

# Contents

|          |   |           |
|----------|---|-----------|
| <b>1</b> | <b>Introduction</b>                       | <b>3</b>  |
| 1.1      | Intent . . . . .                          | 3         |
| 1.2      | How to Use this Document . . . . .        | 3         |
| 1.3      | Overview . . . . .                        | 4         |
| <b>2</b> | <b>Circuit Description</b>                | <b>5</b>  |
| 2.1      | Power . . . . .                           | 6         |
| 2.1.1    | Overview . . . . .                        | 6         |
| 2.1.2    | Barrel Jack / Power Input . . . . .       | 6         |
| 2.1.3    | TPS5420D Buck Converter . . . . .         | 6         |
| 2.1.4    | LP2985A-10DBVR Linear Regulator . . . . . | 9         |
| 2.1.5    | BOM . . . . .                             | 11        |
| 2.2      | Top Level Schematic . . . . .             | 12        |
| 2.2.1    | KT2520K 40MHz TXCO . . . . .              | 12        |
| 2.2.2    | NC7S04 Inverter . . . . .                 | 12        |
| 2.2.3    | NB3N551 1:4 Clock Buffer . . . . .        | 12        |
| 2.3      | TX . . . . .                              | 13        |
| 2.3.1    | ADF4158 Frequency Synthesizer . . . . .   | 13        |
| 2.3.2    | HMC431LP4RF VCO . . . . .                 | 21        |
| 2.3.3    | SE2567L Power Amplifier . . . . .         | 21        |
| 2.3.4    | Notes . . . . .                           | 21        |
| 2.4      | USB . . . . .                             | 23        |
| 2.4.1    | FT2232H . . . . .                         | 23        |
| 2.4.2    | 93LC46B 1k EEPROM . . . . .               | 23        |
| 2.5      | FPGA . . . . .                            | 25        |
| 2.5.1    | Overview . . . . .                        | 25        |
| 2.5.2    | XC7A15T-FTG256 Xilinx FPGA . . . . .      | 25        |
| 2.5.3    | W25Q32JV Flash Memory . . . . .           | 34        |
| 2.6      | ADC . . . . .                             | 36        |
| 2.7      | Mixer . . . . .                           | 40        |
| 2.7.1    | ADL5802 . . . . .                         | 40        |
| 2.8      | IF . . . . .                              | 41        |
| 2.9      | RX1 & RX2 . . . . .                       | 42        |
| <b>3</b> | <b>PCB</b>                                | <b>43</b> |
| 3.1      | General Layout . . . . .                  | 43        |
| 3.2      | Component Layout Considerations . . . . . | 43        |
| 3.2.1    | Power Input . . . . .                     | 43        |

|          |                                 |           |
|----------|---------------------------------|-----------|
| 3.2.2    | LTC2292 ADC . . . . .           | 44        |
| 3.2.3    | RX1 / RX2 . . . . .             | 44        |
| 3.3      | RF Impedance Matching . . . . . | 44        |
| <b>4</b> | <b>Antennas</b>                 | <b>53</b> |
| <b>5</b> | <b>Links</b>                    | <b>54</b> |
| <b>6</b> | <b>Full Schematic</b>           | <b>55</b> |

# Chapter 1

## Introduction

### 1.1 Intent

This document explains, in a great amount of detail, the design, operation and layout of an FMCW radar PCB. The radar was originally designed by Henrik Forstén and is described [in his blog post](#). His source code is hosted on GitHub [here](#). I have made this document in an effort to understand his design and to build it myself. While most of the design remains his work, I have made several modifications for deprecated parts or other design choices. I have also made an effort to update the schematic/footprints to use the default KiCad schematic and footprint libraries where possible. The design is a work in progress and will likely be updated through several different versions in order to make improvements and add functionality. I also hope to make the design more my own as it is modified and updated. This document will be kept up-to-date with those changes.

### 1.2 How to Use this Document

This document contains several sections. The first is an in-depth description of the circuit and the function of each component in it. Each section corresponds to a schematic sheet in the design. Below each section header is a hyperlink to a PDF version of that sheet of the schematic. The hyperlink is labeled “schematic” and is italicized. The full schematic in PDF form is contained at the end of this document. I have opted for this format instead of embedding diagrams of individual components throughout the document, which I believe is more aesthetically pleasing and is easier to maintain as the schematic is updated. Each section is then further subdivided into subsections composed of the individual components in the schematic sheet. They provide a detailed description of the component’s operation and how it interacts with other components on the PCB. I also frequently include a table listing the full pinout of the component, which includes the purpose of each pin and its connections in the schematic.

The following section describes the layout of the PCB in detail. It contains a subsection describing overall layout structure, including ground planes. I’ve also included a subsection for specific component layout considerations. I’ve left out considerations that are generally good practice and are thus applicable to most digital circuits. For instance, I’ve omitted justifications for bypassing unless the component’s datasheet recommends a specific layout that differs from the default recommendations. Lastly, I’ve included a section for impedance matching.

The last section (prior to the full schematic) contains a selection of useful hyperlinks.

### **1.3 Overview**

This design uses one antenna for transmitting and two for reception.

## Chapter 2

# Circuit Description

## 2.1 Power

*schematic*

### 2.1.1 Overview

A barrel jack is used to feed a 12V input to the board which is then administered to a 10V output linear regulator and two buck converters that output 5.6V and 3.6V. The buck converters in turn pass their voltages on to several LDO voltage regulators for input to the various digital ICs on the board. The benefit of chaining switching converters to linear regulators is greater energy efficiency and better noise suppression than can be achieved by using either alone. An LED indicates when power is administered to the board.

### 2.1.2 Barrel Jack / Power Input

A ferrite bead pi filter is placed at the output of the barrel jack connection. The ferrite bead is rated for  $5.1A$ , which is more than double the absolute max current draw of the radar. The barrel connector is a switched jack, but we do not use a battery on this PCB so the 3rd pin is grounded.

### 2.1.3 TPS5420D Buck Converter

#### Description

The TPS5420D is an internally-compensated buck converter with a fixed switching frequency of 500kHz, whose block diagram is shown in Figure 2.1. The converter first compares the divided voltage output with a 1.221V reference and uses an error amplifier to amplify the difference. It then feeds that difference into a PWM comparator along with a sawtooth ramp waveform. If the PWM comparator outputs a high voltage the switch is turned off, effectively decreasing the duty cycle. Conversely, a low voltage saturates the transistor and increases the duty cycle. This has the effect of converging the output voltage to its set point.

#### Downstream Current Draw

Table 2.1: The current draw of components downstream from the 5.6V buck converter. When minimum current draw is omitted from the datasheet I've assumed 0A.

| MFN     | $I_Q$        | $I_{max}$ | Voltage Inputs        |
|---------|--------------|-----------|-----------------------|
| ADL5802 | 170mA        | 300mA     | 5V                    |
| ADF4158 | $312.5\mu A$ | 5mA       | 5V (VP)               |
| SE5004L | 300mA        | 800mA     | 5V (VCC1, VCC2, VCC3) |
| Total   | 470mA        | 1.105A    | -                     |

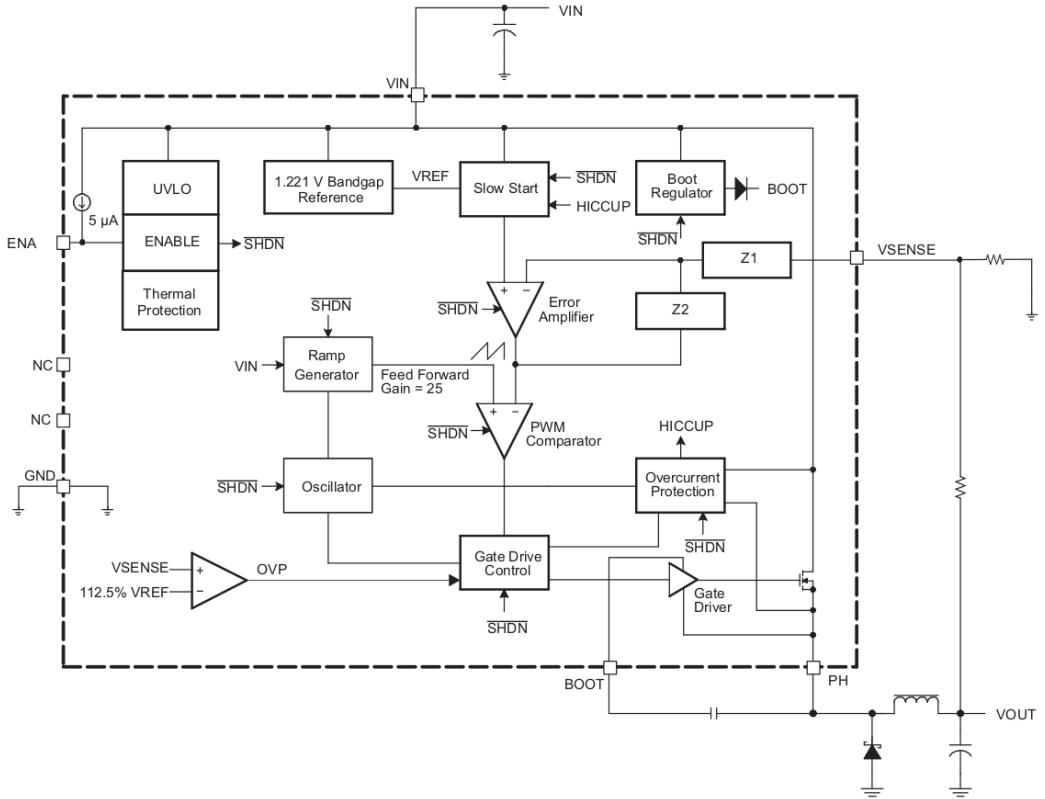


Figure 2.1: TPS5420D Block Diagram

Table 2.2: Components downstream from the 3.6V buck converter.

| MFN                   | I <sub>Q</sub> | I <sub>max</sub> | Voltage Inputs                   |
|-----------------------|----------------|------------------|----------------------------------|
| <b>KT2520K</b>        | -              | 2mA              | 1.8V                             |
| <b>NC7S04</b>         | 1 $\mu$ A      | 12.5mA           | 3.3V                             |
| <b>NB3N551</b>        | -              | 40mA             | 3.3V                             |
| <b>XC7A15T-FTG256</b> | 97mA           | 277mA            | 1V (VCCINT, VCCBRAM)             |
| <b>XC7A15T-FTG256</b> | 22mA           | 87mA             | 1.8V (VCCADC, VCCAUX)            |
| <b>XC7A15T-FTG256</b> | 1mA            | 201mA            | 3.3V (VCC0)                      |
| <b>W25Q32JV</b>       | 10 $\mu$ A     | 25mA             | 3.3V                             |
| <b>FT2232H</b>        | 510 $\mu$ A    | 280mA            | 3.3V (VPHY, VPPLL, VCORE, VCCIO) |
| <b>93LC46B</b>        | -              | 2mA              | 3.3V                             |
| <b>LTC2292</b>        | 5mA            | 95mA             | 3.3V (OVDD), 3V (VDD)            |
| <b>ADA4940-2</b>      | 4.2mA          | 5.52mA           | 3.3V                             |
| <b>ADF4158</b>        | -              | 32mA             | 3.3V (AVDD, DVDD)                |
| <b>HMC431LP4</b>      | 19mA           | 27mA             | 3V                               |
| <b>TRF37A73</b>       | 250 $\mu$ A    | 130mA            | 3V                               |
| <b>SKY65404</b>       | 20mA           | 36mA             | 3V (VENABLE, VCC)                |

Table 2.2: Components downstream from the 3.6V buck converter.

| <b>MFN</b> | <b><math>I_Q</math></b> | <b><math>I_{max}</math></b> | <b>Voltage Inputs</b> |
|------------|-------------------------|-----------------------------|-----------------------|
| Total      | 169mA                   | 1.252A                      | -                     |

## Pinout

### Fixme Fatal: What is the point of BOOT?

Table 2.3: TPS5420D pinout.

| <b>Pin</b> | <b>Description</b>  |
|------------|---|
| BOOT       |   |
| VSENSE     | Feedback voltage for the regulator. This compares the divided output with a 1.221V reference. |
| ENA        | Enable pin. This can be left floating to enable the device.                                   |
| VIN        | Input supply voltage.   |
| PH         | Output voltage.   |

## Component Selection

An inductor is chosen such that it satisfies the following 3 requirements:

1. The inductance is given by Equation 2.1.
2. The current rating is at least 2x the maximum load current.
3. The self-resonant frequency is at least 10x the switching frequency.

$$L_{min} = \frac{T}{2} \frac{V_{out}}{I_{out(min)}} \left( 1 - \frac{V_{out}}{V_{in}} \right) \quad (2.1)$$

The requirements are given in Table 2.1.3. All of these requirements are satisfied by the [SRR1210A-330M](#) 33 $\mu$ H ferrite bead by Bourns.

Table 2.4: TPS5420D inductor requirements. I've assumed an input ripple of 300mV.

| <b>Buck Vout</b> | <b>Lmin</b>  | <b>Current Rating</b> | <b>SRF min</b> |
|------------------|--------------|-----------------------|----------------|
| 5.6V             | 6.5 $\mu$ H  | 2.21A                 | 5MHz           |
| 3.6V             | 15.1 $\mu$ H | 2.50A                 | 5MHz           |

The input, output and boot capacitors were chosen by the [WEBENCH tool](#). The flyback diode was chosen to support 2A of current.

## 2.1.4 LP2985A-10DBVR Linear Regulator

### Downstream Current Draw

Table 2.5: Downstream current draw for the 10V linear regulator.

| MFN       | $I_Q$ | $I_{max}$ | Voltage Inputs |
|-----------|-------|-----------|----------------|
| TLV172DCK | 1.6mA | 75mA      | 10V            |

The buck converter outputs feed into several different chips, the first of which is an LDO regulator for which an example is shown in Figure 2.2. The reason for attaching an LDO regulator in series with a buck converter may be to reduce the noise of the circuit and increase the efficiency at the expense of board area and cost. Particularly, the [LDO regulator](#) should be able to smooth out the noise caused by using an inductor with a low value in the buck converter. It is meant to effectively reject noise from the input source over the frequency range of 10Hz to 10MHz. Since the switching frequency of the buck converter is less than 1MHz and consequently the current/voltage ripple should be of the same frequency, the LDO regulator should be sufficient to smooth out the input noise provided, however, that it does not dip below the output voltage of the LDO regulator since the margin for error is small.  $V_{IN} - V_{OUT} = 0.6V$  and linear regulators are not able to output a voltage greater than their input voltage. The max dropout of the LDO is 0.2V, which allows the output voltage of the buck converter a deviation of 0.4V.

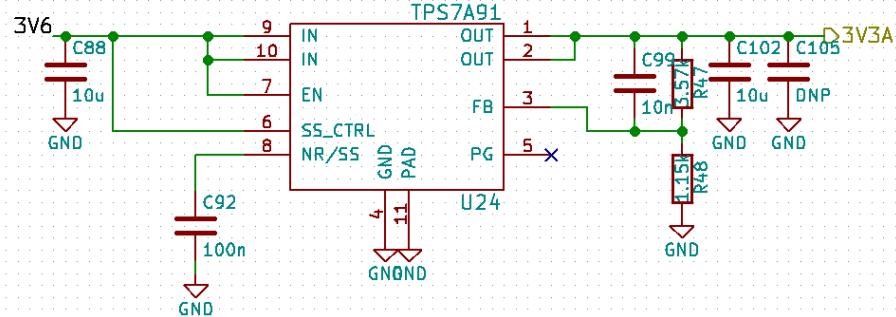


Figure 2.2: A LDO regulator that takes as an input the voltage from one of the buck converters and whose output is directly used to drive the operation of one of the ICs elsewhere in the circuit.

The input voltage is connected to both IN pins with a bypass capacitor of  $10 \mu F$ , which is the minimum specified by the datasheet. It is additionally connected to the EN pin which activates the LDO; the LDO is active for  $V_{EN} \geq V_{IH}$  and disabled for  $V_{EN} \leq V_{IL}$  (connecting the same input to IN and EN will make  $V_{EN} = V_{IH}$ , thus satisfying the first condition). The 2 resistors attached to OUT and FB make a voltage divider that determines the output voltage of the linear regulator, according to Equation 2.2.

$$R_1 = R_2 \left( \frac{V_{OUT}}{V_{REF}} - 1 \right) \quad (2.2)$$

Where  $V_{REF} = 0.8V$ . Specifically, 1.15k and 3.57k are specified in the datasheet in order to get an output voltage of 3.3V. SS\_CTRL is connected to IN instead of GND which increases the

soft-startup charging current to  $100 \mu\text{A}$  from  $6.2 \mu\text{A}$  and decreases the start-up time, which is given by Equation 2.3.

$$t_{\text{SS}} = (V_{\text{REF}} \times C_{\text{NR/SS}}) / I_{\text{NR/SS}} \quad (2.3)$$

$$= 0.8V \times 100 \times 10^{-9}F / (100 \times 10^{-6}A) \quad (2.4)$$

$$= 0.8\text{ms} \quad (2.5)$$

An output capacitor of  $10 \mu\text{F}$  is chosen which is the minimum specified by the datasheet. Additionally, a feed-forward capacitor of  $10\text{nF}$  is added between the OUT and FB pins to improve the noise and PSRR performance of the voltage regulator. The value is recommended by the datasheet. The  $C_{\text{NR/SS}}$  capacitor of  $100\text{nF}$  is used to create an output RC filter for output noise and is also used to set the soft-start time. A value of between  $10\text{nF}$  and  $10\mu\text{F}$  is recommended. PAD and GND should both be connected to ground, as indicated by the datasheet. PG indicates whether the output voltage is in a usable state. Since we are not using it, it can be left floating.

Another buck converter output feeds into the input of an ultra low LDO, with a dropout voltage of  $40\text{mV}$  as shown in Figure 2.3. R104 acts as a pull-up resistor, pulling the voltage on EN high when PG is not driven. However, when PG is low, EN will be driven low. The bypass pin is left open, although a  $1\mu\text{F}$  capacitor could have been placed there to reduce output noise.

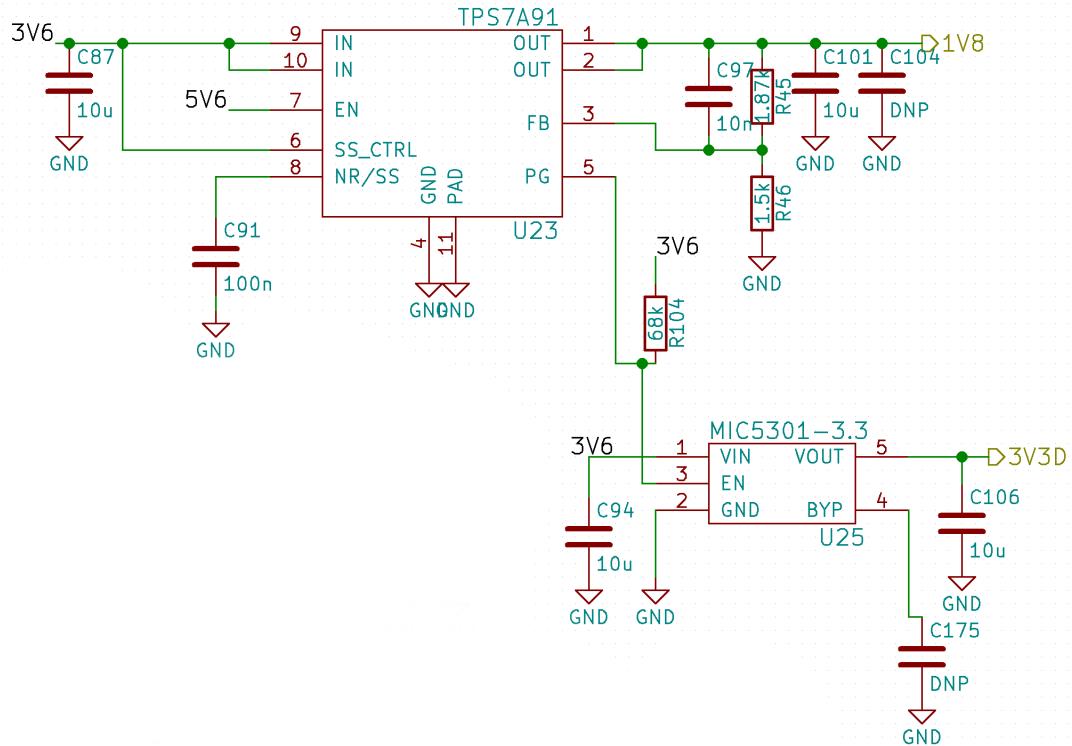


Figure 2.3: An ultra LDO regulator whose output feeds into an FPGA input. It uses the PG pin from another LDO regulator to alternately enable/disable it.

