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Department of Information Technology and Electrical Engineering

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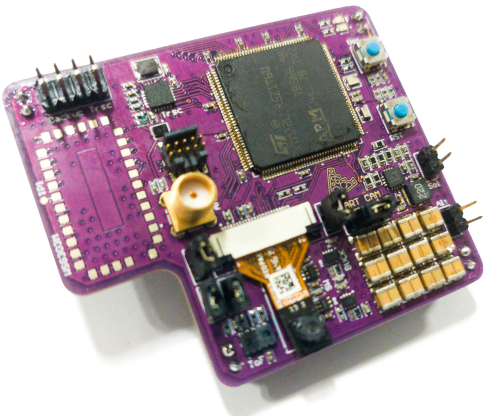
Battery-less always-on smart camera with Sigfox networks

Semester Project



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Abstract

One of the key issues with wireless sensor nodes is the dependence on batteries for powering. This requires regular maintenance that drives cost and limits application scenarios. However, nowadays low power electronics and data transmission protocols exist that enable the operation of sensor nodes using harvested energy only e.g., solar panels. One such application of "deploy and forget" sensor nodes could be the detection of a subject with a low power camera sensor node, identification of the detected person and transmission via a low power wide area network.

In this project a smart sensor has been designed, built and evaluated based on the knowledge gained from a previous project by Giordano et al. [1] while employing a combination of new components. A low power micro controller, image sensor and high performance solar panels that supply a capacitor array via a energy harvester and are connected to the Sigfox network via a transceiver and integrated balun.

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List of Acronyms

API . . . . Application Programming Interface
AWS . . . . Amazon Web Service

CNN . . . . Convolutional Neural Network

DCMI . . . . . . Digital camera interface

GPIO . . . . . . General Purpose Input/Output

IC . . . . Integrated Circuit

LED . . . . Light-Emitting Diode
LoRaWAN . . . Long range wide area network
LPWAN . . . . . Low power wide area network

MCLK . . . . . Master Clock Signal
MCU . . . . . . Micro Controller Unit
MPP . . . . . . Maximum Power Point
MPPT . . . . . . Maximum Power Point Tracking

PBL . . . . Project Based Learning
PCLK . . . . . . Pixel Clock Signal
PDF . . . . Portable Document Format

PWM . . . . . . Pulse Width Modulation

ReLU . . . . . . Rectified Linear Unit

SDR . . . . Software defined radio

SMPS . . . . . . Switched Mode Power Supply

TCP . . . . Transmission Control Protocol

ToF . . . . Time of Flight

VSYNC . . . . . Vertical Synchronisation Signal

Chapter 1

Introduction

Analysing our surroundings and communicating the gained knowledge without human intervention is one of the cornerstones of the internet of things (IoT). Sensors nodes like this have historically been low-data-rate integrated circuits (IC) like barometers or distance detectors that only needed low-intensity on-device computations like averaging or logging before sending it to a smarter device with short distance communication like Bluetooth low energy (BLE). Sending all the gathered data along to a smart device has the drawback of possible congestion while transmitting and energy consumption for the prolonged sending of data. Yet the tasks that are demanded of these edge devices are ever growing in complexity. Today we want autonomous surveillance, monitoring and controlling devices to guide the smart city of tomorrow or to secure a wildlife habitat from undesired intruders. For such tasks these sensors don't always suffice but cameras are necessary that can process and recognise patterns on-device with tiny machine learning to not be dependent on high throughput data transmission. A higher demand in computation power creates a higher need for energy to supply the system. This has classically been done with the use of batteries but those require regular replacement and maintenance which is simply not feasible with a rapidly increasing number of IoT devices. Their ability to be deployed in the most remote locations, not to mention the environmental impact that the creation of such a ever growing number of batteries would create. Advancements in on-site energy harvesting enable the local solar, thermal or even radio frequency energy to be gathered by each edge device of the IoT themselves. This way a sensor only needs to store enough energy to be able to run through one cycle of its internal logic, or multiple if desired, after which it can quickly gather more energy. This energy can in the meantime be stored in long living capacitors.

The goal of this project is to design, fabricate and program a smart camera sensor capable of harvesting local energy and sending the processed data over a long range network.

The tasks that the sensor should be able to accomplish can be summarised to:

- Detect existing subject
- Take picture of subject
- Recognize specific faces
- Send recognition home

This freshly designed prototype employs the gained knowledge from a prior work [1] with the camera HM01B0 from Himax and the energy harvester BQ25504 from Texas Instruments, more on those in chapter 5. In a first step of the project we gained knowledge to reduce the power consumption of the MCU and transceiver while familiarity was gained with the development kit for the MCU and the Sigfox long range network. In step two, a new schematic and layout for the PCB was designed for the new sensor node, integrating the new low power MCU and Sigfox communication. In step three, the firmware was adapted for the new hardware and transceiver. Lastly the performance of the implementation was evaluated with respect to power consumption, accuracy and range.

Finally, this report presents the design of this new smart camera sensor. In chapter 2 related work in this field is shown. Chapter 3 will explain some of the working theory for the uninitiated. Chapter 4 will show the methodology that the sensor will work under while chapter 5 presents the final design and function that was realised. Following this in chapter 6 we present a summary of the performance of the designed sensor. The conclusion as well as possible future work will be available in chapter 7.

Chapter 2

Related Work

Over the years there have been multiple solutions to get autonomous sensor closer to a deploy and forget system of distribution that is paramount for the rapid growth of the Internet of Things.

2.1. Energy harvesting

One of the recurring ways of harvesting energy for perpetual operation is using ambient RF signals as the only source of power. Muncuk et al. [3] tested the feasibility to power a sensor mote that consumes 2.7 mA (338 μA/MHz) in a urban setting and came to the conclusion, that in multiple city locations (65% in Boston) have enough energy density to power a low-power sensor. In a second step they used a log periodic antenna of size 450 cm^2 to support a μCU sensor in different operating modes from active to standby.

Another autonomous solution to this problem is solar harvesting, where Sharma et al. [4] have compared the efficiency of maximum power point tracking (MPPT) vs pulse width modulation (PWM) for wireless sensor network nodes with simulations and tests. They came to the conclusion, the efficiency of a MPPT controlled harvester is better than a pulse width modulation PWM controlled buck converter. They found that using MPPT resulted in up to 8% more efficient respective to the energy input from the solar cell.

2.2. Long range batteryless sensors

One key advantage of a energy harvesting device is that they can be deployed in areas where maintenance would be hard to do or be simply unfeasible. This necessitates long range communication since a hard to reach place often times also is out of the way of short range communication networks. There are multiple open and closed source network providers to achieve this low power wide area network, a study [5] by Vejlgaard et al. from Denmark analyzed the coverage and capacity of Sigfox, LoRa, NB-IoT and GPRS which came to the conclusion from table 2.1

Coverage	LoRa	Sigfox	NB-IoT	GPRS
Outside	99%	99%	99%	99%
Inside -20dB penetration loss	97%	99%	99%	60%
Deep indoor -30 dB pen loss	76%	85%	90%	30%

Table 2.1.: Differences in coverage by wide area access networks in Denmark

Similarly a comparative study was done by Mekki et al. [6] for LoRa, Sigfox and NB-IoT. Which came to the conclusion that each technology has its place in the IoT market. Sigfox and LoRa would serve as the lower-cost device, with long range, infrequent communication rate and long battery life time. An additional strength of LoRa was determined for devices that move at high speed. NB-IoT on the other hand would serve as the higher-value IoT markets that would be willing to pay for very low latency and high qualiy of service. Lastly they criticize the coverage of NB-IoT in Korea which shows a disparity in the network density of Korea vs Denmark where it was at 99% coverage per Vejilgaard et al. [5]

2.3. Camera enabled sensors

We want to focus on two particularly interesting camera sensors with batteryless design and long range communication capability that have been developed in recent years. One is Camaroptera [7] by Nardello et al., which is designed for direct sunlight operation, recognises people in the picture and transmits the pictures of interest via LoRA. It differs from this work in that the onboard neural network recognizes people yet it also transfers a full picture of interest back to the operator.

The other paper is the predecessor of this work. In this work Giordano et al. [1] designed and developed a battery-less wireless video sensor node that can host both thermal and solar energy harvesting. With the special hallmark feature that it is also fully functional in indoor conditions and can serve as a security gate with its included face recognition.

Lastly we want to focus on a sensor [8] by Jokic et al. that is intended for inside use and thus lacks the long range capabilities but is non the less a batterless, harvesting smart camera. In this paper the researchers designed a credit card sized platform that recognises a single face and returns a secret code via a monochrome display. Additionally with a cycle time of one second it can have an idle time of 0%.

Paper	Camaroptera [7]		Lora Face Detection [1]		Indoor Face Detection [8]	
Harvester	197 μW	-			0.94mW	-
Image capture	5.1 mW	0.66-1.62 ms		0.1s	incl below	
Image processing	5.77 mW	46.14 ms			incl below	
CNN inference	4.85 mW	11.9 s		0.75s	0.68 mW	1s
RF TX (LORA)	363.8 mW	-			-	
Recharge time	at 1500 lux	307 s			1000 lux	201 s
MCU	MSP430	FR5994	Ambiq	Apollo 3	RISC-V	
Parameters NN		20kB		311 kB		392kB
Storage	16.5 mJ	Super Cap	2.75 mJ	Cap Array	211.5 mJ	Super Cap
Display	-		-		7.45mJ and	23.87mJ

Table 2.2.: Similar works and their general hallmarks

Chapter 3

Theory / Algorithms

3.1. Sigfox Network

Sigfox [9] is a LPWAN network operator that offers end-to-end connectivity solutions. It equips its base stations [10] with cognitive software defined radio (SDR), long range radio transmitters, ultras low receiver sensitivity, 120 dB receiver linearity and connects them via access point to the IP-based internet where they can be operated via a web based management tool.

The sender and receiver antenna are unequally sized in that the base station is much larger thus achieving great sensibility for catching packets. All packets are sent in a ultra-narrow band of 100 Hz so that the limited frequency bandwidth is well utilised. This frequency range sits in the unlicensed ISM band (industrial, scientific and medical) but with worldwide differing regulations about usage and definition of the ISM band the Sigfox network is divided into currently seven radio configuration zones. For example the band in Europe sits at 868 MHz with 16 dBm designated Radio Configuration 1 or 902 MHz at 24 dBm in Brazil (RC2) [11].

The antenna size disparity between client and base station leads to efficient transmission, low antenna cost and low-noise levels for the clients while still being able to reach up to 10km range in urban and 40km in a rural settings [6]. The limiting factor, that is enforced by the Sigfox network [12], is that the clients can send a maximum of 140 messages with maximal 12 bytes per message each day. The downlink is even more restricted at 4 messages per day and 8 bytes. This makes acknowledgements for received packets unfeasable, as other protocols like transmission control protocol (TCP) use. Which is why Sigfox relies on sending each message multiple time with three being the default over different slightly shifted frequency channels.

Once received by the Sigfox network, this message can be further utilised by different APIs like AWS or Azure that are directly connected to Sigfox backend.

3.2. Bit banging

While in hardware integrated peripherals are the more efficient way to interact with a slave device, since not much software intervention is needed to achieve a task, this does not always work out. One can imitate the behaviour of these peripherals by directly sampling or setting general purpose input/output (GPIO) states in software while assuring that the timing requirements are still met. In recent years this approach was made possible by the higher clocked CPU in contrast to the lower speed communication standards.

3.3. Face Recognition with Neural Network on microcontrollers

While developing a new neural network was not the aim of this project its implementation still is an integral part of this prototype. Thus here is a summary of the steps that were taken by Giordano et al. [1] to develop this neural network.

The convolutional neural network (CNN) was designed to identify the face of a person and recognising them from a set of 5 preprogrammed faces and was trained and tested over the CelebA [13] dataset. Since not a lot of different pictures, usually 20 to 30 each, were available per person they slightly changed those images in the range of -20 to +20 degrees while also changing the gamma ratio thus generating more data. The network was trained using TensorFlow and then deployed on the prototype with TensorFlow Lite. As seen in figure 3.1 the network is composed of convolutional and dense layers where all are activated by a rectified linear unit (ReLU) except the last being Softmax. The network is totaling 39'821 integer 32 sized parameters totaling 155.6 kB in size. As an input it is taking a 30x40x1 pixel picture the x1 indicating a monochrome picture.

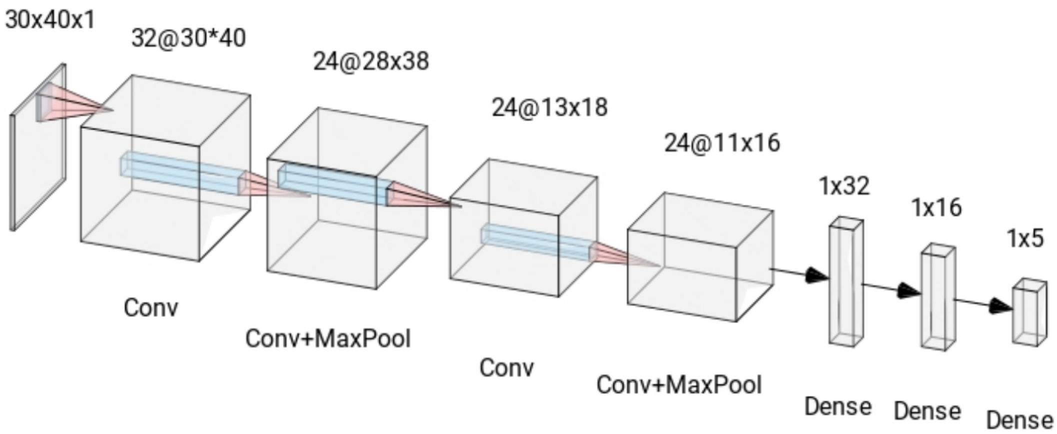


Figure 3.1.: Overview of the neural network architecture.

