Background

RFID 13.56 MHz ISO 14443A:

- https://static.sparkfun.com/images/antenna_4-layer.pdf

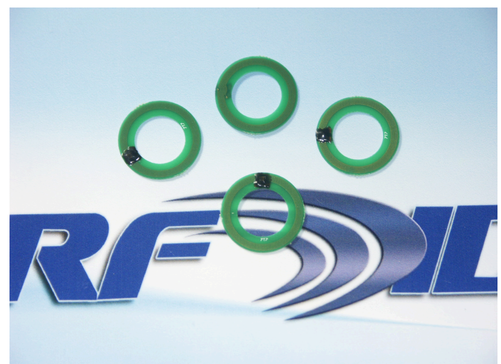
Autodesk Eagle PCB layers explained:

- https://www.autodesk.com/products/fusion-360/blog/every-layer-explained-autodesk-eagle/

RFID Tags

20 mm PCB Tag

https://www.rfidinc.com/hf-13-56-mhz-rfid-pcb-fr4-tags
https://www.rfidinc.com/pub/media/pdfs/HF-13.56-MHz-Data-Sheet-v7-19.pdf
Model: Model HF-1501-20-N213 PCB/FR4 20mm RFID Ring Tag, 144 Bytes NTAG 213 ISO 14443A NDEF NFC memory chip
Part number: 850-0001-20-N213
Availability: 59 in stock
Price: $1.99 each
Chip: MIFARE NTAG 213
Chip Datasheet:
https://www.nxp.com/docs/en/data-sheet/NTAG213_215_216.pdf



Proven Designs

Eccel Pepper C1 Mux

https://eccel.co.uk/product/pepper-c1-mux-uart/
https://eccel.co.uk/wp-content/downloads/Pepper_C1/C1_MUX_User_manual.pdf

- RFID Reader: PN5180
- Multiplexer: ADG1607

DIY RFID Poker Table

https://www.pokerchipforum.com/threads/experimenting-with-a-diy-rfid-table-and-broadcast-overlay.88715/

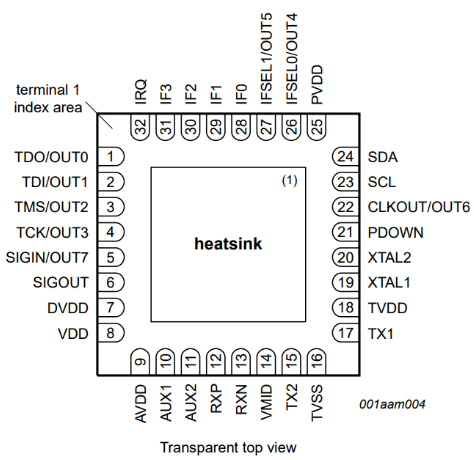
- RFID Reader: PN5180
- Multiplexer: ADG1607 and NX3L4051
- Pictures:
  - https://www.pokerchipforum.com/attachments/1000006016-png.1265021/

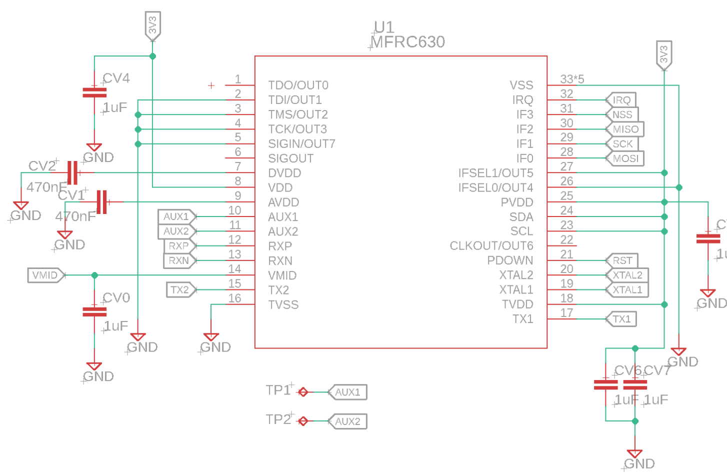
- https://www.pokerchipforum.com/proxy.php?image=https%3A%2F%2Fi.imgur.com%2FILFpHQC.jpg&hash=10c0f8b772a619c223f14d08b51529d5
- https://www.pokerchipforum.com/attachments/38x41-png.1188668/
- https://imgur.com/a/hzkE3nq

RFID Reader

MFRC630

- Supports 2.5V to 5.5V supply
- 350mA maximum antenna power
- Only supports ISO 14443A (13.56 MHz Type A)
- SPI, I2C, UART interface
  - *We are using SPI interface*
- “High performance”
- *We are using revision MFRC63003 (provides more antenna power)*





