because that would affect the sent signal. An important part in our decision between coax or waveguides, is that it is preferred to have the main amplifier and filter after the slipring/rotary waveguide [9][10]. Because amplification and filtering still needs to be done after the rotary part it is preferable to not convert to waveguide connections back to coaxial connections and thereafter again to waveguide connections to send the signal to the antenna. This is why the choice was made to make the transmitter chain using coaxial cables, considering the costs and difficulty of implementation in thight spaces, the using a slipring as rotary part, and possibly at the very end of the chain convert to waveguide depending on whether the used antenna has a coaxial or waveguide input port. This also makes it easier to choose a gimbal as a rotational device to turn the antenna.

5.4. Impedance matching

[5][7][11][12] One of the most important aspects of the transmitter chain, is to guide power to the antenna as efficiently as possible. As the signal is an electromagnetic wave, which travels through the components, some portion of the travelling wave may be reflected off each next component. This means that not all energy will travel on as is desired, resulting in a lower power at the end of the chain. This phenomenon can be characterised by the reflection coefficient, which gives an indication of how much power of the incoming wave will be reflected. Higher values indicate that more power will be reflected with a reflection coefficient of 1 indicating full reflection. A reflection coefficient of 0 on the other hand, indicates that none of the wave power will be reflected. The reflection coefficient is defined as follows:

$$\Gamma = \frac{Z_l - Z_o}{Z_l + Z_o} \tag{5.1}$$

where Z_l is the load in some equivalent circuit and Z_o is the characteristic impedance of some component. This can be applied to Figure 5.2, which contains a source, a load and a transmission line, which is modelled by its characteristic impedance. According to Equation 5.1, the reflection coefficient will be 0, if the characteristic impedance Z_o equals the load impedance Z_l. Because of this, it is easiest to match all the components and coaxial cables to one fixed value, for the best power efficiency. In the case of an component with a different impedance, a different coax cable will have to be chosen, or a matching will have to be designed to match the impedances again. In practice however, most components will have an impedance of 50 Ω, which makes it easy to match all the components as there is no need for a matching circuit. Caution is still advised nevertheless, as there are still many components with a different impedance.

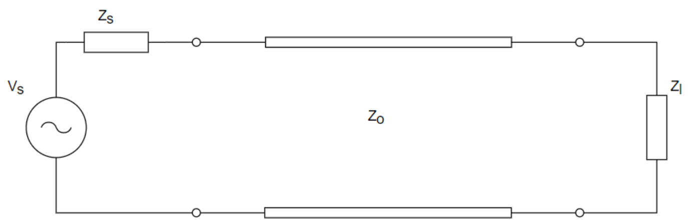


Figure 5.2: Simple transmission line.

5.5. Up-conversion

Another addition to the transmitter design is an up-converter component, because the SDR does not operate in the desired frequency, this means that an up-conversion stage has to be inserted into our transmitter chain. Since the SDR, explained in Section 6.1, has two output ports and its output frequency ranges up to 6 GHz it is possible to design an up-converter that uses both the SDR outputs as both the IF and the LO of a mixer. This means that no separate local oscillator is necessary, saving some space and cost. This does however need the IF and the LO frequency with a sum of exactly the desired center frequency of either 9.7 GHz or 9.4 GHz to their respective used antennas. Also, as explained in Section 4.4, intermodulation will occur because there are multiple input frequencies here. When choosing IF and LO frequencies it is better to choose frequencies which lie not too close to each other. Otherwise the IMD products could lie very close to the actual desired output signal frequency.

5.5.1. Mixer input power

[13] When trying to design an up-converter stage with a mixer, the power of the inputs of the mixer should be looked at. Because of the different inputs and imperfect isolation of the inputs and nonideal circuitry, intermodulation is caused within the mixer circuit. This intermodulation however, can be minimised. Mixers contain diodes, which provide the desired frequency mixing behaviour by switching on and off. When the diodes are fed and turned on and off from one signal only, with just the LO signal for example, the diodes will switch properly. However, if the IF signal is in the same order of magnitude as the LO signal, the diodes might switch due to the IF signal as well, causing undesired frequencies to appear. This can be greatly reduced by making the IF signal significantly smaller than the LO signal and so small that it does not have enough power to switch the diodes effectively.

5.5.2. Attenuator and Driver amplifier

Because of the mixer input requirements, an attenuator has to be put in between the SDR and the mixer to create a desired input power of the IF input for the mixer. Because of this attenuation of the signal before the mixer, a lot of signal power will be lost, meaning that the amplifier after the mixer will probably have to be very bulky and costly, because it needs a lot of gain. To counter this adjustment of a bulky amplifier, a solution is to use a driver amplifier before the main amplifier to compensate for the attenuation before the mixer.

5.6. Mixer and amplifier nonlinearity

[13][14] Nonlinearity in devices means, that the output of the device will not be proportional to the input of the device. Mixers and amplifiers have a certain conversion loss, or a certain gain. However, they are active, weakly nonlinear devices, meaning these values will only be true for their linear region. The linear region is where the output of the device is proportional to the input. After a certain amount of power flows into the device, the component starts to slowly saturate, the more power enters at the input. This can be seen in Figure 5.3. This could be an input vs output power plot for an amplifier where the striped line indicates the ideal linear gain and the continuous line mimics a real gain. One way to indicate where the linearity of the component starts to degrade, is through the 1dB compression point, P1dB. The P1dB point, is where the actual gain is 1 dB lower, than the desired ideal gain. If the device keeps being fed more power, the gain will keep decreasing and finally saturate, meaning no more gain can be achieved. For the best linear performance of the device, the power should be kept way below the saturated power point and also well below the P1dB. This way, the undesired nonlinear behaviour, as described in Section 4.4, will be as limited as possible.

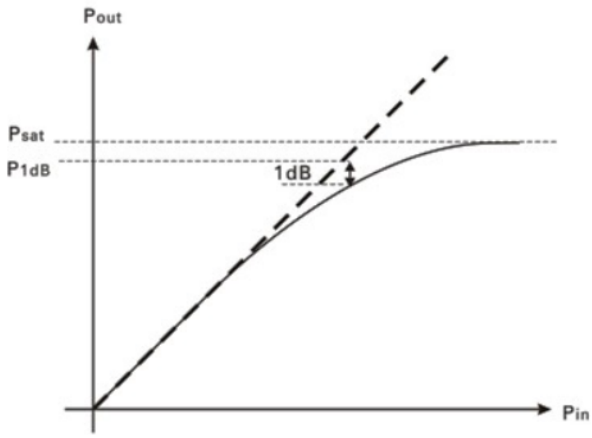


Figure 5.3: Power saturation of weakly nonlinear device.

5.7. IF Filter

The inserted up-converter could insert harmonics into the spectrum meaning that it could also up-convert noise and other harmonics that could be coming from the SDR, which we unfortunately can not check, and create images of this as well. Therefore a filter could be inserted to filter out the harmonics coming from the

SDR, the harmonics can not be determined in a good fashion because we can not measure the output of the SDR and the SDR consists of different parts including mixers and other parts that introduce harmonics. This is why it is necessary to insert an filter between the SDR and the mixer. This filter will filter out harmonics that could interfere with the up-conversion and could lead to even worse harmonics after the up-conversion. This filter will also filter out the DC leakage that the SDR might have, which we also unfortunately cannot check.

5.8. LO Filter

Since the SDR is also used as the LO of the mixer it can also have harmonics in its signal, this could heavily interfere with the output of the mixer creating a lot more images than if the signal is a clean LO drive signal. Just as for the IF filter the harmonics of the SDR are not known and not obtainable as of this moment and therefore should be taken care of by filtering the filter before sending it to the mixer. This is why the filter will be designed to have close cutoff frequency compared to the desired frequency even though in reality there might be more leeway in the design of this filter.

5.9. RF Filter and RF amplifier order

[15] The order of the last RF filter and RF amplifier does impact the performance of the system. Placing the filter before the power amplifier will reduce distortion from non-linearity and filter out the images from the mixer that pass through the driver amplifier. Placing the filter after the power amplifier will reduce the noise figure and improve the signal to noise ratio (SNR), because the noise of the filter will not be amplified. Another implication to worry about is that placing the filter after the amplifier could let the power of the signal go beyond the threshhold of the filter and create distortion. However in the component discussion next chapter it is concluded that this is not the case. When the filter is placed after the amplifier the filter will also filter out harmonics that can be introduced by the amplifier itself. So it was decided through discussion that the filter after the amplifier would be the best case.

5.10. Final chain design

After all the alterations to the simple transmitter design, the design in our case looks as shown in Figure 5.4. This transmitter chain design accounts for all the restrictions and possibilities by our design choices.

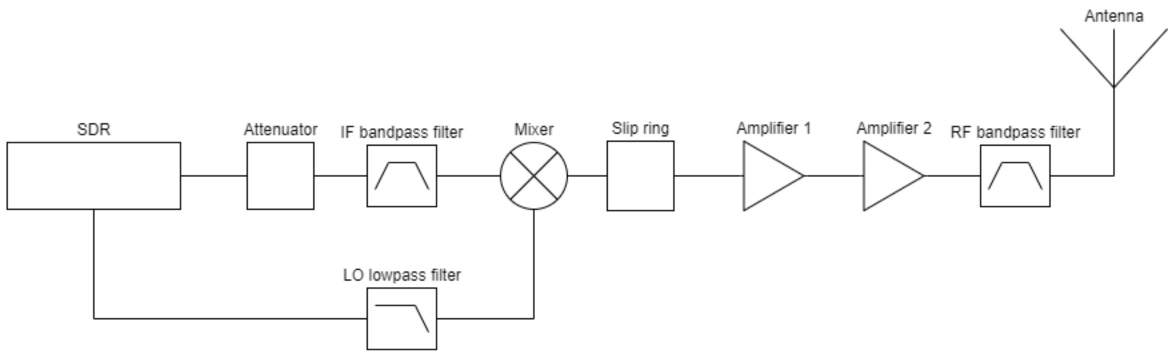


Figure 5.4: Simple transmitter design.

6
Component Discussion

6.1. SDR

The selection of the SDR on the transmitter side was not part of the transmitter chain design but rather of the signal design group. The signal design chooses the SDR based on their designed signal. The chosen SDR by the signal design group is the USRP B210 from Ettus Research. This SDR has a double receiver input and also a double transmitter output. That the SDR has a double transmitter output up to 6 GHz means that if we choose a high enough IF frequency before the upconversion, the second transmitter output could be picked to use as a Local Oscillator for the mixer. Further specifications can be viewed in Table 6.1. The data sheet can be viewed in Appendix 9.1.1. The idea of one of the SDR ports being used as supply for one or both of the amplifiers was also proposed saving cost and space for an external power supply. However, the SDR does not have a DC output and also not the needed power to supply the amplifiers.