Chapter 4

Hardware Architecture

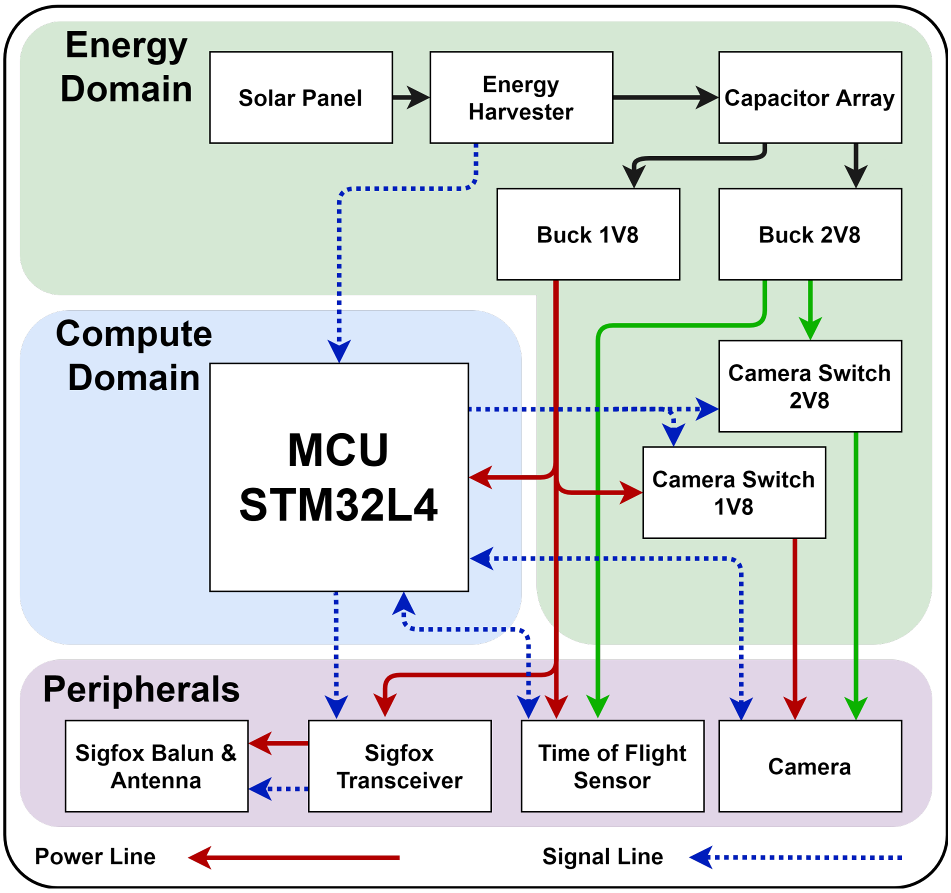


Figure 4.1.: Block diagram of signal and power domain

4.1. Power delivery

The power delivery visualisation is shown in figure 4.1 as continuous arrows while the data lines are represented by doted arrows. The energy harvester starts charging the capacitor array when it reaches system load level at 1.8 on the storage capacitance that is only used by the harvester. The capacitor array can reach a voltage level of maximum 5.2V. Then to get a consistent power domain we have two bucks that lower the voltage to 1V8 and 2V8. Every component gets supplied by the 1.8V domain. The camera and time of flight sensor additionally need 2.8V, yet since both these components are the first to actually finish their tasks in a active cycle it is of no concern that they will loose power if the capacitor array falls below 2.8V. While the camera is low-power by design, as further specified in chapter 5.3 and consumes as much or less power than the ones in the related work mentioned in chapter 2, we still found it advantageous to turn it of with two additional power switch ICs since the camera is only needed for a small part of the whole cycle. The transceiver and time of flight sensor (ToF) both have a integrated shutdown pin to achieve the same functionality.

4.2. Operational loop

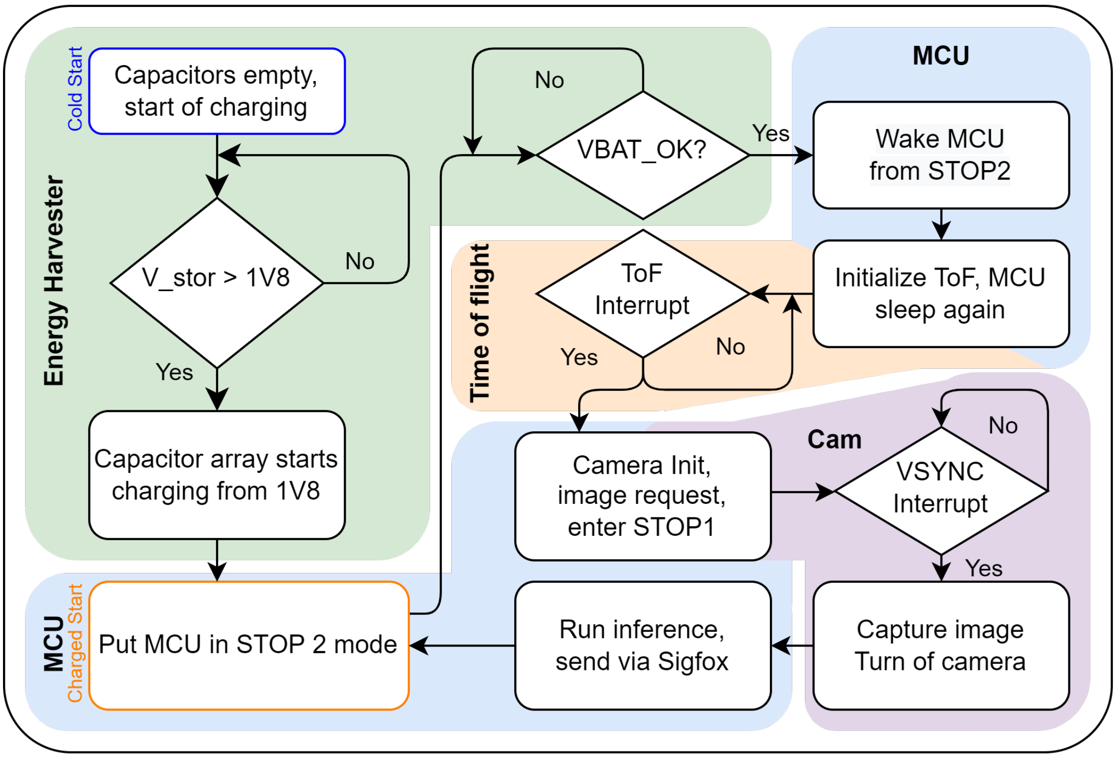


Figure 4.2.: Logic diagram of board operation from cold start to sending via Sigfox

When the microcontroller (MCU) powers on it starts the time of flight sensor via I2C line to sample every second for a target. After this initialisation step the MCU goes into deep sleep (STOP 2) to conserve energy and waits for an interrupt from the ToF sensor. When this interrupt arrives the MCU wakes and turns off the ToF while turning on the camera and initializing the capture setup via I2C. This needs to be done every time the camera turns on since it resets back to factory settings when shut off. We wrote our own driver to capture the pixel values, more details on this driver can be found in chapter 5.3. The pixels are stored in a buffer after which the neural net runs the inference to recognize a person of interest. If a person of interest is found, the prototype send three times the same Sigfox message on different frequencies in the ISM band as per Sigfox specification mentioned in chapter 3.1. After this or if no person was recognised we go back to deep sleep and wait for another signal from the energy harvester indicating a charged capacitor array.

Chapter 5

Design Implementation

The board is designed for on board sensing, computing and long-range communication and is assembled of entirely of the shelf components to cut down on per-device cost. The full schematic, 3d render and component placement plans are available in the appendix chapters D and E.

The main active components of the board are a microcontroller (MCU), ultra-low-power image sensor, low-power proximity light or time of flight sensor (ToF), energy harvester integrated circuit and the Sigfox long range transceiver with an antenna.

5.1. MCU

The prototypes MCU is an STMicroelectronics ultra-low-power ARM M4 based MCU of the L4 line. The STM32L4R5ZIT6U [14] runs at 120MHz and consumes 110 μA/MHz in low dropout regulator mode. To accommodate the weights of the face recognition neural network and the full picture it has 2 Mbytes of flash memory and 640 Kbytes of SRAM. For capturing the picture, the MCU possesses an integrated digital camera interface (DCMI) with direct memory access (DMA) connection. This ensures the core is not interrupted. In chapter 5.3 this implementation is described. The MCU is seated in a 144 - pin low-profile quad flat package (LQFP) of size 2 cm^2.

The preferred choice would have been using a similar 64 - pin switched-mode power supply (SMPS) enabled MCU, the STM32 L496 ZG, to utilise the 37 μA/MHz energy efficiency in SMPS and to cut down on the board space needed for the chip but with the current silicon shortage we had to part with the optimally envisioned solution.

5.2. Sigfox Transceiver

To connect to the Sigfox network, we utilise the ultra-low power S2-LPQTR radio frequency (RF) transceiver by ST [15] which is intended for the sub 1 GHz (specifically the ISM) band. The chip supports most of the radio control zones of Sigfox, only missing the ones which require a RF output power bigger than +16 dBm. The power consumption is 10 mA while sending is at +10 dBm. While the transceiver is able to run at 10 mA consumption while sending at +10 dBm, we won't achieve this efficiency since it relies on the usage of SMPS. Fitting an additional buck converter for another power domain at 1.2V would have cost us more energy over a whole cycle than what we would have saved. The transceiver connects to the integrated balun BALF-SPI2-01D3, specifically designed for the S2-LP transceiver, and lastly to a classic RF-antenna. Lines marked with the RF symbol in figure 5.1 were impedance matched to minimize signal reflection which can be devastating in RF design.

Lastly while the transceiver and balun are fitted to the prototype, their implementation is left for future work. For the demo a Nucleo-L053R8 is used to connect the prototype to the S2868A2 development board from ST which employs the aforementioned components.

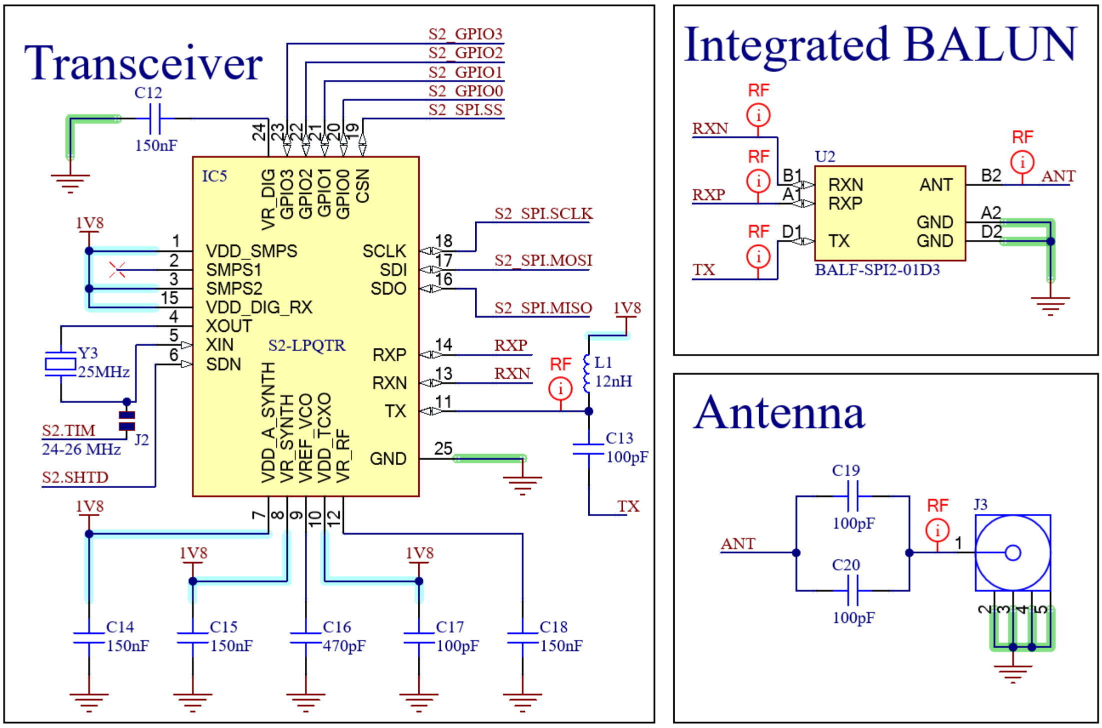


Figure 5.1.: Schematic of the transceiver, balun and antenna.

5.3. Image Sensor

The prototype uses the Himax HM01B0 [16] ultra-low-power image sensor with 324x324 active pixel resolution with support for QVGA (320x240 pixel)and QQVGA (160x120 pixel) resolutions, hardware layer vertical flip and horizontal mirror readout. This camera was chosen for its low average power consumption of less than 2mW for QVGA at 30FPS. We will however only use it for single frame shots. While this camera is power efficient it still is a power drain for the whole system when constantly turned on, since it uses 142.3 μJ in standby mode. Since we only need it for one picture per cycle we fitted the board with two power switches that can cut the power to the camera voltage domain. In chapter 5.3.2 the picture quality of a QVGA picture can be seen.

While the MCU has an integrated solution to efficiently receive pixels, for which it was partially chosen, we had immense problems working with the DCMI and DMA peripheral that is provided with the hardware access layer firmware of ST, even after direct contact with ST personnel. Thus we wrote our own driver to bit bang the pixels when data is valid as shown in figure 5.2 and further described below.