Another output from a buck converter leads to a  $3\text{V}$  output LDO regulator with a dropout voltage of  $120\text{mV}$  shown in Figure 2.4. All of the pin connections are evident.

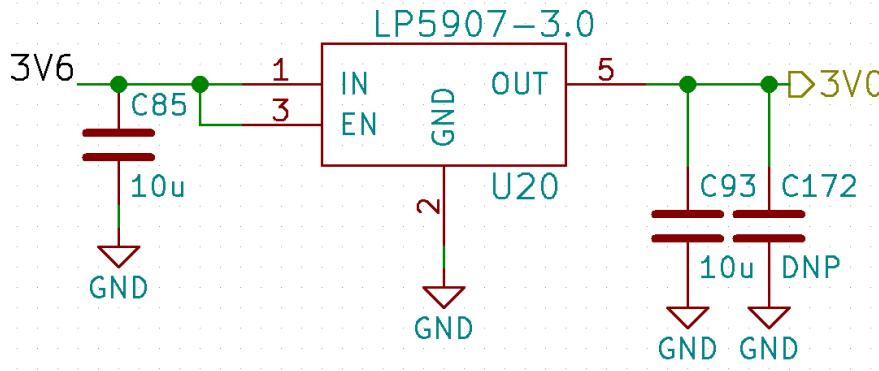


Figure 2.4: The LP5907 is a 3V LDO regulator with a dropout voltage of 120mV.

The last component on the power sheet is an [LP2985](#) LDO regulator shown in Figure 2.5, that takes the 12V input voltage from the barrel jack and outputs 10V. ON/OFF is an active-low shutdown pin, so it is tied to  $V_{IN}$ . A 10nF capacitor is tied to BYPASS to decrease the output noise.

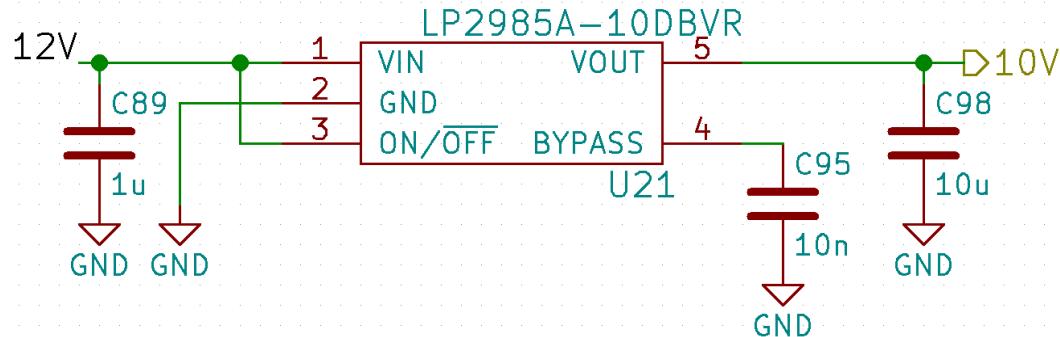


Figure 2.5: The LP2985 LDO regulator.

### 2.1.5 BOM

| Designators | Description              | MFN                           | QTY | Links  |
|-------------|--------------------------|-------------------------------|-----|--|
| FB11        | barrel jack ferrite bead | 74279228600                   | 1   | <a href="#">Datasheet</a> , <a href="#">Digi-Key</a> |
| U18, U19    | buck converter           | <a href="#">TPS5420D</a>      | 2   | <a href="#">Datasheet</a> , <a href="#">Digi-Key</a> |
| U21         | linear regulator         | <a href="#">LP985A-10DBVR</a> | 1   | <a href="#">Datasheet</a> , <a href="#">Digi-Key</a> |

## 2.2 Top Level Schematic

### *schematic*

The top level sheet instantiates the various subcomponents of the design. Additionally, it generates a 40MHz clock signal that feeds into a clock buffer and is output to various components, as shown in Figure 2.6. The LP5907 is a voltage regulator that takes a 3.6V input signal generated by a buck converter on the power sheet and outputs a 1.8V signal to power the KT2520K crystal oscillator which generates a 40MHz clock signal. The coupling capacitor attached in series to the output of the crystal oscillator will prevent a DC bias from leaving the crystal oscillator. The Schmitt inverter is used to turn the clipped sine wave output of the crystal oscillator into a square wave. By connecting the output of the Schmitt inverter back to its input via two resistors with a bypass capacitor between them, the input sine wave to the trigger becomes centered around VCC/2, or 1.65V in this case. The capacitor filters out the high frequency signals centers it just at the DC bias level. The 40MHz square wave feeds into the clock fanout buffer NB3N551 which generates 3 clock outputs that oscillate at 40 MHz between about 0V and 3V.

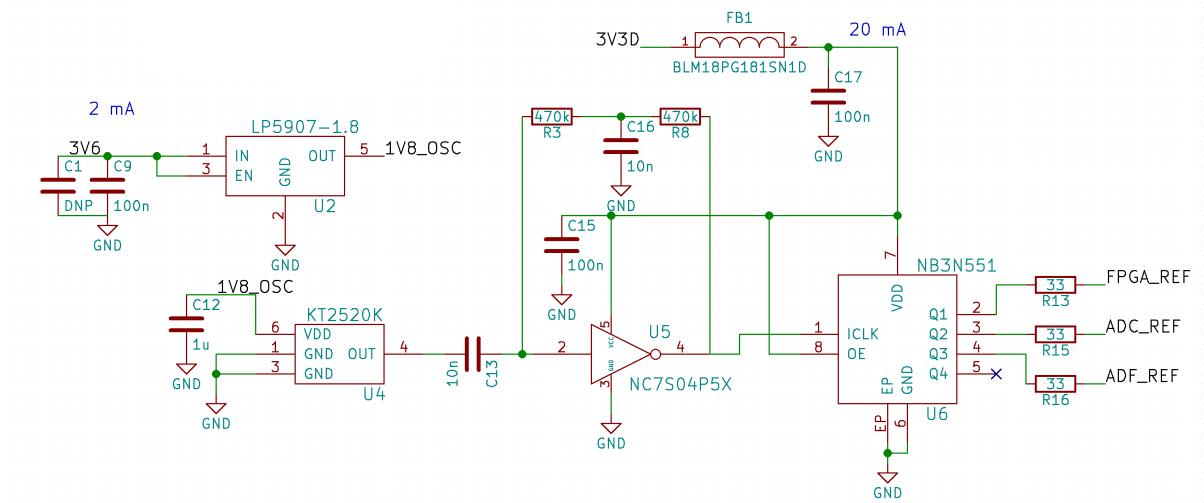


Figure 2.6: A 40MHz clock signal is used to synchronize different components on the board.

### 2.2.1 KT2520K 40MHz TXCO

### 2.2.2 NC7S04 Inverter

### 2.2.3 NB3N551 1:4 Clock Buffer

## 2.3 TX

*schematic*

### 2.3.1 ADF4158 Frequency Synthesizer

#### Overview

The [ADF4158](#) is a 6.1GHz fractional-n frequency synthesizer. A block diagram describing its functionality is shown in Figure 2.7.

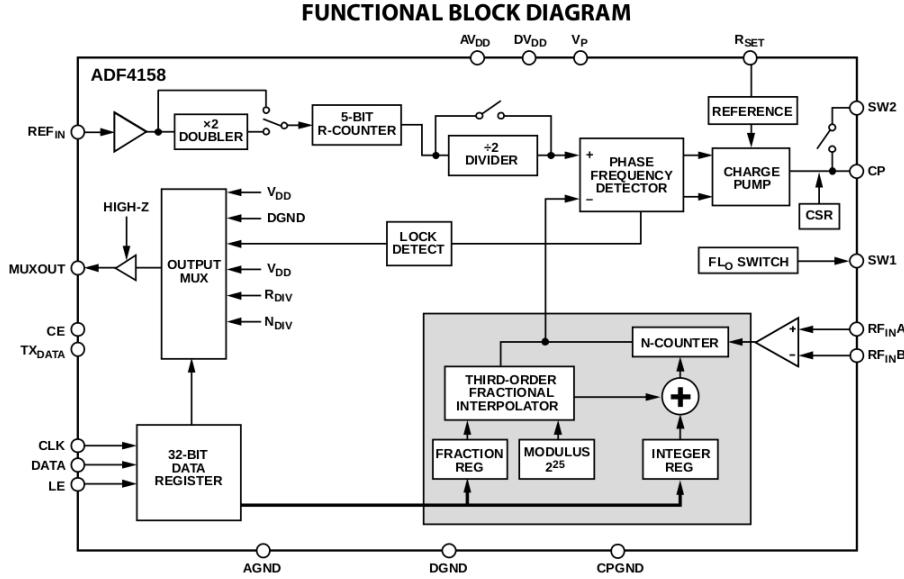


Figure 2.7: ADF4158 block diagram.

The ADF4158 relies on an external VCO, described in § 2.3.2, whose output frequency is given by Equation 2.6. The output resolution is  $f_{RES} = f_{PFD}/2^{25}$  (see Equation 2.6 and its corresponding parameter table for an explanation of  $f_{PFD}$ ). The  $2^{25}$  arises from the FRAC value (set in registers 0 and 1) which is given 25 bits.

$$\begin{aligned} RF_{OUT} &= f_{PFD} \times (INT + (FRAC/2^{25})) \\ f_{PFD} &= REF_{IN} \times [(1 + D) / (R \times (1 + T))] \end{aligned} \quad (2.6)$$

---

| Parameter/Variable | Description  |
|--------------------|--|
| $RF_{OUT}$         | The VCO's output frequency. This is the frequency that's amplified for transmission. |
| $f_{PFD}$          | The input frequency to the PFD post prescaling. In our case this is 20MHz.           |
| INT                | The N counter that has a multiplicative effect on the VCO output frequency.          |

---

---

| Parameter/Variable | Description  |
|--------------------|--|
| FRAC               | FRAC is the numerator of the fractional number added to INT. This is what distinguishes fractional-n synthesis from integer-n synthesis. It allows greater precision for the VCO output frequency without significantly increasing the prescalers and N counter. |
| REF <sub>IN</sub>  | The reference input frequency, which in our case is a 40MHz clock signal from the fanout buffer on the top level of the schematic.   |
| D                  | The doubler bit, which can be 0 or 1. If set to 1, the REF <sub>IN</sub> frequency is doubled before arriving at the R counter.  |
| R                  | The input prescaler.   |
| T                  | The divide- by-2 bit, which can be 0 or 1 and divides the frequency by 2 between the R prescaler and PFD.  |

---

### Waveform Generation

The ADF4158 is capable of producing several different waveforms. The one used in this design is a sawtooth ramp in frequency as a function of time, shown in Figure 2.8. There are 3 different parameters that determine the shape of a ramp: (1) frequency deviation (the amount the frequency increases at each time step), (2) timeout interval (the amount of time between each time step) and (3) the number of time steps. This is shown diagrammatically in Figure 2.9. The equations governing these parameters are given in Equation 2.7. The number of steps is set directly in register 6. In our configuration  $f_{DEV} = 300\text{kHz}$  and Timer =  $0.5\mu\text{s}$ , which given that the number of steps is equal to 2000 and the starting frequency is 5.3GHz, the sawtooth will ramp from 5.3GHz to 5.9GHz in 1ms. We also use a delay between bursts of 2ms. Equation 2.8 is used to derive this.

$$f_{DEV} = (f_{PFD}/2^{25}) \times (\text{DEV} \times 2^{\text{DEV\_OFFSET}}) \quad (2.7)$$

$$\text{Timer} = \text{CLK}_1 \times \text{CLK}_2 \times (1/f_{PFD})$$

---

| Parameter/Variable | Description  |
|--------------------|--|
| $f_{DEV}$          | The frequency deviation for each frequency jump during ramp.               |
| $f_{PFD}$          | The input frequency to the PFD post prescaling. In our case this is 20MHz. |
| DEV                | A 16-bit value set in register 5.  |
| DEV_OFFSET         | A 4-bit word set in register 5.  |
| Timer              | The time between each frequency hop.                                       |
| $\text{CLK}_1$     | A 12-bit clock divider set in register 2.                                  |
| $\text{CLK}_2$     | Another 12-bit clock divider set in register 4.                            |

---

$$\text{Delay} = t_{PFD} \times \text{CLK}_1 \times \text{Delay Start Word} \quad (2.8)$$

---

| Parameter/Variable | Description  |
|--------------------|--|
| Delay              | The delay between bursts. This is shown graphically in Figure 2.10.        |
| $f_{PFD}$          | The input frequency to the PFD post prescaling. In our case this is 20MHz. |
| $CLK_1$            | A 12-bit clock divider set in register 2.                                  |
| Delay Start Word   | A 12-bit value set in register 7.  |

---

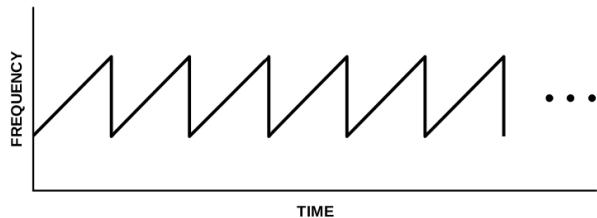


Figure 2.8: Sawtooth ramp.

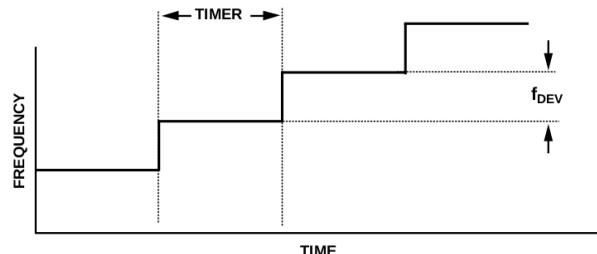


Figure 2.9: Waveform timing.

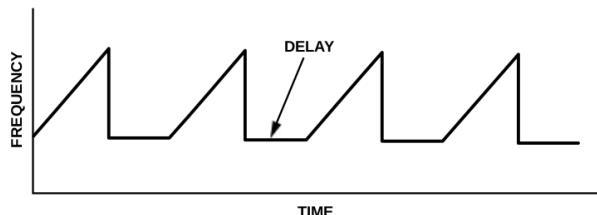


Figure 2.10: Delay between ramps for sawtooth mode.

## Configuration Registers

The ADF4158 contains 8 configuration registers. The configurations are shown in the tables below. All reserved bits should be set to 0. The control bits are the least significant 3 bits of each register and are set to the register number for each register (e.g. register 0 is 000 and register 1 is 001). I've left these out of the tables because their values are obvious.

Table 2.10: FRAC/INT REGISTER (R0) MAP

| <b>Bits</b> | <b>Mnemonic</b> | <b>Value</b> | <b>DESCRIPTION</b>  |
|-------------|-----------------|--------------|---|
| 3–14        | FRAC(MSB)       | 0            | This sets the 12 most significant bits of FRAC. We leave the fractional value at 0.   |
| 15–26       | INT             | 265          | This is the feedback, or N, counter.  |
| 27–30       | MUXOUT Control  | 15           | This enables “readback to muxout” which allows interrupting waveform generation and reading back the frequency at the time of interrupt. The functionality is not fully setup on the board(muxout connects to a DNP NMOS) and TX_DATA, which can trigger the interrupt, is set to 0 by the FPGA HDL and left there. |
| 31          | Ramp On         | 1            | This bit enables the ramp.  |

Table 2.11: LSB FRAC REGISTER(R1) MAP

| <b>Bits</b> | <b>Mnemonic</b> | <b>Value</b> | <b>DESCRIPTION</b>   |
|-------------|-----------------|--------------|--|
| 3–14        | Reserved        | 0            | All reserved bits set to 0.  |
| 15–27       | FRAC(LSB)       | 0            | This sets the 13 least significant bits of FRAC. We leave the fractional value at 0. |
| 28–31       | Reserved        | 0            | All reserved bits set to 0.  |

Table 2.12: R-DIVIDER REGISTER(R2) MAP

| <b>Bits</b> | <b>Mnemonic</b>          | <b>Value</b> | <b>DESCRIPTION</b>   |
|-------------|--------------------------|--------------|--|
| 3–14        | CLK <sub>1</sub> Divider | 10           | One of the determinants of the duration of a timestep in waveform generation. See § 2.3.1 for more details.  |
| 15–19       | R-Counter                | 1            | This 5-bit segment is used to divide the frequency of the reference signal before it enters the PFD. We leave it at 1 and thus do not use it to divide the frequency.  |
| 20          | Reference Doubler        | 0            | We leave this at 0 and thus do not use the doubler to double the reference signal frequency before input to the PFD. The maximum input frequency for the PFD is 30MHz and so doubling our 20MHz signal (we used the divider to divide the 40MHz signal by 2) would violate this condition. |
| 21          | RDIV2                    | 1            | Inserts a divide-by-2 toggle flip-flop between the R-counter and PFD. This provides a 50% duty cycle that allows cycle slip reduction to be used which improves lock times.  |

Table 2.12: R-DIVIDER REGISTER(R2) MAP

| <b>Bits</b> | <b>Mnemonic</b>             | <b>Value</b> | <b>DESCRIPTION</b>   |
|-------------|-----------------------------|--------------|--|
| 22          | Prescaler                   | 1            | The prescaler limits the INT value and through that the maximum frequency to 3GHz. Since we have an INT value of 265 and our maximum frequency is almost double 3GHz we set this to 1. |
| 23          | Reserved                    | 0            | All reserved bits set to 0.  |
| 24–27       | Charge Pump Current Setting | 0            | Sets the current to the minimum value which is 0.31mA and is the level necessary to use cycle slip reduction which we are.   |
| 28          | CSR Enable                  | 1            | Enables cycle slip reduction which provides better lock times.   |
| 29–31       | Reserved                    | 0            | All reserved bits are set to 0.  |

Table 2.13: FUNCTION REGISTER(R3) MAP

| <b>Bits</b> | <b>Mnemonic</b>         | <b>Value</b> | <b>DESCRIPTION</b>  |
|-------------|-------------------------|--------------|---|
| 3           | Counter Reset           | 0            | When this is set to 1, the synthesizer counters are held in reset. For normal operation we set this to 0.   |
| 4           | Charge Pump Three-State | 0            | Holds the charge pump in three-state mode if set to 1. For normal operation it must be set to 0.  |
| 5           | Power-Down              | 0            | Setting this to 1 powers down the device. Setting it to 0 allows normal operation.  |
| 6           | PD Polarity             | 1            | Set to 1 for positive VCO characteristics. Set to 0 for negative VCO characteristics. Since our VCO outputs a positive voltage signal we set this to 1.   |
| 7           | LD <sub>P</sub>         | 0            | Sets the minimum number of PFD cycles before a lock detect can be set.  |
| 8           | FSK Enable              | 0            | Disables FSK modulation.  |
| 9           | PSK Enable              | 0            | Disables PSK modulation.  |
| 10-11       | Ramp Mode               | 0            | Sets the waveform as a continuous sawtooth.   |
| 12-13       | Reserved                | 0            | All reserve bits are set to 0.  |
| 14          | SD Reset                | 0            | Setting this to 0 resets the $\Sigma - \Delta$ modulator on each write to register 0, which is the recommended operation. Setting this to 1 disables resetting the modulator.                           |
| 15          | N SEL                   | 0            | When set to 1, this creates an additional delay in setting INT and FRAC which can prevent the PLL overshooting. Since we set INT once and do not update it, this is not necessary and we leave it as 0. |
| 16-31       | Reserved                | 0            | All reserve bits are set to 0.  |