$6.62 on DigiKey:
https://www.digikey.com/en/products/detail/MFRC63003HNY/568-MFRC63003HNYCT-ND/13282419?curr=usd
Datasheet:
https://www.nxp.com/docs/en/data-sheet/MFRC630.pdf

Alternatives

- MFRC522
  - https://www.nxp.com/docs/en/data-sheet/MFRC522.pdf
  - $7.10
  - Outdated
  - Very common and well documented

    - Only supports 13.56 MHz Type A
    - 100mA maximum antenna power
    - Supports 2.5V to 3.6V supply
    - “Standard performance”
    - Older model of the MFRC630
- PN5180
    - https://www.nxp.com/docs/en/data-sheet/PN5180A0XX_C3_C4.pdf
    - $10.52
    - Very common and well documented
    - Supports many other RFID protocols
    - 250mA maximum antenna power
    - Supports 2.7V to 3.6V logic supply
    - Supports 2.7V to 5.5V antenna supply
    - “High performance”
- CLRC663
    - https://www.nxp.com/docs/en/data-sheet/CLRC663.pdf
    - $10.72
    - Supports many other RFID protocols
    - 350mA maximum antenna power
    - Supports 2.5 to 5.5V supply
    - “High performance”
    - Package is identical to MFRC630
    - Antenna design is identical to MFRC630
- TRF7970A
- HTRC110

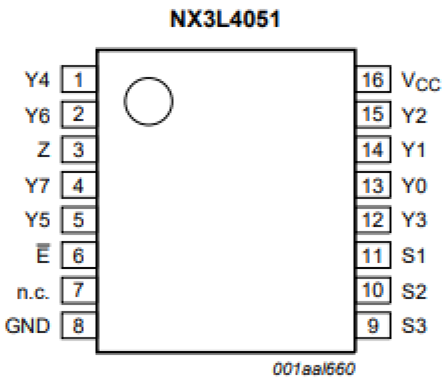
Multiplexer

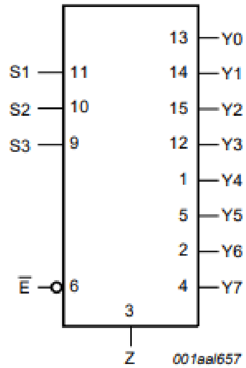
NX3L4051

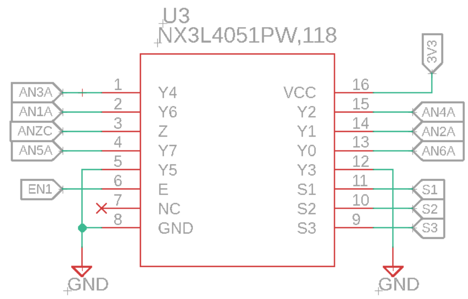
Single low-ohmic 8-channel analog switch, suitable for use as an analog or digital multiplexer/demultiplexer.

- Very low on resistance: 0.5 Ohms at 3.3V
- High current handling capability: 350 mA at 3.3V
- Supports up to 4.3V supply and pin voltage

2 are used to interface with 8 antennas (one for positive channel, one for negative), 4 for 16 antennas.







$1.29 on DigiKey:
https://www.digikey.com/en/products/detail/NX3L4051PW,118/568-12393-1-ND/5269671?curr=usd
Datasheet:
https://www.nxp.com/docs/en/data-sheet/NX3L4051.pdf

Alternatives

- ADG726: 16:1 differential multiplexer
  - https://www.analog.com/media/en/technical-documentation/data-sheets/ADG726_732.pdf
  - $14.42
  - 5 Ohm on resistance
  - One required per 16 antennas
  - 30 mA continuous current
- ADG1607: 8:1 differential multiplexer
  - https://www.analog.com/media/en/technical-documentation/data-sheets/ADG1606_1607.pdf
  - $9.83
  - 5 Ohm on resistance
  - Two required per 16 antennas
  - Up to 378 mA continuous current

Crystal Oscillator

Requirements

From MFRC630 datasheet:

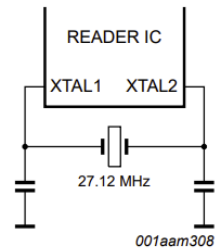
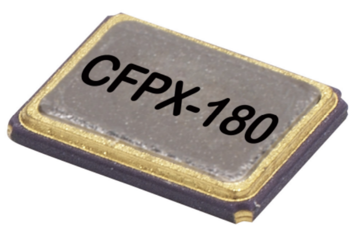