5.3.1. Bit bang driver

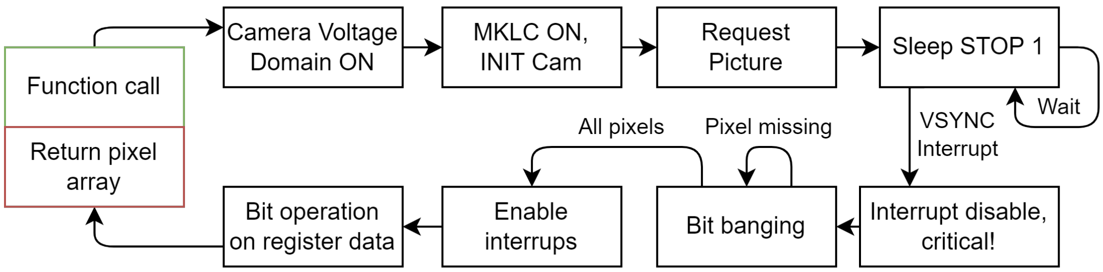


Figure 5.2.: Operational loop of getting an image

After the function call, the MCU turns on the camera voltage domains via the switches, initialises the camera via I2C, starts the master clock output (MCLK) and calls for a picture. After this sequence it goes into SLEEP 2 mode and waits for an interrupt from the VSYNC signal of the camera signaling the shortly arriving pixel data.

When the expected interrupt arrives, the MCU turns of all interrupts, entering a critical phase since no pixel should be allowed to get lost, and parses the pending interrupt register for the pixel clock pin (PCLK) which triggers on a falling edge representing a data good signal from the camera, as seen in line 5 on page 15. Thus the MCU parses and stores the GPIO input registers of B and C, at which all eight data input pins are located.

This step takes 27 cycles which at 120 MHz is just a bit faster as the 4 MHz at which new pixel data arrives. So the MCU runs at maximum frequency while the camera runs at almost minimum. This of course is not desirable for energy efficiency but necessary since the integrated driver doesn't appear to work and represents the biggest possible improvement for a future work.

After all pixel data is received, the MCU enables interrupt, disables MCLK and camera and processes the input registers saved beforehand into valid pixel data with the use of bit operations as seen on line 14 to 18 on page 15

```
1  primask_bit = __get_PRIMASK();                //backup PRIMASK bit
2  __disable_irq();                 // Disable all interrupts by setting PRIMASK bit
3  
4  while (pclk_counter < NMB_PIXELS){            //Bit banging the pixels
5      if(PendingInterruptReg & (1 << 6)){      //PCLK interrupt register high
6        GPIOC_Mem[pclk_counter] = port_c_idr; //Store GPIO input registers state
7        GPIOB_Mem[pclk_counter] = port_b_idr;
8        pclk_counter++;
9        SET_BIT(PendingInterruptReg, (1<<6));  //Reset PCLK interrupt reg
10     }
11 }
12 __set_PRIMASK(primask_bit);                   //Restore PRIMASK bit
13 for(uint32_t i = 0; i < NMB_PIXELS; i++){
14     uint16_t D3210 = (uint16_t) 0b1111 << 6 & GPIOC_Mem[i];
15     uint16_t D4 = (uint16_t) 0b1 << 11 & GPIOC_Mem[i];
16     uint16_t D5 = (uint16_t) 0b1 << 6 & GPIOB_Mem[i];
17     uint16_t D76 = (uint16_t) 0b11 << 8 & GPIOB_Mem[i];
18     picture[i] = D76 >> 2 | D5 >> 1 | D4 >> 7 | D3210 >> 6; //Bit operation
19 }
```

5.3.2. Picture

For the input to the neural network the image is down scaled to fit the premade dimensions of this neural network. Thus the received QVGA resolution picture from figure 5.3 gets parsed to extract 40 x 30 pixels, represented by black dots, ending in the picture on the right of figure 5.3.

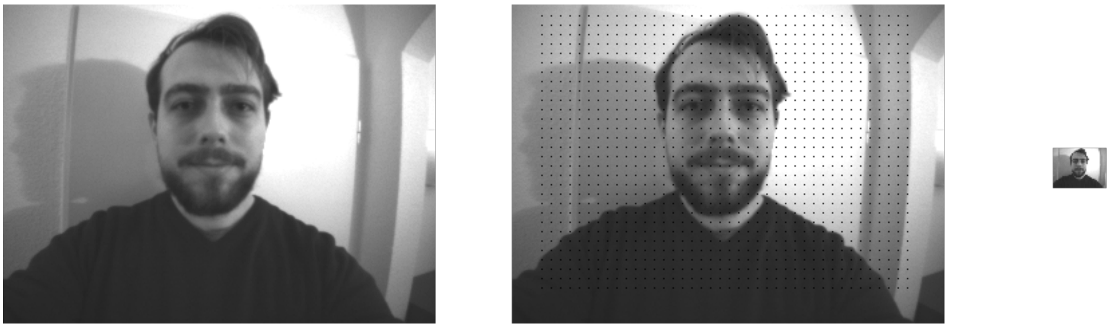


Figure 5.3.: QVGA resolution and 40x30 input to NN

5.4. Time of Flight Sensor

For proximity sensing, the board utilises the Si1153-AB9X-GMR [17] from Silicon Labs with integrated LED driver which can operate in direct sunlight. They also claim industry's lowest power consumption with 9 μA average current in operation and <500 nA standby current. The IC needs to be activated once via I2C connection to begin periodic measurements and then can be left independent while the MCU goes to sleep 2 mode. After a detection event a wake-up is triggered via dedicated interrupt line from ToF to MCU. Due to timing constraints this component isn't yet realised in firmware and substituted with the user button press on the prototype.

5.5. Energy Harvester

A small solar array has a power generation that lies in the microswatts μW to milliwats mW range and is thus not suited to power a MCU without some form of energy management.

This is where energy harvesters comes in. We employ the BQ22504 [2] from Texas Industries. After a brief period where a DC-DC boost converter/charger powers the IC itself it can begin operating. This first charge up period, known as the cold start in figure 5.5, needs a kickstart energy spike of 330 mV after which 130 mV from the energy source suffice. To regulate the harvester it is programmed with external resistors to create a under and over voltage monitor point by the user. In figure 5.4 resistor R41 & R43 for the over and R42 & R44 for the under voltage make up two voltage dividers. For an additional level of control the IC has a battery good flag, green line in figure 5.5, to signal the MCU when the capacitor voltage has risen above 5V2 which is just about maximum charge. Thus the MCU can wake from "STOP 2" mode to start with one measurement cycle.

To control the load that goes into the capacitors the IC uses maximum power point tracking (MPPT) which is a technique in which a predetermined algorithm controls the DC-DC converter at its efficient/optimum point. For solar arrays the maximum power point is generally at 70 to 80% of their open-circuit voltage. Thus we set the ratio of of the voltage divider R35 and R37 + R39 in Figure 5.4 to the MPP.

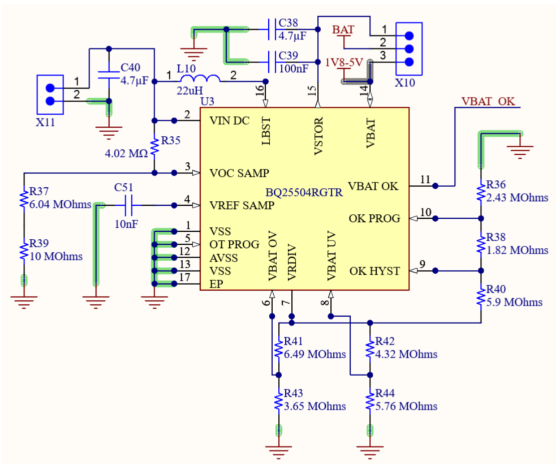


Figure 5.4.: Schematic of the energy harvester

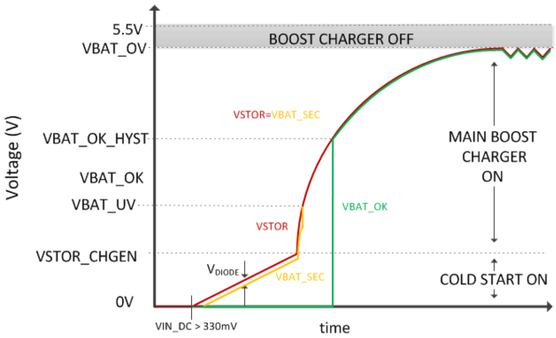


Figure 5.5.: BQ25504 charge operation after a depleted storage element is attached. From [2]

5.6. Batteryless Energy Storage and power delivery

The system is powered by 72 220 μF capacitors arranged in parallel, totaling 15.84 mF, which translates to roughly 82.37 mC and 214.16 mJ of energy storage capacity. We utilise a capacitor array instead of one large capacitor of equivalent capacitance. Since a non ideal capacitor also additionally behaves like a serial resistance besides its capacitance. This phenomon is also known as equivalent series resistance. If one makes an array of multiple capacitors these resistances diminish in total magnitude but the capacitors are just as potent. The second problem one creates with a capacitor array is an increased leakage current. Producers of capacitors are always stingy with information about the leakage current since it is so highly dependent on the solder job. In our case we were able to see a voltage drop of 1 mV/s at fully charge state which can easily be negated by the harvester. This array is charged by the before mentioned harvester up to 5.2 V at maximum and then gets bucked again by two TPS62840 [18] step-down converters to two voltage domains at 1.8V for every component and to 2.8V for the camera and ToF sensor.

5.7. Revisions

During development and testing of the board we have found a few possible improvements that have subsequently been corrected with wires on the prototype and with an additional revision of the Gerber files is already implemented for future prints of the board. Here the list of improvements:

- To work with SWD debug connector instead of the originally planed JTAG connector the reset line needed to be connected to NRST (pin 25 of MCU) not as originally though to PB5 (pin 135) for NJTRST.
- The user button was missing a ground connection.
- The camera enable line (pin 48 PB2) also connected to the buck for 2.8V which is sub optimal since the time of flight sensor also depends on the 2.8V domain.
- The BOOT0 (pin 138) is now connected to ground since some interrupts of the MCU aren't activated if it isn't grounded.
- The transmission line of transceiver had a mistake where the inductance was connected after the capacitor not before.

Chapter 6

Experimental Results

6.1. Power tracing

As proposed in previous chapters, considering the power consumption versus the stored energy is critical or one risks an unintentional brown out of the circuit and thus shutdown of the system. To measure the power consumption of the prototype the energy harvester was bypassed by connecting the capacitor array directly to a Power Profiler Kit 2 from Nordic which supplies it with 3.3V. Measurements are taken of the current that was being drawn by the whole prototype and by multiplaying with the input voltage the power draw is displayed in the first graph of figure 6.1. The second graph shows the voltage curve in the capacitor array while the energy harvester was supplied a maximum of 600 mV and 10 mA and given time to fully charge. The graph then represents the voltage level in the capacitor array for one active duty cycle. Both graphs show the button press as x = 0. While the graphs do not display the exact same cycle they display the same active duty cycle and parallels can thus be drawn.

Zone 1:	Camera Setup	32.5	ms	65.18	mW	2.12	mJ
Zone 2:	Idle in STOP 1	690	ms	25.31	mW	17.53	mJ
Zone 3:	Reception of Pixels	230	ms	45.51	mW	10.47	mJ
Zone 4:	Inference of NN	335	ms	54.97	mW	18.41	mJ
Zone 5:	Sigfox send 3 messages	6	s			8.6*	mJ
Total:		7.29	s	191.07	mW	48.53	mJ

Table 6.1.: Power Consumption over one cycle of figure 6.1

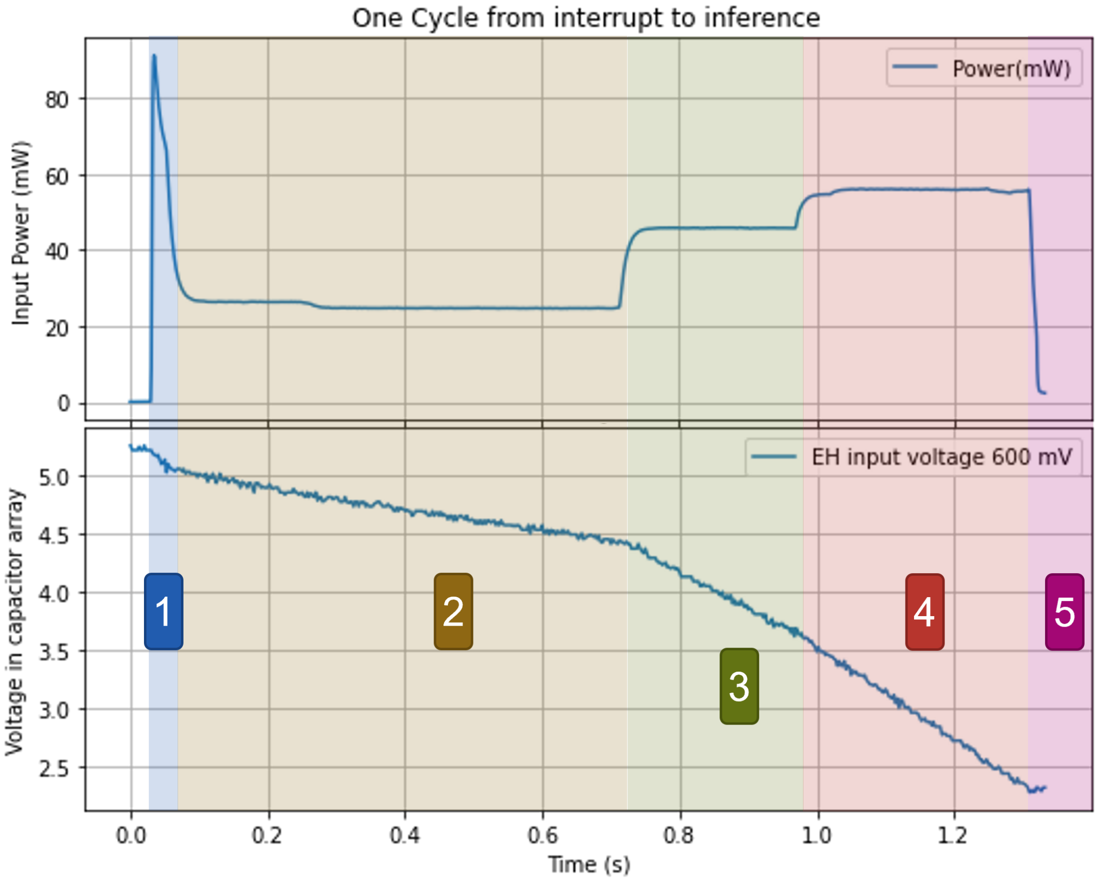


Figure 6.1.: Active Duty cycle power consumption and voltage level in cap array

6.1.1. Expected consumption of transceiver *

Table 6.1 contains in grey the expected energy consumption of the transceiver that wasn't fully implemented as mentioned in chapter 5.2. The transceiver works autonomously after setup and reception of the payload so that the MCU could go back into deep sleep (STOP 2) mode. Since each message we sent is one byte large. Each message is repeated three times as per Sigfox standard protocol. In radio control zone 1 of Europe one can send at maximum throughput of 100 bits/s. Lastly, the transceiver consumes 20 mA in non SMPS mode while transmitting at +14dBm. Thus one can calculate that the remaining energy needed would be

$$E_{TX} = 3\,msg \cdot 8\,\frac{bit}{msg} \cdot \frac{1\,s}{100\,bit} \cdot 20\,mA \cdot 1.8\,V = 8.6mJ \tag{6.1}$$

6.1.2. Discussion of power tracing

Zone 1

Zone 1 represents the time interval in which the camera voltage domains 1.8V and 2.8V connect to the corresponding domains of the prototype. This expectedly shows an inrush current which we explain by the decoupling capacitors before the camera and in the camera itself charging. During this time the micro controller runs at normal frequency and initialises the camera after which it starts the master clock signal and requests an image.