Table 2.14: TEST REGISTER(R4) MAP

| <b>Bits</b> | <b>Mnemonic</b>          | <b>Value</b> | <b>DESCRIPTION</b>  |
|-------------|--------------------------|--------------|---|
| 3–6         | Reserved                 | 0            | All reserved bits are set to 0.   |
| 7–18        | CLK <sub>2</sub> Divider | 1            | This is used to set the timeout interval in ramp generation. See § 2.3.1 for more information.  |
| 19–20       | CLK DIV Mode             | 3            | This enables ramp divider mode, which specifies that CLK <sub>1</sub> and CLK <sub>2</sub> are used for ramp generation.  |
| 21–22       | Readback to MUXOUT       | 3            | Confusingly, this has been set to 3, which corresponds to neither of the supported values. Since we don't actually use the MUXOUT, this seems to be fine. If, at some point in the future, we do use the MUXOUT we will probably need to fix this.  |
| 23–24       | Negative Bleed Current   | 0            | This setting can help improve performance in the dead zone. We've disabled it. Note that this setting and readback to MUXOUT cannot simultaneously be enabled. To understand this setting better refer to <a href="#">AN-1154 Application Note</a> .  |
| 25          | Reserved                 | 0            | All reserved bits are set to 0.   |
| 26–30       | Σ – Δ modulator mode     | 0            | 0 enables this during normal operation. We can set it to 14 when FRAC=0. Even though we've set FRAC to 0, we have left this as 0 which seems strange. It shouldn't cause anything to malfunction, but may cause the ADF4158 to draw more power. We should experiment with setting this to 14 when using the actual board. |
| 31          | LE SEL                   | 0            | LE is the load enable pin which we use to load data onto the ADF4158's internal registers. Setting this to 0 enables the default operation of using the pin to set LE. Setting it to 1 would synchronize it with the reference signal.  |

Table 2.15: DEVIATION REGISTER (R5) MAP

| <b>Bits</b> | <b>Mnemonic</b>       | <b>Value</b> | <b>DESCRIPTION</b>  |
|-------------|-----------------------|--------------|---|
| 3–18        | Deviation Word        | 31457        | This is used to set the size of successive frequency jumps during ramp. See § 2.3.1 for more information.                   |
| 19–22       | Deviation Offset Word | 4            | This is also used to set the size of successive frequency jumps during ramp. See § 2.3.1 for more information.              |
| 23          | Deviation Select      | 0            | Setting this bit to 1 is used for FSK as described on page 28 of the datasheet. Since we do not use FSK we leave this as 0. |

Table 2.15: DEVIATION REGISTER (R5) MAP

| Bits  | Mnemonic        | Value | DESCRIPTION  |
|-------|-----------------|-------|--|
| 24    | Ramp 2 Enable   | 0     | Setting this bit to 1 allows a second ramp with different settings than the first. We only need the first ramp.  |
| 25    | FSK Ramp Enable | 0     | Setting this bit to 1 uses FSK. Again, we do not use FSK and so leave this bit as 0.   |
| 26–27 | Interrupt       | 0     | Sets the type of interrupt used to read the value of INT and FRAC of the ramp at a given moment. We don't read these values and therefore leave this as 0, which corresponds to interrupt off. |
| 28    | PAR Ramp        | 0     | Setting this bit to 1 allows a parabolic ramp which we don't use.  |
| 29    | Tx Ramp CLK     | 0     | Setting this to 0 uses the clock divider (instead of the TX data clock) for clocking the ramp.   |
| 30–31 | Reserved        | 0     |  |

Table 2.16: STEP REGISTER (R6) MAP

| Bits  | Mnemonic  | Value | DESCRIPTION  |
|-------|-----------|-------|--|
| 3–22  | Step Word | 2000  | This determines the number of steps in a ramp. To understand this see § 2.3.1 on waveform generation.  |
| 23    | Step SEL  | 0     | This bit is used when 2 different ramps are needed (for instance with FSK). As we don't need this functionality we leave it off and set this bit to 0. |
| 24–31 | Reserved  | 0     |  |

Table 2.17: DELAY REGISTER (R7) MAP

| Bits  | Mnemonic             | Value | DESCRIPTION   |
|-------|----------------------|-------|---|
| 3–14  | Delayed Start Word   | 4000  | Sets the ramp start delay. We do not use a start delay, but we do use this to delay between ramps.  |
| 15    | Delayed Start Enable | 0     | We do not use a start delay.  |
| 16    | Delay Clock Select   | 1     | Increases the period of the delay clock by multiplying the period of the PFD clock by CLK <sub>1</sub> . This creates an effective period of 500ns. |
| 17    | Ramp Delay           | 1     | We enable a delay between ramp bursts.  |
| 18    | Ramp Delay Fast Lock | 0     | Disables the ramp delay fast lock function.   |
| 19–31 | Reserved             | 0     |   |

**FIXME** I need to finish describing this component along with all other component on this sheet.

Table 2.18: All ADF4158 pin connections.

| PIN     | Mnemonic           | DESCRIPTION   |
|---------|--------------------|---|
| 1       | CPGND              | The charge pump ground, which we set to the same ground as the rest of the circuit.   |
| 2, 3    | AGND               | Prescaler ground; also set to common ground.  |
| 4       | RF <sub>IN</sub> B | The complement to the VCO output. We couple this to ground with a small capacitor: in this case, 10pF.  |
| 5       | RF <sub>IN</sub> A | The VCO output. This goes through prescaling and then becomes the PLL input signal.   |
| 6, 7, 8 | AV <sub>DD</sub>   | The positive power supply for the RF part of the PLL. This takes 3.3V.  |
| 9       | REF <sub>IN</sub>  | The reference input, which is our 40MHz clock signal.   |
| 10      | DGND               | Digital ground. This uses the common ground.  |
| 11      | SDGND              | $\Sigma - \Delta$ modulator ground.   |
| 12      | TX <sub>DATA</sub> | This pin can be used when employing FSK or PSK to transmit data. Since we are not using this we connect this pin to the FPGA but just set the value to GND.   |
| 13      | CE                 | We must set this pin to high in order to enable the device.   |
| 14      | CLK                | A clock used to synchronize register configuration.   |
| 15      | DATA               | Serial data input to set the configuration registers.   |
| 16      | LE                 | This pin is brought high in order to load data into the configuration registers.  |
| 17      | MUXOUT             | This allows internal parameters of the ADF4158 to be read externally. We don't currently use this in our design.  |
| 18      | SDV <sub>DD</sub>  | Power supply pin for the $\Sigma - \Delta$ modulator. We also set this to 3.3V.   |
| 19      | DV <sub>DD</sub>   | Power supply pin for the digital circuitry. Also 3.3V.  |
| 20, 21  | SW1, SW2           | FIXME: These pins are used for the fast-locking feature, which we use in our design. The typical topologies for this are shown in Figure 2.11. However, our design does not use either of these topologies. |
| 22      | V <sub>P</sub>     | The charge pump power supply, which we set to 5V.   |
| 23      | R <sub>SET</sub>   | This pin sets the maximum charge pump current according to the equation $I_{CP\max} = 25.5/R_{SET}$ . We use 5.49k $\Omega$ for the resistor which gives a charge pump current of 4.6mA.                    |
| 24      | CP                 | The charge pump output that is amplified and feeds into the VCO. Obviously, because this is a charge pump we need to place a bypass capacitor to ground before the amplifier. Here we use 51pF.             |
| 25      | EPAD               | This is connected to GND.   |

## TLV2172 Operational Amplifier

The [TLV2172](#) op-amp is used to produce a gain of 2 to match the CP output of the ADF4158 to the VTUNE input of the VCO. This is necessary since the charge pump supports a tune voltage of up to 5.5V but the VCO has a tune range of 0V to 10V. A non-inverting amplifier configuration is used to produce the necessary gain.

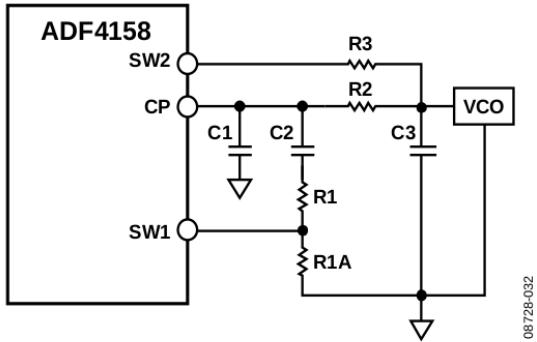


Figure 46. Fast-Lock Loop Filter Topology—Topology 1

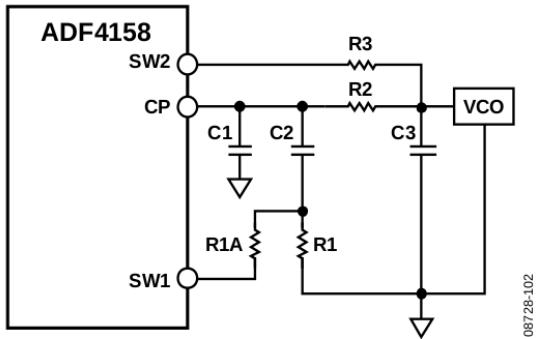


Figure 47. Fast-Lock Loop Filter Topology—Topology 2

Figure 2.11: Fast lock topologies.

### 2.3.2 HMC431LP4RF VCO

The [HMC431LP4RF](#) is a radio-frequency VCO.

### 2.3.3 SE2567L Power Amplifier

**Fixme Note!**

**Fixme Note:** I've changed this component with the [SE5004L](#), which has higher power output. Everything from this section forward (within the TX section) will need to be changed.

### 2.3.4 Notes

#### MGA25203 → SE2567L Substitution

The MGA-25203 power amplifier is now obsolete and there are no alternatives with an identical interface. Therefore the design will need to be modified. The alternative I will use is the [SE2567L](#) which seems to be very similar. There are a few small differences in addition to the pin differences: the original device has a power output of 23dBm in contrast to the new device which has a power output of 21.5dBm when  $VCC0,1=3.3V$  and  $VCC2,3=4.5V$ . I believe this is close enough to not create any issues, especially as they are both quoted as having 30dB gain and are IEEE 802.11-compliant. Additionally, the original device has a load current about twice that of the new device. Since the output powers are relatively similar (and the overview of original design describes a 20dB gain), I don't believe this should be an issue. The original

chip contains BCTRL, BSW, and BSPLY that differ from the new chip. BCTRL regulates the device current and is kept at a constant 2.8V. There is no analogous pin on the new chip. BSW is an enable pin that turns on the device when set to 1.8V. When it is set to 0V, the device is turned off. The original design uses a MOSFET transistor with a drain of 1.8V, source at GND and gate controlled by the FPGA (when the gate is activated the BSW pin gets a voltage of 0V and is disabled). The new chip contains an analogous pin, EN, which enables the power amplifier at the input voltage level 3.3V and disables it at GND. So, to get analogous functionality, we should connect the MOSFET drain to 3.3V instead of 1.8. Everything else should stay the same. BSPLY simply received the input voltage of 3.3V. In the new chip, the pins that are different from the original chip (and not already discussed) are VCC0-3 and DET. DET is a pin that outputs a voltage indicating the power output. We should connect this to a DNP capacitor to GND to be able to detect the output power of the amplifier with an ammeter. VCC0-1 should be connected to the 3.3V power supply. In order to get the additional power output, we should connect VCC2-3 to a 4.5V power supply instead of 3.3V. Unfortunately, it isn't possible to simply repurpose the voltage divider to the BCTRL pin for this since I do not know the internal impedance of the power amplifier IC and in general voltage dividers are bad for supplying power. Additionally, the simple LP5907 voltage divider may not work since it is only rated to 250mA of current, which doesn't leave much room above the 220mA expected by the SE2567L. It seems to make the most sense to use the [TPS7A91](#) which is rated to 1A. It has the downside of requiring additional hardware which will need to be adjusted in the PCB accordingly. To get the correct output voltage of 4.5V, we need to use Equation 2.2. Since the datasheet doesn't specify the resistors for a 4.5V output voltage this takes a bit of art to finding the correct resistors. Ideally, we want resistors with a higher-value so that less power is dissipated, and are commonly used to reduce cost and make them easier to replace if necessary. Lastly, I'd like to keep the values in the ballpark of those specified in the datasheet in case there are any other reasons I'm not thinking of. The values  $R_2 = 1.47\text{k}\Omega$  and  $R_1 = 6.8\text{k}\Omega$  should work well.

## 2.4 USB

In order to configure the FPGA we load the configuration bit stream onto the board using a USB cable and USB micro receptor on the PCB. The signal is then passed along to an [FT2232H](#) IC that translates the USB signal into JTAG data which it sends to the FPGA using the TCK, TDI, TDO and TMS pins. The schematic for this is shown in Figure 2.12. The FT2232H IC requires several power inputs: 3 VCORE input pins that require a 1.8V input voltage (this comes from VREGOUT, which is a pin that outputs a 1.8V signal from an internal voltage regulator), 1 3.3V VREGIN input (which serves as the input pin to drive the 1.8V regulated output), 4 3.3V VCCIO input pins, and 23.3V inputs (VPLL and VPHY) that are filtered with an LC filter.

**FIXME** I'm a bit confused as to the operation of the LC filter. It is implemented as a ferrite bead with two parallel capacitors in parallel with the load. This feeds in from an LDO regulator that in turn received its input from a buck converter operating at roughly 700kHz. The frequency at which the ferrite bead is in its resistive state is around 100MHz, well above the switching regulator noise. Maybe the filter is meant to filter out noise other than that from the buck converter. For instance, it is possible that the LDO regulator used after the buck converter (which has a PSRR near 0 around 500kHz and above) is sufficient for filtering the switching noise. The Art of Electronics states that ferrite beads should be placed at different points throughout the design to raise impedance at high frequencies. It is possible that this is the functionality provided by these ferrite beads. OSCI and OSCO are the oscillator input and output, respectively. These must be connected to a 12MHz oscillator with a frequency tolerance less than 30ppm (ours is 10ppm). REF is a current reference that must be connected to a  $12\text{k}\Omega$  resistor to ground. DM and DP are the USB data signal minus and plus lines, respectively. TEST should be connected to ground. RESET# (the # indicates an active low pin) is connected to a pull-up resistor to 3.3V so the reset is deasserted whenever the input voltage is at a sufficiently high and stable level. PWREN# is an output that is 0 during normal operation. We don't need it here so we leave it floating. SUSPEND# is similar to PWREN#; it is low when the USB is in suspend mode. This is used as an input to the FPGA. BDBUS0-3 are used for the JTAG interface to configure the FPGA. In order, they are TCK, TDI, TDO and TMS.

### 2.4.1 FT2232H

**FIXME** The FT2232H device also communicates with the FPGA using a synchronous FIFO interface as described [here](#). This seems to be the way that data is sent between the FPGA and the host computer although I'm not clear how this works. In any event, it uses the ADBUS0-7 and ACBUS0-7 pins. The ADBUS pins are bidirectional pins that serve as the FPGA side translation of the USB data. In other words, they should allow the FPGA to read USB data from a host computer and send data back to that host computer through a USB cable. The ACBUS lines seem to be used to signal reads/writes/etc. It also seems to require the external EEPROM storage IC, [93LC46B](#) although I'm not sure why this interface requires additional, external memory.

### 2.4.2 93LC46B 1k EEPROM

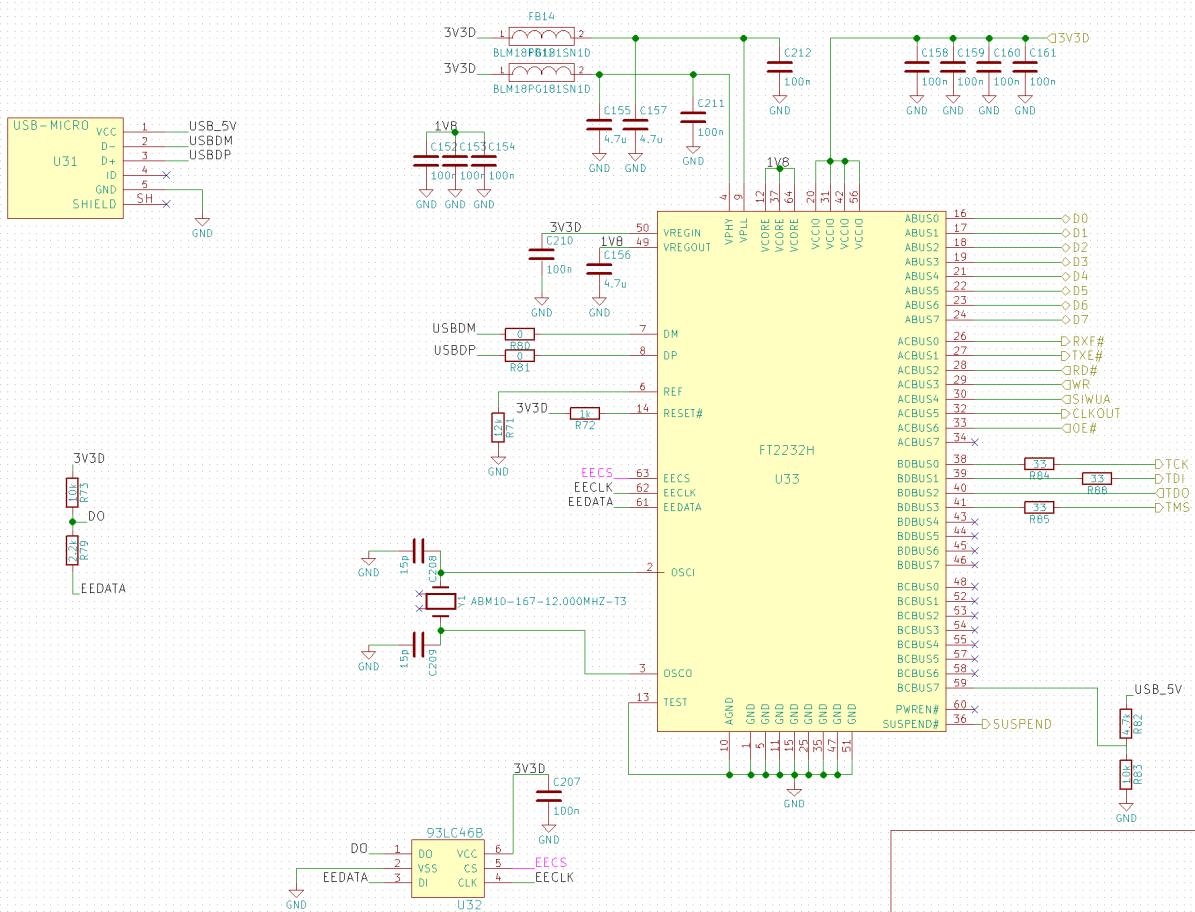


Figure 2.12: The configuration bit stream is loaded onto the FPGA using a USB-JTAG interface.

## 2.5 FPGA

### 2.5.1 Overview

The FPGA has two main roles. It performs digital signal processing on data sent from the ADC and relays the processed data back to a host computer via an [FT2232H](#) which acts as a FIFO-USB interface. Secondly, the FPGA is used to configure other components on the board. In order to program the FPGA, we use a host computer with a JTAG interface via the FT2232H.

The FPGA stores and loads its configuration from an SPI flash memory device, [W25Q32JV](#).

### 2.5.2 XC7A15T-FTG256 Xilinx FPGA

#### Documents

Table 2.19: Important documents.

| URL                                 | Description   |
|-------------------------------------|---|
| <a href="#">Artix-7 FPGA family</a> | The main page that contains a collection of documents about the 7 series devices.               |
| <a href="#">Package / Pinout</a>    | The various packages that the device comes in, along with the associated pin definitions.       |
| <a href="#">Overview</a>            | Contains general device capability information, such as number of logic cells, DSP blocks, etc. |
| <a href="#">PCB Design Guide</a>    | Contains information about bypassing and other design considerations.                           |
| <a href="#">XADC</a>                | Contains information about the FPGA's internal ADC.   |
| <a href="#">Configuration Guide</a> | Describes how to configure the FPGA with a bitstream.   |

#### Bypassing

The PCB Design Guide above specifies fairly stringent requirements for bypassing and should be adhered to.

#### Pinout

The FPGA pins follow a logical syntax: they can be of the form `IO_LXXY_ZZZ_#`, `IO_XX_ZZZ_#`, or a specific name. If they have a specific name, they have a dedicated function described starting on page 26 of the package-pinout document. If they have the general form `IO_LXXY_ZZZ_#` or `IO_XX_ZZZ_#`, they can be used for several different dedicated functions, or as general purpose IO pins. L indicates that the pin can be used as a differential pair (differential signaling), where Y=P or N depending on whether the pin is the positive or negative side of the differential pair. XX gives a unique number identifier that can be used to associate the two different pins forming a differential pair. ZZZ represents one or more functions that the pin can be used for in addition to general purpose IO. # indicates the bank number, which separate the pins into one of several different regions. The package used in this design is FTG256C, which contains banks 0, 14, 15, 34 and 35. Bank 0 contains the dedicated configuration pins. Each bank has

4 pairs of clock capable inputs for differential or single ended clocks (there are no global clock pins).