Table 6.1: SDR specifications

	USRP-B210
Input Channels	2
Output Channels	2
Max Frequency Output (Ghz)	6
Output Power (W)	>10dBm
Noise Figure	8 dB
Price (€)	1,240

6.2. Gimbal mechanic

The gimbal mechanic can be very intricate and a design on itself, there are various gimbals that can be used and also be made for even more precise target radiation [16]. This however is not the greatest concern of this project and therefore a provided gimbal can be used for the proof of concept. The gimbal system was provided to us by our supervisors and can be viewed in Figure 6.1. The gimbal was already in use for the first experiment with a mono-static radar, and therefore usable for our transmitter. The gimbal has three different rotational speeds: 24/36/48 RPM. The system needs this gimbal mechanic to be able to scan the entire 360° below the mothership drone. The gimbal consists of two gears where once is driven by a motor and the gears are linked by a cord to turn.

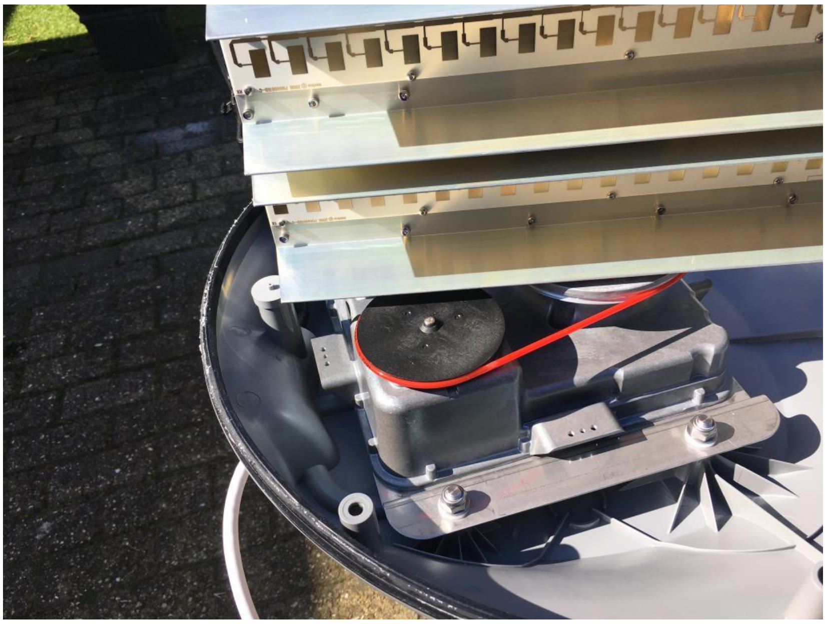


Figure 6.1: The gimbal mechanic

6.3. IF bandpass filter

A selection of filters, which have a center frequency in the desired range for the output signal of the SDR, can be found in Table 6.2. The difference in passband frequencies immediately stands out. The first filter, the ZVBP-3875-S+, has a total passband of 60 MHz, against the 20 MHz passband of the latter two. Because the signal has a bandwidth of 20 MHz it would seem attractive to pick a filter with an equal passband. However, because of the non-ideal reality of the working of these components, it may be better to choose a passband, which is a bit bigger than the signal bandwidth. Moreover, while the transition band, stopband and physical dimensions are all about equally good, the first filter has a bit lower insertion loss and less than half the cost of one of the latter filters. Because of this and the passband, the ZVBP-3875-S+ has been chosen. Ideally, the passband of the filter would be narrower than the 60 MHz passband of the current filter, but still higher than the signal bandwidth. A passband of about 25-30 MHz probably would be more desirable. Nonetheless, taking the other parameters into account, this was the best commercially sold filter available and found. The data sheets of the IF filters can be found in Appendix 9.1.2. Because of the chosen filter, the center frequency

Table 6.2: Possible IF bandpass filter components.

	ZVBP-3875-S+	WBCGV4	WBCJV5
passband (MHz)	+-30	+-10	+-10
transition band (MHz)	60/65	40	40
stopband (GHz)	3.785/4.530	3.95	3.95
stopband attenuation (dB)	43	40	40
insertion loss (dB)	0.6	1.75	2.5
dimensions (mm)	98x25x67	105x30x80	105x20x30
price (€)	327	790	890

was set to 3.875 GHz because this is the center frequency of this filter. This frequency is in the range that the SDR can handle. Because the IF frequency is now set to 3.875 GHz and our desired frequency is 9.7 GHz or 9.4 GHz (depending on the antenna) the LO frequency should be put to either 5.825 GHz or 5.525 GHz which is also in the range that the SDR can transmit, so the SDR can still be used as the LO and IF input of the mixer. The reason the IF filter turned out to be a bandpass filter is because of the input range of the mixer chosen in Section 6.6. The input range of the mixer has a big gap between the lowest acceptable frequency of the mixer and the desired frequency that is used for the signal, this could mean that below the desired frequency there may be an image that could interfere with the mixing.

6.4. LO lowpass filter

Choosing the LO lowpass filter was a fairly difficult task. This is because we could not measure any harmonics that emerge, so it is impossible to say where they emerge. This is why the cutoff frequency of the lowpass filter was chosen to be close to the output signal but not too close as to interfere with the signal. When searching for lowpass filters there were almost two identical filters found, both of the WLKX10 series. The only difference being the length of the stopband. They are even the same price but only differ a little in weight and dimensions. This is why we have chosen the WLKX10 with the largest stopband as to eliminate as much higher harmonics as possible. The specifications of both filters can be found in Table 6.3. The data sheets of the filters can be found in Appendix 9.1.3. The reason that a lowpass filter is used for the LO signal

Table 6.3: Possible LO Filter Components

	WLKX10_1	WLKX10_2
Cutoff Frequency (Mhz)	6300	6300
Max Stopband Frequency (Mhz)	21000	18000
Stopband Attenuation (dB)	40	40
Transition band (Mhz)	330	330
Price (€)	830	830

instead of a bandpass filter is because of the LO input range of the mixer in Section 6.6. The lowest acceptable input frequency is not far off the desired input frequency for the LO. This is why an emerging image possibility is low and it is easier to put in a lowpass filter than a bandpass filter.

6.5. Attenuator

The attenuator is perhaps the most basic component. This device is purely in the circuit to attenuate the output of the SDR which is the IF input signal of the mixer, to make sure that the IF signal does not contain too much power as described in Subsection 5.5.1. The aimed IF mixer input is about 0 dBm, so with a SDR signal power of 10 dBm and an IF filter with a loss of less than 1 dB, the chosen attenuator has an attenuation of about 10 dB. The data sheet of the attenuator can be found in Appendix 9.1.4.

6.6. Mixer

A selection of mixers can be found in Table 6.4. In terms of operating frequency, all three mixers suffice. However, the first mixer, the MM1-0320L, has an IP1dB of just 0 dBm. Because the power of the signal must be so low, this mixer will not be very attractive and falls off. The conversion loss is one of the most important parameters for the mixer, as it can be significantly higher than most other components. When comparing the other two mixers, the third one, the MM2-0530L, has a lower conversion loss of 6 dB against 9 dB for the second one. Also, looking at the input and output IP3 points, these values are higher than the IP1dB point. Given that the mixer has a conversion loss, which means that the output power level will be lower than the input power level, the IP3 points will suffice. Because the MM2-0530L has the lowest conversion loss, taking the extra cost into account, this will be the best mixer for the system. The data sheets of the all the mixers can be found in the appendix. The data sheets of the mixers can be found in Appendix 9.1.5.

Table 6.4: Possible mixer components.

	MM1-0320L	MT3H-0113L	MM2-0530L
RF/LO freq range (GHz)	3-20	1.5-13	5-30
IF freq range (GHz)	DC-4	0.8-8.5	2-20
conversion loss (dB)	8	9	6
IP1dB (dBm)	0	10	8-10
IIP3 (dBm)	9-10	18-22	15
OIP3 (dBm)	2-3	10	9
LO drive (dBm)	5-9	7-15	9-17
dimensions (mm)	33.42x22.81x9.9	33.42x22.81x9.9	33.42x22.81x9.9
price (€)	281	526	663

Because of the insertion of the mixer, as mentioned in Section 4.4, image frequencies will emerge after the mixer. As mentioned in the data sheet of mixer MM2-0530L, the attenuation per image frequency, or 'spur', is given. This is done in a table of combinations between multiples of the LO and IF frequencies. The input frequencies for the mixer depend on the desired output frequency, the IF input is always the same and will be 3.875 GHz. The LO input is dependant on the desired output frequency, and are as follows: for 9.7 GHz output the LO is 5.825 GHz and for 9.4 GHz output the LO is 5.525 GHz. In a MATLAB script shown in Appendix 9.2.4, the calculations are made for the image frequencies close to the desired frequency are plotted below in Figure 6.2 for 9.7 GHz and in Figure 6.3 for 9.4 GHz. The figures show that the largest images are approximately 2 GHz from the desired signal for the 9.7 GHz desired frequency and the most dominant image frequency for 9.4 GHz is at a difference of also lager than 2 GHz. Which gives us more room for a broader RF band-pass filter.

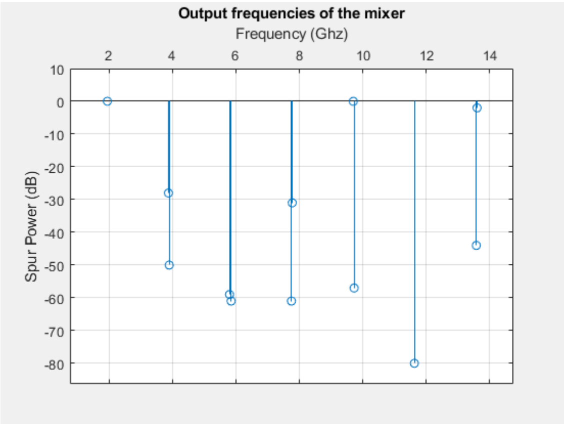


Figure 6.2: Output of the mixer with a desired frequency of 9.7 GHz.

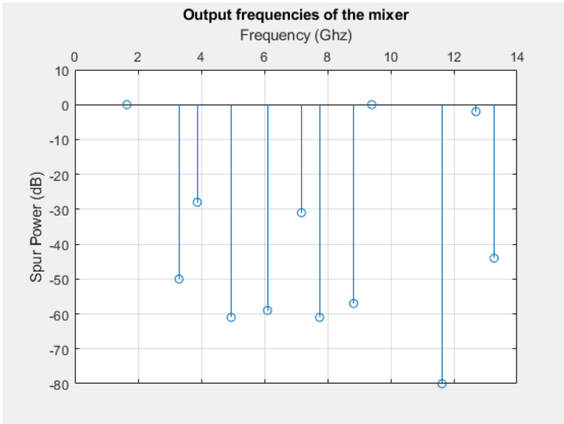


Figure 6.3: Output of the mixer with a desired frequency of 9.4 GHz.

6.7. Driver amplifier

This amplifier was inserted to counteract the attenuation necessary by the attenuator before the mixer. This is why the driver amplifier could be chosen to have a low gain. It can not be chosen as another amplifier with a high gain, because the antenna can handle a limited amount of power at the input, and instead of using a high gain amplifier in combination with yet another attenuator, it is easier to use a lower gain amplifier. The lower gain amplifiers that were found, were most of the times wideband power amplifiers. This does mean that it also will amplify potential images created by the mixer, but the RF bandpass filter will filter these out before the antenna. The R01G20GSPG & R00G20GSPMB were the best amplifiers that could be found on the market at the moment, however there is a big price difference even though the parameters that are of interest for us do not differ a lot. This is why the R00G20GSPMB for us is the best driver amplifier to choose, because it has the lowest price-gain performance for our system. The data sheets of the driver amplifiers can be found in Appendix 9.1.6. Power amplifiers also generates lots of heat. Because of this, a separate device is needed to dissipate the heat. A heat sink can do this job. The selected amplifier has a dedicated heat sink and can be found in the last column of Table 6.5.