Zone 2

In Zone 2 the MCU is in STOP 1 mode to conserve energy while still being able to emit the master clock signal to the camera. It is waiting for a signal from the camera.

Zone 3

After the reception of the vertical synchronisation signal on the MCU an interrupt is generated and wakes the MCU from STOP 1. This elevates the energy consumption levels since the MCU runs at full 120 MHz to be able to meet the timing requirements of 27 cycles to process a single pixel before the next arrives, as described in chapter 5.3.

This implementation could be improved by utilising the DCMI/DMA peripheral which is supported by the MCU yet we were not able to implements so far and is left as future work. This peripheral is interrupt based and the direct memory access (DMA) channel moves data from the peripheral directly to SRAM. Thus the MCU can spend a part of this processing time in sleep modes [19]. This would increase energy retention without loosing data.

Zone 4

The calculation of the inference of the the neural network uses the full capacity of the MCU and completes as seen in table 6.3 in 39 million cycles. In comparison to the original work [1], where an Ambiq Apollo 3 was used for this neural network, the STM32L4 performs 22% worse in cycle count, yet still 130 times faster than the unoptimisied version without the CMSIS - Neural Network library [20].

6.2. Harvesting capability

The Energy harvester is heavily dependent on which charging medium is connected and on its potency. To generalise this we measured the time a voltage current pairing took to charge from cold start while the load (MCU) was connected.

	420 mV	450 mV	500 mV	600 mV
4 mA	155 s	149 s	142 s	128s
5 mA	128s	102 s	83 s	65s
10 mA	119 s	61s	47 s	33 s
50 mA	58 s	43 s	29 s	18 s

Table 6.2.: Generalised charge time from cold start

Note that exiting cold start mode of the energy harvester is capped at 5 mA for the harvester and only after it is initialised the full current can be sunk. This can be seen in figure 6.2. The legend displays which input voltage to the energy harvester was applied while the input current is limited by the harvester itself. First as expected a higher input voltage charges the capacitor array quicker yet the curve is not linear since during the cold start phase the energy harvester is restricted in its power draw. This is because the cold-start circuit is a smaller unregulated, hysteretic boost converter which only purpose is to engage the main boost charger.

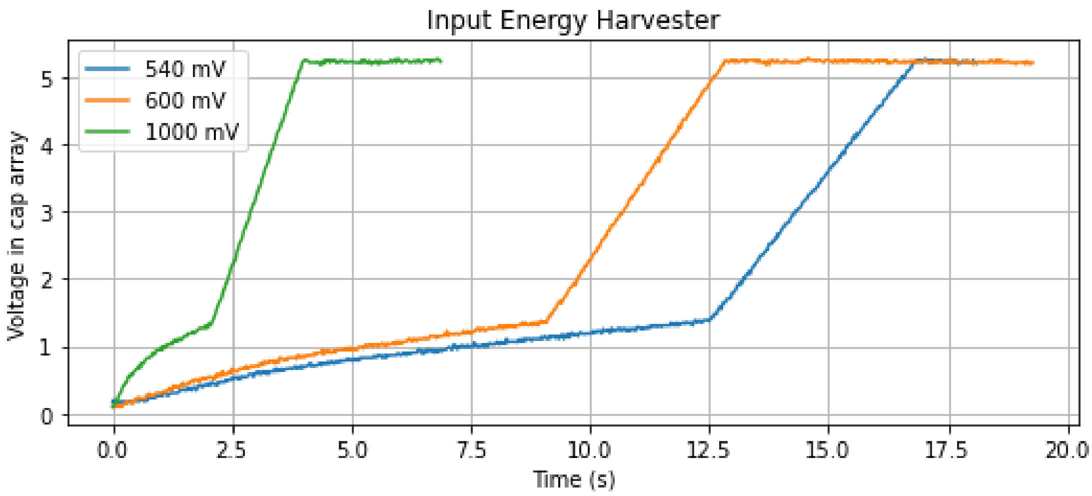


Figure 6.2.: Charging of capacitor array under different voltages

6.2.1. Real world example

For a more tangible example we tested a 42 cm^2 which is a bit larger than the prototype itself and measured the charging patter in figure 6.3 under shaded daylight condition. Additionally in figure 6.4 the recharge time is graphed for library light (500 lux), well lit offices (750 lux) and shaded daylight (3000 lux). Not that the cold start of office and library light is possible but took multiple minutes to exit cold start mode.

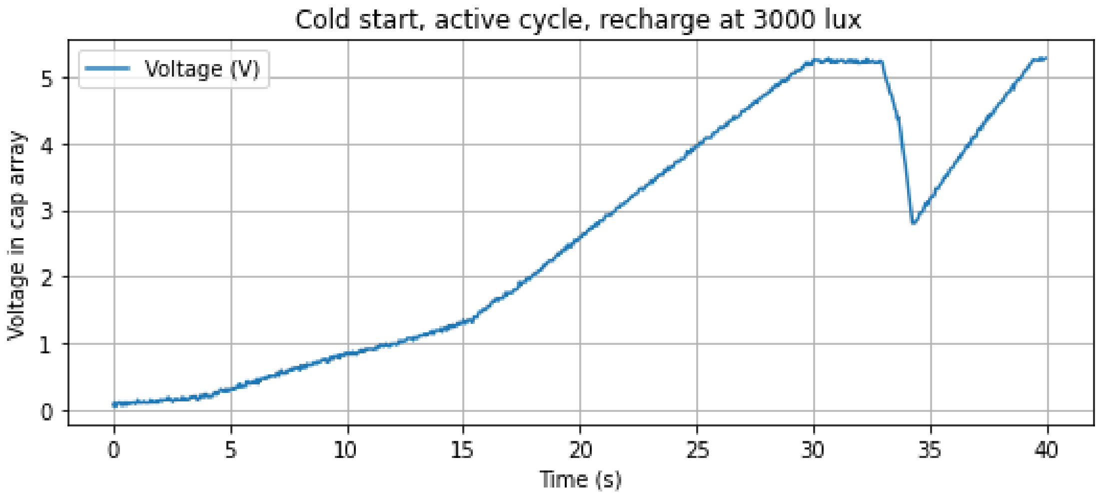


Figure 6.3.: Chargeing example in shaded daylight

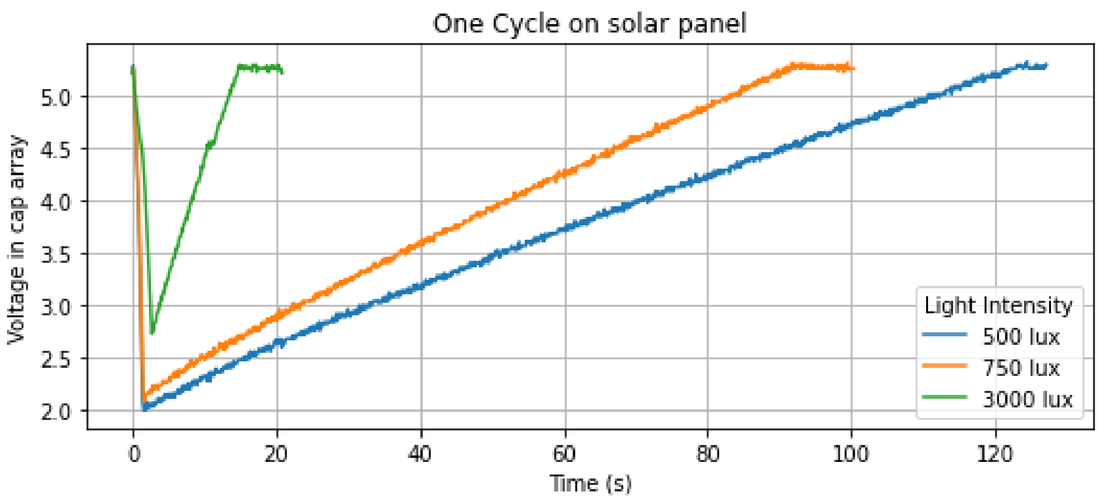


Figure 6.4.: Recharging cycle of different lighting conditions

6.3. Cycle count for different operations

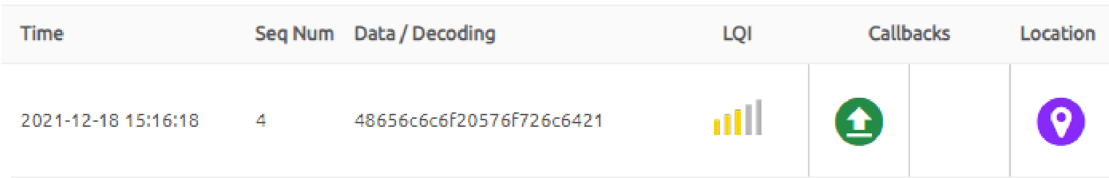
The MCU cycle count that an operation takes while generally interesting can additionally be used to find places for energy saving steps that can be implemented. Here is a list of the cycle counts for the zones from figure 6.1

Zone 1:	camera setup	518'211	cycles
Zone 2:	Idle in STOP 1	83'044'516	cycles
Zone 3:	Reception of pixels	31'073'869	cycles
Zone 3.1:	Bit operation for pixels	24'906	cycles
Zone 4:	Inference of NN	39'973'730	cycles
Zone 5:	Sigfox send 3 messages	not	implemented
Total in	one cycle:	154'635'232	cycles

Table 6.3.: MCU Cycle count for one duty cycle

6.4. Sigfox Backend Message Received!

In figure 6.5 one can see the representation of a message being received by the Sigfox network and being ready for further processing. Note that the message reads as "48656c6c6f20576f726c6421" which is HEX encoding. Transcoded to ASCII it reads "Hello World!".



Time	Seq Num	Data / Decoding	LQI	Callbacks	Location
2021-12-18 15:16:18	4	48656c6c6f20576f726c6421			

Figure 6.5.: Hello World! on the Sigfox backend service.

Chapter 7

Conclusion and Future Work

7.1. Conclusion

In this semester project, a smart battery-less camera prototype was designed and built which is able to harvest solar and thermal energy and has the capability to send the on-chip processed data to IP connected base station by using the Sigfox network. The prototype is built from off the shelf components to keep later production and maintenance cost low. Those components include a energy harvester, daylight capable time of flight sensor, camera, Sigfox transceiver and a MCU capable of on-chip data processing with a neural network that can be changed to suite the users needs.

7.2. Future Work

While working on this project we have though of many ways and ideas to improve it while we also had to take interim solutions not intended for a finalised product:

- **DCMI and DMA peripheral.** While the quality of the pictures taken from the camera are just as imagined the way we acquire these is not. The low level driver we have written is crude and uses energy and memory resources lavishly, yet without DMA it was the best that could have been done. Therefore, the ST written HAL driver should be explored further and the integrated solution with the DCMI peripheral should be implemented, since this peripheral was one of the reasons this MCU was chosen in the first place.
- **Smart Camera with alot of possibilities.** While face recognition serves as great demonstration it doesn't use the capabilities of the board to its full capacity. Firstly, the MCU has still a lot of space left for more complicated neural networks. Secondly, there are better utilisations of a camera in the wild than to recognise faces from short distance. We imagine it as a warning system for farmers to automatically fend off crows on a field or detect trespassers in a restricted area like nature conservation to name a few possibilities.
- **Housing.** When one intends to use a product out in nature it should be sufficiently protected against wind and weather. Therefore, a suitable case should be designed for the board and the solar panels.

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D-ITET center for Project-Based Learning

Tasks Description For a Semester project
At the
Department of Information Technology and
Electrical Engineering

Galliard Nando

Battery-less always-on smart camera with Sigfox Networks

Advisors:	Dr. Michele Magno Marco Giordano
Professor:	Prof. Dr. Sebastian Kozerke
Handout Date:	01.11.2021
Due Date:	20.12.2021 (full-time)

1 Project Goals

One of the key issues with wireless sensor nodes is the dependence on batteries for powering. This requires regular maintenance that drives cost and limits application scenarios. However, nowadays low power electronics and data transmission protocols exist, that enable the operation of sensor nodes with harvested energy only, e.g., solar panels. One such application of “deploy and forget” sensor nodes is the detection and identification of people with a low power camera sensor node, transmitting and identification of the detected person over LoRa [1]. Based on this existing sensor node, improvements could be made covering advances in low power MCUs (microcontrollers), camera sensors, data transmission protocols and solar panels.