Table 2.20: All FPGA pin connections in alphabetical order.

| PIN | DESCRIPTION   |
|-----|---|
| A01 | GND.  |
| A02 | Connected to an external 1x1 pin header that is currently unused by FPGA logic.   |
| A03 | Connected to external 2x4 pin header that is currently unused by FPGA logic.  |
| A04 | Connected to same pin header as A03. Also unused.   |
| A05 | Same.   |
| A06 | One of the voltage supplies for bank 35. It uses 3.3V as with all the other voltage supplies to the main banks of the FPGA.   |
| A07 | Connected to same pin header as A03. Unused.  |
| A08 | A different 2x4 pin header. Unused.   |
| A09 | Connected to the same pin header as A08. Unused.  |
| A10 | Floating.   |
| A11 | GND.  |
| A12 | Connected as an output to the FT2232H USB-JTAG converter. Pulling this low allows the FT2232H device to output data to the FPGA through the ADBUS pins. Driving it high sets the ADBUS pins as inputs. Remember, the ADBUS pins serve as the bidirectional translation between JTAG data and USB data.  |
| A13 | SIWU (channel A). This pin is output to the FT2232H device and can be used to optimize USB data transfers (more info in the FT2232H datasheet). It is not currently used by the FPGA logic.   |
| A14 | Write output pin to the FT2232H device. When this is driven low, the FPGA writes data to the FT2232H. When it's driven high, the FPGA can perform a read from the FT2232H.  |
| A15 | Inputs a 60MHz clock signal that originated at the FT2232H. This clock is used to synchronize all data transfers between the FPGA and the FT2232H.  |
| A16 | A 3.3V input to bank 15.  |
| B01 | ADC_SHDN1. One of two ADC_SHDN outputs that, together with OEA (B02), controls the shutdown mode selection of the ADC. It is used by the digital FPGA logic. When both SHDN and OE are grounded, the ADC performs normally. When they are both pulled high, the ADC goes into sleep mode. There are two other states but they are not used by the FPGA logic. |
| B02 | ADC_OE1. See pin B01. This is used for channel A.   |
| B03 | 3.3V input for bank 35.   |
| B04 | Floating.   |
| B05 | Connected to the same 2x4 pin header as A03. Unused.  |
| B06 | Floating.   |
| B07 | Connected to the same 2x4 pin header as A03. Unused.  |
| B08 | GND.  |
| B09 | Connected to the same pin header as A08. Unused.  |
| B10 | Connected to the same pin header as A08. Unused.  |
| B11 | Floating.   |
| B12 | Floating.   |
| B13 | 3.3V input for bank 15.   |
| B14 | RD#. A read active-low output pin to the FT2232H device. When this is driven low, the FPGA reads data from the FT2232H.   |

Table 2.20: All FPGA pin connections in alphabetical order.

| PIN | DESCRIPTION  |
|-----|--|
| B15 | TXE#. An active-low input from the FT2232H. FT2232H drives this pin low to signal sending data to the FPGA (i.e. a read for the FPGA).                           |
| B16 | RXF#. An active-low input from the FT2232H. FT2232H drives this pin low to signal that it should read data. To the FPGA, this signals that it should write data. |
| C01 | Floating.  |
| C02 | OF1. An input from the ADC. It is pulled high when an overflow or underflow occurs at channel A. It is currently unused by the FPGA logic.                       |
| C03 | Floating.  |
| C04 | Floating.  |
| C05 | GND.   |
| C06 | Floating.  |
| C07 | Floating.  |
| C08 | Floating.  |
| C09 | Floating.  |
| C10 | 3.3V input to bank 15.   |
| C11 | Connected to the same pin header as A08. Unused.   |
| C12 | Connected to the same pin header as A08. Unused.   |
| C13 | Floating.  |
| C14 | Floating.  |
| C15 | GND.   |
| C16 | FT_SUSPEND. An active-low input to the FPGA. FT223H drives this low when the USB is in suspend mode. It is currently unused by the FPGA logic.                   |
| D01 | LED. Connects to an LED that is used by the FPGA to signal data processing.  |
| D02 | GND.   |
| D03 | Floating.  |
| D04 | Floating.  |
| D05 | Floating.  |
| D06 | Floating.  |
| D07 | 3.3V input to bank 35.   |
| D08 | Floating.  |
| D09 | Floating.  |
| D10 | Floating.  |
| D11 | Floating.  |
| D12 | GND.   |
| D13 | Floating.  |
| D14 | Floating.  |
| D15 | FT_D7. Bidirectional pin 7/7 of ADBUS, used to transmit data between the FPGA and FT2232H.   |
| D16 | FT_D6. Bidirectional pin 6/7 of ADBUS, used to transmit data between the FPGA and FT2232H.   |
| E01 | D10. Input pin 10/11 of the ADC's channel A digital outputs. It is used to transmit data from the ADC to FPGA.   |
| E02 | D11. Input pin 11/11 of the ADC's channel A digital outputs. It is used to transmit data from the ADC to FPGA.   |

Table 2.20: All FPGA pin connections in alphabetical order.

| PIN | DESCRIPTION   |
|-----|---|
| E03 | Floating.   |
| E04 | 3.3V input to bank 35.  |
| E05 | Floating.   |
| E06 | Floating.   |
| E07 | CFGPVS_0. A dedicated pin that is part of the configuration logic of the FPGA. It is used to specify the voltage level used for all banks. Since we use 3.3V, we connect this pin to the same 3.3V voltage level. |
| E08 | CCLK_0. An output pin exported from the FPGA to the flash memory device, W25Q32JV, to drive its operation and coordinate writes and reads to and from the device.   |
| E09 | GND.  |
| E10 | VCCBRAM. One of the two power supply pins to the FPGA's internal RAM. It requires 1.0V.   |
| E11 | Floating.   |
| E12 | Floating.   |
| E13 | Floating.   |
| E14 | 3.3V power supply to bank 15.   |
| E15 | FT_D5. Bidirectional pin 5/7 of ADBUS, used to transmit data between the FPGA and FT2232H.  |
| E16 | FT_D4. Bidirectional pin 4/7 of ADBUS, used to transmit data between the FPGA and FT2232H.  |
| F01 | VCC0_35. 3.3V power supply to bank 35.  |
| F02 | D9. Input pin 9/11 of the ADC's channel A digital outputs. It is used to transmit data from the ADC to FPGA.  |
| F03 | Floating.   |
| F04 | Floating.   |
| F05 | Floating.   |
| F06 | GND.  |
| F07 | VCCINT. 1.0V power supply for the internal core logic of the FPGA.  |
| F08 | VCCBATT_0. Can be used for memory backup. We do not use it so we tie it to GND.   |
| F09 | VCCINT. 1.0V power supply for the internal core logic of the FPGA.  |
| F10 | GND.  |
| F11 | VCCBRAM. One of the two power supply pins to the FPGA's internal RAM. It requires 1.0V.   |
| F12 | Floating.   |
| F13 | Floating.   |
| F14 | FT_D3. Bidirectional pin 3/7 of ADBUS, used to transmit data between the FPGA and FT2232H.  |
| F15 | FT_D0. Bidirectional pin 0/7 of ADBUS, used to transmit data between the FPGA and FT2232H.  |
| F16 | GND.  |
| G01 | D10. Input pin 10/11 of the ADC's channel A digital outputs. It is used to transmit data from the ADC to FPGA.  |

Table 2.20: All FPGA pin connections in alphabetical order.

| PIN | DESCRIPTION  |
|-----|--|
| G02 | D7. Input pin 7/11 of the ADC's channel A digital outputs. It is used to transmit data from the ADC to FPGA.   |
| G03 | GND.   |
| G04 | Floating.  |
| G05 | Floating.  |
| G06 | VCCINT. 1.0V power supply for the internal core logic of the FPGA.   |
| G07 | GNDADC_0. The reference voltage for the onchip ADC.  |
| G08 | VCCADC_0. A 1.8V power supply used to power the onchip ADC.  |
| G09 | GND.   |
| G10 | VCCAUX. A 1.8V power supply for auxiliary circuits in the FPGA IC.   |
| G11 | Floating.  |
| G12 | Floating.  |
| G13 | GND.   |
| G14 | Floating.  |
| G15 | FT_D2. Bidirectional pin 2/7 of ADBUS, used to transmit data between the FPGA and FT2232H.   |
| G16 | FT_D1. Bidirectional pin 1/7 of ADBUS, used to transmit data between the FPGA and FT2232H.   |
| H01 | D4. Input pin 4/11 of the ADC's channel A digital outputs. It is used to transmit data from the ADC to FPGA.   |
| H02 | D5. Input pin 5/11 of the ADC's channel A digital outputs. It is used to transmit data from the ADC to FPGA.   |
| H03 | D6. Input pin 6/11 of the ADC's channel A digital outputs. It is used to transmit data from the ADC to FPGA.   |
| H04 | Floating.  |
| H05 | Floating.  |
| H06 | GND.   |
| H07 | VREFN_0. A dedicated pin that is used as a 1.25V reference GND voltage. Tied to GND.   |
| H08 | VP_0. A dedicated pin that is used as the XADC differential analog input (positive side). It is left floating and is unused.   |
| H09 | VCCINT. 1.0V power supply for the internal core logic of the FPGA.   |
| H10 | DONE_0. A bidirectional dedicated pin. It is pulled high when configuration is done. It is connected to a pull-up resistor and an external connector, presumably for debugging purposes. |
| H11 | Floating.  |
| H12 | Floating.  |
| H13 | Floating.  |
| H14 | Floating.  |
| H15 | VCC0_15. 3.3V power supply for bank 15.  |
| H16 | CARD_DETECT. Connects to the SD card. Currently unused by FPGA logic.  |
| J01 | Floating.  |
| J02 | VCC0_35. 3.3V power supply for bank 35.  |
| J03 | D3. Input pin 3/11 of the ADC's channel A digital outputs. It is used to transmit data from the ADC to FPGA.   |

Table 2.20: All FPGA pin connections in alphabetical order.

| PIN | DESCRIPTION  |
|-----|--|
| J04 | MIX_ENBL. An enable pin that is output to the ADL5802 mixer. It is pulled low to enable the mixer and pulled high to disable it. |
| J05 | Floating.  |
| J06 | VCCINT. 1.0V power supply for the internal core logic of the FPGA.   |
| J07 | VN_0. A dedicated pin that is used as the XADC differential analog input (negative side). It is tied to GND and is unused.       |
| J08 | VREFP_0. A dedicated pin that is used as a 1.25V reference input. It is tied to GND and unused.                                  |
| J09 | GND.   |
| J10 | VCCAUX. A 1.8V power supply for auxiliary circuits in the FPGA IC.   |
| J11 | GND.   |
| J12 | VCC0_15. 3.3V power supply for bank 15.  |
| J13 | SPI_MOSI. Used by the FPGA to send data to the flash memory device.  |
| J14 | SPI_DIN. Used by the FPGA to read data from the flash memory device.   |
| J15 | Floating.  |
| J16 | Floating.  |
| K01 | D2. Input pin 2/11 of the ADC's channel A digital outputs. It is used to transmit data from the ADC to FPGA.                     |
| K02 | D1. Input pin 1/11 of the ADC's channel A digital outputs. It is used to transmit data from the ADC to FPGA.                     |
| K03 | ADF_MUXOUT. Input from the frequency synthesizer. It indicates that a sweep is done.   |
| K04 | GND.   |
| K05 | Floating.  |
| K06 | GND.   |
| K07 | DXN_0. The cathode of two temperature-monitoring diode pins. It is not used and is therefore tied to GND.                        |
| K08 | DXP_0. The anode of two temperature-monitoring diode pins. It is not used and is therefore tied to GND.                          |
| K09 | VCCINT. 1.0V power supply for the internal core logic of the FPGA.   |
| K10 | INIT_B. Indicates initialization of configuration memory. It is pulled high and is unused.                                       |
| K11 | VCCAUX. A 1.8V power supply for auxiliary circuits in the FPGA IC.   |
| K12 | Floating.  |
| K13 | Floating.  |
| K14 | GND.   |
| K15 | Floating.  |
| K16 | Floating.  |
| L01 | GND.   |
| L02 | D0. Input pin 0/11 of the ADC's channel A digital outputs. It is used to transmit data from the ADC to FPGA.                     |
| L03 | Floating.  |
| L04 | Floating.  |
| L05 | Floating.  |

Table 2.20: All FPGA pin connections in alphabetical order.

| PIN | DESCRIPTION  |
|-----|--|
| L06 | VCC0_0. 3.3V power supply for bank 0 (i.e. the bank for dedicated configuration pins).   |
| L07 | TCK. An input pin originating at the output of FT2232H and is used to transmit the JTAG clock. It is not used by the FPGA logic.   |
| L08 | VCCINT. 1.0V power supply for the internal core logic of the FPGA.   |
| L09 | PROGRAM_B. Connected to a pushbutton switch and can be used to perform an asynchronous reset of the configuration logic.   |
| L10 | VCCAUX. A 1.8V power supply for auxiliary circuits in the FPGA IC.   |
| L11 | GND.   |
| L12 | SPI_CS. An output pin that can be brought low to indicate that a transmission will take place between the FPGA and flash storage device. It is currently left in the high-impedance state in FPGA logic, seemingly indicating that the flash storage device is not yet used.   |
| L13 | Floating.  |
| L14 | Floating.  |
| L15 | PUDC_B. Pulled low, which configures all I/O pins to enable their internal pull-up resistors.  |
| L16 | VCC0_14. 3.3V power supply to bank 14.   |
| M01 | OF2. An input from the ADC. It is pulled high when an overflow or underflow occurs at channel B. It is currently unused by the FPGA logic.   |
| M02 | ADF_DATA. A serial data output pin the frequency synthesizer.  |
| M03 | VCC0_34. 3.3V power supply to bank 34.   |
| M04 | Floating.  |
| M05 | Floating.  |
| M06 | Floating.  |
| M07 | TMS. Output pin that is fed into the FT223H as a mode select pin. It is unused by the current FPGA logic.  |
| M08 | GND.   |
| M09 | M0. Along with M1 and M2, this specifies the configuration mode of the FPGA. M[2:0] = 001 which indicates the FPGA acts as a master in an SPI interface. Because a DNP resistor is placed between M0 and 3.3V, it is not actually connected to the power supply. However, since all pull-up resistors should be enabled by pulling PUDC_B low, it should register a logic 1. |
| M10 | M1. See M09.   |
| M11 | M2. See M09.   |
| M12 | Floating.  |
| M13 | VCC0_14. 3.3V power supply to bank 14.   |
| M14 | Floating.  |
| M15 | Floating.  |
| M16 | SD_DAT1. A data line to the SD card reader. Not currently used by the FPGA logic.  |
| N01 | ADF_LE. An output that connects to the ADF4158 frequency synthesizer. When it is pulled high, data stored in the ADF4158 shift registers is loaded into one of the 8 latches.  |
| N02 | ADC_SHDN2. See B01.  |
| N03 | Floating.  |

Table 2.20: All FPGA pin connections in alphabetical order.

| <b>PIN</b> | <b>DESCRIPTION</b>  |
|------------|---|
| N04        | Floating.   |
| N05        | GND.  |
| N06        | Floating.   |
| N07        | TDI. JTAG data input from FT2232H. It is not currently used by the FPGA logic.  |
| N08        | TDO. JTAG data output to FT2232H. It is not currently used by the FPGA logic.   |
| N09        | Floating.   |
| N10        | VCC0_14. 3.3V power supply for bank 14.   |
| N11        | CLK_REF. An input pin that takes the main 40MHz reference clock used by the FPGA. It is one of the outputs of the clock fanout buffer.                    |
| N12        | Floating.   |
| N13        | Floating.   |
| N14        | SD_CLK. A clock that synchronizes activity with the SD card reader. It is not currently used by the FPGA logic.   |
| N15        | GND.  |
| N16        | SD_DAT0. A data line to the SD card reader. Not currently used by the FPGA logic.   |
| P01        | ADC_OE2. See pin B01. This is used for channel B.   |
| P02        | GND.  |
| P03        | ADF_TXDATA. Output pin that transmits data to be used by the ADF4158 frequency synthesizer for FSK or PSK transmission. This is unused by the FPGA logic. |
| P04        | Floating.   |
| P05        | Floating.   |
| P06        | Floating.   |
| P07        | VCC0_14. 3.3V power supply for bank 14.   |
| P08        | Floating.   |
| P09        | Floating.   |
| P10        | Floating.   |
| P11        | Floating.   |
| P12        | GND.  |
| P13        | Floating.   |
| P14        | Floating.   |
| P15        | Floating.   |
| P16        | SD_CMD. A pin used to communicate with the SD card reader. Currently unused by the FPGA logic.  |
| R01        | ADF_CLK. An output clock used to synchronize the operation of the ADF4158 frequency synthesizer.  |
| R02        | Floating.   |
| R03        | ADF_CE. An output pin to the ADF4158. When this pin is driven low, it powers down the frequency synthesizer.  |
| R04        | VCC0_34. 3.3V power supply for bank 34.   |
| R05        | Floating.   |
| R06        | Floating.   |
| R07        | Floating.   |
| R08        | Floating.   |
| R09        | GND.  |
| R10        | Floating.   |

Table 2.20: All FPGA pin connections in alphabetical order.

| PIN | DESCRIPTION   |
|-----|---|
| R11 | Floating.   |
| R12 | Floating.   |
| R13 | Floating.   |
| R14 | VCC0_14. 3.3V power supply for bank 14.   |
| R15 | SD_DAT3. A data line to the SD card reader. Not currently used by the FPGA logic.   |
| R16 | SD_DAT2. A data line to the SD card reader. Not currently used by the FPGA logic.   |
| T01 | VCC0_34. 3.3V power supply for bank 34.   |
| T02 | PA_OFF. Output pin that connects to the base of a transistor and can be used to enable (high) or disable (low) the operation of the power amplifier, SE2567L. |
| T03 | Floating.   |
| T04 | ADF_DONE. Input pin that is unused by the FPGA logic.   |
| T05 | Floating.   |
| T06 | GND.  |
| T07 | Floating.   |
| T08 | Floating.   |
| T09 | Floating.   |
| T10 | Floating.   |
| T11 | VCC0_14. 3.3V power supply for bank 14.   |
| T12 | Floating.   |
| T13 | Floating.   |
| T14 | Floating.   |
| T15 | Floating.   |
| T16 | GND.  |

PROGRAM\_B\_0 is connected to a pushbutton switch and can be used to perform an asynchronous reset to the configuration logic. TDI, TDO, TMS, and TCK are used for the JTAG clock, data input, data output, and mode select, respectively. They are connected to the FT2232H IC that translates between USB signals and JTAG signals. They are used to configure the FPGA (which is also stored in the flash memory). M[2:0] specify the configuration mode for the FPGA. In our configuration, M0 is pulled high while the other 2 are pulled low, indicating a Master SPI interface. CFGBVS\_0 is used to specify the voltage level used for all banks. Since we use 3.3V, we connect this pin to the same 3.3V. The PUDC\_B pin is pulled low, which configures all I/O pins to enable their internal pull-up resistors. **{STARTINCOMPLETE}** The FPGA seems to have a built-in ADC. However, it doesn't appear to be used **{END INCOMPLETE}**. There is an SD card reader connected up to the FPGA, however, it is unused by the current FPGA code. VCCAUX is used for auxiliary circuits and must be 1.8V. VC-CADC\_0 is also 1.8V and is used to power the onchip ADC. VCCINT powers the internal core logic of the FPGA and must be 1.0V. VCCBRAM is the power supply for the FPGA internal RAM, which requires 1.0V.

### 2.5.3 W25Q32JV Flash Memory

The CCLK\_0 pin is exported from the FPGA to the flash device to drive its operation and coordinates writes and reads to and from the device. DO is used by the FPGA to perform SPI

reads from the flash memory device. It is connected to J14 of the FPGA. DI is connected to J13 of the FPGA and is used by the FPGA to send data to the flash memory device. CS is active low and is used by the FPGA to signal data transmission is about to occur. It is connected to L12 on the FPGA. WP (write protect) and HOLD are both active low pins and are used to prevent the status configuration registers from being written to and can pause the device when multiple devices share the same SPI signal, respectively. They are unused and thus connected to the 3.3V power supply. The device is powered with 3.3V (it supports a range of 2.7V to 3.6V). Table 2.5.2 contains a list of all FPGA pins and their connections.