Table 6.5: Possible driver amplifier components.

	R01G20GSPG	R00G20GSPMB	RFHTSKA0027
gain (dB)	12	12	-
OP1dB (dBm)	29	29	-
frequency range (GHz)	0.5-12	0.01-20	-
price (€)	3,489	1,890	158

6.8. Power amplifier

The main goal of the power amplifier is to amplify the signal to a satisfactory level. This means that the gain of the amplifier is the most important parameter. A selection of amplifiers can be found in Table 6.6. When roughly adding the gains of the components up to each other, by Equation 4.12, a gain of 30+ dB was certainly needed. The chosen power amplifiers have gains ranging from 30 to 36 dB. As mentioned in Section 5.6, a very important metric is the P1dB. For the amplifiers, most data sheets have the P1dB point specified at the output, meaning the output power should definitely not exceed this power level for a linear performance. When comparing the PE15A4006 and the PE15A4007, they both have the same gain, but the first one will start to saturate earlier than the second one making the second one a more attractive choice. When compared to the ZVE-3W-183+, the ZVE-3W-183+ has a better gain and is a lot cheaper. However, it does have an output P1dB point of 34 dBm, which could be just too low. The last amplifier, PE15A5044, has the highest gain, highest output P1dB point, but also the highest price. For now, this amplifier will be chosen, because of the gain and the probability of the output power exceeding the output P1dB point is the lowest for this one. The PE15A4007 is still an acceptable contender, giving up some gain while being cheaper. When putting together the whole chain, the output power of the amplifier will be inspected to see whether the power could be lower, or not, giving the option to swap the 36 dB gain amplifier for the cheaper 30 dB gain amplifier, or not. The data sheets of the power amplifiers can be found in Appendix 9.1.7. The heatsink for the chosen power amplifier is the PE15C5013F included in Table 6.6.

Table 6.6: Possible power amplifiers components.

	PE15A4006	PE15A4007	ZVE-3W-183+	PE15A5044	PE15C5013F
gain (dB)	30	30	33	36	-
OP1dB (dBm)	30	36	34	38.5	-
frequency range (GHz)	8.5-11	8.5-11	5.9-18	8.5-10.5	-
price (€)	2,465	3,381	1,259	4,085	1,147

6.9. RF bandpass filter

When selecting the RF bandpass filter at first it was the idea to have a filter with a small passband and small transition bands to only let the signal through and block everything else out. There the first filter WBCX7, which can be found in Table 6.7, was picked out, because of the small passband and small transition bands that would fit the signal. The con of having this filter was that it introduced a lot of insertion loss even in the passband. After some discussion it was clear that the only thing that should be filtered out, in its position in the transmitter chain, were the generated harmonics by the mixer and the amplifiers. This meant that the passband and the transition bands could be less restricted. If you take a look at the 'spur' analysis in Figures 6.2 and 6.3, there is a large margin in which there are no big harmonics. This gave us new possibilities and there the second, WBCQV3, and the third, WBCX5, were introduced. These filters have a lower insertion loss. However the WBCQV3 has a narrow passband of 20 MHz making the insertion loss of this filter still a bit higher than the WBCX5 filter. The WBCX5 has a larger passband and transition band but they do not exceed the margin that is between the 'spur' frequencies. This filter also has the lowest insertion loss and is hereby the best filter to use. The data sheets of the RF filters can be found in Appendix 9.1.8.

Table 6.7: Possible RF bandpass filter components.

	WBCX7	WBCQV3	WBCX5
passband (MHz)	+-25	+-10	+-87.5
transition band (MHz)	50	240	250
stopband (GHz)	9.625	DC-9.15 & 9.65-13	DC-9.3625 & 10.0375-19.4
stopband attenuation (dB)	40	50	40
insertion loss (dB)	5	2.5	1.75
dimensions (mm)	108.5x22x18.4	45x15x35	78.5x22x18.4
price (€)	1,190	790	1,090

6.10. Antenna

For the antenna, desirable features are a high gain, a very narrow azimuth beamwidth and a larger elevation beamwidth. Besides, the antenna has to operate in X-band and the price of antennas can range up to very high amounts. Different types of antennas have been looked at for this. Examples of antennas which can have high gains are horn antennas, or parabolic antennas. The beamwidth conditions however are not met with these kind of antennas. A horn antenna typically has broader beamwidths in the order of tens, giving an acceptable beamdwidth in elevation, but a too large beamwidth in azimuth direction. A parabolic antenna is the opposite, generating a very focused signal in both directions. In the end, array antennas were chosen, because they can give the beamwidth requirements necessary. With this comes the consequence that most array antennas within the size requirement do not have high gains. Because this is a proof of concept, after consultation the following decision was made. Two antennas, which can be found in Table 6.8, will be considered, but with the same transmitter circuit. The first antenna is an antenna which is readily available for the company. It comes from the company MetaSensing, which is a partner of Selfly. The antenna of the company MetaSensing is a Patch Array Antenna [17]. We did not get a full data sheet, but the most important characteristics are given in the table. This antenna has good beamwidth specifications with a narrow beamwidth of 5.2° in azimuth direction and 30° in elevation. The gain is on the low side though. This is why the second antenna is considered as well. This antenna has a substantially larger gain. It also has an azimuth beamwidth of just 2°, but a beamwidth of 16° elevation is a little drawback. The downside to this antenna is its greater size and its fairly high price. The data sheets can be found in Appendix 9.1.9, one remark that the MetaSensing antenna does not have a practical data sheet because it is custom made and the company can not disclose all the information about it.

Table 6.8: Two possible antennas.

	MetaSensing antenna	Slotted waveguide antenna
gain (dBi)	12.5	27
HPBW-azimuth (degrees)	5.2	2
HPBW-elevation (degrees)	30	16
max side lobe level (dB)	-18	-15
center frequency (GHz)	9.4	9.7
bandwidth (MHz)	500	200
dimensions (mm)	280x488	279x977
price (€)	already in possession	13,554

As mentioned in Section 5.2, the antenna's have a certain radiation pattern, for the Slotted Waveguide Antenna this was in the data sheet and can be viewed in Figure 6.4. Here it is indeed visible that the maximum sidelobe levels are -15 dB and furthermore the sidelobes are only lower. The MetaSensing antenna unfortunately did not have a very well defined data sheet and that is why it is only known how high the sidelobes are of the antenna.

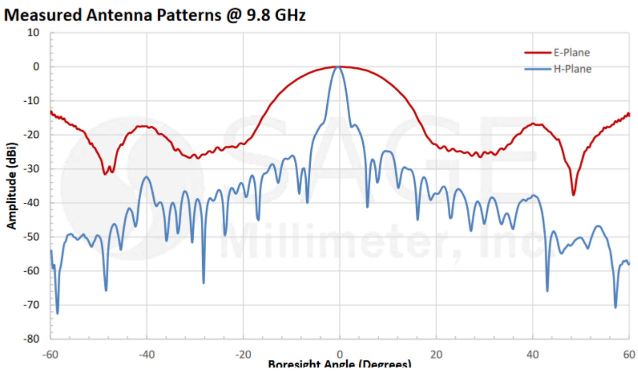


Figure 6.4: The radiation pattern of the Slotted Waveguide Antenna

6.11. Coax cables

When selecting the coax cables for the system, three specifications are important for the design. Namely the operating frequency range of the cable, its insertion loss and its impedance. At first the frequency range in which the coax cables operate, the coax cables should be able to handle the frequency at which the signal is at that point. For our system, there are three different frequencies, specifically the IF frequency, the LO frequency and the RF frequency. Because these frequencies are all separated from each other by a couple of GHz, there may be a need for different coax cables for different parts of the system. A certain cable may have a lower insertion loss than another one, but more limited in the maximum frequency it operates in.
The selected coax cables for the system can be found in Table 6.9. The LMR-600 is selected for IF signal path and the PE-1/2SFHC will be handling the LO and RF signal paths. The first has a lower loss than the second cable. However, this cable is limited in frequency, having a maximum frequency of 5.8 GHz. This means that the LO frequency will be just over, or just under the maximum frequency of the first cable and it will certainly not be able handle the RF frequency. This is why the second cable is chosen for these frequencies.
It should also be noted that the cables have an impedance of 50 Ω. This is good, because the other components have an input/output impedance of 50 Ω as well, so the impedances are matched giving the least reflection possible according to Section 5.4.The data sheets of the coax cables can be found in Appendix 9.1.10.

Table 6.9: Possible coax cables.

	LMR-600	PE-1/2SFHC
frequency	IF	LO/RF
attenuation per 100 meter (dB)	18.7	40.35
price per meter (€/meter)	6.27	15.98

To model the losses of the Coax cables in the system, it was decided to model a cumulative loss before and after the mixer. This is done because the only difference that the modelling of every separate part will make is that the noise figure of the system will change, but by a very small margin because the losses in every separate cabling parts are very low. Because a physical product can not be made, an estimation was done on the total of cabling necessary in the system. For the part before the mixer our estimate is that we need about 1 m of cabling, and after the mixer an estimate of 1.5 m. With coax cable loss per unit length being linear in dB[5], this would mean that the insertion loss before the mixer cumulatively would be 0.187 dB attenuation and the insertion loss after the mixer cumulatively would be 0.601 dB. These losses are put before and after the mixer in the budget link analysis done in Section 7.1.1.

6.12. Coax-to-waveguide

When using the slotted waveguide antenna mentioned in Section 6.10, it can not be directly connected because the slotted waveguide antenna has a waveguide input port and the transmitter chain has coax cables as connections. To feed the slotted waveguide antenna there has to be a converter from coax to waveguide. The coax-to-waveguide specifications are almost all around the same parameters. This is why making a choice is not that hard and will be done on the price of the product. So we will choose the SWC-90SF-E5. The data sheets of the adapters can be found in Appendix 9.1.11.

Table 6.10: Coax-to-waveguide component.

	SWC-90SF-E5	PE9804
frequency range (GHz)	8.2-12.4	8.2-12.4
insertion loss (dB)	0.3	0.3
price (€)	268	320,86

6.13. Power Supply

Both amplifiers that are in the circuit are in need of a power supply, the power necessary can be found in the data sheets of the components itself in Appendix 9.1.6. This part of the chain should not be a interesting part as it only supplies the needed power to the amplifiers. There are multiple sorts of power supplies ranging from small prices to higher prices that go beyond the budget available. Since for our signal it is not necessary to be able to have a power supply that can turn off the amplifier, a simple power supply that supplies a constant power can be used. A power supply with two outputs would be most convenient because it can supply both the amplifiers. The power supply that is used in this chain is the TRACOPOWER, 100W Embedded Switch Mode Power Supply SMPS. This power supply has two outputs and can deliver the power necessary for the amplifiers to work. Since this part of the chain is not an interesting one further specifics of this power supply can be viewed in the Appendix 9.1.12.