Figure 27. Quartz connection

Table 35. Crystal requirements recommendations

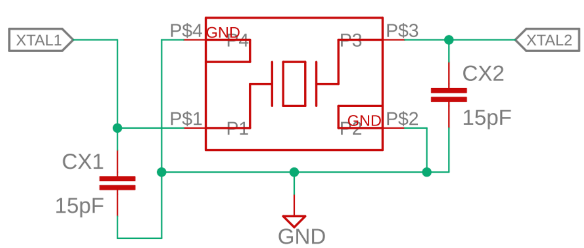
Symbol	Parameter	Conditions	Min	Typ	max	Unit
f_{xtal}	crystal frequency		-	27.12	-	MHz
$\Delta f_{xtal}/f_{xtal}$	relative crystal frequency variation		-250	-	+250	ppm
ESR	equivalent series resistance		-	50	100	Ω
C_L	load capacitance		-	10	-	pF
P_{xtal}	crystal power dissipation		-	50	100	µW

830053099



$0.61 on DigiKey:
https://www.digikey.com/en/products/detail/w%C3%BCrth-elektronik/830053099/13979347

Datasheet:
https://www.we-online.com/components/products/datasheet/830053099.pdf



Antenna References

- AN11019: CLRC663, MFRC630, MFRC631, SLRC610 Antenna Design Guide
  - https://www.nxp.com/docs/en/application-note/AN11019.pdf

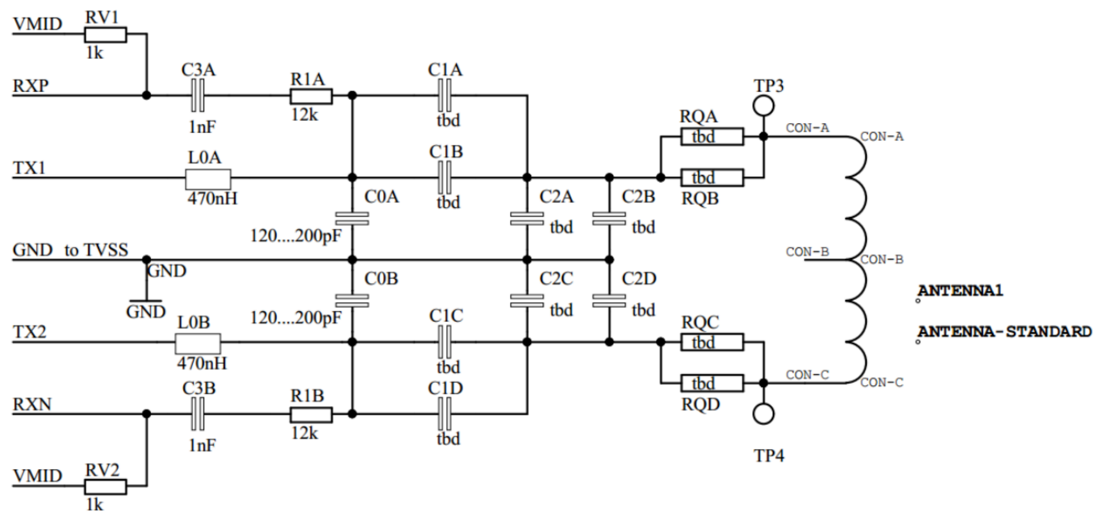
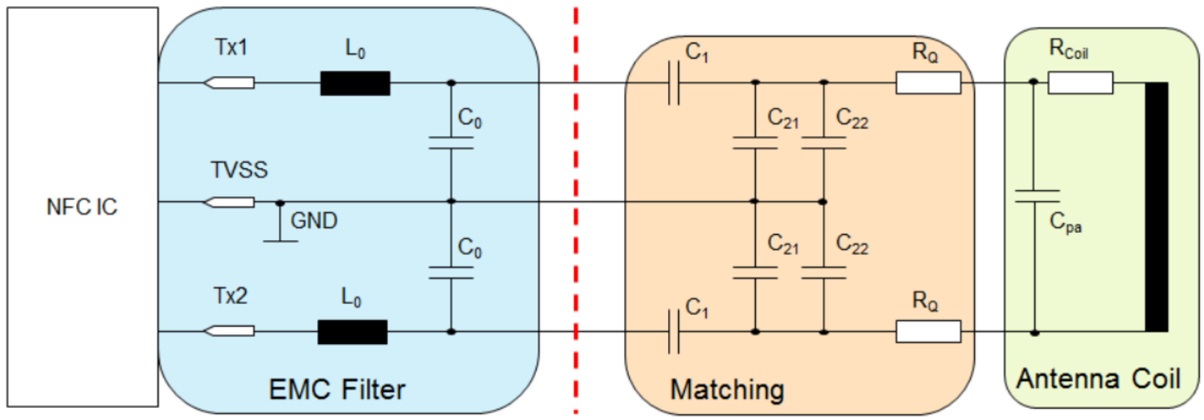


Fig 17. Typical CLRC663 analog circuit

The antenna matching is done with the following steps:

1. Measure the antenna coil
2. Define target impedance and Q-factor
3. Define the EMC filter
4. Calculate the matching components
5. Simulate the matching
6. Assembly and measurement
7. Adaptation of simulation
8. Correction and assembly



(1) This circuit only covers the Tx part.