## 2.6 ADC

The LTC2292 is a 40MHz, 12-bit differential input ADC. The schematic for this device is shown in Figure 2.13. We use this device instead of the built-in FPGA ADCs because those sample at a rate of 1Msps, which is insufficient for our needs. The difference signal received by the ADC and passed to the FPGA has a frequency in the range of kHz to a few MHz, for which a 40MHz sampling rate is significantly more than the Nyquist frequency. The received signal is received on two antennas, which allows for the angle of the received signal to be computed. These are amplified, mixed and then amplified again before feeding into the ADC. By connecting the CLKA, CLKB, and MUX pins together, we multiplex both channels together through the same output pins, D01-D11A. The timing for this multiplexed output is shown in Figure 2.14. Table 2.6 contains a list of all the ADC pins and their connections.

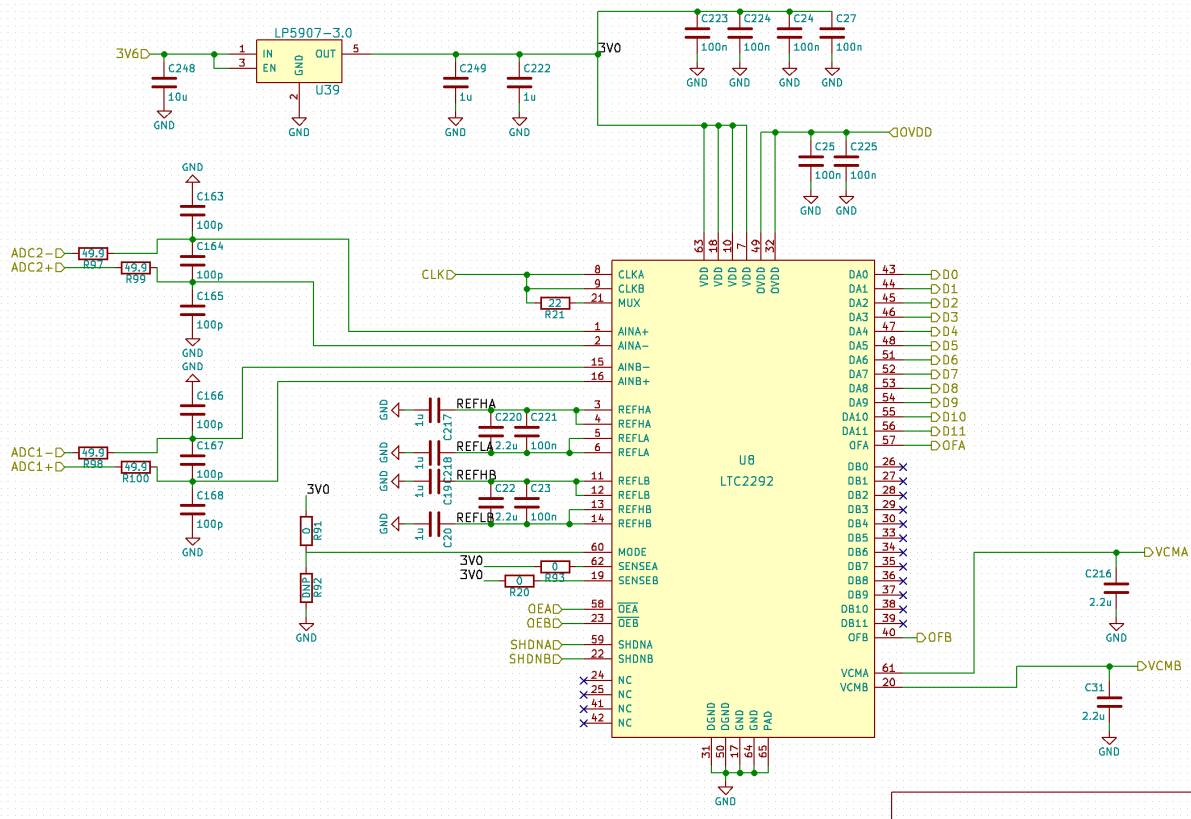


Figure 2.13: The LTC2292ADC schematic.

Table 2.21: All LTC2292 ADC pin connections in logical groupings.

| LABELS | PIN #s        | DESCRIPTION  |
|--------|---------------|--|
| VDD    | 7, 10, 18, 63 | The power supply required is 3.0V and each pin requires its own $0.1\mu F$ capacitor. When designing the PCB, ensure that each capacitor is placed as close to its corresponding pin as possible to minimize the trace inductance. The 3.0V signal itself is generated by using an LP5907 LDO regulator that takes in a 3.6V signal. |

Table 2.21: All LTC2292 ADC pin connections in logical groupings.

| LABELS                       | PIN #s                | DESCRIPTION   |
|------------------------------|-----------------------|---|
| OVDD                         | 39, 42                | The power supply for the output that the ADC feeds to, which is the FPGA and takes a 3.3V power supply. So, we connect this to the 3.3V power rail and bypass it with two $0.1\mu\text{F}$ capacitors, one for each pin. Again, each should be placed adjacent to their corresponding pins (39 and 42). |
| CLKA,<br>CLKB, MUX           | 8, 9, 21              | Feeds a 40MHz clock signal to the device and specifies that the digitized channel A and B data should be multiplexed and pass through both output buses A and B. We leave B unconnected, so only bus A matters.   |
| DA0-DA11                     | 43-48, 51-56          | The digitized output data that contains the input data from both channels A and B, multiplexed. This is fed into the FPGA for processing.   |
| OFA                          | 57                    | This pin is driven high when overflow or underflow occurs. Otherwise it is kept low. We export this to the FPGA, although it is not currently used by the FPGA logic.   |
| DB0-DB11                     | 26-30, 33-39          | The channel B data bus. Since we multiplex everything through the channel A data bus, this data bus is redundant and therefore left unconnected.  |
| OFB                          | 40                    | Similar to OFA, but for channel B. This is exported to the FPGA, but is also unused.  |
| VCMA,<br>VCMB                | 61, 20                | A 1.5V signal that is used to set the common-mode voltage of the IF differential amplifiers, whose outputs are sent to this ADC. They are each bypassed to GND with a $2.2\mu\text{F}$ capacitor, which should be placed directly next to their respective pins.  |
| GND, OGND                    | 17, 64, 65, 31,<br>50 | The ADC power ground and output power ground, respectively. These can all be routed to the same ground plane.   |
| NC                           | 24-25, 41-42          | No connect.   |
| SHDNA,<br>SHDNB,<br>OEA, OEB | 59, 22, 58, 23        | These are input pins that are connected to the FPGA. The FPGA logic can ground both SHDNA and OEA to allow channel A to operate normally or bring them both high to put channel A in sleep mode. Channel B works the same way.  |
| SENSEA,<br>SENSEB            | 62, 19                | These are connected to VDD, which specifies that the input voltage range of the differential signals for both channels A and B is $1.5\text{V} \pm 1\text{V}$ . $1.5\text{V}$ is the common-mode voltage and the channels allow a 2V range around that.   |
| MODE                         | 60                    | Connecting mode to VDD specifies the output format as 2s complement and turns off the clock duty stabilizer, which is unnecessary because the input clock has a 50% duty cycle.   |

Table 2.21: All LTC2292 ADC pin connections in logical groupings.

| LABELS                              | PIN #s     | DESCRIPTION   |
|-------------------------------------|------------|---|
| REFHA,<br>REFLA,<br>REFLB,<br>REFHB | 3-6, 11-14 | These are the high and low reference for channels A and B, respectively. Their connection is specified exactly by the datasheet. It is critical that the $0.1\mu\text{F}$ capacitor is placed as close to the pins as possible.   |
| AINA+,<br>AINA-,<br>AINB-,<br>AINB+ | 1-2, 15-16 | The positive and negative differential inputs for channels A and B. <b>{STARTINCOMPLETE}</b> These lines have a capacitor between the positive and negative analog inputs, as well as capacitors connecting each line to GND. The capacitor value between the lines of $0.1\mu\text{F}$ is different from the suggested value of $12\text{pF}$ and the capacitors connecting the lines to GND are not suggested from the datasheet (see page 18 of the datasheet). Additionally, the resistance value of $49.9\Omega$ differs from the suggested resistance of $25\Omega$ . Lastly, the negative output of the differential amplifier for channel A is feeding into the positive input line <b>{END INCOMPLETE}</b> . |

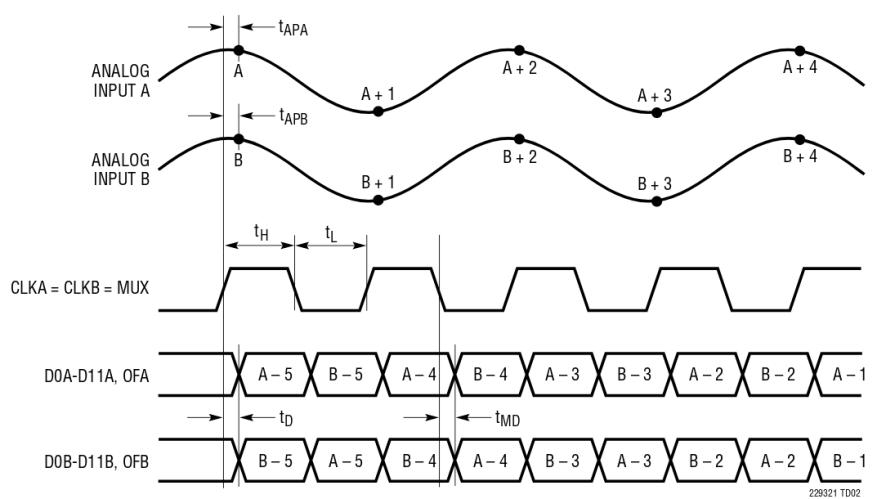


Figure 2.14: Multiplexed digital output bus timing for the LTC2292 ADC.

## 2.7 Mixer

### 2.7.1 ADL5802

The mixer schematic shown in Figure 2.15 is composed of three high-frequency baluns that convert two rx and one local oscillator (the original transmitted signal) single-ended signal into differential signals and then feed them into the mixer. The baluns are **5400BL15B050E** and the mixer is **ADL5802**. The mixer outputs the difference of the local oscillator frequency and each R input which ranges from hundreds of kHz to a few MHz.

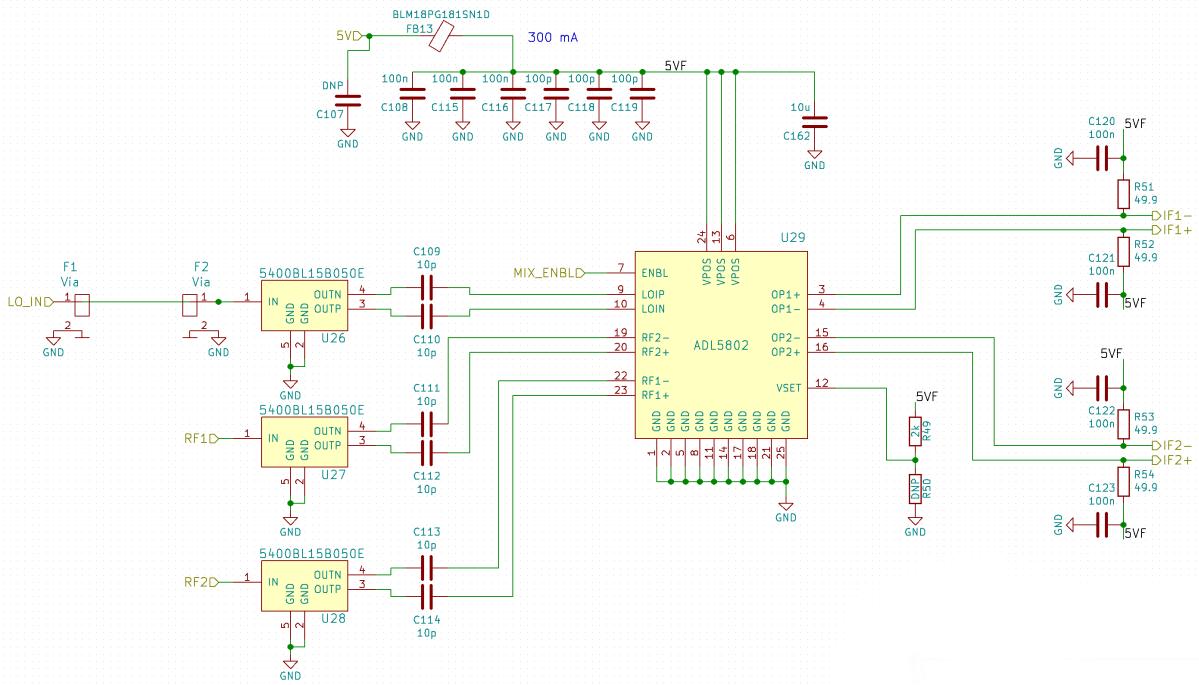


Figure 2.15: The mixer schematic.

The RF and LO input interfaces are designed for a differential input impedance of  $50\Omega$ . This is already the differential balanced impedance of the baluns, so we do not need to perform any additional impedance matching at the inputs. The inputs require AC coupling and the datasheet recommends 3pF coupling capacitors placed between the balun outputs and pin inputs. It also shows that the positive balun output of the local oscillator should be hooked up to the positive pin input.

## 2.8 IF

The IF amplifier, [ADA4940-2](#), receives the output of the mixer, whose frequency is in the range of hundreds of kHz to a few MHz.

## 2.9 RX1 & RX2

The sheets RX1 and RX2 are identical. They each consist of two amplifiers connected in series, shown in Figure 2.16. The first amplifier is a SKY65404 LNA which operates in the 4.9GHz-5.9GHz range, has a gain of 13dB, a NF of 1dB and a P1dB of -4dBm. It is hooked up exactly as specified in the datasheet, with the addition of a ferrite bead filtering its power supply.

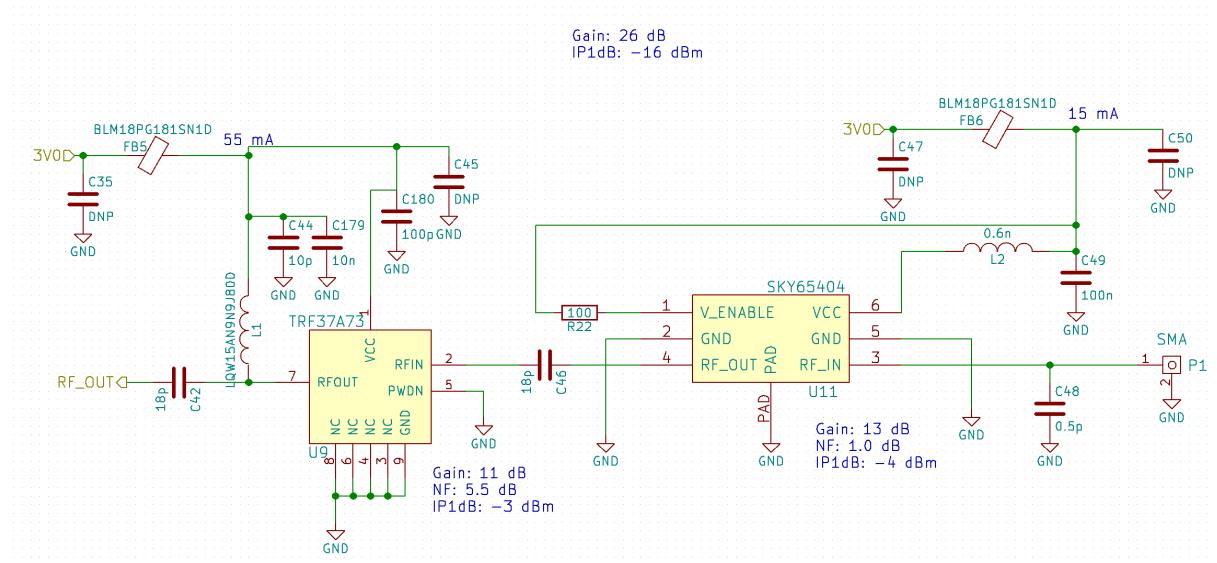


Figure 2.16: One of two RX schematic sheets. Both sheets are identical and consist of two amplifiers connected in series.

The second amplifier is a TRF37A73 RF gain amplifier. It is wired up as recommended in the datasheet, with the addition of a ferrite bead to filter the power supply. Values for the various capacitors and inductor are left out of the datasheet. A 100pF capacitor is used to short high frequency noise to the power supply, which is typical of microwave devices. **{START INCOMPLETE}** I am not sure how the values for the RF bypass capacitors, the inductor, and the DC blocking capacitors was chosen. Additionally, I'm not sure how he arrives at a gain of 26dB, since I've read that gains in series should be additive (and hence 24dB), and I'm not sure where the IP1dB value of -16dBm comes from **{ENDINCOMPLETE}**.

# Chapter 3

## PCB

### 3.1 General Layout

The radar is constructed using a 4-layer board and uses both surfaces of the board. The front layer contains nearly all of the board's components while the back layer contains a few surface mount resistors and capacitors. The top layer primarily contains signal traces for top layer SMD components. In particular, it connects many of the signal traces of the ADC to the FPGA, which is placed next to it. Note, however, that most of the signal traces extending from the FPGA only start on the top layer but travel through layer 3. The buck converters and subsequent linear regulators are placed near the top of the board, not necessarily near the components they drive. In addition to the large number of signal traces, the top copper layer contains a large ground plane around the periphery of the board. The 2nd layer is entirely a ground plane. The 3rd layer is largely a ground plane, although it also contains a significant number of traces extending from the FPGA as well as a few other components. The 4th layer primarily contains large power planes for each of the different voltages driving logic in the design. It is worth noting that even though it contains significant power planes, it still has a ground plane that is the largest copper fill zone in this layer. The PCB also has 3 large corner mounting vias with smaller vias placed in a circle in the large via's annular ring. The reason for the small vias is to ensure a continued connection to GND (the mounting vias are connected to GND) even if a screw thread strips too much copper from the main via. Additionally, it helps prevent the PCB from being crushed if too much torque is used to tighten the screw. The 4th corner is occupied by the connections to the DC barrel jack. Power rail traces are made 0.5mm in width whereas signal traces are 0.2mm in width. Grounded vias are placed liberally throughout the design. They have a diameter of 0.46mm and a drill hole size of 0.254mm. I've included several screenshots of the PCB and highlighted important components (Figures 3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 3.7, 3.8, 3.9, 3.10, 3.11, 3.12).

### 3.2 Component Layout Considerations

#### 3.2.1 Power Input

The barrel jack used has an inner diameter of 2.1mm and an outer diameter of 5.5mm and should output 12V. Since barrel jack dimensions and voltage output vary widely, special attention should be given to make sure the actual hook up matches these specifications.

The pi filter should be placed as close to the barrel jack connection as possible so as to minimize crosstalk noise with the rest of the board.

All components should be placed sufficiently close to the TPS5420D buck converter, except for the trace between the voltage divider and VSNS which should be given a sufficiently wide berth from the PH trace.

### 3.2.2 LTC2292 ADC

- The LTC2292 contains 4 positive voltage supply pins each requiring a  $0.1\mu\text{F}$  bypass capacitor. One capacitor each should be placed directly adjacent to each of the 4 voltage supply pins.
- The device contains 2 input pins for the voltage of the device where the output data is sent. These, similarly require a  $0.1\mu\text{F}$  capacitor each. As before they should be placed next to their respective pins, not next to one another.
- VCMA and VCMB each are connected to a  $2.2\mu\text{F}$  capacitor to GND. They should be placed as close to the pins as possible.
- REFHA and REFLA (and REFHB and REFLB) have a  $0.1\mu\text{F}$  capacitor connected between them. These are the most critical capacitors connected to the ADC. They must be placed 1.5mm away at most, and preferably closer to the pins.

### 3.2.3 RX1 / RX2

- The 100pF capacitor used to bypass TRF37A73 should be place as close as possible to VCC.