7

Simulations & Results

7.1. Transmitter budget link analysis

7.1.1. Mathematical link budget analysis

In the end it was decided to make a simulation for both the transmitter chain in combination with the Slotted Waveguide Antenna and the MetaSensing Patch Array Antenna shown in Section 6.10. The simulation performed is the link budget analysis mentioned in Section 4.3. Since the MetaSensing Patch Array Antenna does have a low power output requirement it would be better to simulate the chain for the Slotted Waveguide Antenna first. In Figure 7.1 it is shown what the power is throughout the system, this shows that the P_t results in 37.979 dBm = 7.979 dB which equates to a power P_t = 6.28W.

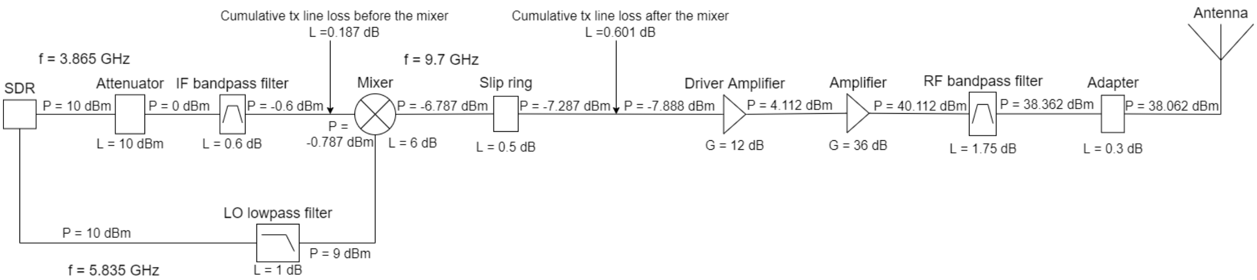


Figure 7.1: Link budget of the Slotted Waveguide antenna transmitter chain.

Unfortunately this simulation shows that the output power of the power amplifier is 40.112 dBm, which is above the 1 dB output power compression point of this power amplifier which is 38.5dBm, meaning that it will introduce large amounts of distortion and harmonics into the signal. This is not advised and therefore needs adjustment.

To counter this high output power in the power amplifier there are two possible scenarios, introduce an attenuator before the amplifier or move the bandpass filter from after the power amplifier to before the power amplifier, creating a loss before the power amplifier and lowering the power output. However our bandpass filter only has an insertion loss of only 1.75 dB, which is not enough to lower the output power below the 1 dB compression point of the power amplifier. Therefore there is another solution, use one of the other filters mentioned in Section 6.9. The best choice then would be to insert the WBCX7 filter which has an insertion loss of 5 dB which should be enough to get below the 1 dB compression point of the power amplifier as is shown in Figure 7.2. Because of this alteration to the design, the power output before the antenna will result in a P_t of 3.03 W.

The transmitter chain for the MetaSensing antenna has an ever so slight change, because there will be no adapter in between the amplifier and the antenna. This will cause the power of the chain supporting the MetaSensing antenna to be higher than the one of the Slotted Waveguide. In Figure 7.3 the small change is shown and the consequences are visible. The power of the chain will improve to a P_t of 3.24 W. This power is still acceptable by the MetaSensing Antenna. In MATLAB we used a script to calculate the output power of different setups in a quick manner, this script is shown in Appendix 9.2.1.

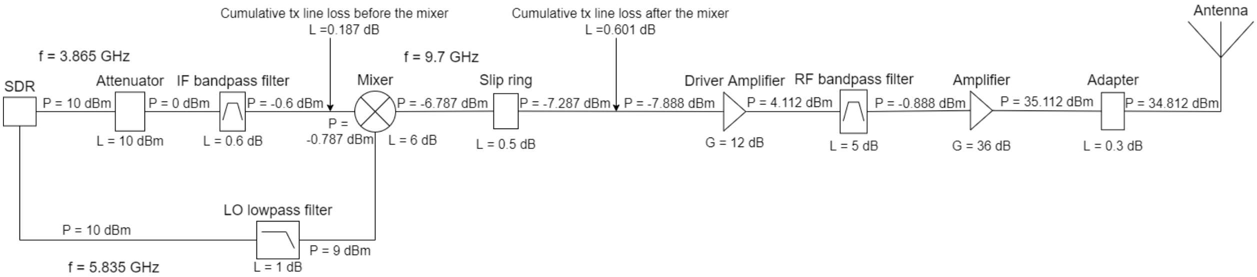


Figure 7.2: Link budget of the improved Slotted Waveguide antenna transmitter chain.

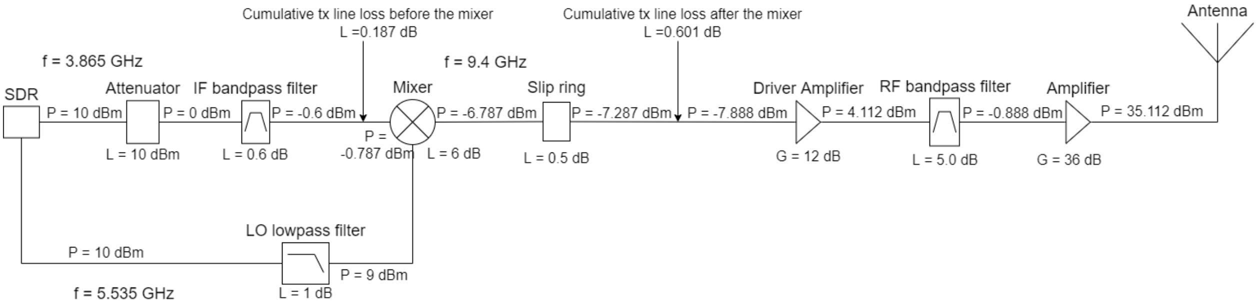
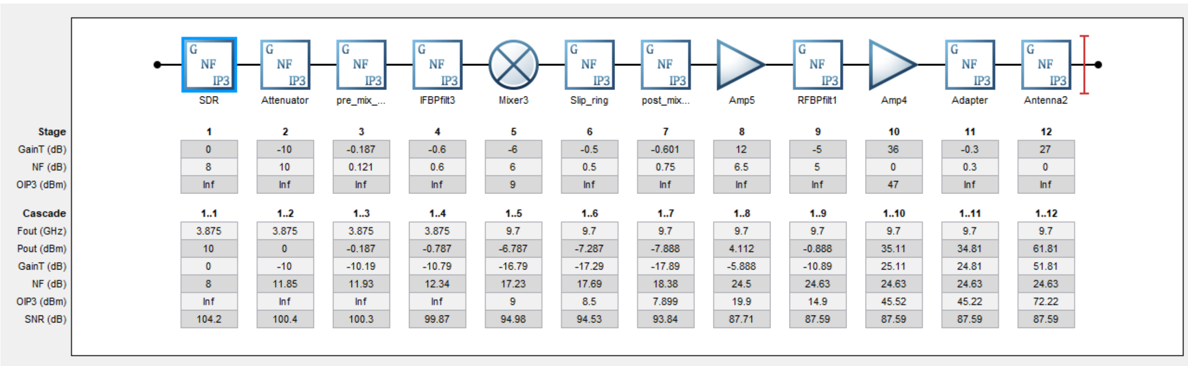


Figure 7.3: Link budget of the MetaSensing antenna transmitter chain.

7.2. Budget analyser app of MATLAB

For the budget link analysis, MATLAB has a useful tool that could check our calculations. The budget analysis application of MATLAB however does not show the calculations but only results. The budget analysis application does give a good overview of parameters, like power and gain, between the stages of the cascaded system. It gives a fast and easy access to change parameters and see the influence on the system. In Figure 7.4 the budget link analysis is given for the system with the Slotted Waveguide Antenna and in Figure 7.5 the budget link analysis is given for the system with the MetaSensing Patch Array Antenna. The calculated P_t values from Section 7.1.1 above are confirmed as can be seen in the second to last columns in the figures. The P_{out} in the last column is actually the power multiplied by the antenna gain, the EIRP, and not just the P_{out}. The code used for this simulation can be found in Appendix 9.2.2 and Appendix 9.2.3.



	SDR	Attenuator	pre_mix_...	IFBPfilt3	Mixer3	Slip_ring	post_mix...	Amp5	RFBPfilt1	Amp4	Adapter	Antenna2
Stage	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
GainT (dB)	0	-10	-0.187	-0.6	-6	-0.5	-0.601	12	-5	36	-0.3	27
NF (dB)	8	10	0.121	0.6	6	0.5	0.75	6.5	5	0	0.3	0
OIP3 (dBm)	Inf	Inf	Inf	Inf	9	Inf	Inf	Inf	Inf	47	Inf	Inf
Cascade	**1..1**	**1..2**	**1..3**	**1..4**	**1..5**	**1..6**	**1..7**	**1..8**	**1..9**	**1..10**	**1..11**	**1..12**
Fout (GHz)	3.875	3.875	3.875	3.875	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7
Pout (dBm)	10	0	-0.187	-0.787	-6.787	-7.287	-7.888	4.112	-0.888	35.11	34.81	61.81
GainT (dB)	0	-10	-10.19	-10.79	-16.79	-17.29	-17.89	-5.888	-10.89	25.11	24.81	51.81
NF (dB)	8	11.85	11.93	12.34	17.23	17.69	18.38	24.5	24.63	24.63	24.63	24.63
OIP3 (dBm)	Inf	Inf	Inf	Inf	9	8.5	7.899	19.9	14.9	45.52	45.22	72.22
SNR (dB)	104.2	100.4	100.3	99.87	94.98	94.53	93.84	87.71	87.59	87.59	87.59	87.59

Figure 7.4: Link budget of the Slotted Waveguide antenna transmitter chain through the budget analyser app.

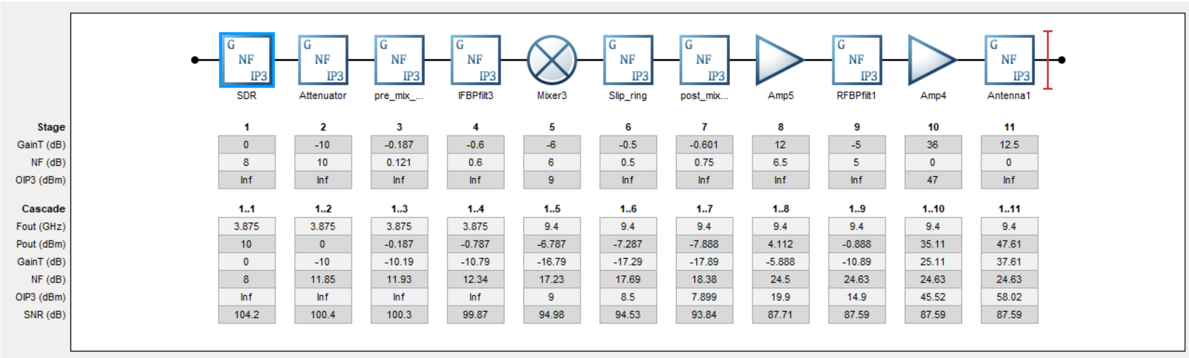


Figure 7.5: Link budget of the MetaSensing antenna transmitter through the budget analyser app.