Fig 19. CLRC663 Reader only antenna matching circuit

- MFRC630 Datasheet
  - https://www.nxp.com/docs/en/data-sheet/MFRC630.pdf

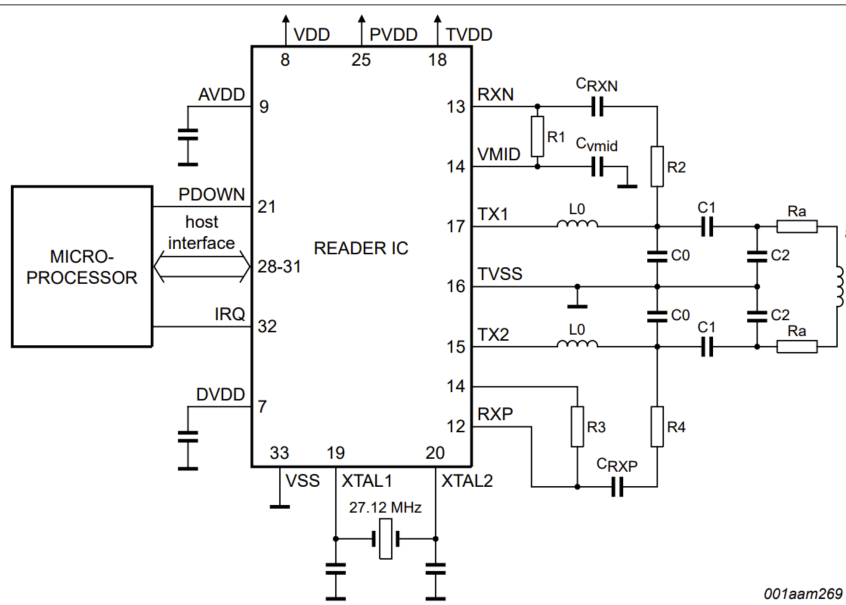


Figure 31. Typical application antenna circuit diagram

Antenna Design

Antenna design calculators

- NXP NFC Antenna Tool: https://community.nxp.com/t5/NFC/bd-p/nfc (best option)

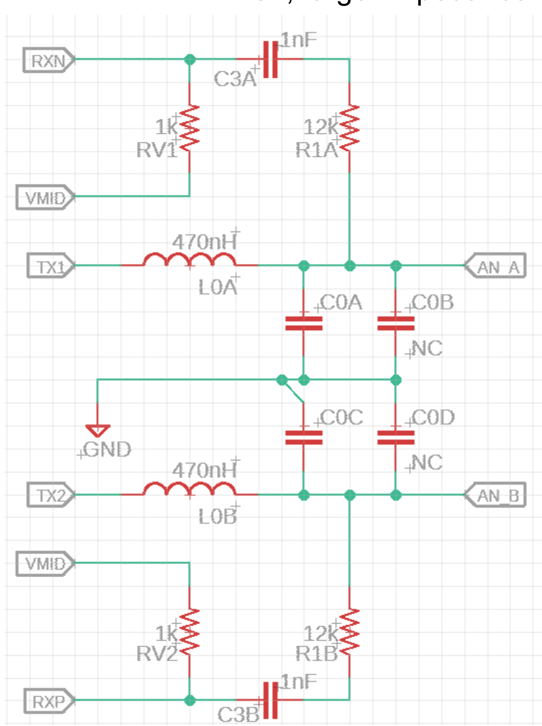
- ST eDesignSuite NFC Inductance: https://eds.st.com/antenna/#/

Notes

- From AN11019: "Out of experience it turns out to be optimum to have an inductance around L ≈ 1 µH for a proper matching, but a wide range of L ≈ 300 nH up to L≈ 4 µH still can be matched properly, so typically 1 up to 4 turns in the normal range of antenna sizes are used."

EMF Filter

- For maximum power transfer, the target impedance must be set to the lowest value that maximizes $I_{TVDDmax}$ without exceeding the MFRC630 limit of 350mA.
    - At 3.3V, target impedance is 10 Ohms, with a total power of 1.1W.
    - At 4.3V, target impedance is 12.5 Ohms, with a total power of 1.5W.
    - At 5V (unsupported by the NX3L4051), target impedance is 15 Ohms, with a total power of 1.65W.
- The recommended antenna current is 250 mA.
    - **At 3.3V, target impedance is 13.2 Ohms, with a total power of 0.8W.**
    - At 4.3V, target impedance is 17.2 Ohms, with a total power of 1.1W.