The main goal of this thesis is therefore the evaluation of a combination of new, low power MCUs, image sensors and novel high performance solar panels with respect to the achievable application scenarios and sensor node size. Finally, the thesis concludes with a real-world demonstration presenting a working battery-less sensor node with face detection.

2 Tasks

The project will be split into three phases, as described below:

Phase 1 (Week 1-2)

1. Familiarize yourself with the previous work [REF], especially the hardware and microcontroller firmware.
2. Evaluate possible new solar panels to enhance efficiency
3. With the overall goal to reduce power consumption, select a new MCU and camera sensor.
4. Familiarize yourself with the software development kit for the new MCU and the Sigfox network

Phase 2 (weeks 3-5)

1. Draw the schematic and design the PCB for the new sensor node, integrating the new low power MCU, image sensor and Sigfox communication
2. Test the new Sigfox network by setting up a gateway and transmitter based on evaluation boards

3. Adapt the firmware for the new hardware of the sensor node, including the neural net for face detection.
4. Record a small data set for face detection with your hardware, train the neural network on it (a new neural network architecture is not expected to be developed) and implement it on the MCU.
5. Evaluate the performance of the implementation with respect to power consumption, accuracy and range. Estimate achievable power from selected novel solar panels and extrapolate required panel size (and sensor node size)
6. If necessary, optimize your demo sensor node.

Phase 3 (week 6-7)

1. System integration and clean-up of the final version (Firmware, NN, Hardware).
2. In-field test of the sensor node powered only by the solar panels and transmitting detection results over Sigfox.
3. Final evaluation and conclusion on sensor node.

Milestones

By the end of **Phase 1** the following should be completed:

- Solid understanding of the previous work this thesis is based on as well as the Sigfox network.
- Selection of a solar panel, MCU and image sensor

By the end of **Phase 2** the following should be completed:

- Schematic and designed PCB of the improved sensor node
- Firmware working on the new MCU and image sensor
- Trained and implemented neural network
- Evaluation of the sensor node with respect to consumed power, latency, accuracy and transmission range.

By the end of **Phase 3** the following should be completed:

- Final design and in-field test results.

- Final report & presentation

3 Project Organization

3.1 Weekly Report

There will be a weekly report sent by the candidate at the end of every week. The main purpose of this report is to document the project's progress and should be used by the student as a way to communicate any problems that arise during the week.

3.2 Project Plan

Within the first month of the project, you will be asked to prepare a project plan. This plan should identify the tasks to be performed during the project and sets deadlines for those tasks. The prepared plan will be a topic of discussion of the first week's meeting between you and your advisers. Note that the project plan should be updated constantly depending on the project's status.

3.3 Final Report and paper

The final report has to be presented at the end of the project and a digital copy need to be handed in. Note that this task description is part of your report and has to be attached to your final report.

3.4 Final Presentation

There will be a presentation (15~min presentation and 5~min Q\&A) at the end of this project in order to present your results to a wider audience. The exact date will be determined towards the end of the work.

Bibliography

[1] M. Giordano, P. Mayer, and M. Magno, "A Battery-Free Long-Range Wireless Smart Camera for Face Detection," in *Proceedings of the 8th International Workshop on Energy Harvesting and Energy-Neutral Sensing Systems*, Virtual Event Japan, Nov. 2020, pp. 29–35. doi: 10.1145/3417308.3430273.

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Declaration of originality

The signed declaration of originality is a component of every semester paper, Bachelor's thesis, Master's thesis and any other degree paper undertaken during the course of studies, including the respective electronic versions.

Lecturers may also require a declaration of originality for other written papers compiled for their courses.

I hereby confirm that I am the sole author of the written work here enclosed and that I have compiled it in my own words. Parts excepted are corrections of form and content by the supervisor.

Title of work (in block letters):

BATTER-LESS ALWAYS-ON SMART CAMERA WITH SIGFOX NETWORKS

Authored by (in block letters):
For papers written by groups the names of all authors are required.

Name(s):	**First name(s):**
GALLIARD	NANDO

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ZÜRICH, 20.12.2021	NGalliard

For papers written by groups the names of all authors are required. Their signatures collectively guarantee the entire content of the written paper.

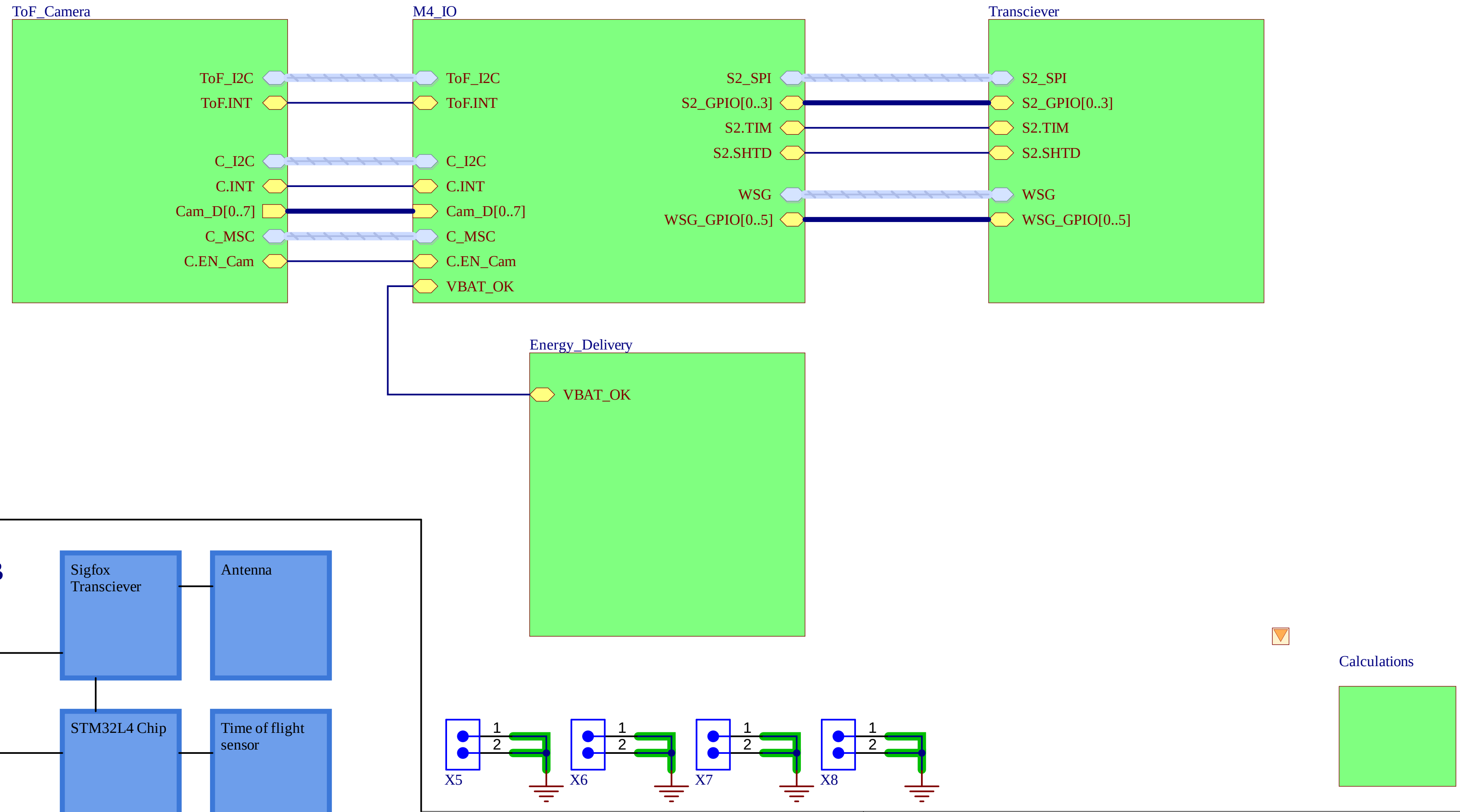
Appendix C

File Structure

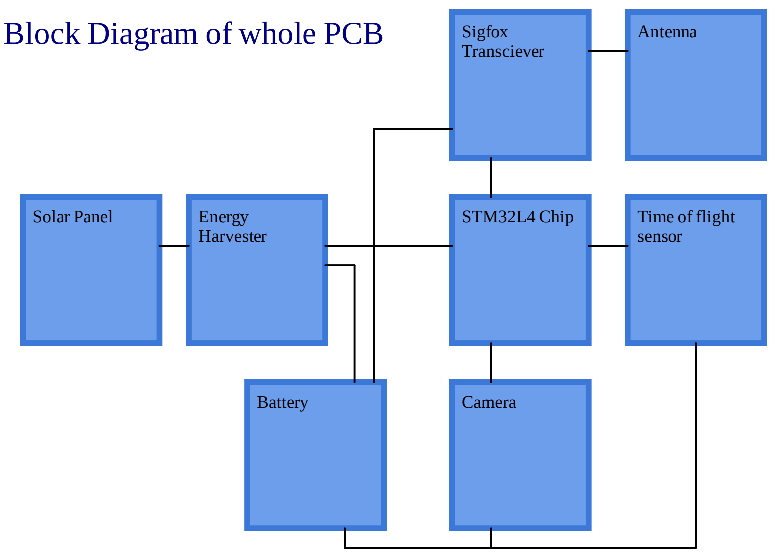
In this chapter we give a overview over the project git directories and files.

```
/
├── README ......... A README with some general information about the project.
├── Altium ................................Altium Designer project files for PCB.
├── Firmware ..................................................... Firmware files.
│   ├── Smart_Cam_Firmware .......................................... Firmware.
│   └── tools ....................... Tools needed to compile firmware on windows.
├── Manuals ................... All the manuals for each component on the board.
├── Report ................................The source files of the project report.
└── Presentation ........................... The source files of the presentation.
```

Self sustainable wireless smart camera



Block Diagram of whole PCB



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Project: Battery-less Smart Camera with Sigfox Networks

Drawing number: 1	Rev: 2	Format: A4 Q	Laboratory: PBL
Date: 19/12/2021 19:32:13			Drawn by: Nando Galliard
Sheet: MAIN_schematic.SchDoc	Page 1 of 6		