7.3. System costs

The transmitter chain component costs should ideally be around € 20k. The total costs for the components of both the transmitter chain with the MetaSensing antenna and the slotted waveguide antenna are put in Table 7.1.

Table 7.1: System costs for transmitter circuit with 1: MetaSensing antenna, 2: slotted waveguide antenna.

Component	Cost (€)
SDR	1,240
IF filter	327
LO filter	830
Attenuator	38
Mixer	663
Driver amplifier	2,048
Power amplifier	5,232
Power supply	118
RF filter	1,190
Coax cables	30
Total	**11,716**

Component	Cost (€)
SDR	1,240
IF filter	327
LO filter	830
Attenuator	38
Mixer	663
Driver amplifier	2,048
Power amplifier	5,232
Power supply	118
RF filter	1,190
Coax cables	30
Adapter	268
Antenna	13,554
Total	**25,538**

7.4. System analysis

7.4.1. Ovals of Cassini

Normally this project would have a practical demonstrator that would show whether our product would be sufficiently designed, however this is not the case because of COVID-19 measures. This is why one of the system analysis has been done inside GNU Radio, and the Cassini oval ranges, mentioned in Section 4.2, are worked out in MATLAB. The MATLAB code for calculating the Ovals of Cassini can be found in Appendix 9.2.5. The calculation of the Ovals of Cassini is based on the Radar Range Equation mentioned in Chapter 4.

For the first setup using the Metasensing Antenna as shown in Section 7.3, the Ovals of Cassini are calculated to see if the chain meets the requirements of being detectable on a certain range. As seen in Figure 7.6, even with a range of 1 km between the transmitter and the receiver it is not possible to detect any signals with the receiver. This is because the gain of the antenna is just too low and the power available is not enough to reach the intended ranges. The Metasensing antenna however can not use any more power and is thereby not usable in this setting. The SNR curves are plotted not lower than an SNR of 10 dB, because below that it becomes increasingly uncertain whether the signal is strong enough compared to the noise and therefore will not be measurable.

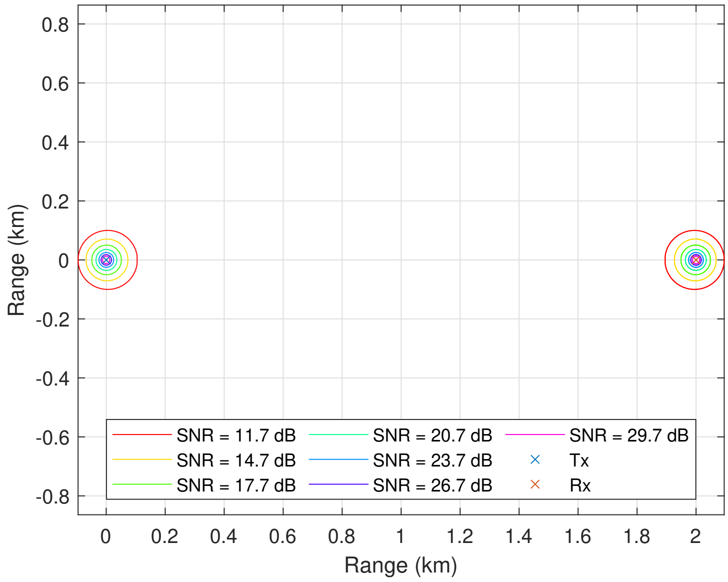


Figure 7.6: Cassini ovals range $L = 1km$ (baseline range) and $R_{tx} = 100m$ (target to receiver range)

In Figure 7.7 the Ovals of Cassini are given for the Slotted Waveguide Antenna setup, as shown in Section 7.2. The gain of the Slotted Waveguide Antenna is roughly doubled in dB in comparison with the Metasensing Antenna. In the figure it is visible that this setup can indeed be used on a range of 2 km between transmitter and receiver and a range of 600 m between the target and the receiver.

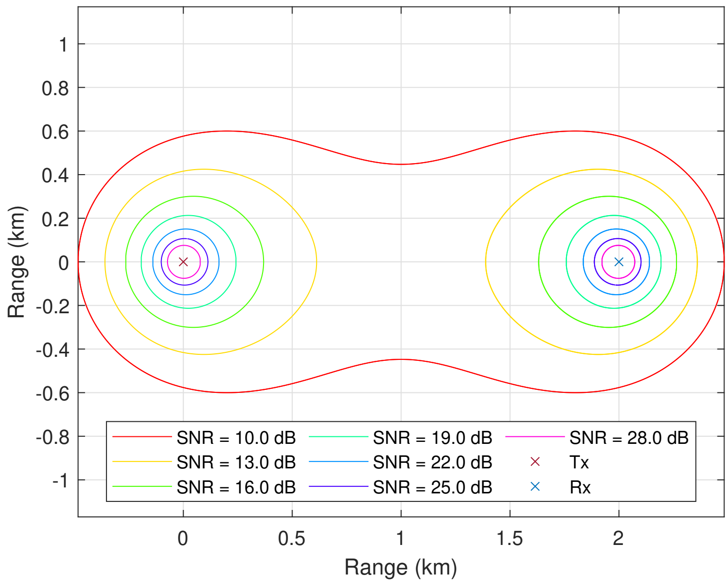


Figure 7.7: Cassini ovals range $L = 2km$ (baseline range) and $R_{tx} = 600m$ (target to receiver range)

7.4.2. GNU Radio Simulation

After evaluating the Ovals of Cassini, a full system analysis was done in GNU Radio to evaluate the system and see the response after the signal processing, which gives an additional gain of $G_p = 36$ dB after filling in Equation 4.3. The setup used in this GNU Radio program can be viewed in Figure 7.8. Here, some parts are marked in boxes which are part of the transmitter chain. The red and yellow boxes are the signal inputs. The signal is defined as a Linear Frequency Modulated signal, but after sending one pulse chain it is turned 'off' only sending zero's. The Red box simulates the LFM waveform and the Yellow box simulates a rectangular waveform which can turn the LFM 'on' and 'off'. Both parts are connected to the Green box which simulates the transmitter. The transmitter here is modelled as a factor to give the signal the appropriate amount of power. Those components are the models of the transmitter chain. Furthermore the signal is split in two, one signal that gains a delay because it would 'hit' a target and the other is the modelled free-space loss without hitting a target. After that, both signals are added again and sent to the receiver part of the system. The missing part of the system is the time delay due to rotation of the gimbal mechanic, this can be altered by delaying one of the given signals. This system in GNU Radio is simulated in two different scenarios. The scenarios consist

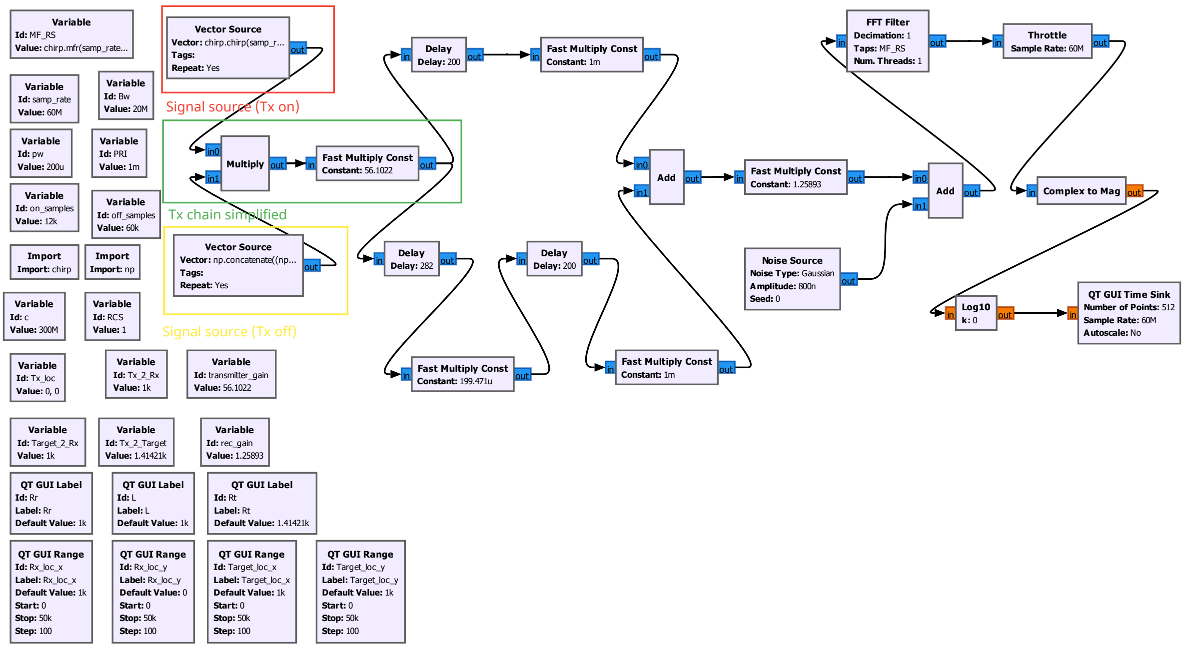


Figure 7.8: System overview in GNU Radio

of different ranges between the transmitter, receiver and target. The first scenario is where the transmitter to receiver range is 2.5 km, the range of the transmitter to the target is also 2.5 km and finally the target to receiver range is 1.5 km. The result of the system analysis in GNU Radio can be viewed in Figure 7.9. There is a clear distinction of two incoming signals with a difference in attenuation and the visible window used by the signal design group. This ensures us that the system on this range is functioning well.

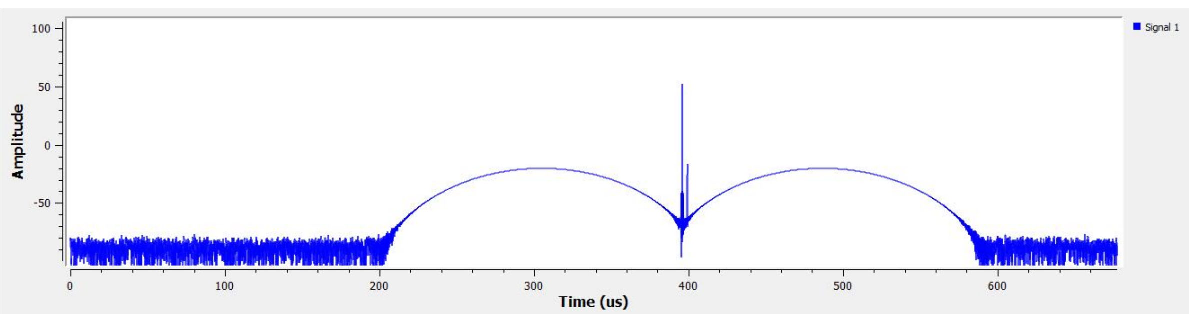


Figure 7.9: Result of GNU simulation setup 1

The second scenario tested in the GNU Radio Simulator is with smaller ranges but with a longer range to the target from the transmitter. The transmitter to receiver range is 1.0 km, the range of the transmitter to the target is also 1.5 km and finally the target to receiver range is 0.5 km. The result of the system analysis in GNU Radio can be viewed in Figure 7.10. In contrast and also as expected, the full window and signals are earlier in time than with longer ranges. Here the distinction between the direct path and the reflected signal is greater. This is because the ratio between the distances of the direct path and the reflected signal is greater. The simulation also shows that on this different setup the system is still functional.