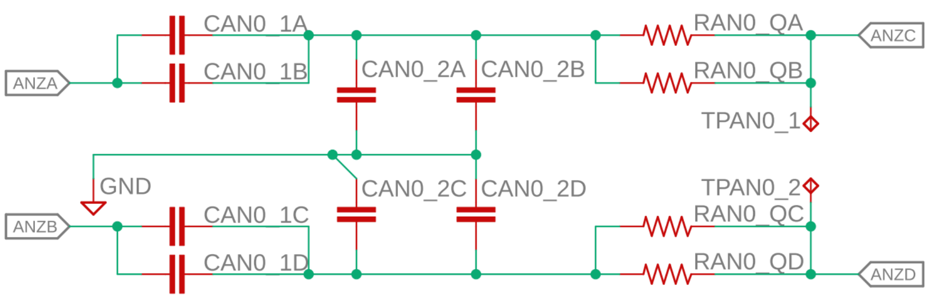
Matching Circuit

The RFID reader board prototype includes a two matching circuits:

- One within each antenna loop. Each antenna is a different distance from the reader with a different number of surrounding antennas. Thus, the impedance, capacitance, and inductance of each antenna may be different and may require a different matching circuit. This is standard practice among multiplexed antennas and antennas that are greater than 1 cm from the reader.
- One before the multiplexers. Ideally, the parasitics between the different antennas will be low enough that we can use a single matching circuit before the multiplexer. This will significantly reduce manufacturing time, costs, and complexity.

To implement one of the matching circuits, the other unused matching circuit must first be shorted with 0 Ohm resistors where necessary for continuity.

Parallel capacitors and resistors are used to be able to fine-tune the RC values when tuning the antenna circuitry.



Proposed testing methodology

1. Short all antenna matching circuits with 0 Ohm resistors on board A.
2. Measure antenna coil RLC for both the close and far 50x50x3 antennas.
3. Average values, and use to tune multiplexing matching circuit (see MFRC630 Antenna Design Guide and NXP NFC Antenna Tool).
    - NXP NFC Antenna Tool values:
        - Length: 50 mm
        - Width: 50 mm
        - Track width: 406 um
        - Gap between tracks: 594 um
        - Track thickness: 35 um (1 oz Cu)
        - Number of turns: 3
        - PCB Thickness: 1.59 mm
        - Er: 4.3
    - Calculated antenna values:
        - Inductance: 1.216 uH
        - Inductance minimum: 1.138 uH
        - Inductance maximum: 1.498 uH
        - Capacitance: 1.7 pF
        - Resistance: 1.35 Ohm
        - Self Resonance: 110 MHz

- Initial filter parameters:

Table 1. Q-factor
Values for the passive linear antenna circuit only.

Q	Condition
10	Start value for the matching calculation for NFC Reader design, supporting higher bit rates (212, 424, 848 kbit/s).
15	Start value for the matching calculation for NFC Reader design, supporting higher bit rates (212, 424 kbit/s).
20	Start value for the matching calculation for typical NFC Reader design.
25	Start value for the matching calculation for typical NFC Reader design, limited to 106 kbit/s.
30	Nominal value for MIFARE Classic communication.

Note: The chosen values of the inductance, the cut off frequency and the corresponding capacitance have shown to be a reasonable trade-off between the transfer function for the transmit signal as well as for the receive signal on one hand and the filter function to suppress the higher harmonics on the other hand.

(MFRC 630 Antenna Design Guide)

  - Q-factor: 20
  - Target impedance: 13.2 Ohms (target current of 250 mA at 3.3V)
  - EMC Cutoff Frequency: 20.9 MHz
  - L0 inductance: 470 nH
  - C0 capacitance: 123.4 pF (56 pF + 68 pF)
- Resulting matching circuit:
  - C1 capacitance: 56.3 pF (56 pF)
  - C2 capacitance: 140.4 pF (**68 pF + 68 pF** or 110 pF + 30 pF or 100 pF + 39 pF)
  - Rs resistance: 1.92 Ohms (1.82, 1.87, 1.91 Ohms)
- 40x40x4 Antenna Loop:
  - Lant = 1432 nH (1317 - 1863 nH)
  - Cant = 1.6 pF
  - Rant = 1.43 Ohms
  - Fres = 104 MHz
  - C0 = 123.4 pF (same as others)
  - C1 = 53.2 pF
  - C2 = 112.9 pF (56 pF + 56 pF)
  - Rs = 2.34 Ohms
- 30x30x5 Antenna Loop:
  - Lant = 1356nH (1231 - 1841 nH)
  - Cant = 1.5 pF
  - Rant = 1.34 Ohms
  - Fres = 112 MHz
  - C0 = 123.4 pF (same as others)
  - C1 = 54.2 pF
  - C2 = 121.8 pF (120 pF)
  - Rs = 2.22 Ohms