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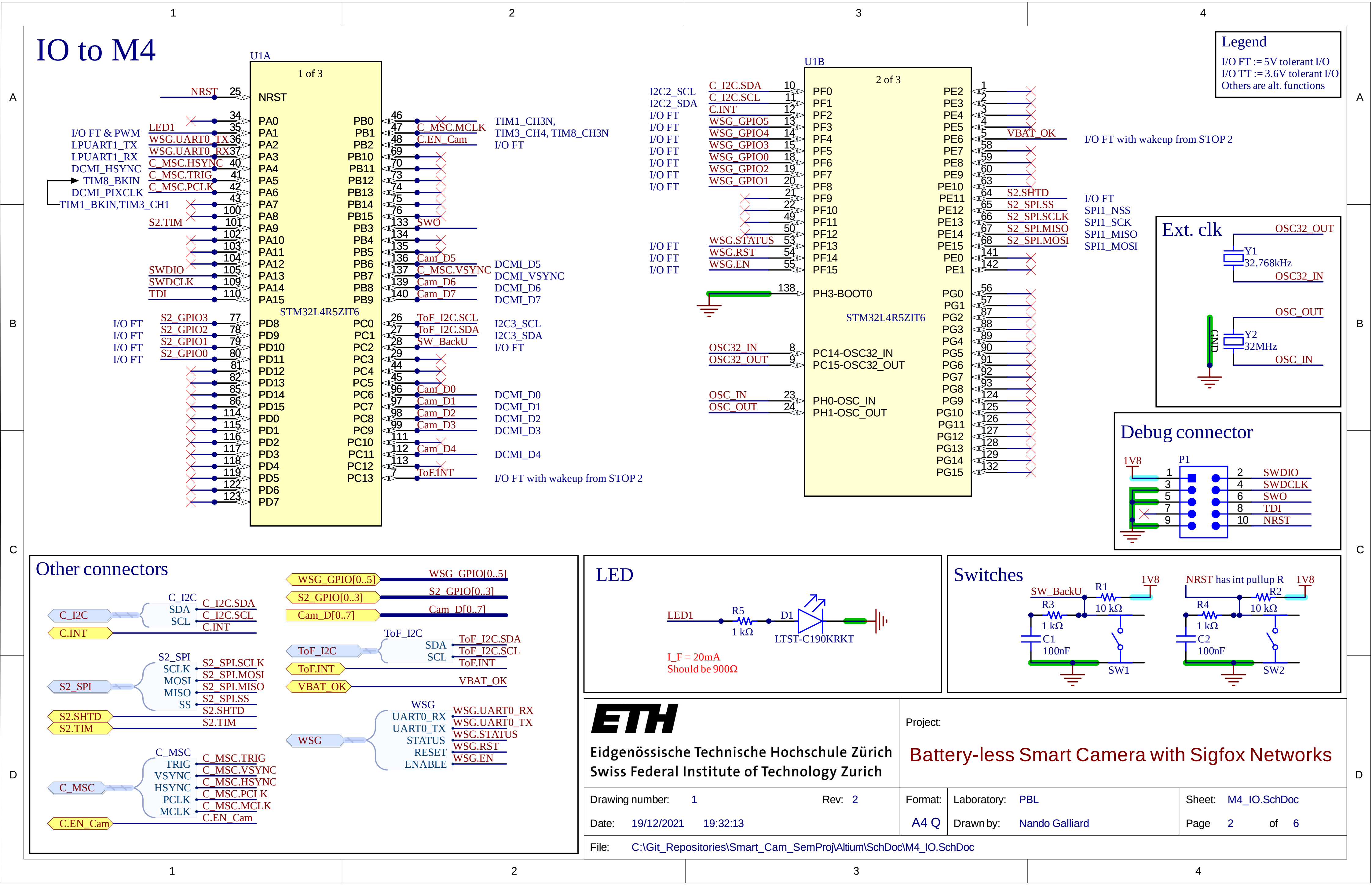
IO to M4
U1A
1 of 3
NRST
PA0 PA1 PA2 PA3 PA4 PA5 PA6 PA7 PA8 PA9 PA10 PA11 PA12 PA13 PA14 PA15
PB0 PB1 PB2 PB10 PB11 PB12 PB13 PB14 PB15 PB3 PB4 PB5 PB6 PB7 PB8 PB9
STM32L4R5ZIT6
PD8 PD9 PD10 PD11 PD12 PD13 PD14 PD15 PD0 PD1 PD2 PD3 PD4 PD5 PD6 PD7
PC0 PC1 PC2 PC3 PC4 PC5 PC6 PC7 PC8 PC9 PC10 PC11 PC12 PC13
NRST
LED1
WSG.UART0_TX
WSG.UART0_RX
C_MSC.HSYNC
C_MSC.TRIG
C_MSC.PCLK
S2.TIM
SWDIO
SWDCLK
TDI
I/O FT & PWM
LPUART1_TX
LPUART1_RX
DCMI_HSYNC
TIM8_BKIN
DCMI_PIXCLK
TIM1_BKIN,TIM3_CH1
S2_GPIO3
S2_GPIO2
S2_GPIO1
S2_GPIO0
I/O FT
C_MSC.MCLK
C.EN_Cam
SWO
Cam_D5
C_MSC.VSYNC
Cam_D6
Cam_D7
TIM1_CH3N,
TIM3_CH4, TIM8_CH3N
I/O FT
DCMI_D5
DCMI_VSYNC
DCMI_D6
DCMI_D7
ToF_I2C.SCL
ToF_I2C.SDA
SW_BackU
I2C3_SCL
I2C3_SDA
I/O FT
Cam_D0
Cam_D1
Cam_D2
Cam_D3
Cam_D4
ToF.INT
DCMI_D0
DCMI_D1
DCMI_D2
DCMI_D3
DCMI_D4
I/O FT with wakeup from STOP 2
U1B
2 of 3
PF0 PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10 PF11 PF12 PF13 PF14 PF15
PE2 PE3 PE4 PE5 PE6 PE7 PE8 PE9 PE10 PE11 PE12 PE13 PE14 PE15 PE0 PE1
PH3-BOOT0
STM32L4R5ZIT6
PC14-OSC32_IN
PC15-OSC32_OUT
PH0-OSC_IN
PH1-OSC_OUT
PG0 PG1 PG2 PG3 PG4 PG5 PG6 PG7 PG8 PG9 PG10 PG11 PG12 PG13 PG14 PG15
I2C2_SCL
I2C2_SDA
C_I2C.SDA
C_I2C.SCL
C.INT
WSG_GPIO5
WSG_GPIO4
WSG_GPIO3
WSG_GPIO0
WSG_GPIO2
WSG_GPIO1
WSG.STATUS
WSG.RST
WSG.EN
OSC32_IN
OSC32_OUT
OSC_IN
OSC_OUT
VBAT_OK
I/O FT with wakeup from STOP 2
S2.SHTD
S2_SPI.SS
S2_SPI.SCLK
S2_SPI.MISO
S2_SPI.MOSI
SPI1_NSS
SPI1_SCK
SPI1_MISO
SPI1_MOSI
Legend
I/O FT := 5V tolerant I/O
I/O TT := 3.6V tolerant I/O
Others are alt. functions
Ext. clk
OSC32_OUT
Y1
32.768kHz
OSC32_IN
OSC_OUT
Y2
32MHz
OSC_IN
GND
Debug connector
1V8
P1
SWDIO
SWDCLK
SWO
TDI
NRST
Other connectors
C_I2C
SDA
SCL
C_I2C.SDA
C_I2C.SCL
C.INT
S2_SPI
SCLK
MOSI
MISO
SS
S2_SPI.SCLK
S2_SPI.MOSI
S2_SPI.MISO
S2_SPI.SS
S2.SHTD
S2.TIM
C_MSC
TRIG
VSYNC
HSYNC
PCLK
MCLK
C_MSC.TRIG
C_MSC.VSYNC
C_MSC.HSYNC
C_MSC.PCLK
C_MSC.MCLK
C.EN_Cam
WSG_GPIO[0..5]
S2_GPIO[0..3]
Cam_D[0..7]
ToF_I2C
SDA
SCL
ToF_I2C.SDA
ToF_I2C.SCL
ToF.INT
VBAT_OK
WSG
UART0_RX
UART0_TX
STATUS
RESET
ENABLE
WSG.UART0_RX
WSG.UART0_TX
WSG.STATUS
WSG.RST
WSG.EN
LED
LED1
R5
1 kΩ
D1
LTST-C190KRKT
I_F = 20mA
Should be 900Ω
Switches
SW_BackU
R1
10 kΩ
R3
1 kΩ
C1
100nF
SW1
1V8
NRST has int pullup R
R2
10 kΩ
R4
1 kΩ
C2
100nF
SW2
ETH
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Swiss Federal Institute of Technology Zurich
Project:
Battery-less Smart Camera with Sigfox Networks
Drawing number: 1
Rev: 2
Format: A4 Q
Laboratory: PBL
Sheet: M4_IO.SchDoc
Date: 19/12/2021 19:32:13
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Page 2 of 6
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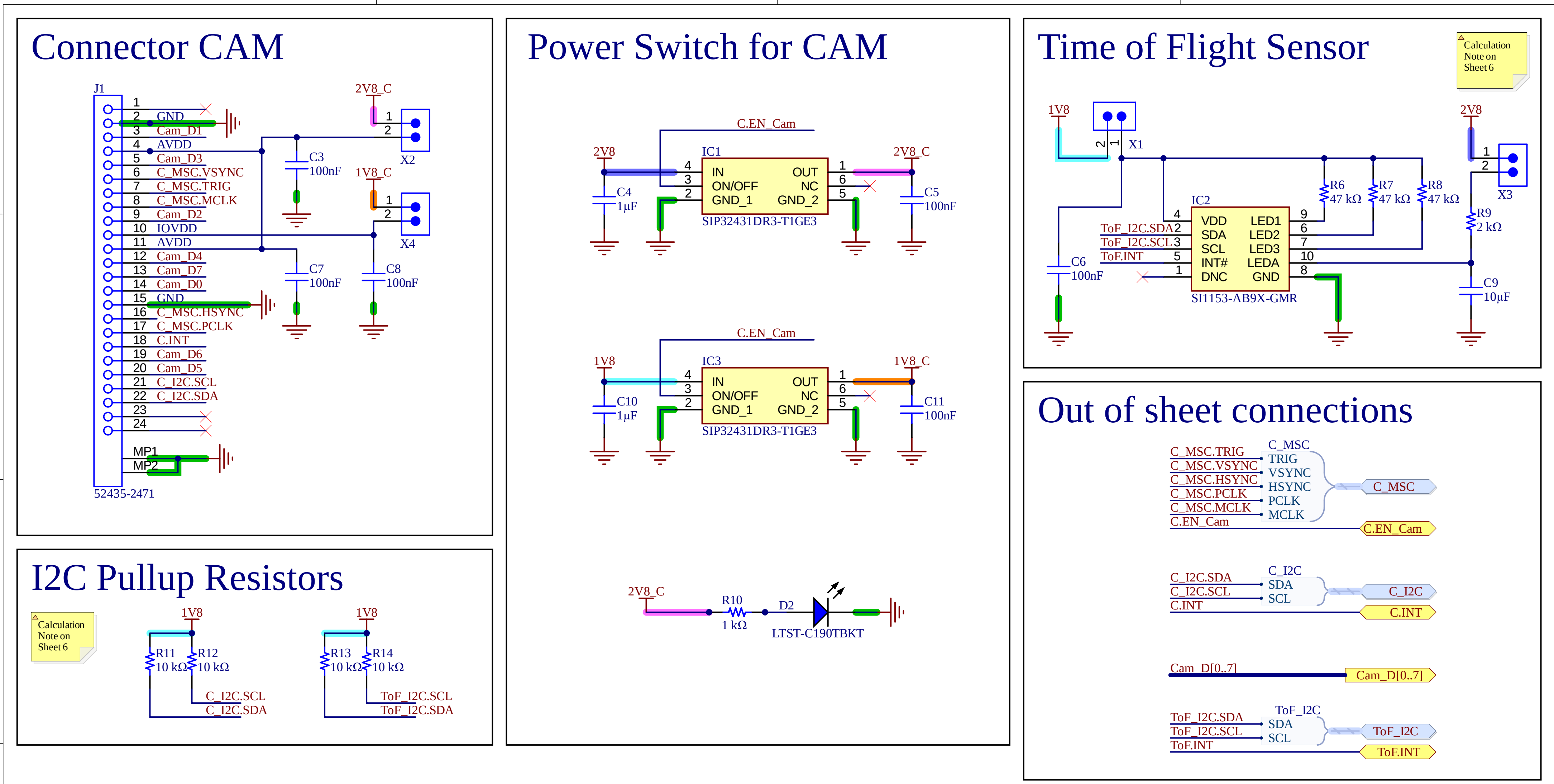

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Date: 19/12/2021 19:32:13			Drawn by: Nando Galliard	Page 3 of 6

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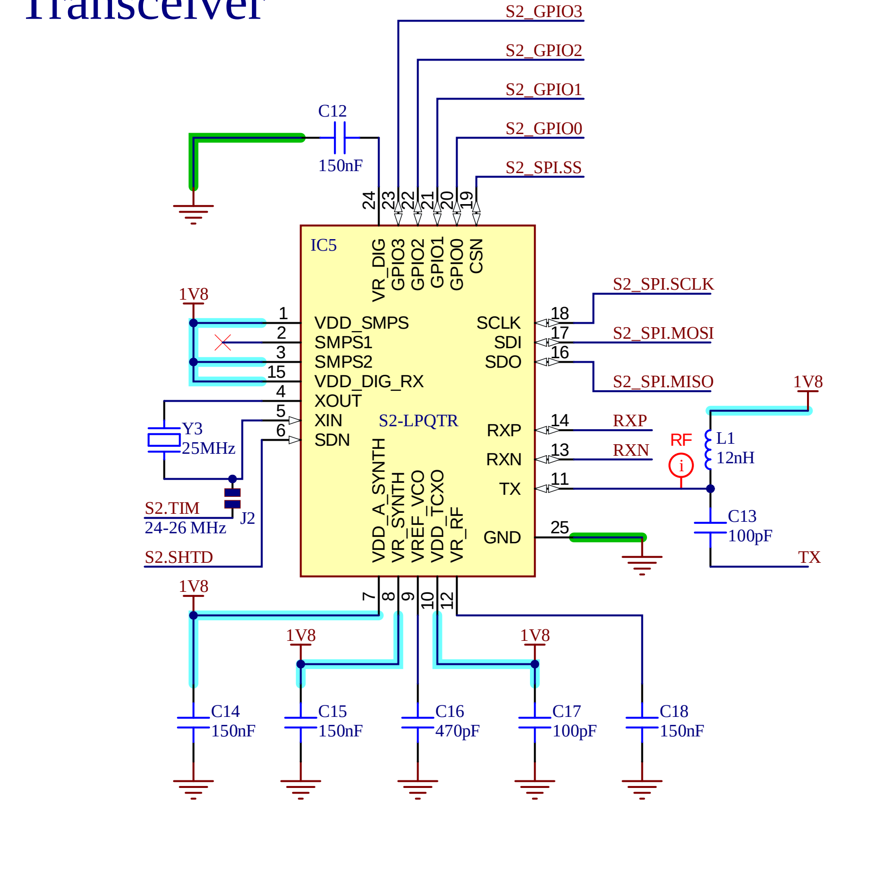
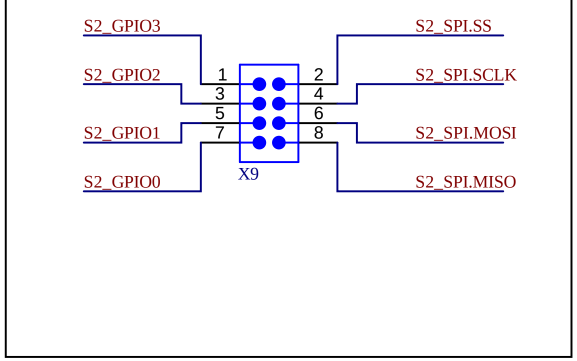
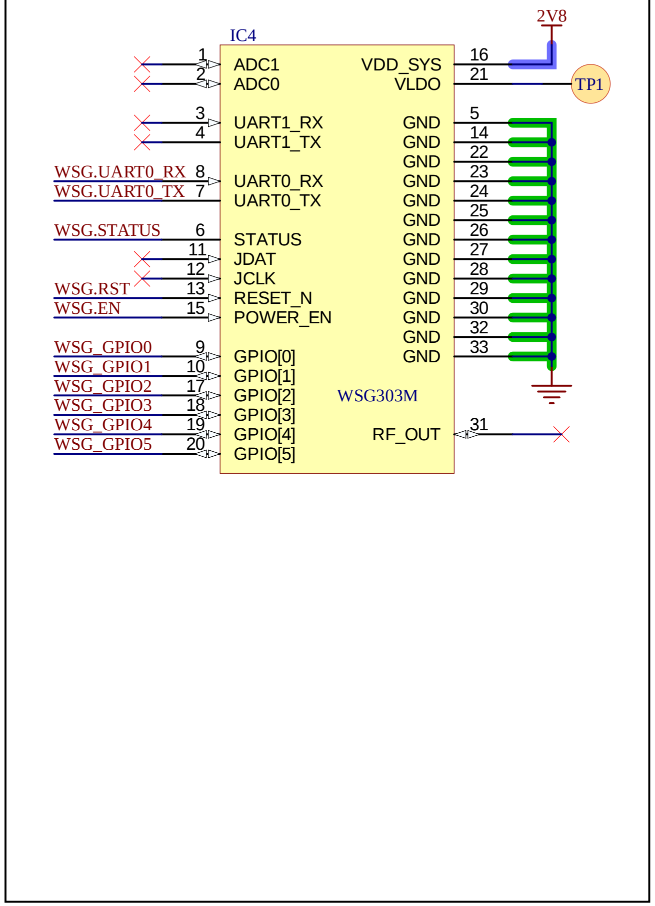
Transceiver