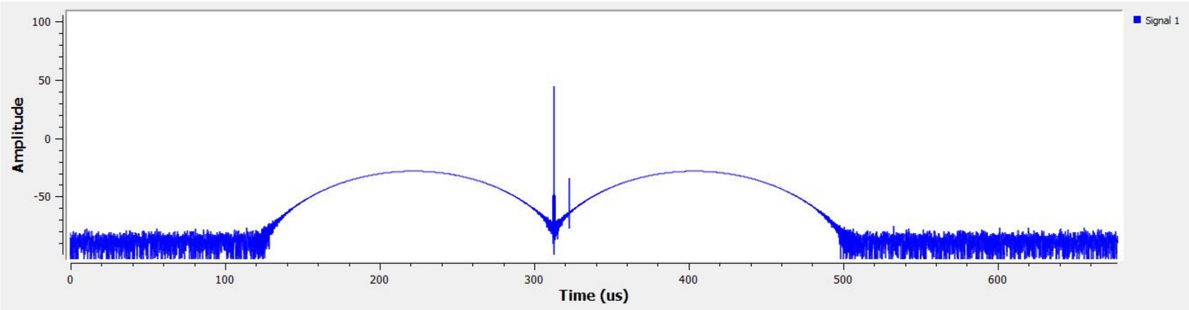


Figure 7.10: Result of GNU simulation setup 2

Because of the measurements done and the results obtained of analysing and simulating the system an estimate of the max range on which our radar works is: 2.5 km.

8
Conclusion & Discussion

8.1. Conclusion

8.1.1. Transmitter chain

After looking into two systems with two different antenna, it is visible in the results in Section 7.4 that the system with the Slotted Waveguide Antenna is more capable than the system with the MetaSensing Patch Array Antenna. The system with the MetaSensing Patch Array Antenna unfortunately can also not be improved by a large margin, because the maximum power that the antenna can hold is also almost reached and it is advised against to use a higher power in that system. That is why for our transmitter design part the best transmitter chain is the Slotted Waveguide Antenna.

8.1.2. Overall system performance

The mandatory requirements of the intended system are almost all met with this proof of concept, except for a range requirements. The main system was intended to have a transmitter to receiver range of 50 km which unfortunately can not be met with Commercial of the shelf (COTS) equipment. This is why the overall system design should be viewed as a proof of concept verifying that with bulkier components the system should be able to work as intended. The same goes for the requirement of the target to receiver range of 5 km, this is also in the same direction as the requirement above, with COTS equipment it is not possible to create a design that would suffice this requirement. The only other requirement that is still to discuss is the budget for the transmitter, which was a debatable requirement but nonetheless we still went a small margin above budget, meaning that the requirement was not entirely met. The other non-functional and functional requirements are met. This tells us that the system design is only lacking in performance of range while the other factors are held by the design, making it a good proof of concept.

8.2. Discussion & future work

8.2.1. Range Performance

As seen in the results in Section 7.4 and concluded in the section above, the range requirements of the intended system are far off the ranges met with this proof of concept. The requirements that counter each other in this project are the requirement of using COTS equipment versus the range requirements. If the components could be custom made, also making the system a lot more expensive, the system possibly could meet the range specifications but the components necessary would be too expensive and more bulky than we could design at the moment. It however should be possible to design a system that can achieve even greater heights [18], but not in the time-span available and the budget and requirements for this project.

8.2.2. Filter spots

One thing that was found out whilst ending the project was the amount of filters necessary in the transmitter chain. Because of price limitations and time pressure the system had a limited amount of filters. As mentioned in Section 5.9, there is a consideration between the filter and amplifier order, in an ideal situation you would like filters on both sides of the amplifier, which could improve the performance of the system and lessen the possible distortion made in the transmitter chain.

8.2.3. Omitted interference

Because this project is a proof of concept and is purely based off of certain equations found in radar mathematics design, some possible interferences have been omitted and could be of interest when further developing this system. Examples of omitted interferences is the interference of the mobile antenna station itself [19] and the interference of earth's innate electromagnetic field [20].

8.2.4. Amplifier power supply

The current design has a power supply which is continuously on and the LFM signal is transmitted all the time, but transmits a string of zeros when the signal is low. It could be more power efficient to switch the supply for the amplifiers on and off when the signal is high or low. This could potentially be done with a power supply controlled by the General Purpose Input Output (GPIO) of the SDR. The SDR could set a configurable power supply on or off, cutting the power to the power amplifiers and saving energy in this way making it much more efficient in power.

8.2.5. Circumstances around the project due to COVID-19

The final point of discussion is that this project was developed in the time that the COVID-19 virus was coursing through the Netherlands meaning that physical contact was not permitted by the TUDelft. This also caused the limitation on the project of not being able to make a physical demonstrator. This drastically impacted our project which was focused on building a physical object and testing it in real life. The project was altered to be a project that ended in simulations only, without a physical demonstrator. Furthermore the prohibition on physical contact made the contact between subgroups of the project a little harder but the our group survived on a created Discord Channel, Discord is a program where you can easily make text-channels and voice-channels to communicate with your peers and also exchange information.

9 Appendix

9.1. List of component data sheets

9.1.1. SDR Data Sheet

USRP-B210 - https://www.ettus.com/wp-content/uploads/2019/01/b200-b210_spec_sheet.pdf

9.1.2. IF-filter Data sheets

ZVBP-3875-S+ - https://www.minicircuits.com/pdfs/ZVBP-3875-S+.pdf
WBCGV4 - https://www.wainwright-filters.com/standard-filter/wbcgv4-3000-4000-20-40-40-quote?f1=4000
WBCJV5 - https://www.wainwright-filters.com/standard-filter/wbcjv5-3000-4000-20-40-40-quote?f1=4000

9.1.3. LO-filter Data sheets

WLKX10_1 - https://www.wainwright-filters.com/standard-filter/wlkx10-2000-10000-40-18000-20?f1=6300
WLKX10_2 - https://www.wainwright-filters.com/standard-filter/wlkx10-3000-10500-40-21000-20?f1=6300

9.1.4. Attenuator Data sheet

PE7091-10 - https://www.pasternack.com/images/ProductPDF/PE7091-10.pdf

9.1.5. Mixer Data sheets

MM1-0320L - https://www.markimicrowave.com/Assets/DataSheets/MM1-0320L.pdf?v=051820
MT3H-0113L - https://www.markimicrowave.com/Assets/DataSheets/MT3H-0113L.pdf?v=051820
MM2-0530L - https://www.markimicrowave.com/Assets/DataSheets/MM2-0530L.pdf?v=051820

9.1.6. Driver amplifier Data sheets

R01G20GSPG - https://www.rflambda.com/pdf/poweramplifier/R01G20GSPG.pdf
R00G20GSPMB - https://www.rflambda.com/pdf/poweramplifier/R00G20GSPMB.pdf

9.1.7. Power amplifier Data sheets

PE15A4006 - https://www.pasternack.com/images/ProductPDF/PE15A4006.pdf
PE15A4007 - https://www.pasternack.com/images/ProductPDF/PE15A4007.pdf
ZVE-3W-183+ - https://www.minicircuits.com/pdfs/ZVE-3W-183+.pdf
PE15A5044 - https://www.pasternack.com/images/ProductPDF/PE15A5044.pdf

9.1.8. RF-filter Data sheets

WBCX7 - https://www.wainwright-filters.com/standard-filter/wbcx7-5000-10000-50-50-40-25?f1=9700
WBCQV3 - https://www.wainwright-filters.com/standard-filter/wbcqv3-6000-10000-20-240-50-quote?f1=9700
WBCX5 - https://www.wainwright-filters.com/standard-filter/wbcx5-5000-10000-175-250-40-25?f1=9700

9.1.9. Antenna Data Sheets

MetaSensing antenna -
Slotted waveguide antenna - https://sftp.eravant.com/content/datasheets/SAW-9629822716-90-L2-WR.pdf

9.1.10. Coax cables Data sheets

LMR-600 - https://www.pasternack.com/images/ProductPDF/LMR-600.pdf
PE-1/2SFHC - https://www.pasternack.com/images/ProductPDF/PE-1-2SFHC.pdf

9.1.11. Coax-to-waveguide adapter Data sheets

SWC-90SF-E5 - https://sftp.eravant.com/content/datasheets/SWC-90SF-E5.pdf
PE9804 - https://www.pasternack.com/images/ProductPDF/PE9804.pdf

9.1.12. Power Supply

TRACOPOWER, 100W Embedded Switch Mode Power Supply SMPS - https://nl.rs-online.com/web/p/embedded-switch-mode-power-supplies-smps/4182409/