4. Tuned Matching Circuit
   - C1 capacitance: 62 pF (**47 + 15 pF** or 22 + 39 pF)

    - C2 capacitance: 214.4 pF (**180 + 34 pF**)
    - Rs resistance: 0 Ohms

Antenna	L_{ant} (uH)	C_{ant} (pF)	R_{ant} (Ohms)	C1 (pF)	C2 (pF)	Rs (Ohms)
50x50x3	1.22	1.7	1.35	56	140	1.92
40x40x4	1.43	1.6	1.43	53	113	2.34
30x30x3	1.36	1.5	1.34	54	122	2.22

5. Evaluate performance qualitatively using prototype tags.
6. Explore other antennas and using antenna matching circuits if performance fails to meet requirements (need to define).

PCB Layout

From Prof. Carlos Barrios

- Bypass capacitors CVx and especially loading capacitors CXx should be small; consider using 0402 rather than 0805.
- Where possible, avoid using capacitors of different values in parallel to reduce possible anti-resonance (which is research he has conducted). *This is in conflict with the recommendation from the MFRC630 datasheet to put two capacitors in parallel.*

From MFRC630 Antenna Design Guide

- “The connection between the Tx output pins (Tx1 and Tx2) and the EMC low pass filter has to be as short as possible. The GND connection especially between TVSS and the C0 (see Fig 17) capacitors must be as short as possible.”
- “All capacitors are typical ceramic capacitors (e.g. X7R). The capacitors used in the matching circuitry are NP0.”
- “The inductor L0x must be capable of driving the required power: In case the maximum output power is needed, the L0x must be able to drive the 300 mA without going into saturation. The Q-factor of this inductor should be as high as possible.”
- “Be aware of tolerances! The most critical tolerance in the antenna circuits appears at the antenna coil itself, but even for the matching circuitry tolerances of < ±1% are recommended.”
- “Every noise level on top of the supply voltage can disturb the performance of the CLRC663. Therefore, sometimes higher values of the block capacitors in the range of up to 10 µF might help to improve the performance and also stabilizes the power supply.

For that reason, the blocking capacitors for TVDD should be as close as possible to the IC."

From MFRC630 Datasheet:

- "The MFRC630 is supplied by VDD (Supply Voltage), PVDD (Pad Supply) and TVDD (Transmitter Power Supply). These three voltages are independent from each other."
- "To connect the MFRC630 to a Microcontroller supplied by 3.3 V, PVDD and VDD shall be at a level of 3.3 V, TVDD can be in a range from 3.3 V to 5.0 V. A higher supply voltage at TVDD will result in a higher field strength."
- "Independent of the voltage it is recommended to buffer these supplies with blocking capacitances close to the terminals of the package. VDD and PVDD are recommended to be blocked with a capacitor of 100 nF min, TVDD is recommended to be blocked with 2 capacitors, 100 nF parallel to 1.0 μF".
- "AVDD and DVDD are not supply input pins. They are output pins and shall be connected to blocking capacitors 470 nF each."

PCBWay

Capabilities:

- https://www.pcbway.com/capabilities.html

Quote:

- **Board type:** Single pieces
- **Different design in panel:** 1
- **Size:** 120x210mm
- **Quantity:** 5
- **Layers:** 2 Layers
- **Material:** FR-4
- **FR4-TG:** TG 150-160
- **Thickness:** 1.6mm
- **Min track/spacing:** 4/4mil (.1016mm)
- **Min hole size:** 0.3mm
- **Solder mask:** Black
- **Silkscreen:** White
- **Edge connector:** No
- **Surface finish:** HASL with lead
- **Via process:** Tenting vias
- **Finished copper:** 1 oz Cu
- **Remove product No.:** Specify a location
- **SMD-Stencil:** Non-framework

Price: **$89.73**

- **PCB Cost:** $48.31
- **Stencil Cost:** $10.00
- **Shipping:** $31.42

Num designs	Width (cols) (mm)	Length (rows)((mm)	Price	Tot Antennas	Dollars / Antenna
1	60 (1)	90 (1)	$56.98	1	$56.98
1	60 (1)	150 (2)	$62.18	2	$31.09
1	60 (1)	210 (3)	$72.58	3	$24.19
2	60 (1)	210 (3)	$85.56	6	$14.26
1	60 (1)	270 (4)	$85.66	4	$21.42
2	60 (1)	270 (4)	$97.62	8	$12.20
1	120 (2)	150 (2)	$75.17	4	$18.79
2	**120 (2)**	**150 (2)**	**$87.06**	**8**	**$10.88**
1	**120 (2)**	**210 (3)**	**$89.73**	**6**	**$14.96**
1	**120 (2)**	**270 (4)**	**$107.79**	**8**	**$13.47**
1	**240 (4)**	**240 (4)**	**$141.38**	**16**	**$8.84**