## 3.3 RF Impedance Matching

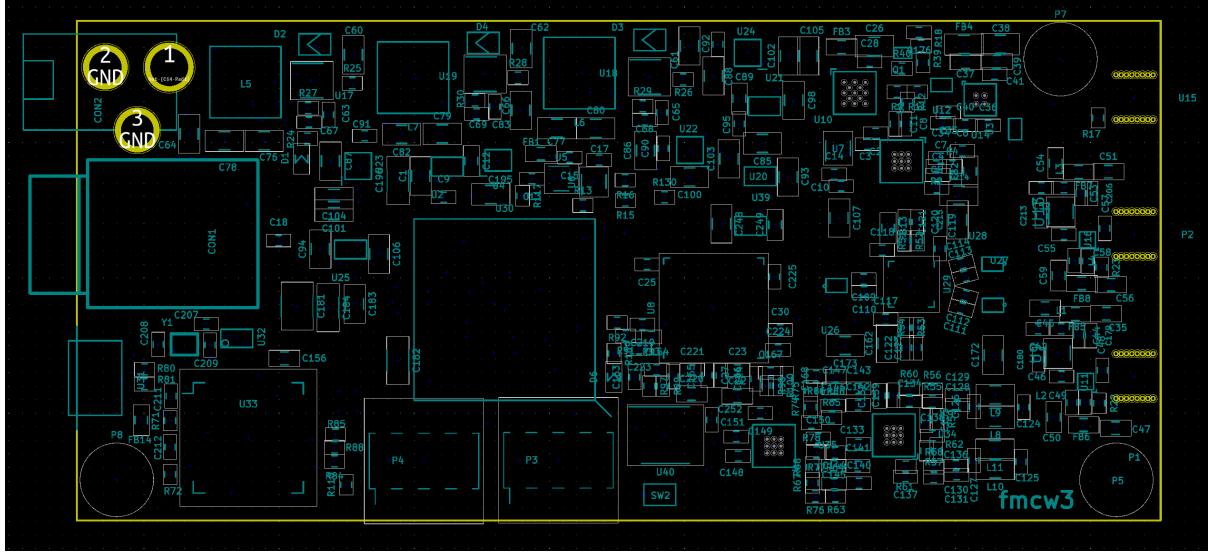
**Fixme Fatal:** I don't think the text below is correct..

I'm keeping it for the value of knowing the trace widths used by the original design. However, the idea that the trace widths are unimportant seems dubious. The PCB calculator built into KiCad should be used for this. Additionally, it is probably worth looking at the following guides: [Maxim: General Layout Guidelines for RF and Mixed-Signal PCBs](#), [Hackaday: Michael Ossmann makes you an RF design hero](#), [Analog](#). I would also look at [this tool](#) for creating a Wilkinson power divider. Also, the trace width for  $50\Omega$  resistors seems to have been more like 15mil.

Use [this Mantaro impedance calculator](#) to calculate trace widths. The proper width should be 11.98mil.

The right side of the board houses the RF circuitry (i.e. transmitter, receivers and SMA connectors). The signals are carried to the antennas (a patch-fed horn for transmission and a patch array for reception) via a  $50\Omega$  coaxial cable. All RF inputs and outputs for components should match this  $50\Omega$  impedance. The original layout does not seem overly concerned with the microstrip transmission line width between RF components. They are kept short and generally have a trace width of about 0.3mm. However, many of them are not even remotely straight and this doesn't seem to be an issue. Where possible the microstrips should be kept short, straight

and with an unbroken ground plane beneath them. That seems to be all that is necessary for impedance matching. The patch antennas however will need to be appropriately hooked up in order to match the  $50\Omega$  impedance. This should be a relatively straightforward calculation. The setup Henrik uses seems to be the most logical one. He uses a single patch-fed horn antenna for transmission and a patch array for reception. The horn antenna is made of thin copper. More sophisticated horn antennas require the ability to weld and probably modeling software (e.g. CST).



**Figure 3.1: Board layout.** The top left of the board is where the power source (barrel jack) is connected. The output of the 12V power source is connected to a power plane at the top left-middle of the board, that feeds into the buck converters. Large inductors connected to the buck converters are placed adjacent to their corresponding buck converters. The outputs of the buck converters feed into linear regulators that are mostly placed directly below the buck converters. This is also the region where the main crystal oscillator is placed and its associated fan-out buffer. Transmission circuitry (the frequency synthesizer and some RF amplifiers) are placed at the upper right side of the board near the antenna connectors which are placed on the right side of the board. Circuitry for signal reception are placed along the right side, adjacent to the antenna connectors. The mixer is placed slight inward from here, vertically centered but toward the right side of the board. Below this are intermediate frequency op-amps that feed the mixed signal into an ADC located just above it and to the left (U8). Located just to the left of the IF amplifiers and below the ADC is a flash memory IC (U40) which feeds data to the FPGA (U30), located just to the left of the ADC. Connectors below the FPGA (P3 and P4) can be used to externally monitor the FPGA. In the bottom left of the board is a component to convert USB data to UART data to configure the FPGA as well as a micro USB connection to connect to a host computer. On the left side of the board between the USB connection and barrel jack is a SD card reader that stores data that can be read back out the FPGA.

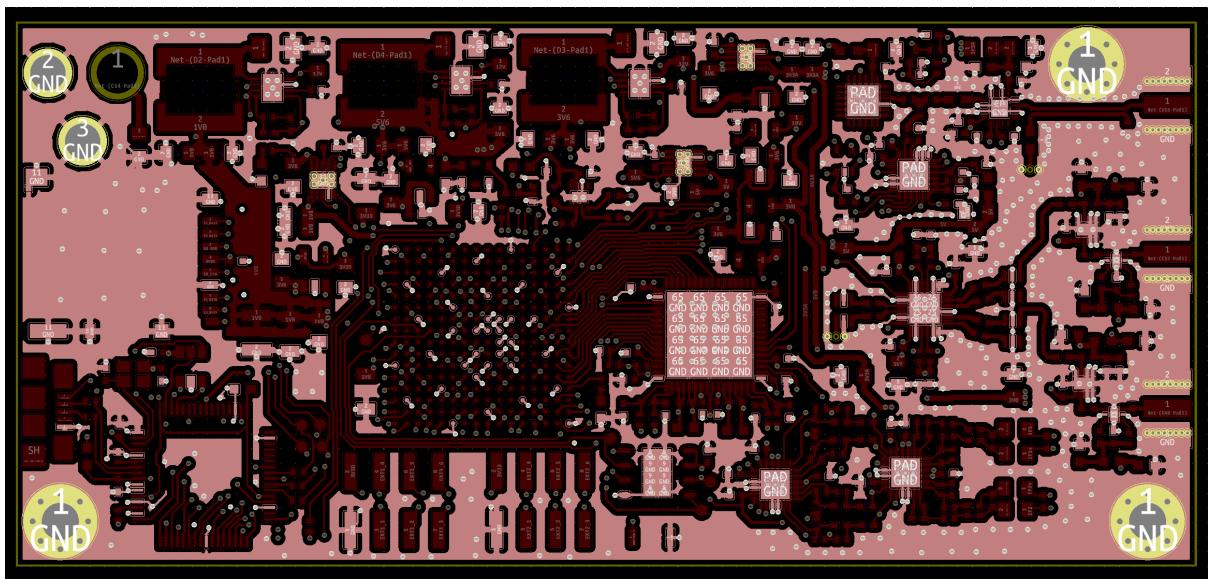


Figure 3.2: A significant portion of layer 1 is a ground plane and the other large part of it is signal traces connecting components. There is also a small 1V power plane toward the upper left not highlighted here.

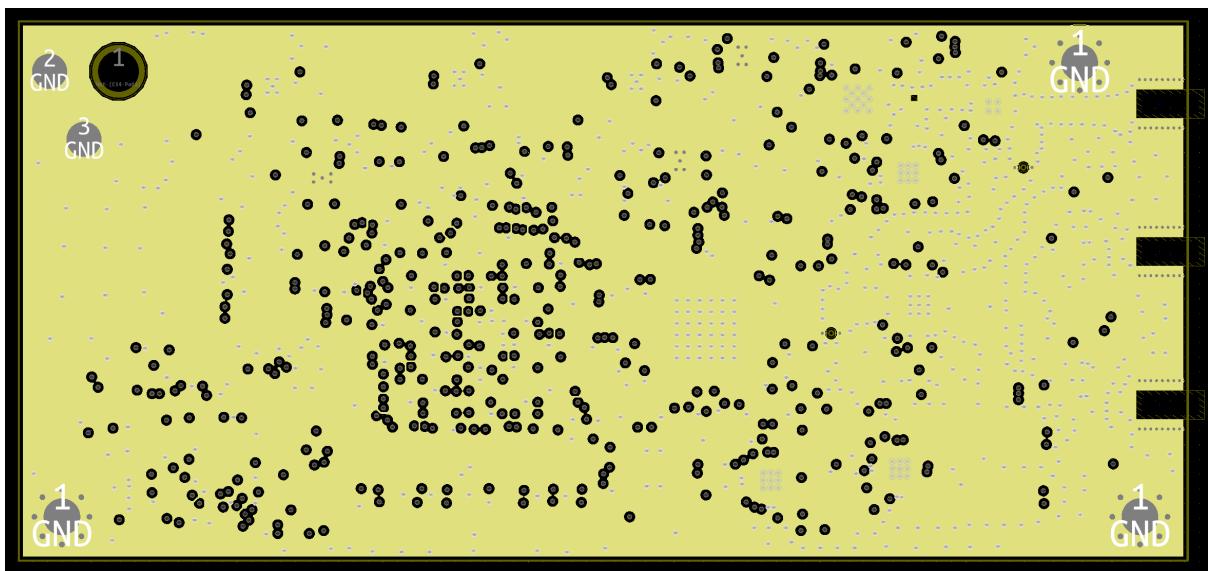


Figure 3.3: All of layer 2 is a ground plane.

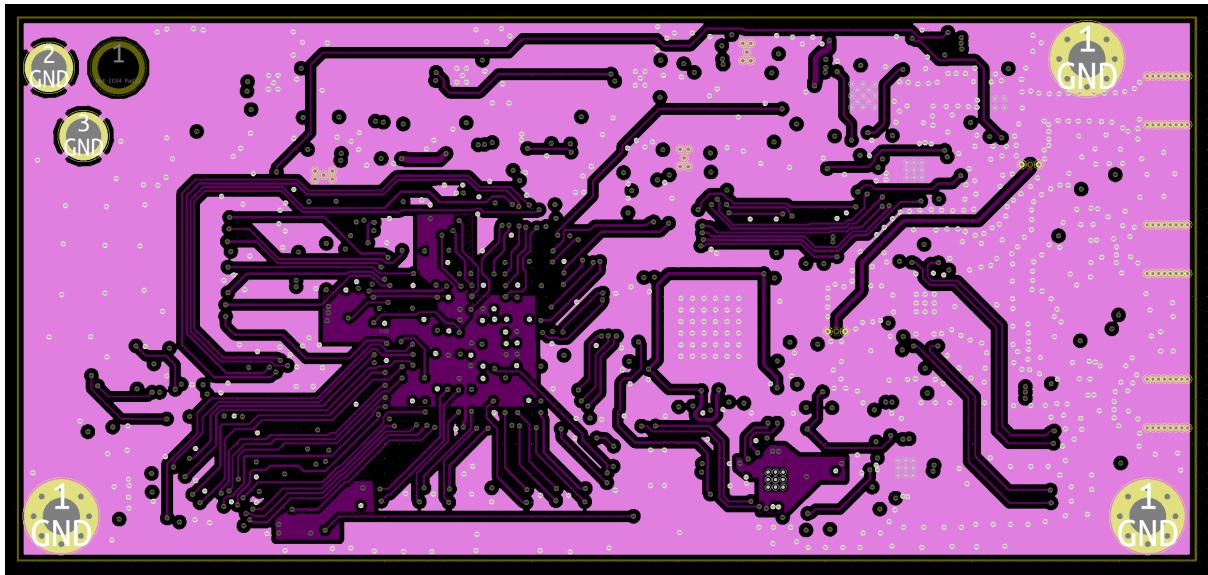


Figure 3.4: Most of layer 3 is a ground plane but there are also a substantial number of trace connecting to the FPGA. It does also contain 1V an 3.3V power planes.

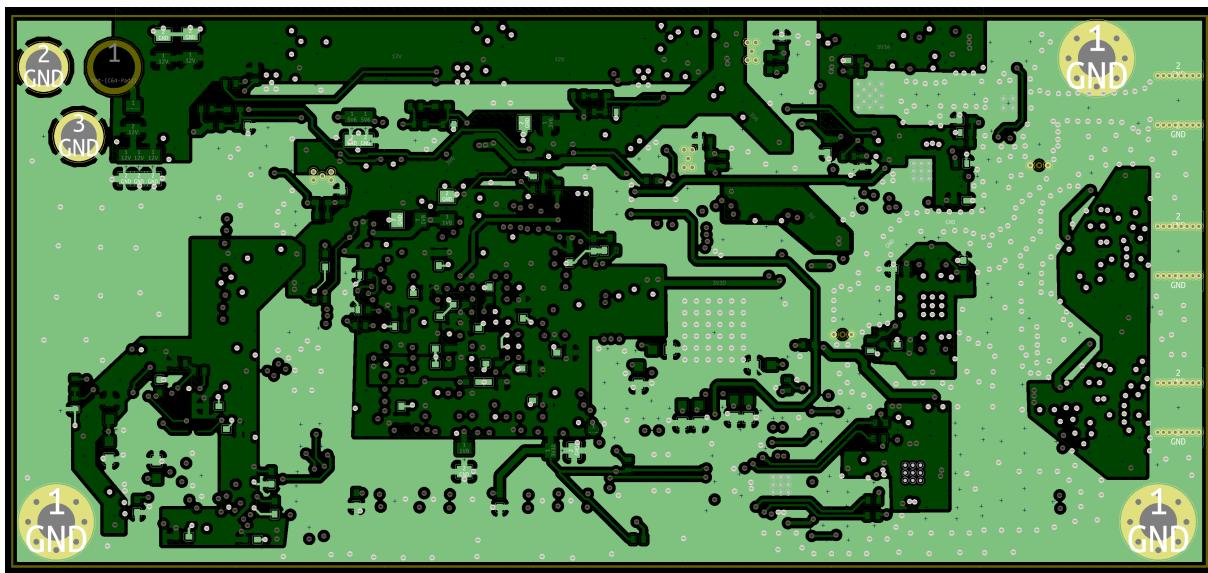


Figure 3.5: The 4th layer of the PCB contains a large ground plane with many vias interspersed.

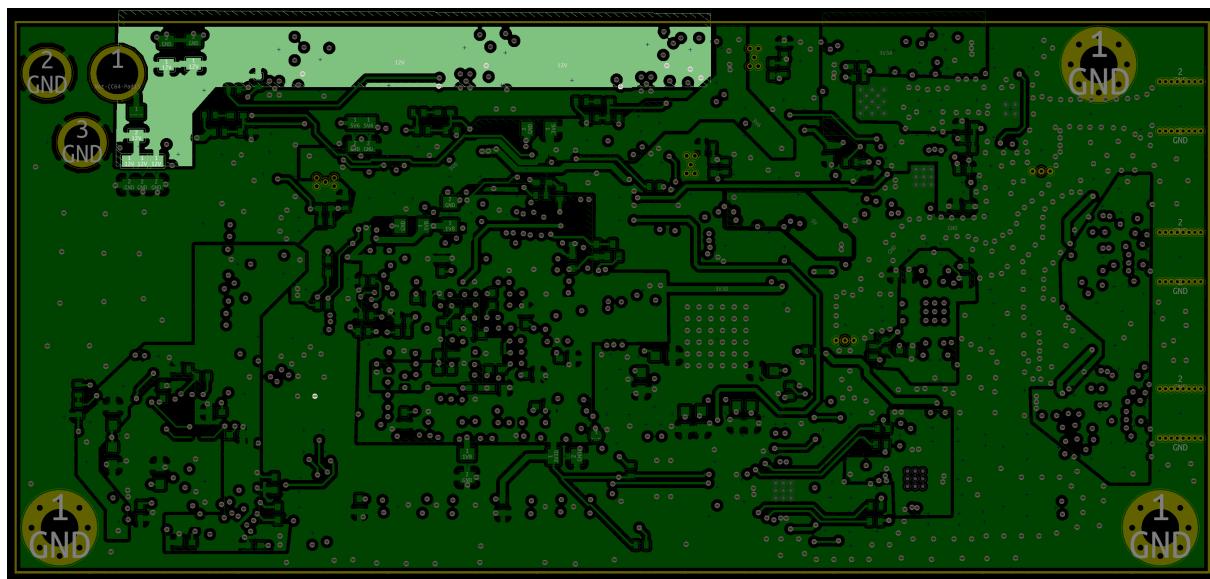


Figure 3.6: The 12V power plane is located at the top of the board adjacent to the D barrel jack and the buck converters it feeds.

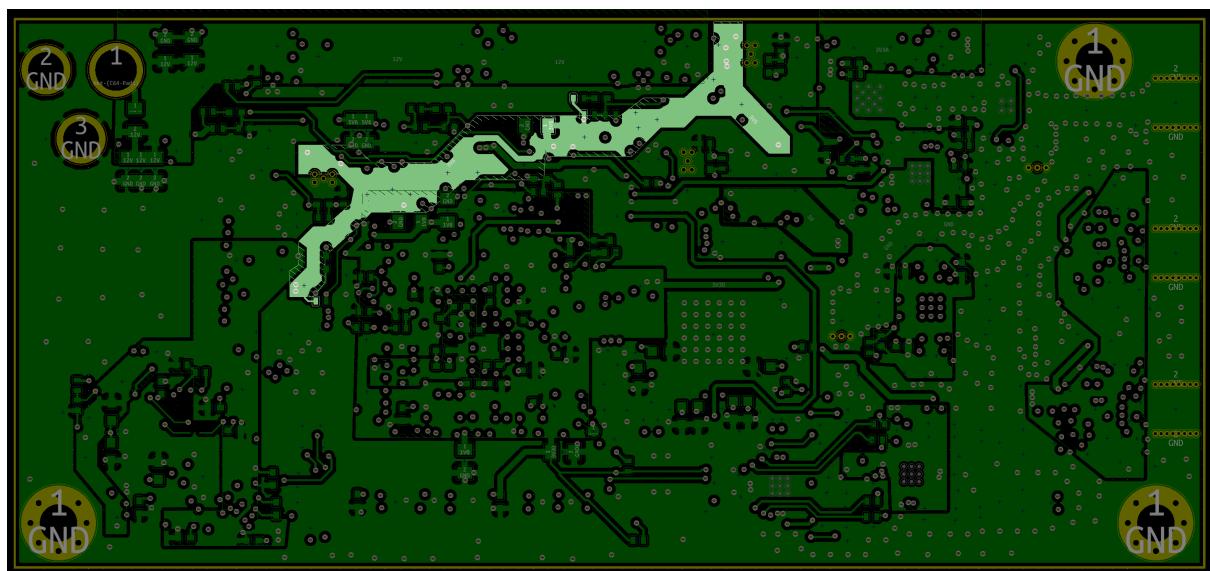


Figure 3.7: There is a 3.6V power plane that is the output of one of the buck converter and is use as the input to several linear regulators that output 1.8V 3.0V and 3.3V.

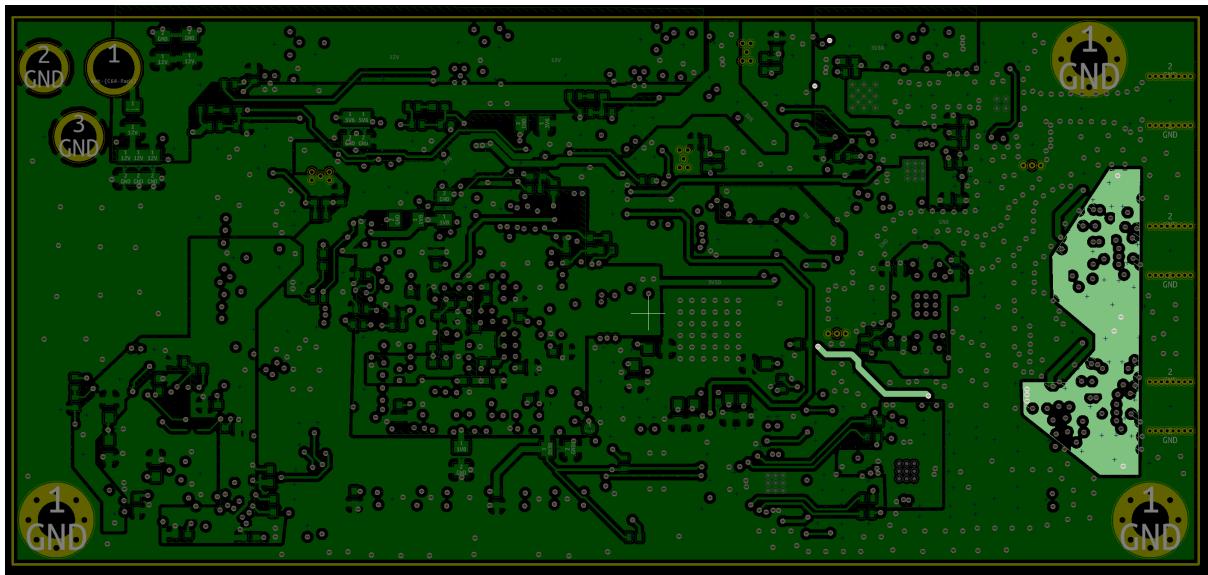


Figure 3.8: A 3V power plane is used to power components near the right side of the board (the right side of the board is where signal transmission and reception occur that amplify receive signals so they can be mixed with the transmitted signal and fed into the ADC before FPGA processing). Notably, the 3V power plane is located near the components but far from the linear regulator that outputs it.