9.2. Matlab code

9.2.1. Code used for Calculating output power of different kinds of setups

```
% TX chain elements and their specifications
clear all %#ok<CLALL>

%% Frequency specifications
s_bw = 20;                  % bandwidth of the signal
f_b_mix = 3.8;              % frequency before the upconversion
f_a_mix1 = 9.7;             % frequency after upconversion when using Slotted Waveguide Antenna
f_a_mix2 = 9.4;             % frequency after upconversion when using metasensing patch antenna

%% Cabling losses:
% LMR-600: The cables before the mixer insertionloss per 100 m on 3.8 Ghz
% is 18.7 dB, assuming only 1 m is necessary before the mixer:
SMA1_premix_loss = 0.187;   % dB losses before the mixer

% PE-1/2SFHC: The cables after the mixer insertionloss per 100 m on 9.7 Ghz
% is 40.35 dB worst case, assuming only 1.5 m is necessary after the mixer:
SMA1_postmix_loss = 0.601;    % dB losses after mixer

%% SDR
SDR_gain = 0;
SDR_P_dBm = 10;             % dBm output power of the SDR
SDR_P_dB = SDR_P_dBm - 30;  % dB output power of the SDR
SDR_NF = 8;                 % Max Noise figure of the SDR (receiver but it doesn't specify transmitter so)

%% Filter 1x between SDR and Upconversion
% Filter between SDR and Upconversion, second choice (best parameters) Code:
% WBCGV4-3950-3990-4010-4050-40SS
BP1x_bw = 20;                % Mhz bandwidth of the filter
BP1x_f_c = 3800;             % Mhz center frequency of the filter
BP1x_il = 1.75;              % dB insertion loss
BP1x_rl = 14;                % dB return loss


%% Filter 2x between SDR and Upconversion
% Filter between SDR and Upconversion, third choice (higher insertion loss, better weight) Code:
% WBCJV5-3950-3990-4010-4050-40SS
BP2x_bw = 20;                % Mhz bandwidth of the filter
BP2x_f_c = 3800;             % Mhz center frequency of the filter
BP2x_il = 2.5;               % dB insertion loss
BP2x_rl = 14;                % dB return loss

%% Filter 3x between SDR and Upconversion (Probably the best)
% ZVBP-3875-S+ First choice lowest insertion loss and no -3dB on the edges
```

```
% of the signal
BP3x_bw = 60;                        % Mhz bandwidth of the filter
BP3x_f_c = 3875;                     % Mhz center frequency of the filter
BP3x_il = 0.6;                       % dB insertion loss

%% Attenuator (all of them have the same attenuation:
Atten_gain = 10;                     % The attenuator has a attenuation of 10 dB

%% Mixer 1: MM2-0530L (best but most expensive)
Mix1_cl = 6;                         % dB max conversion loss

%% Mixer 2: MT3H-0113L (slightly higher conversion loss, but less expensive)
Mix2_cl = 9;                         % dB max conversion loss

%% Mixer 3: MM1-0320L (slightly out of LO driver range and highest conversion loss but least expensive and
    bad OIP3)
Mix3_cl = 9;                         % dB max conversion loss

%% Slipring specifications
Slip_il = 0.5;                       % dB insertion loss of general sliprings

%% Pre-amp 1: R01G20SPG Wideband PA with low gain (intended)
PreAmp1_gain = 12;                   % dB gain

%% Pre-amp 2: R00G20GSPMB Wideband PA with low gain (intended)
PreAmp2_gain = 12;                   % dB gain

%% Filter 1 between Upconversion and Power amp (perfectly inside the bandwidth of the antenna, but high
    insertion loss)
% Code: WBCX7-9625-9675-9725-9775-40SS
BP1_bw = 50;                         % Mhz bandwidth of the filter
BP1_f_c = 9700;                      % Mhz center frequency of the filter (or 9400 based on antenna)
BP1_il = 5;                          % dB insertion loss
BP1_rl = 14;                         % dB return loss

%% Filter 2 between Upconversion and Power amp (just outside the bandwidth of the antenna, but lesser
    insertion loss)
% Code: WBCX7-9625-9675-9725-9775-40SS
BP2_bw = 75;                         % Mhz bandwidth of the filter
BP2_f_c = 9700;                      % Mhz center frequency of the filter (or 9400 based on antenna)
BP2_il = 3.75;                       % dB insertion loss
BP2_rl = 14;                         % dB return loss

%% Filter 3 between Upconversion and Power amp (perfect signal bandwidth, disastrous slopes, but least
    insertion loss)
% Code: WBCX7-9625-9675-9725-9775-40SS
BP3_bw = 20;                         % Mhz bandwidth of the filter
BP3_f_c = 9700;                      % Mhz center frequency of the filter (or 9400 based on antenna)
BP3_il = 2.5;                        % dB insertion loss
BP3_rl = 14;                         % dB return loss

%% Filter 4 between Upconversion and Power amp (Wider passband and slopes but still erasing harmonics,
    lowest il, probably best choice)
% Code: WBCX5-9362.5-9612.5-9787.5-10037.5-40SS
BP4_bw = 175;                        % Mhz bandwidth of the filter
BP4_f_c = 9700;                      % Mhz center frequency of the filter (or 9400 based on antenna)
BP4_il = 1.75;                       % dB insertion loss
BP4_rl = 14;                         % dB return loss

%% Amp 1: ZVE-3W-183+
Amp1_gain = 33.62;                   % dB gain
Amp1_NF = 5.5;                       % dB noise figure

%% Amp 2: PE15A4006
Amp2_gain = 30;                      % dB gain
Amp2_NF = 3;                         % dB noise figure

%% Amp 3: PE15A4007
Amp3_gain = 30;                      % dB gain
Amp3_NF = 5;                         % dB noise figure
```

```
%% Amp 4: CBM06122430
Amp4_gain = 24;                          % dB gain
Amp4_NF = 6.5;                           % dB noise figure

%% Amp 5: PE15A5044 (possible best choice but expensive)
Amp5_gain = 36;                          % dB gain

%% Possible conversion state between electrical to waveguide domain: adapter
Adapter_il = 0.3;                        % dB insertion loss
Adapter_rl = 20;                         % dB return loss

%% Antenna 1: Slotted Waveguide Antenna
SWA_gain = 27;                           % dBi gain
SWA_bw = 200;                            % Mhz bandwidth
SWA_f_c = 9700;                          % Mhz center freq
SWA_rl = 13;                             % dB return loss

%% Antenna 2: Patch array Antenna Metasensing
PAA_gain = 12.5;                         % dBi gain
PAA_bw = 500;                            % Mhz bandwidth
PAA_f_c = 9400;                          % Mhz center freq
PAA_rl = 20;                             % dB return loss at resonance band

%% Scenario one: Possibly the best setup
% SDR -> Filter 1x -> Attenuator -> Mixer 1 -> Slipring -> PreAmp 1 -> Filter 1-> Amp 1 ->
% Conversion to waveguide -> Slotted Waveguide Antenna (with cabling losses)

% Calculate total gain just before antenna
S1_Total_gain_x = (-BP3x_il) + (-Atten_gain) + (-SMA1_premix_loss) + (-Mix1_cl) + (-SMA1_postmix_loss) +
    PreAmp1_gain + (-Slip_il) + (-BP1_il) + Amp5_gain + (-Adapter_il);

% Calculate the power just before the antenna
S1_Total_P_tx = db2pow(SDR_P_dB + S1_Total_gain_x);

% Calculate the total noise figure, and per stage
S1_NF_stage1 = SDR_NF;                         % dB noise figure
S1_NF_stage2 = pow2db(db2pow(S1_NF_stage1)+(db2pow(BP3x_il)-1)/(db2pow(SDR_gain)));
S1_NF_stage3 = pow2db(db2pow(S1_NF_stage2)+(db2pow(Mix1_cl)-1)/(db2pow(SDR_gain)*db2pow(-BP3x_il)));
S1_NF_stage4 = pow2db(db2pow(S1_NF_stage3)+(db2pow(Slip_il)-1)/(db2pow(SDR_gain)*db2pow(-BP3x_il)*db2pow(-
    Mix1_cl)));
S1_NF_stage5 = pow2db(db2pow(S1_NF_stage4)+(db2pow(BP4_il)-1)/(db2pow(SDR_gain)*db2pow(-BP3x_il)*db2pow(-
    Mix1_cl)*db2pow(-Slip_il)));
S1_NF_stage6 = pow2db(db2pow(S1_NF_stage5)+(db2pow(Amp1_NF)-1)/(db2pow(SDR_gain)*db2pow(-BP3x_il)*db2pow(-
    Mix1_cl)*db2pow(-Slip_il)*db2pow(-BP1_il)));
S1_NF_Final = pow2db(db2pow(S1_NF_stage6)+(db2pow(Adapter_il)-1)/(db2pow(SDR_gain)*db2pow(-BP3x_il)*db2pow
    (-Mix1_cl)*db2pow(-Slip_il)*db2pow(-BP1_il)*db2pow(Amp1_gain)));
```

9.2.2. RF budget analyser app code used for Metasensing antenna setup

```
%%% TX chain for Metasensing antenna, Fc = 9.4 GHz

clear all

%SDR USRP B210
SDR = rfelement('Name','SDR','NF',8);

%Attenuator
Attenuator = rfelement('Name','Attenuator','Gain',-10,'NF',10);

%Coax cabling
Pre_mix_coax1 = rfelement('Name','pre_mix_coax1','Gain',-0.187,'NF',0.121); %LMR-600
Pre_mix_coax2 = rfelement('Name','pre_mix_coax2','Gain',-0.16,'NF',0.16); %PE-C600
Post_mix_coax1 = rfelement('Name','post_mix_coax1','Gain',-0.601,'NF',0.75); %PE-1/2SFHC
Post_mix_coax2 = rfelement('Name','post_mix_coax2','Gain',-0.9,'NF',0.9); %PE-P300LL

%IF bandpass filters
IFBPfilter1 = rfelement('Name','IFBPfilt1','Gain',-1.75,'NF',1.75); %WBCGV4
IFBPfilter2 = rfelement('Name','IFBPfilt2','Gain',-2.5,'NF',2.5); %WBCJV5
IFBPfilter3 = rfelement('Name','IFBPfilt3','Gain',-0.6,'NF',0.6); %ZVBP-3875-S+

%Mixers for upconverter stage
```

```
Mixer1 = modulator('Name','Mixer1','Gain',-9,'NF',9,'OIP3',2.5,'LO',5.525e9,'ConverterType','Up'); %MM1-0320L
Mixer2 = modulator('Name','Mixer2','Gain',-9,'NF',9,'OIP3',10,'LO',5.525e9,'ConverterType','Up'); %MT3H-0113L
Mixer3 = modulator('Name','Mixer3','Gain',-6,'NF',6,'OIP3',9,'LO',5.525e9,'ConverterType','Up'); %MM2-0530L

%Slip ring
Slip_ring = rfelement('Name','Slip_ring','Gain',-0.5,'NF',0.5);

%RF bandpass filters
RFBPfilter1 = rfelement('Name','RFBPfilt1','Gain',-5,'NF',5); %WBCX7, pb=+-25MHz, sb=+-75MHz
RFBPfilter2 = rfelement('Name','RFBPfilt2','Gain',-3.75,'NF',3.75); %WBCX7, pb=+-37.5MHZ, sb=+-112.5MHz
RFBPfilter3 = rfelement('Name','RFBPfilt3','Gain',-2.5,'NF',2.5); %WBCQV3, pb=+-10MHz, sb =+-240MHz
RFBPfilter4 = rfelement('Name','RFBPfilt4','Gain',-1.75,'NF',1.75); %WBCX5, pb=+-87.5Mhz, sb = +-250Mhz

%amplifiers
Amp1 = amplifier('Name','Amp1','Gain',33.72,'NF',5,'OIP3',43); %ZVE-3W-183+
Amp2 = amplifier('Name','Amp2','Gain',30,'NF',3,'OIP3',38); %PE15A4006
Amp3 = amplifier('Name','Amp3','Gain',30,'NF',5,'OIP3',45); %PE15A4007
Amp4 = amplifier('Name','Amp4','Gain',36,'OIP3',47); %PE15A5044
Amp5 = amplifier('Name','Amp5','Gain',12,'NF',6.5); %CBM06122430

%Metasensing antenna
Antenna1 = rfelement('Name','Antenna1','Gain',12.5); %fc = 9.4 GHz

elements(1) = SDR;
elements(2) = Attenuator;
elements(3) = Pre_mix_coax1;
elements(4) = IFBPfilter3;
elements(5) = Mixer3;
elements(6) = Slip_ring;
elements(7) = Post_mix_coax1;
elements(8) = Amp5;
elements(9) = RFBPfilter1;
elements(10) = Amp4;
elements(11) = Antenna1;

TXchain = rfbudget('Elements',elements,'InputFrequency',3.875e9, ...
    'AvailableInputPower',10,'SignalBandwidth',15e6);
show(TXchain)
```