Components

Inductor

Requirements

- 470 nH inductance
- 0805 (2012)
- 300 mA minimum saturation current and current rating
- Low tolerance
- High Q-factor
- 13.56 MHz operating frequency
- Low cost

Antenna Designs

Dimensions (mm)	Distance from Reader (mm)	Loops	Shape	Inductance (uH)	Capacitance (pF)	Resistance (Ohms)
50x50	0	3	Square	1.22	1.7	1.35
50x50	60	3	Square	1.22	1.7	1.35
50x50	120	3	Square	1.22	1.7	1.35
40x40	60	4	Square	1.43	1.6	1.43
30x30	0	5	Square	1.36	1.5	1.34
50x50	120	3	Octagon	~1.1	~1.6	~1.2

Experiment 1: Side Length and Loop Count

3 Antennas:

- 50x50 for 3 loops - 1.22 uH
- 40x40 for 4 loops - 1.43 uH
- 30x30 for 5 loops - 1.36 uH

All stay in the target inductance range of 1.0 - 1.5 uH, ideally closer to 1.0 uH.

A smaller antenna loop will in theory have better coupling with a tag of size 25mm or smaller, but the read range may decrease when outside of the antenna loop, which is now smaller.

Experiment 2: Distance from Reader

3 Antennas:

- 0 mm away (0 squares)
- 60 mm away (1 square)
- 120 mm away (2 squares)

Longer distances between the reader and the antenna enable more flexible PCB layout, but will eventually cause tags to fail to be read