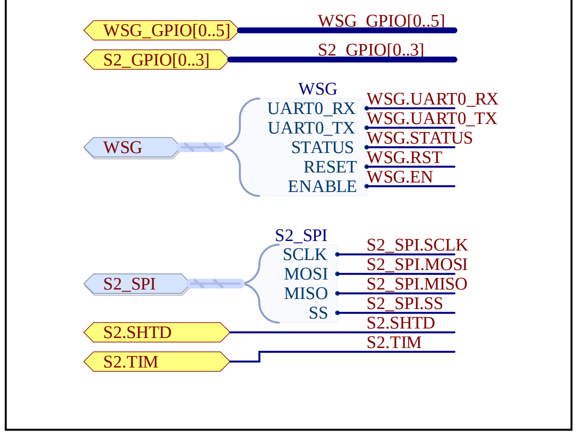
Backup for LORA



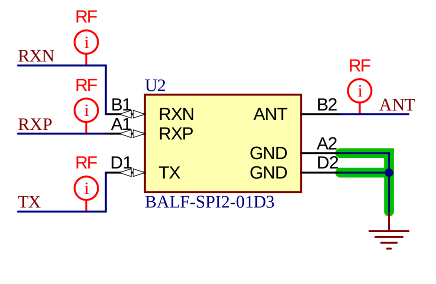
WSG303M Sigfox Module



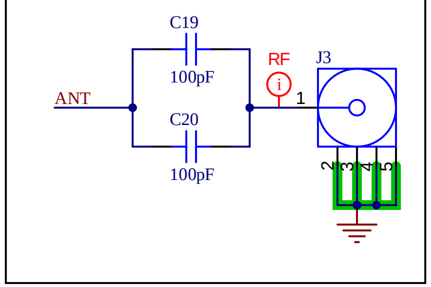
Out of sheet connections



Integrated BALUN



Antenna



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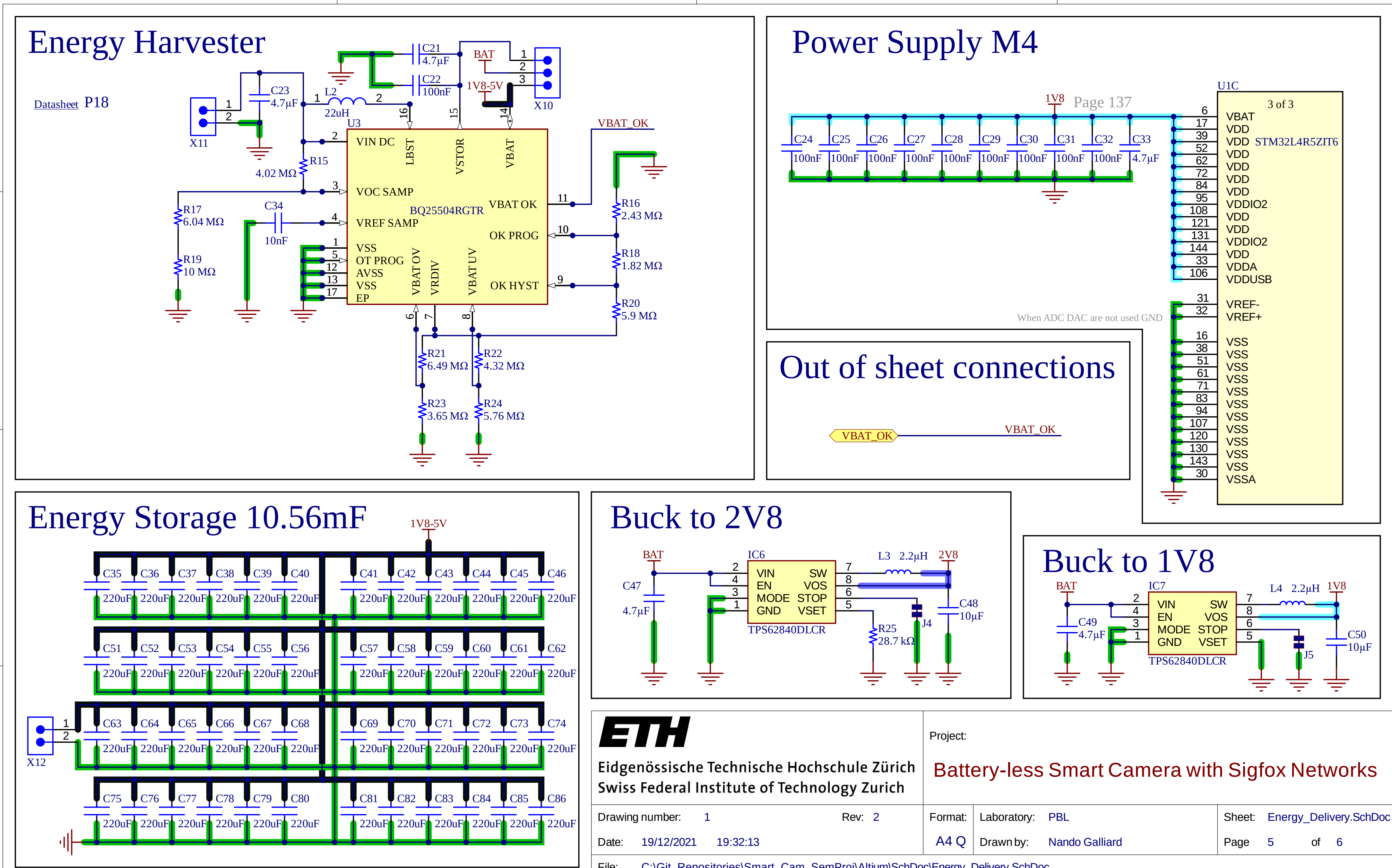

ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich	Project: Battery-less Smart Camera with Sigfox Networks
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Page 5 of 6	
File: C:\Git_Repositories\Smart_Cam_SemProj\Altium\SchDoc\Energy_Delivery.SchDoc	

<-- Compile mask for this sheet!

Pull up resistor calculations

https://sites.ifi.unicamp.br/soares/files/2017/03/Pull-up-slva689.pdf

Pull up resistor calculation
R_P(min) = (Vcc - V_OL(max))/I_OL

V_OL = 0.2 * Vcc
I_OL = 0.2mA

R_P(min, 1V8) = 7200 Ω
R_P(min, 2V8) = 11200 Ω

R_P(MAX) = t_r / (0.8473 * C_b)

C_b(max, Fast Mode | NormalMode) = 400pF
--> C_b = 200pF (Didn't find correct amount in RefManual)
(V_OL < 2V only possible in Fast Mode)

t_r = 0.8473 * R_p * C_b

--> Higher R_P --> Higher Rise time.

t_r (FastMode) = 300ns
t_r (NormalMode) =1us

R_P(max, 1V8) = 17700 Ω
R_P(max, 2V8) = 59000 Ω

R_P(1V8) = 7200 .. 17700 Ω
R_P(2V8) = 11200 .. 59000 Ω

ToF LED R & C Calc

https://www.silabs.com/documents/public/application-notes/AN950-Si1153-UG.pdf

C_LED = #LED * I_r_LED(MAX) * 24.4 us * 2^(HW_GAIN) / (V_LED -V_f -0.5)

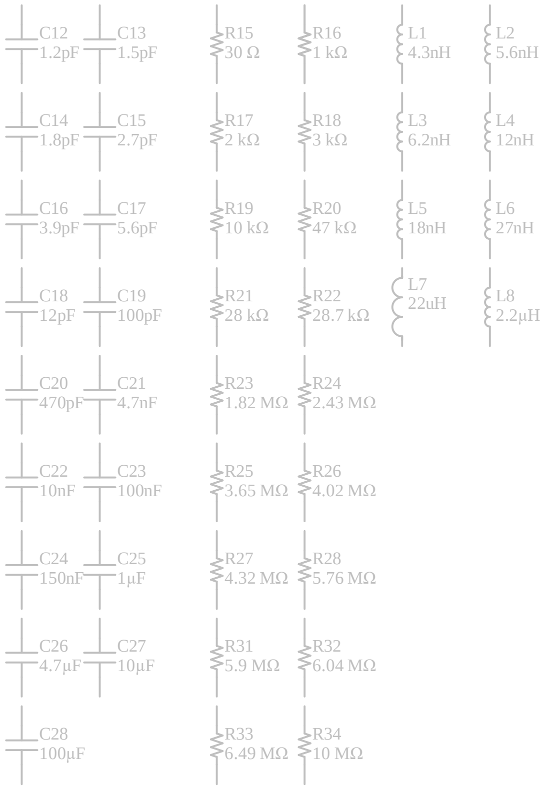
V_f = 1.4 V (Table 8.6), HW_Gain default = 1
I_f = 10 uA, #LED = 1, Ir = 360mA

C_LED(2V8) = 9.76 uF -> 10 uF
Time between measurements: 0.1s -> 10Hz

R_LED < 0.1s / (C_LED * 5)