9.2.3. RF budget analyser app code used for Slotted Waveguide antenna setup

```
%%% TX chain for slotted waveguide array antenna, Fc = 9.7 GHz

clear all

%SDR USRP B210
SDR = rfelement('Name','SDR','NF',8);

%Attenuator
Attenuator = rfelement('Name','Attenuator','Gain',-10,'NF',10);

%Coax cabling
Pre_mix_coax1 = rfelement('Name','pre_mix_coax1','Gain',-0.187,'NF',0.121); %LMR-600
Pre_mix_coax2 = rfelement('Name','pre_mix_coax2','Gain',-0.16,'NF',0.16); %PE-C600
Post_mix_coax1 = rfelement('Name','post_mix_coax1','Gain',-0.601,'NF',0.75); %PE-1/2SFHC
Post_mix_coax2 = rfelement('Name','post_mix_coax2','Gain',-0.9,'NF',0.9); %PE-P300LL

%IF bandpass filters
IFBPfilter1 = rfelement('Name','IFBPfilt1','Gain',-1.75,'NF',1.75); %WBCGV4
IFBPfilter2 = rfelement('Name','IFBPfilt2','Gain',-2.5,'NF',2.5); %WBCJV5
IFBPfilter3 = rfelement('Name','IFBPfilt3','Gain',-0.6,'NF',0.6); %ZVBP-3875-S+

%Mixers for upconverter stage
Mixer1 = modulator('Name','Mixer1','Gain',-9,'NF',9,'OIP3',2.5,'LO',5.825e9,'ConverterType','Up'); %MM1-0320L
Mixer2 = modulator('Name','Mixer2','Gain',-9,'NF',9,'OIP3',10,'LO',5.825e9,'ConverterType','Up'); %MT3H-0113L
Mixer3 = modulator('Name','Mixer3','Gain',-6,'NF',6,'OIP3',9,'LO',5.825e9,'ConverterType','Up'); %MM2-0530
```

```
    L

%Slip ring
Slip_ring = rfelement('Name','Slip_ring','Gain',-0.5,'NF',0.5);

%RF bandpass filters
RFBPfilter1 = rfelement('Name','RFBPfilt1','Gain',-5,'NF',5); %WBCX7, pb=+-25MHz, sb=+-75MHz
RFBPfilter2 = rfelement('Name','RFBPfilt2','Gain',-3.75,'NF',3.75); %WBCX7, pb=+-37.5MHZ, sb=+-112.5MHz
RFBPfilter3 = rfelement('Name','RFBPfilt3','Gain',-2.5,'NF',2.5); %WBCQV3, pb=+-10MHz, sb =+-240MHz
RFBPfilter4 = rfelement('Name','RFBPfilt4','Gain',-1.75,'NF',1.75); %WBCX5, pb=+-87.5Mhz, sb = +-250Mhz

%amplifiers
Amp1 = amplifier('Name','Amp1','Gain',33.72,'NF',5,'OIP3',43); %ZVE-3W-183+
Amp2 = amplifier('Name','Amp2','Gain',30,'NF',3,'OIP3',38); %PE15A4006
Amp3 = amplifier('Name','Amp3','Gain',30,'NF',5,'OIP3',45); %PE15A4007
Amp4 = amplifier('Name','Amp4','Gain',36,'OIP3',47); %PE15A5044
Amp5 = amplifier('Name','Amp5','Gain',12,'NF',6.5); %CBM06122430

%Coax-to-waveguide adapter
Adapter = rfelement('Name','Adapter','Gain',-0.3,'NF',0.3);

%Slotted waveguide array antenna
Antenna2 = rfelement('Name','Antenna2','Gain',27); %fc = 9.7 GHz

elements(1) = SDR;
elements(2) = Attenuator;
elements(3) = Pre_mix_coax1;
elements(4) = IFBPfilter3;
elements(5) = Mixer3;
elements(6) = Slip_ring;
elements(7) = Post_mix_coax1;
elements(8) = Amp5;
elements(9) = RFBPfilter1;
elements(10) = Amp4;
elements(11) = Adapter;
elements(12) = Antenna2;

TXchain = rfbudget('Elements',elements,'InputFrequency',3.875e9, ...
    'AvailableInputPower',10,'SignalBandwidth',15e6);
show(TXchain)
```

9.2.4. Mixer behaviour simulation code

```
%% Mixer behaviour

Fif = 3.875;          % Input frequency is 3.875GHz
Flo = 5.825;          % Local oscillator frequency is 5.825Ghz

Frf = Fif + Flo;        % The desired output frequency

P_if = 0;               % dBm power of the IF input
P_lo = 10;              % dBm power of the LO input

delta_P = P_if - P_lo;  % Power difference, necessary for attenuation of the image frequencies

% The output of the mixer will have every possible combination of integer
% multiples of Fif and Flo with their attenuations approximated by the
% B. Henderson model (Predicting Intermodulation Suppressionin
% Double-Balanced Mixers)

% Only the image frequencies close to the desired frequency are of great
% importance

F = [Flo + Fif, 0;
    Flo - Fif, 0;
    Fif, -28;
    2*Fif, -61;
    3*Fif, -80;
    Flo + 2*Fif, -44;
    3*Fif - Flo, -59;
    2*Flo - Fif, -31;
```

```
    2*Flo - 2*Fif, -50;
    3*Flo - Fif, -2;
    3*Flo - 2*Fif, -57;
    3*Flo - 3*Fif, -61];


% Necessary for plotting a figure
F = transpose(F);

x = F(1,:);
y = F(2,:);

figure
stem(x,y)
ax = gca;
ax.XAxisLocation = 'top';
ylim([-80 10])
title('Output frequencies of the mixer')
xlabel('Frequency (Ghz)')
ylabel('Spur Power (dB)')
grid on
```

9.2.5. Code used to plot the Ovals of Cassini

```
clear all
close all
%% Blind range
tx = [0 0]; rx = [50e3 0];
radius = 5e3;
targets = [ (rx + [-0.8*radius,0*radius]);...
            (rx + [-0.3*radius,-0.15*radius]);...
            (rx + [-0.7*radius,-0.4*radius]);...
            (rx + [-0.5*radius,0.5*radius]);...
            (rx + [-0.1*radius,-0.2*radius]);...
            (rx + [-0.5*radius,0.8*radius]);...
            (rx + [0.3*radius,0.9*radius]);...
            (rx + [0.35*radius,0.45*radius]);...
            (rx + [0.35*radius,-0.4*radius]);...
            (rx + [0.8*radius,0*radius])];
[xr,yr] = minisorange(tx,rx,1,radius);

%% Cassini Ovals
radarequation

Rt = 2e3; Rr = 0.85e3;
SNRmin = K/((Rt^2)*(Rr^2)); SNRmin = pow2db(SNRmin);
% SNRmin = 10;
L = Rt; % Distance between transmitter and receiver
SNR = linspace(SNRmin,SNRmin+6*3,7); % Signal-to-Noise Ratio

% K = 30*(L^4);
plots = zeros(1,2*length(SNR));
label = strings(1,length(SNR));
colors = hsv(length(SNR));

figure
for i = 1:length(SNR)
    SNR_i = db2pow(SNR(i));
    a = L/2;
    b = (K/SNR_i)^(1/4);
    [x,y] = cassini(a,b) ;
    x = real(x); y = real(y);

    label(i) = sprintf('SNR = %.1f dB', pow2db(SNR_i));

    hold on
    plots(i) = plot((x(1,:)+L/2)*1e-3,(y(1,:)*1e-3), 'color', colors(i,:));
    plots(i) = plot((x(1,:)+L/2)*1e-3,(y(1,:)*1e-3), 'color', colors(i,:));

    % When multiple ovals have the same SNR assign the same color
    if a > b
```

```
        plots(i+1) = plot((x(2,:)+L/2)*1e-3,(y(2,:)*1e-3),...
            'color', colors(i,:));
    end
end

lgd = legend(plots(1:i),label(1:i),'location','south');
lgd.NumColumns = 3;
plot(0,0,'x','DisplayName','Tx')
plot(L/1e3,0,'x','DisplayName','Rx')
hold off
xlabel('Range (km)')
ylabel('Range (km)')
% title(['Ovals of Cassini with SNR_{min} = ',num2str(SNRmin),' dB'])
axis equal
box on
grid
%% ROC Plot
SNR = [-8:3:13];
Pfa = linspace(0,1,1e6);
colors = lines(length(SNR));
for i = 1:length(SNR)
    label = ['SNR = ',num2str(SNR(i)),' dB'];
    Pd = Pfa.^(1./(1+db2pow(SNR(i))));
    plot(Pfa,Pd,'DisplayName',label,'Color',colors(i,:))
    hold on
end
hold off
xlabel('Probability of false alarm P_{fa}')
ylabel('Probability of detection P_{d}')
title('ROC for Swerling-1')
legend('location','southeast')
```

```
function [x,y] = cassini(a,b,debug)
%CASSINI calculate the ovals of Cassini in Cartesian coordinates.
%   [x,y] = cassini(a,b)
%   - a     = major of the ellipse
%   - b     = minor of the ellipse
%   - debug = default is 0, if set to 1 the lower and upper bounds of
%             theta are displayed of the sake of debugging
%   [x,y] = cassini(a,b,1)

    arguments
        a       (:,:) {mustBeNumeric,mustBeReal}
        b       (:,:) {mustBeNumeric,mustBeReal}
        debug   (1,1) {mustBeNumeric,mustBeReal} = 0;
    end

    % First find the range where the cassini ovals are valid
    thetaStart = -asin((b./a)^2);   % Compute lower bound theta
    thetaStart = real(thetaStart);  % Discard the imaginary part if present
    thetaEnd = -thetaStart;         % Compute upper boud of theta

    if debug
        disp(['thetaStart = ',num2str(thetaStart),...
                        ' and thetaEnd = ',num2str(thetaEnd)])
    end

    resolution = abs(thetaEnd-thetaStart)/100e3; % Compute intervals
    theta =(thetaStart:resolution:thetaEnd);     % Generate theta array

    % Calculate the radii in polar space
    r1 = a.*sqrt(cos(2.*theta)+sqrt((b./a).^4-sin(2.*theta).^2));
    r2 = -a.*sqrt(cos(2.*theta)+sqrt((b./a).^4-sin(2.*theta).^2));

    % Transform polar coordinates to Cartesian
    [x1,y1] = pol2cart(theta,r1);
    [x2,y2] = pol2cart(theta,r2);
    x = [x1 x2];
    y = [y1 y2];

    x(imag(x)~=0) = []; % Nullify the imaginary curves
```

```
    y(imag(y)~=0) = []; % Nullify the imaginary curves

    if a>b      % Ignore r3 and r4 when the dicriminant is negative
        % Calculate the radii in polar space
        r3=a.*sqrt(cos(2.*theta)-sqrt((b./a).^4-sin(2.*theta).^2));
        r4=-a.*sqrt(cos(2.*theta)-sqrt((b./a).^4-sin(2.*theta).^2));

        [x3,y3]=pol2cart(theta,r3);
        [x4,y4]=pol2cart(theta,r4);

        x2 = [x3 x4];
        y2 = [y3 y4];

        x2(imag(x2)~=0)=[]; % Nullify the imaginary curves
        y2(imag(y2)~=0)=[]; % Nullify the imaginary curves

    % Concatenate x and x2, similarly y and y2 into one matrix when two
    % ovals are computed
    x = [x(1:length(x)/2)       x2(length(x2)/2:-1:1);...
         x(length(x)/2+1:end)   x2(end:-1:length(x2)/2+1)];
    y = [y(1:length(y)/2)       y2(length(y2)/2:-1:1);...
         y(length(y)/2+1:end)   y2(end:-1:length(y2)/2+1)];
    end
end
```

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