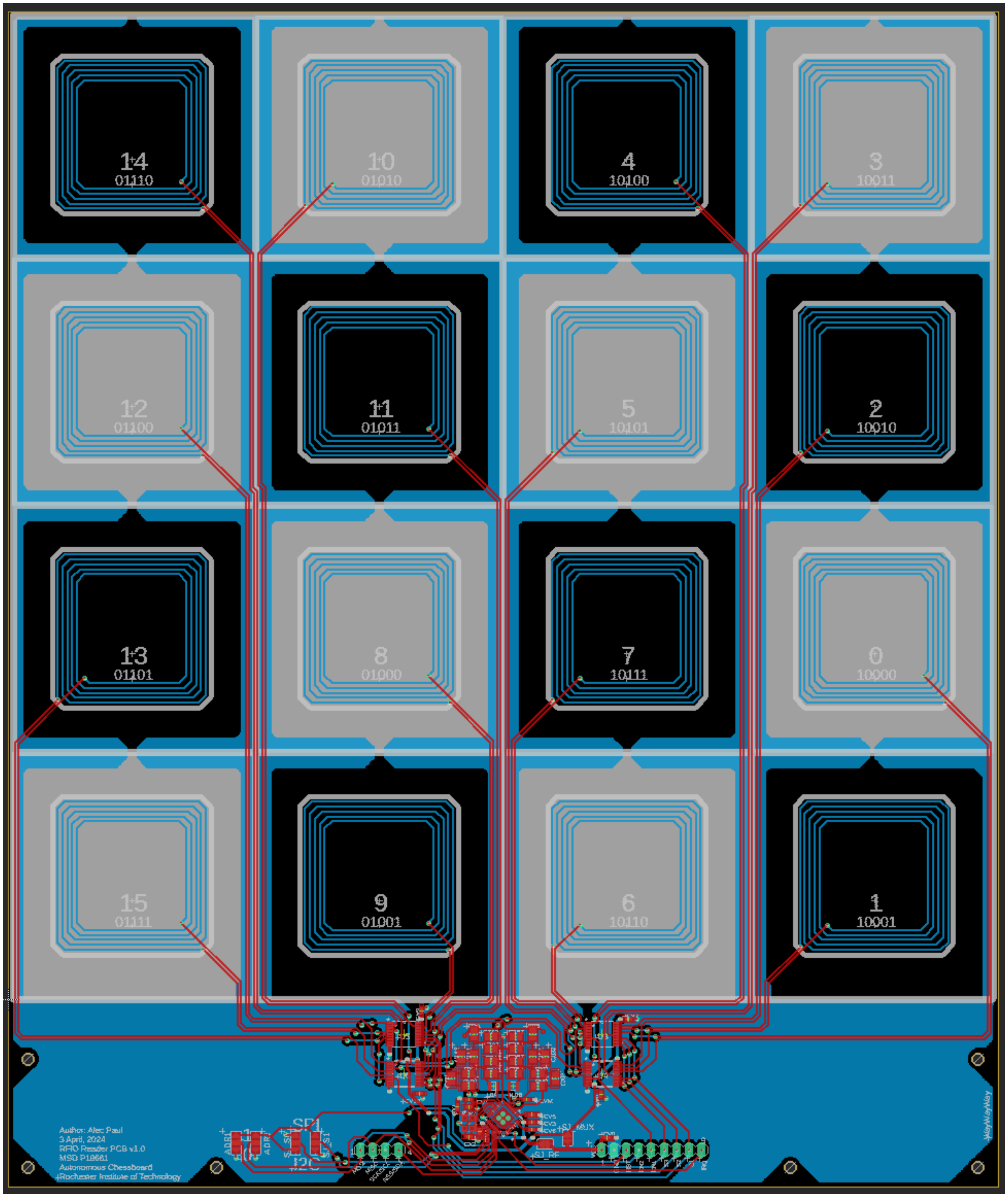
Experiment 3: Shape

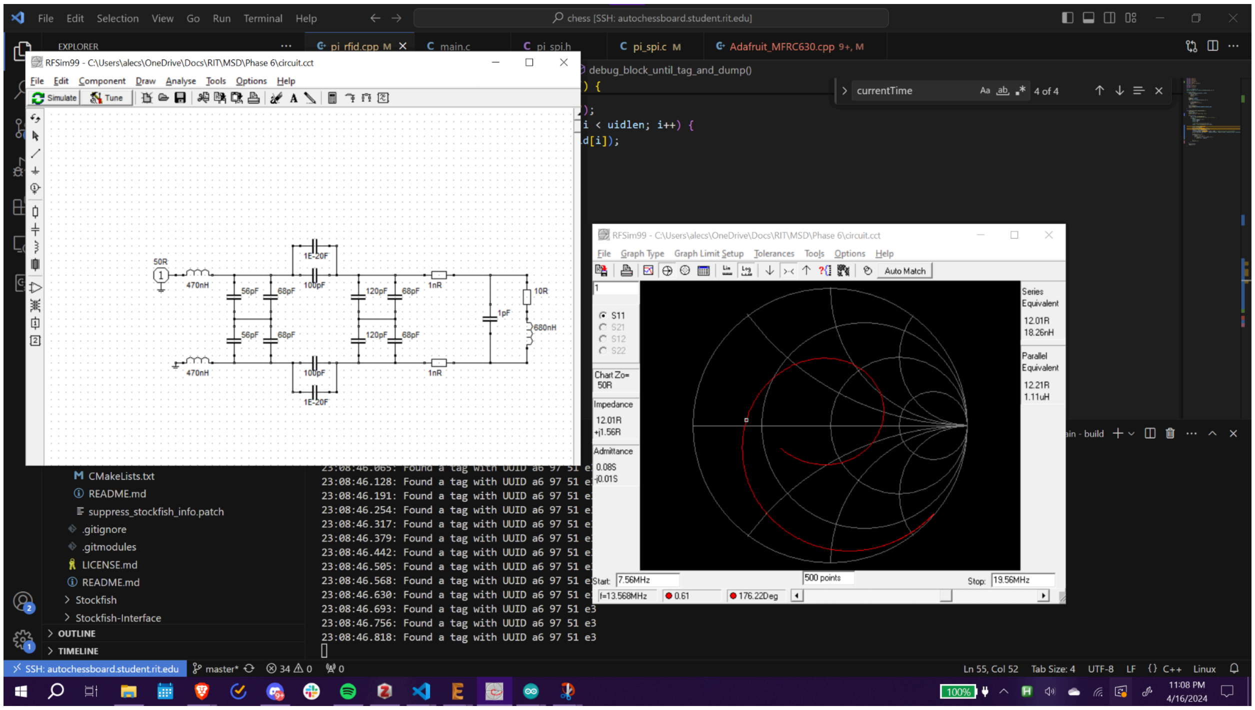
2 Antennas:

- Square (standard PCB antenna shape - design is made with this antenna in mind)
- Octagon (more similar in shape to the circular tags - better coupling)

Shape may affect read range, so let’s find out.

Final PCB Matching Circuit Design:





2 of the 5 boards had manufacturing defects. Communication with the MFRC630 over SPI was successful for a few seconds until the current on the board would rise to several 100 mA under no load. The device should pull ~0 mA when the antennas are not activated, and ~65 mA when activated. The current issue would sometimes persist when the MFRC630 was removed, but other times it only occurred when the chip was on the board. Reflowing the board also got it to work for a few seconds. But when the board worked, it worked well.

Additionally, sometimes long SPI cables prevented adequate communication to the MFRC630. Increasing the voltage of the SPI lines by .1V using a level shifter, or decreasing the voltage of the MFRC630 but keeping the SPI lines at 3.3V would resolve the problem. However, reducing the chip voltage also reduced the RFID tag read range. Be sure not to supply more than 3.3V or 0.6mA to any GPIO pins on the Raspberry Pi.