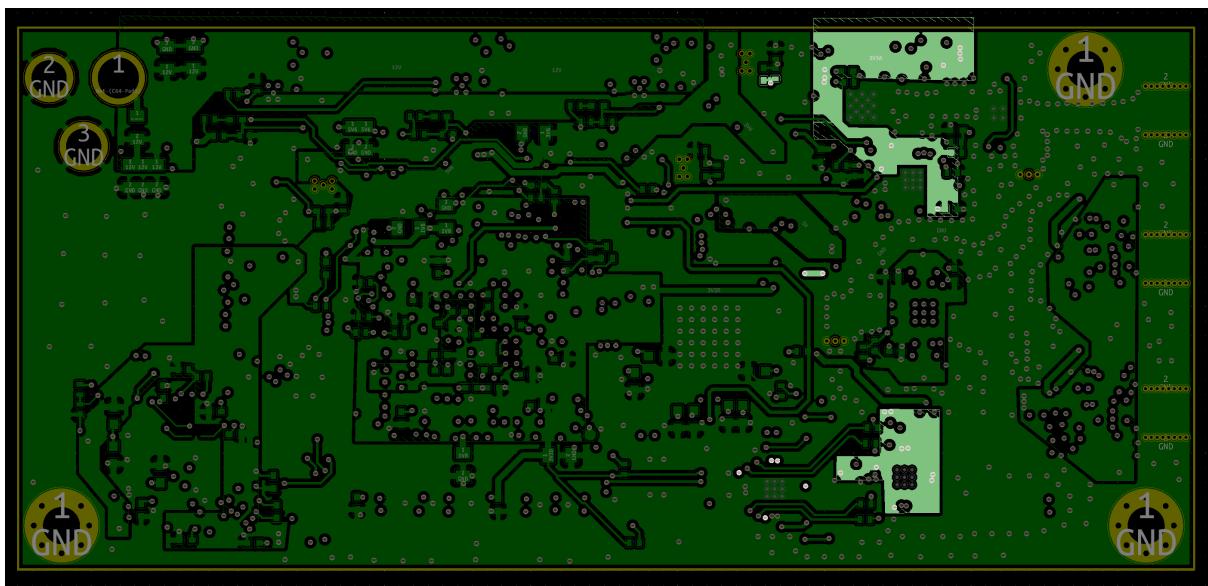


Figure 3.9: A 3.3V power plane is used to power several components for signal transmission, such as a frequency synthesizer, and RF amplifier. These, along with all other reception and transmission circuitry, are located on the right side of the board.

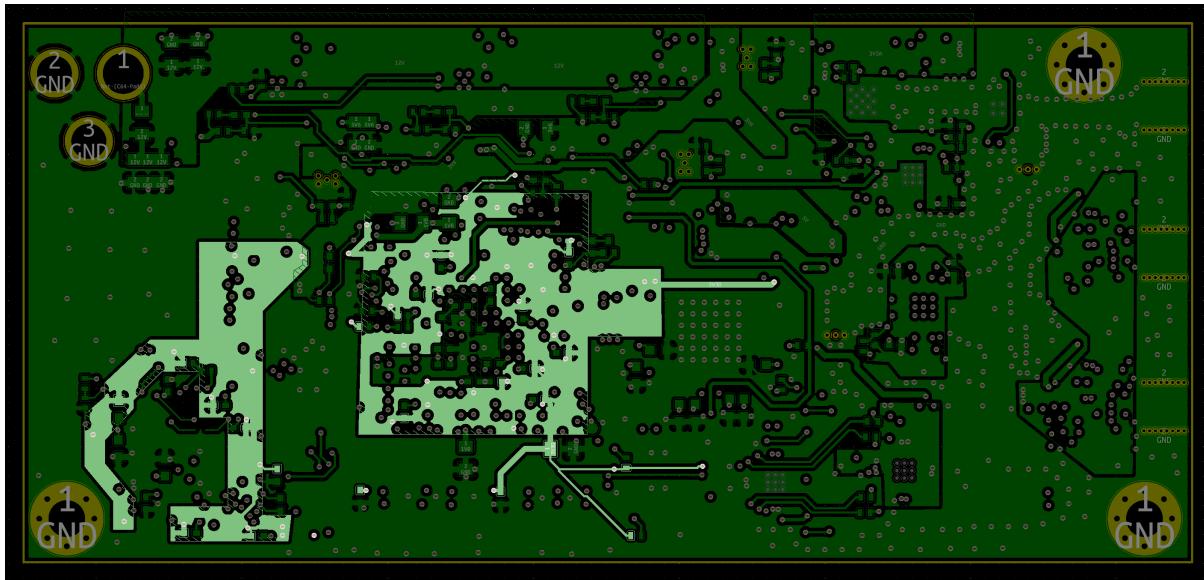


Figure 3.10: Another 3.3V power plane is used as one of the power inputs to the FPGA as well as to a USB-to-UART device (a configuration bit stream is sent from a host computer through a USB cable to the PCB where this device converts it into the proper UART format to be transmitted to the FPGA) and an ADC (the ADC converts the mixed transmitted-received signals to digital and then sends them to the FPGA for processing).

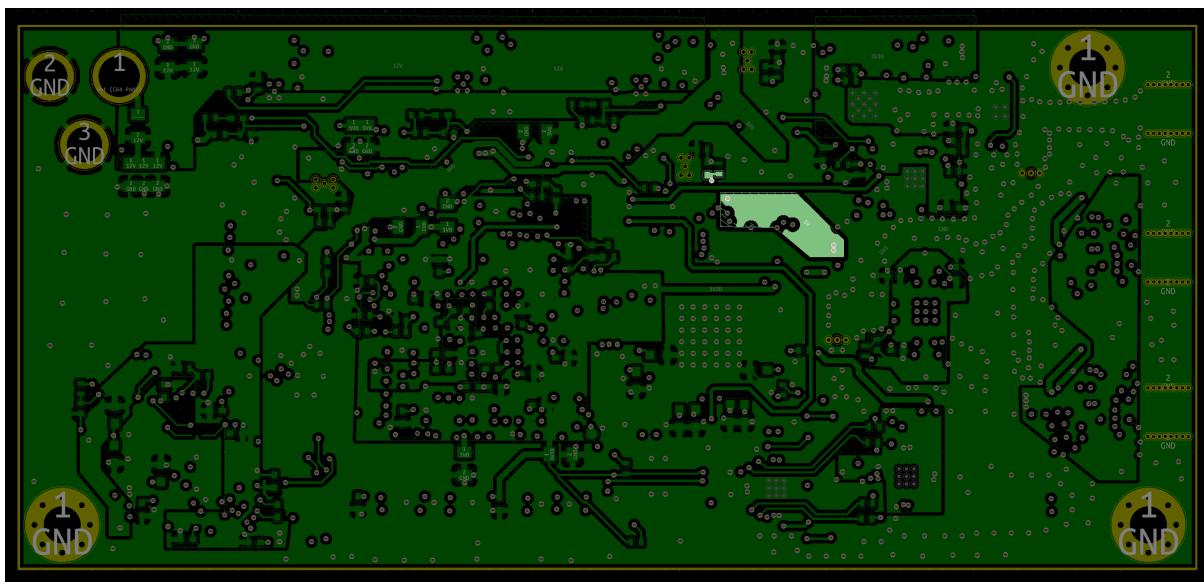


Figure 3.11: A 5V power plane powers one of the inputs to the frequency synthesizer for transmission.

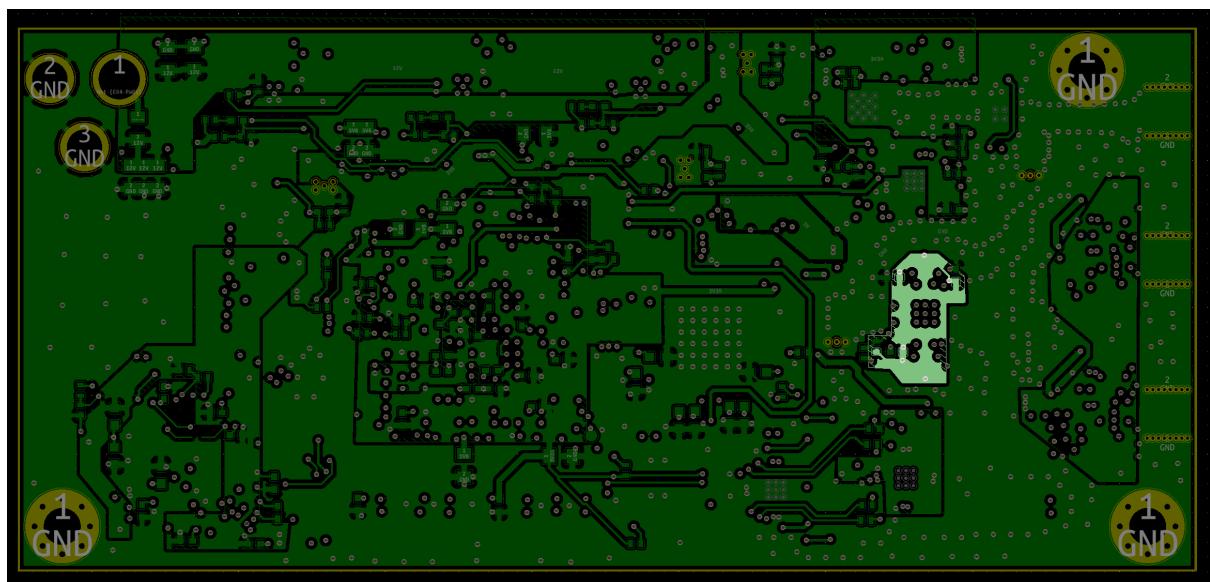


Figure 3.12: Another 5V power plane is used for to power devices after going through a ferrite bead.

# Chapter 4

## Antennas

There are several promising places to start in learning how to do this. Obviously, the [hforsten blog](#) is a good place. Contextual Electronics also has a [youtube video](#) about building a PCB antenna. Finally, [OpenEMS](#) is apparently a very powerful tool for simulating and designing antennas (among other things RF). This is already installed and can be scripted through Octave. Make sure to look at the tutorials.

One antenna is used for transmission and two are used for reception. It might be possible to achieve the same effect with two overall antennas but the design would need to be significantly altered to do so. The transmission antenna should have high gain and high directivity. This ensures sufficient power for reception, longer range, and less side clutter (i.e. you don't want a wide field of vision, you want this to be mostly directed in a single direction). We use two reception antennas instead of one so that we can perform beamforming. Basically, we mix the signal picked up by each reception antenna individually with the transmitted signal. Each of these mixed products tells us the distance from the object. However, if the object is at a slight angle, the phase difference between the two mixed products tells us the incident angle, so we can localize the distant object.

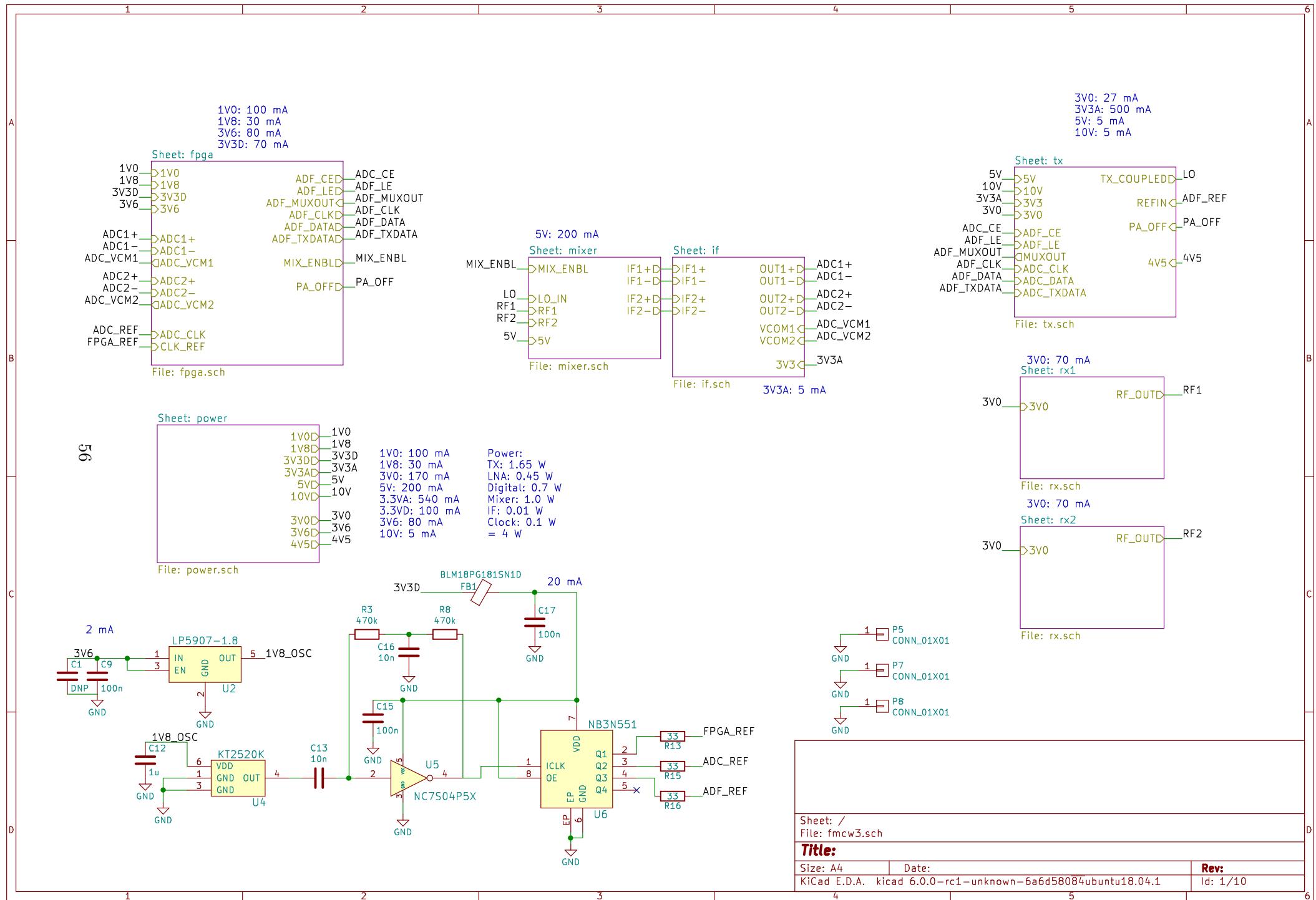
[This antenna](#) looks like it would be good for transmission. [This RF Elements](#) antenna looks even better, but is probably more than I'm willing to pay (it's gain is lower, however). [The Triple Feed Patch Array Antenna](#) is a great deal for the price and is based off a clever open-source design, [here](#). I'm not sure if the gain will be quite enough, however. If you're confused about the operation of that last one, look at the description for it on Antenna Test Lab. They provide excellent information. I'm mostly struggling to find a good patch array antenna for reception. I may have to just build this myself, but I'm worried about the quality using normal FR4.

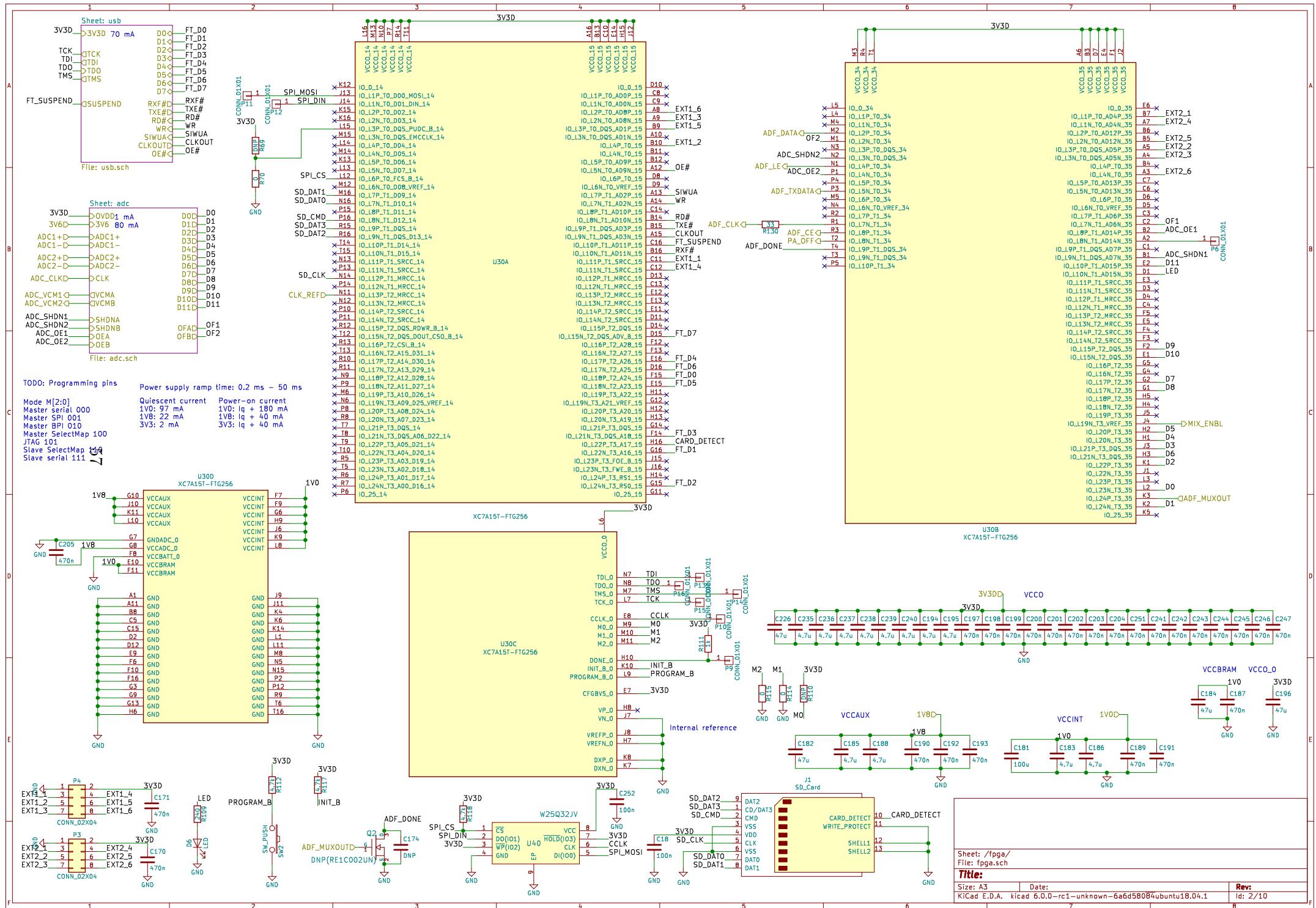
## **Chapter 5**

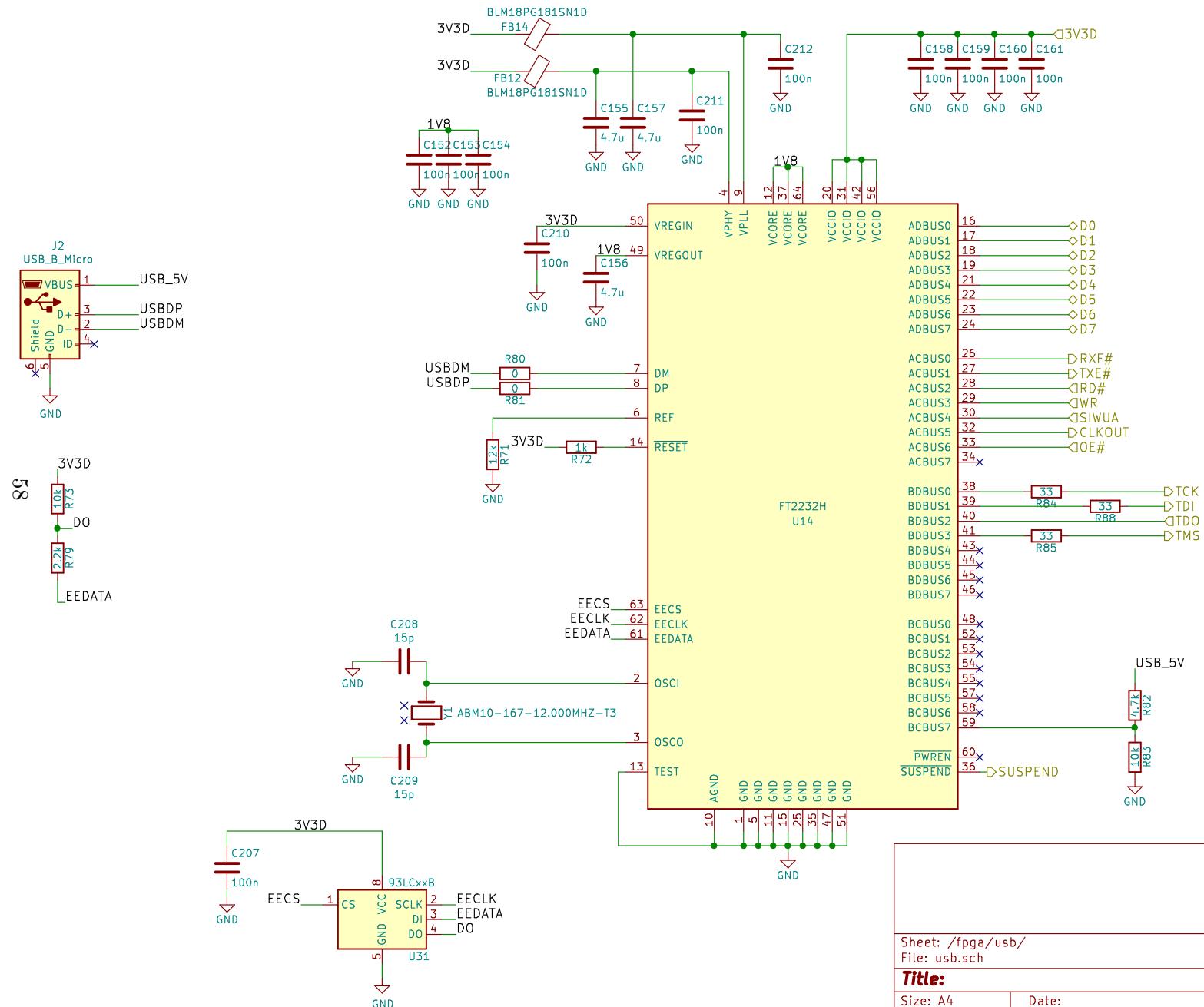
### **Links**

## **Chapter 6**

### **Full Schematic**





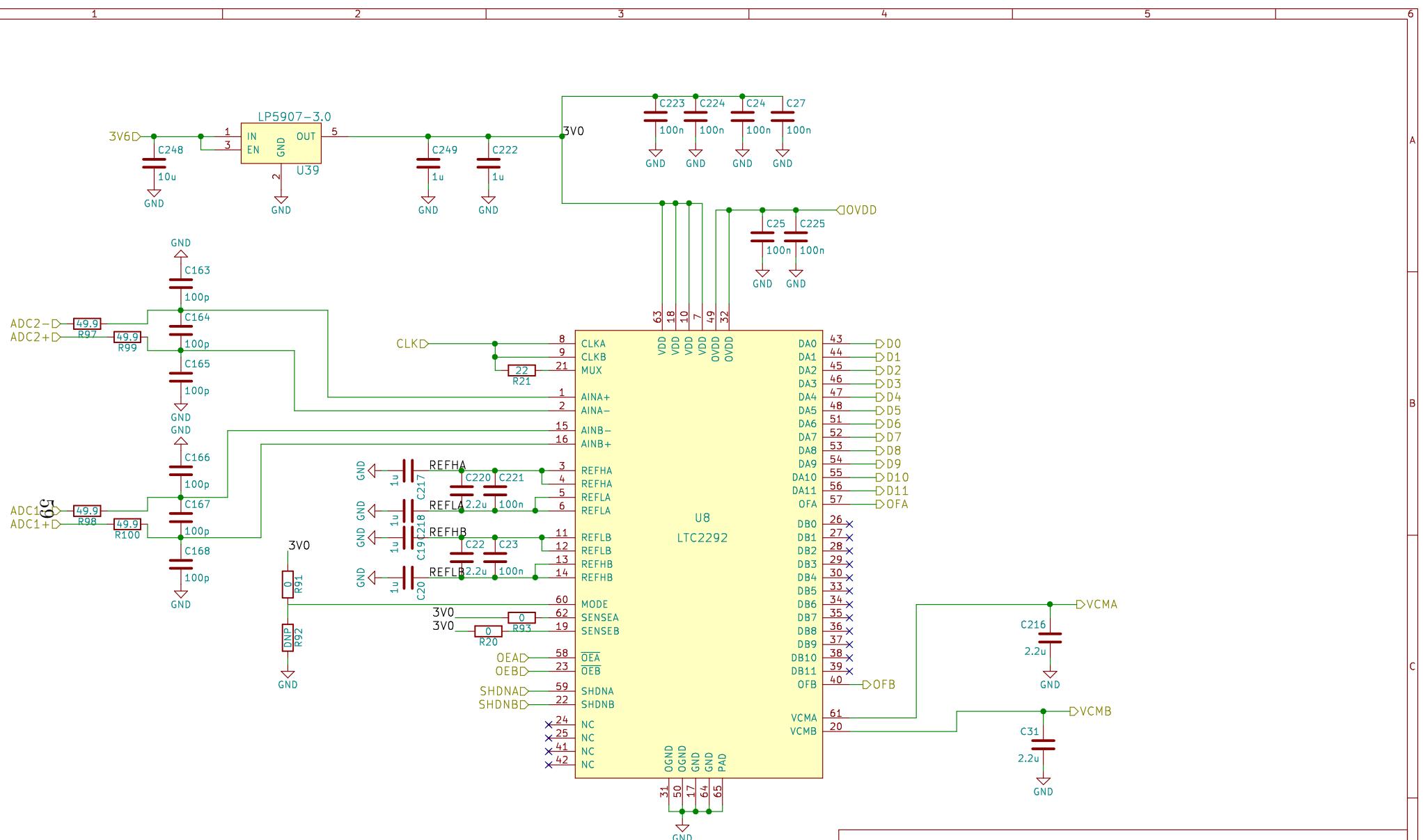


Sheet: /fpga/usb/  
File: usb.sch

### Title:

Size: A4 Date:  
KiCad E.D.A. kicad 6.0.0-rc1-unknown-6a6d58084ubuntu18.04.1

Rev: Id: 3/10



Sheet: /fpga/adc/  
File: adc.sch

### Title:

Size: A4 Date:  
KiCad E.D.A. kicad 6.0.0-rc1-unknown-6a6d58084ubuntu18.04.1

Rev: Id: 4/10

10V current: 1mA  
3.3V current: 600mA  
5V current: 1mA

09

BLM18PG181SN1D  
FB2

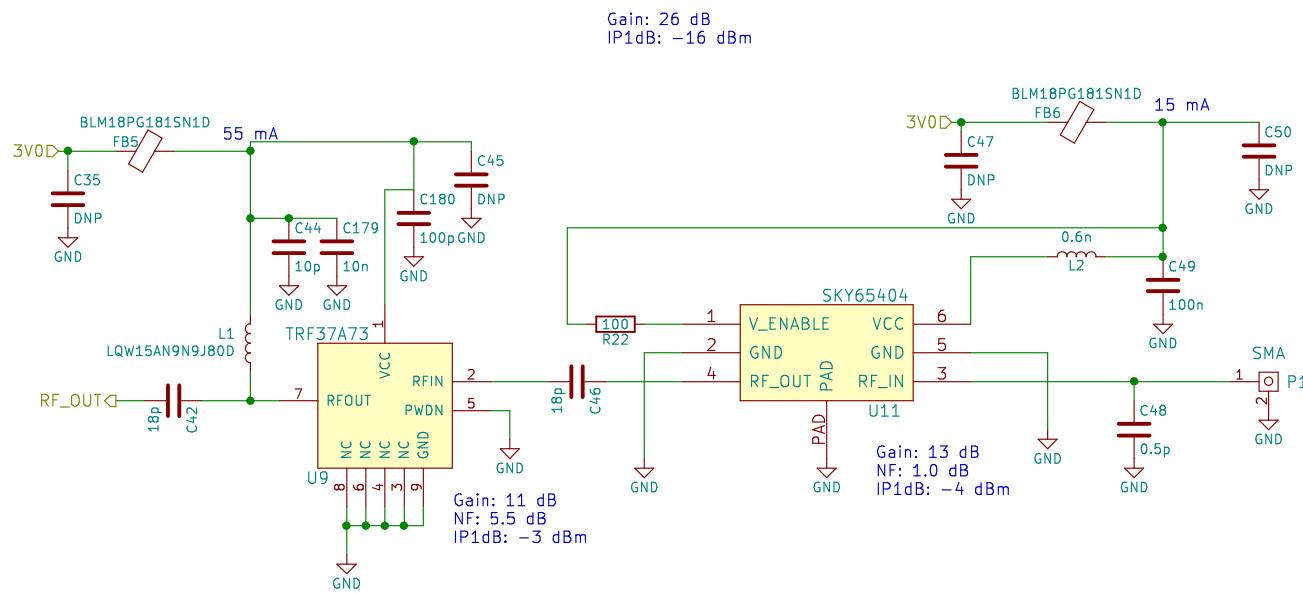
DNP DNP

GND GND

C215 C214

100n

I9



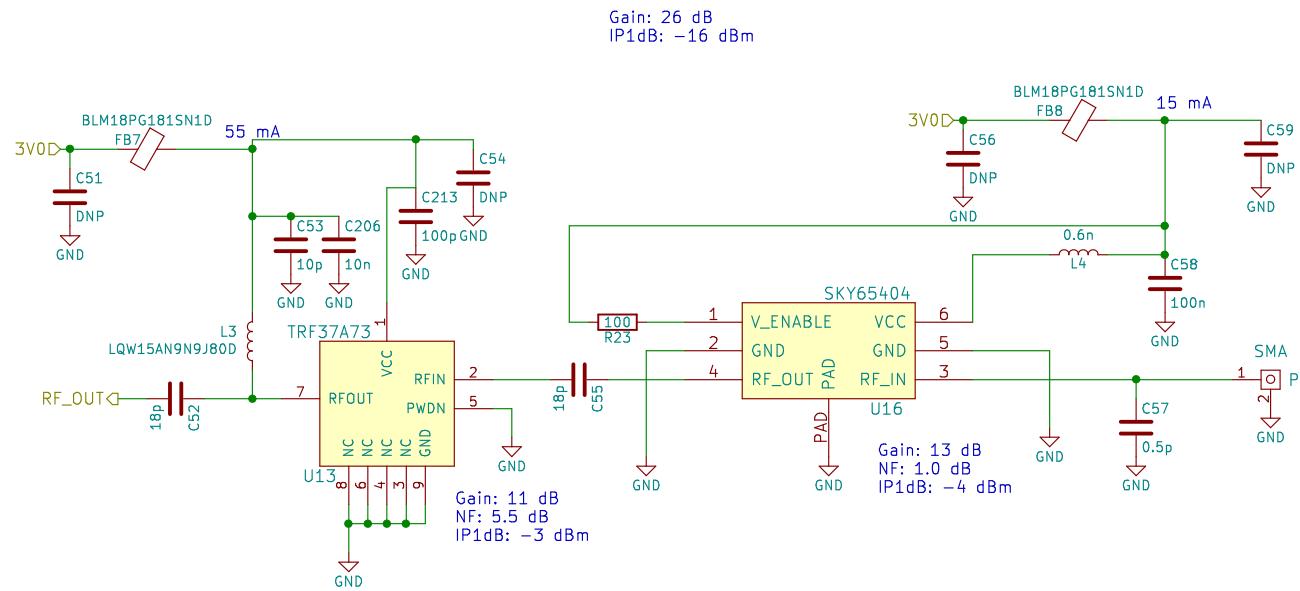
Sheet: /rx1/  
File: rx.sch

**Title:**

Size: A4 Date:  
KiCad E.D.A. kicad 6.0.0-rc1-unknown-6a6d58084ubuntu18.04.1

Rev:  
Id: 6/10

62

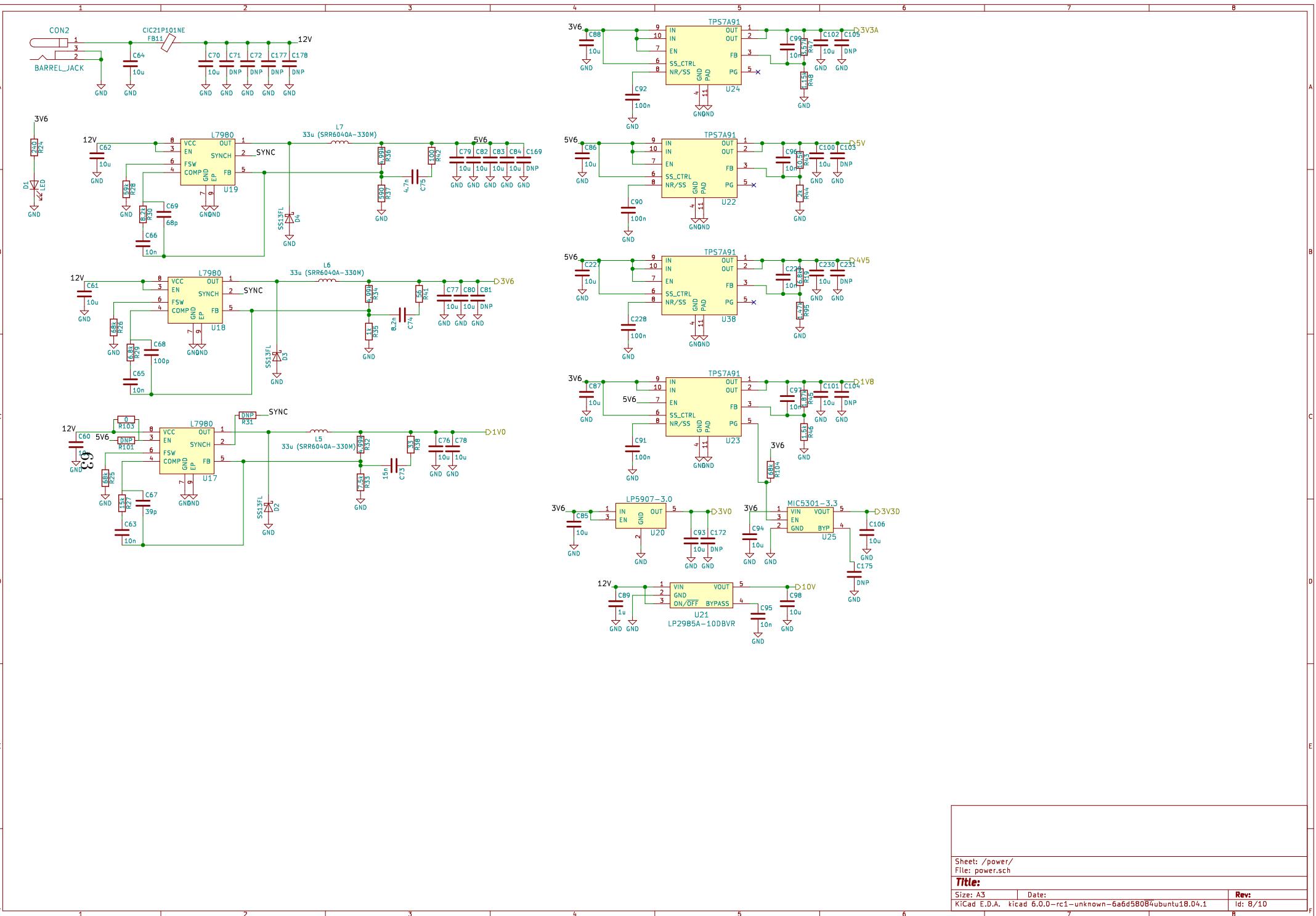


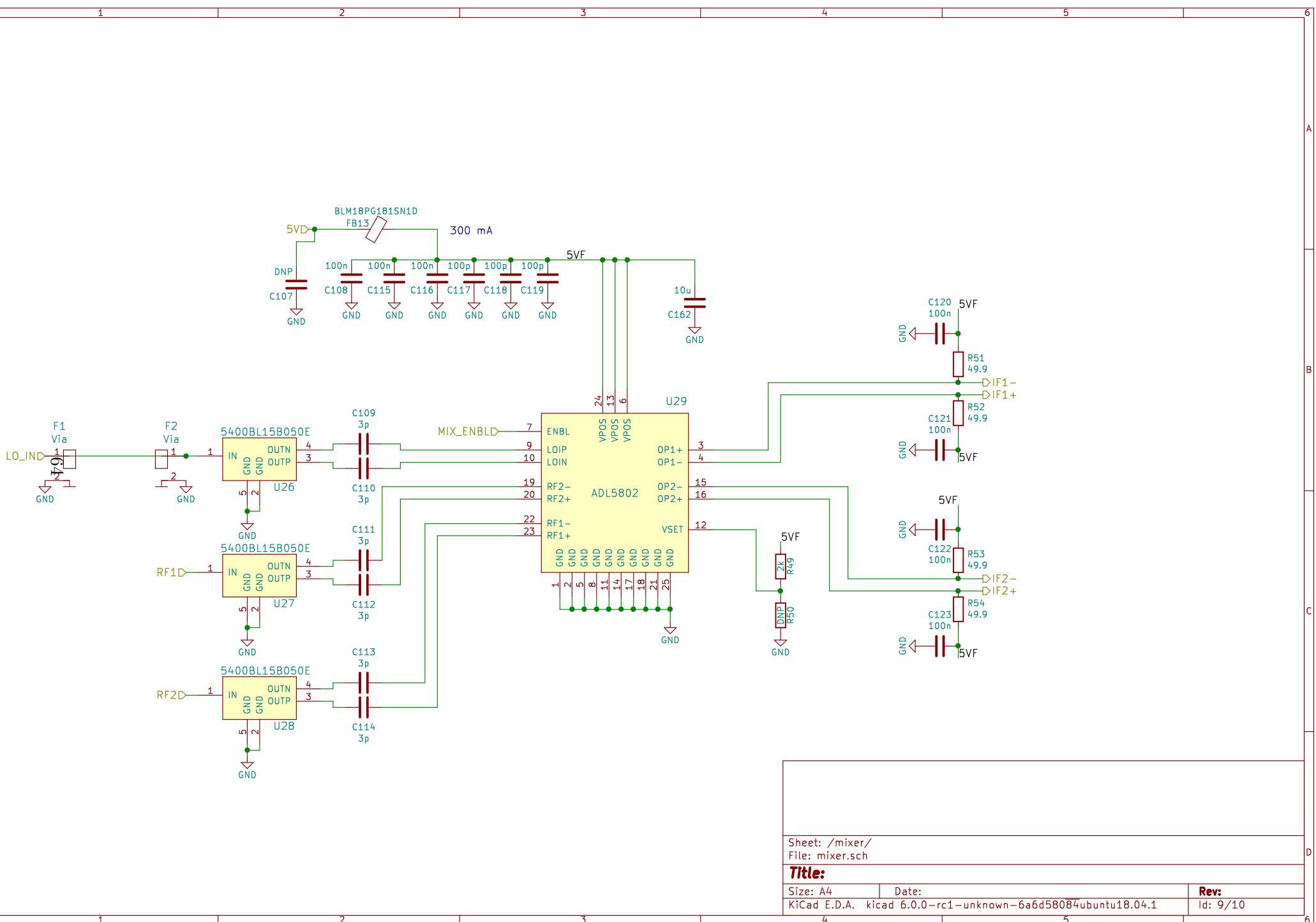
Sheet: /rx2/  
File: rx.sch

**Title:**

Size: A4 Date:  
KiCad E.D.A. kicad 6.0.0-rc1-unknown-6a6d58084ubuntu18.04.1

Rev:  
Id: 7/10





Sheet: /mixer/  
File: mixer.sch

**Title:**

Size: A4 Date:  
KiCad E.D.A. kicad 6.0.0-rc1-unknown-6a6d58084ubuntu18.04.1

**Rev:**  
Id: 9/10