R_LED(2V8) = 2 kΩ

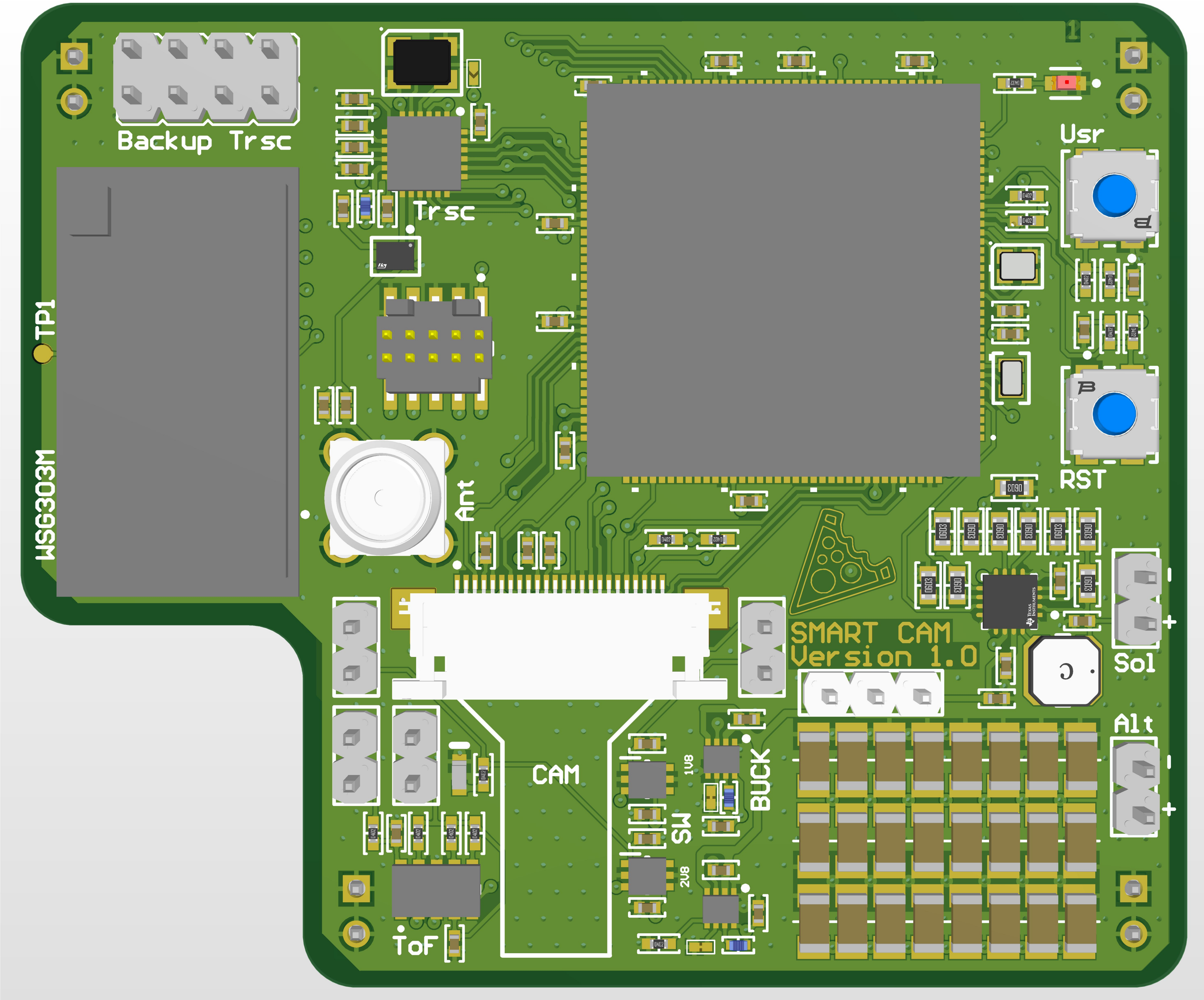
All used components

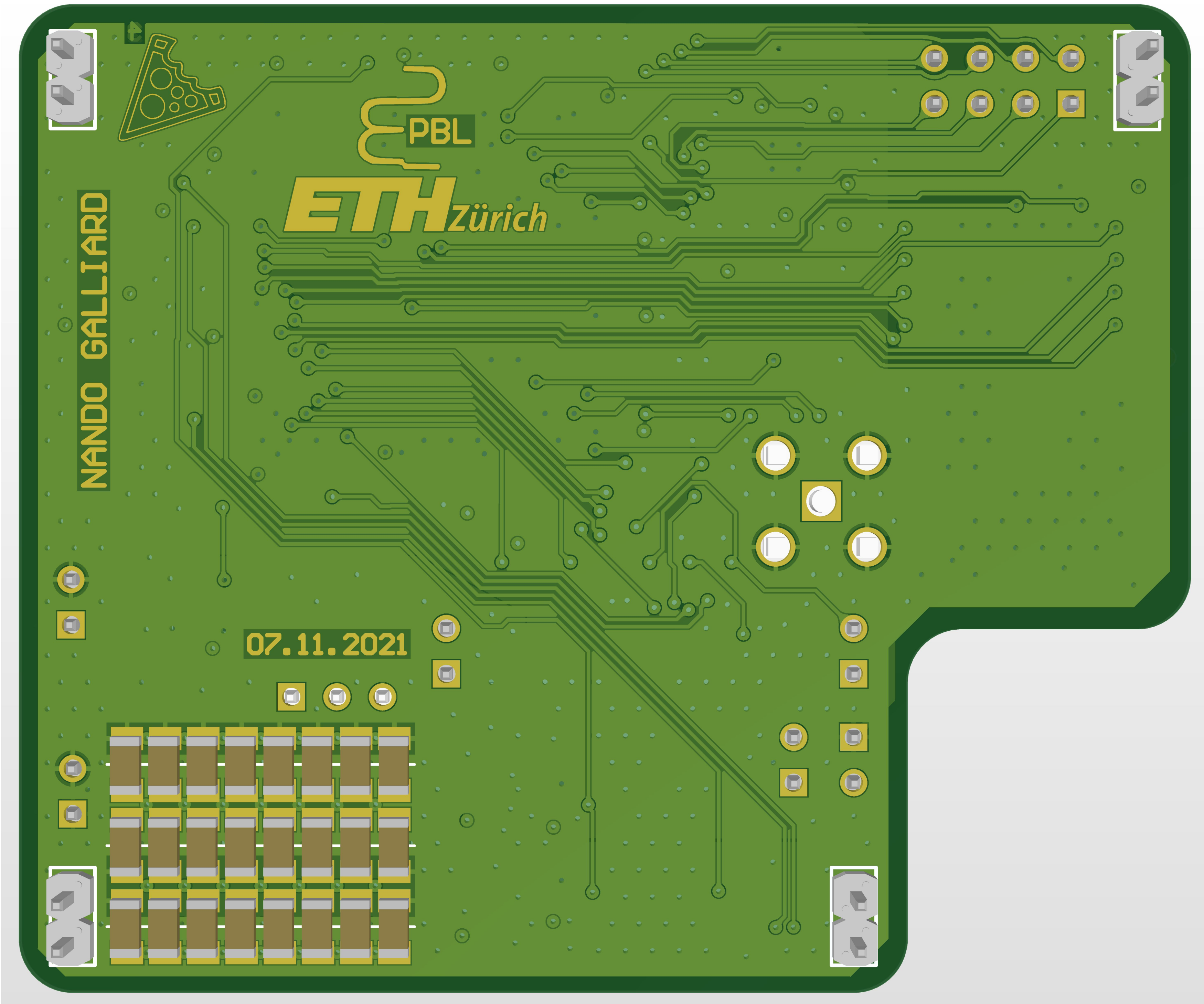


Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

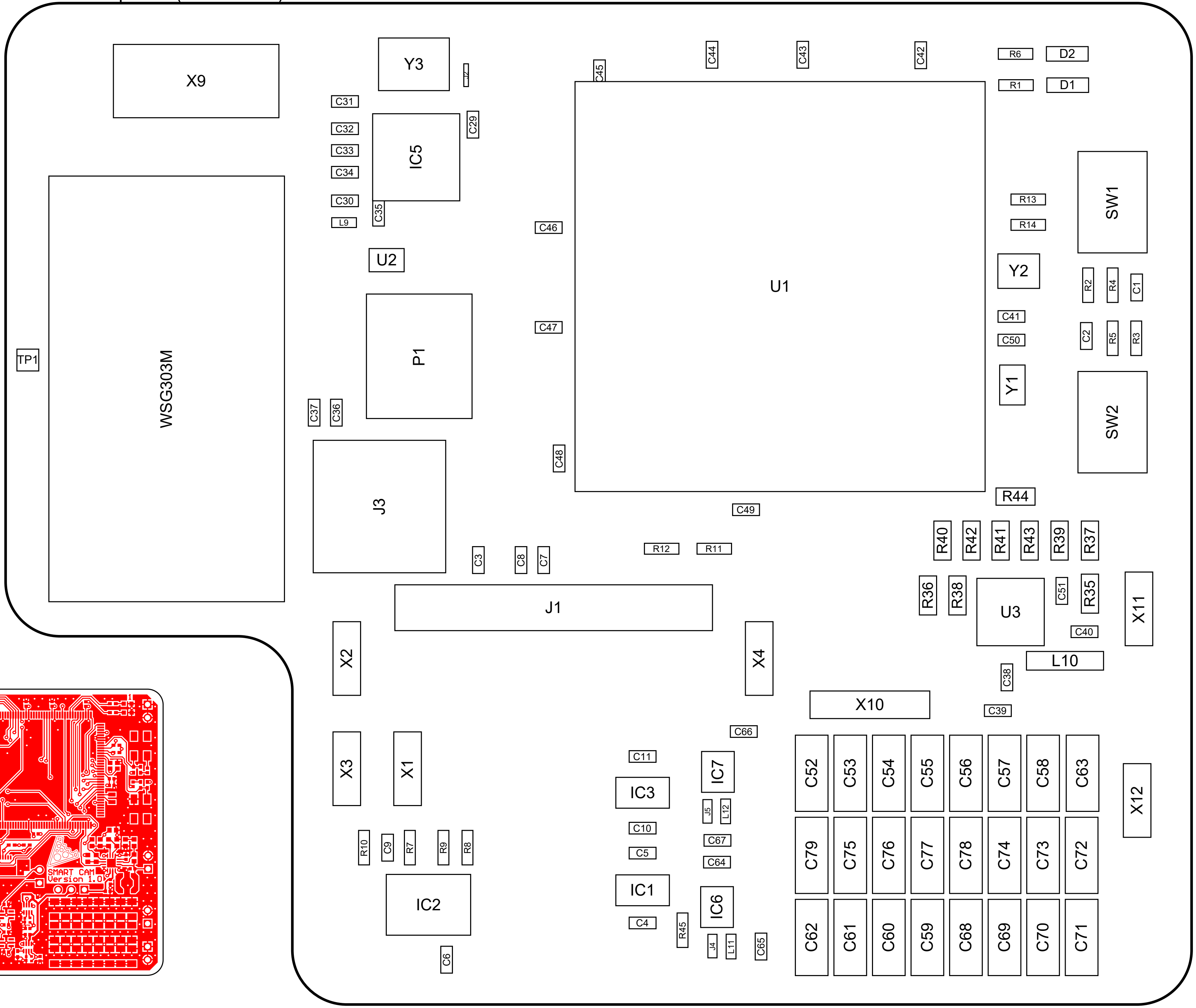
Project: Battery-less Smart Camera with Sigfox Networks

Drawing number: 1	Rev: 2	Format:	Laboratory: PBL	Sheet: Calculations.SchDoc	
Date: 19/12/2021	19:32:14	A4 Q	Drawn by: Nando Galliard	Page 6	of 6
File: C:\Git_Repositories\Smart_Cam_SemProj\Altium\SchDoc\Calculations.SchDoc					

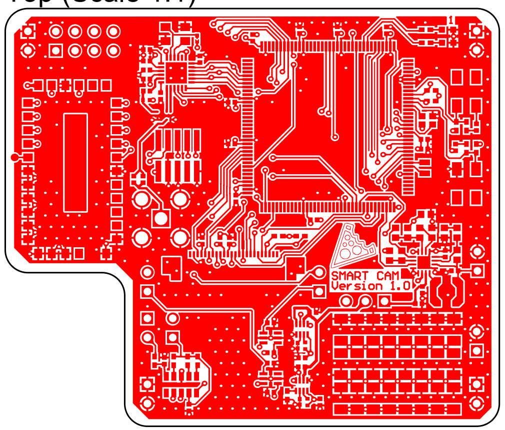

Backup Trsc
Trsc
TP1
WSG303M
Ant
Usr
RST
SMART CAM
Version 1.0
Sol
Alt
CAM
1V8
2V8
SW
BUCK
ToF


PBL
ETH Zürich
NANDO GALLIARD
07.11.2021

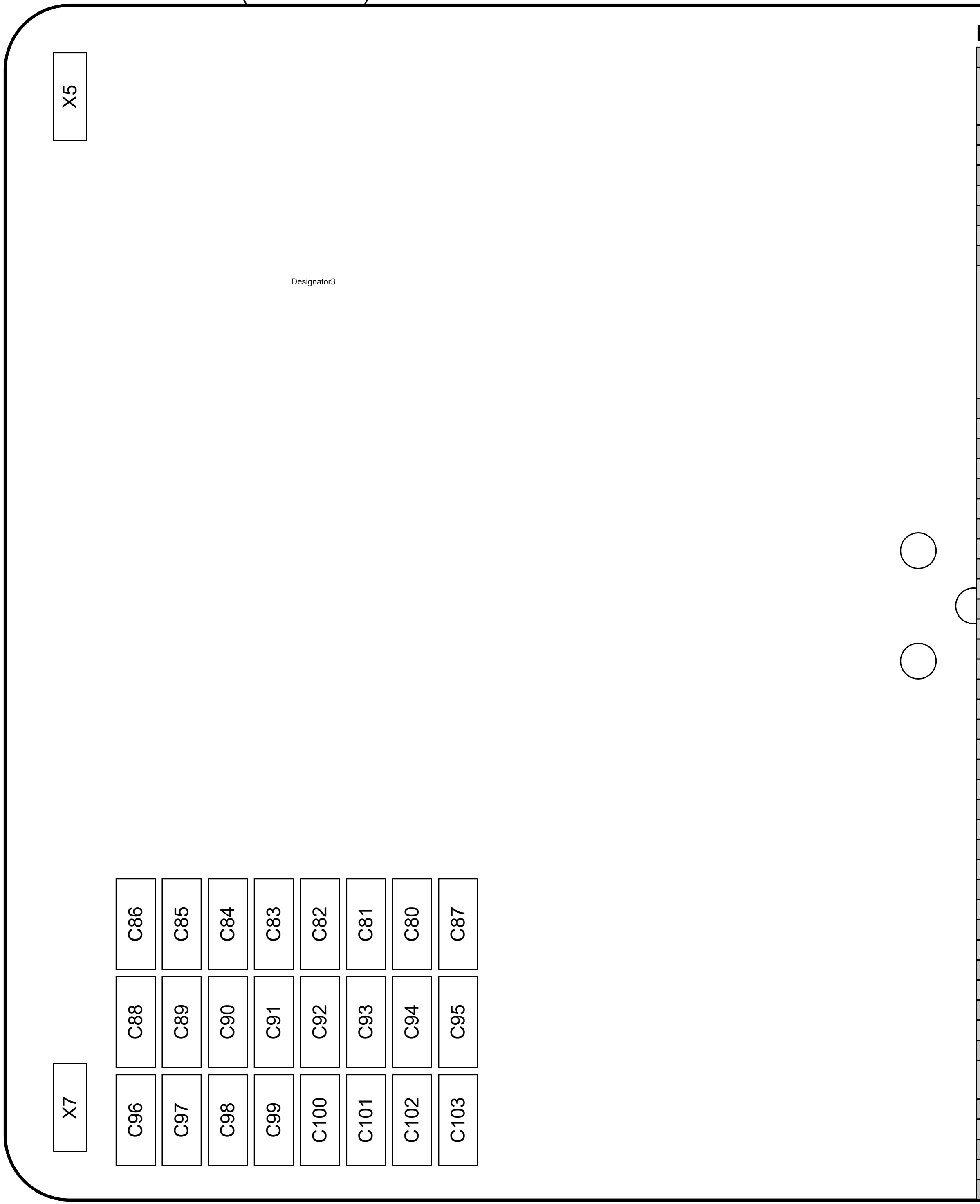
View from Top side (Scale 3.5:1)



Top (Scale 1:1)



View from Bottom side (Scale 3.5:1)



Bill Of Materials

Line #	Designator	Comment	Quantity
1	C1, C2, C3, C5, C6, C7, C8, C11, C39, C41, C42, C43, C44, C45, C46, C47, C48, C49	100nF	18
2	C4, C10	1µF	2
3	C9, C65, C67	10µF	3
4	C29, C31, C32, C35	150nF	4
5	C30, C34, C36, C37	100pF	4
6	C33	470pF	1
7	C38, C40, C50, C64, C66	4.7µF	5
8	C51	10nF	1
9	C52, C53, C54, C55, C56, C57, C58, C59, C60, C61, C62, C63, C68, C69, C70, C71, C72, C73, C74, C75, C76, C77, C78, C79, C80, C81, C82, C83, C84, C85, C86, C87, C88, C89, C90, C91, C92, C93, C94, C95, C96, C97, C98, C99, C100, C101, C102, C103	GRM31CR60J227ME11L	48
10	D1	LTST-C190KRKT	1
11	D2	LTST-C190TBKT	1
12	IC1, IC3	SIP32431DR3-T1GE3	2
13	IC2	SI1153-AB9X-GMR	1
14	IC4	WSG303M	1
15	IC5	S2-LPQTR	1
16	IC6, IC7	TPS62840DLCR	2
17	J1	52435-2471	1
18	J3	1053354-1	1
19	L9	12nH	1
20	L10	LPS4018-223MRB	1
21	L11, L12	2.2µH	2
22	P1	FTSH-105-01-F-DV-K	1
23	R1, R4, R5, R6	1 kΩ	4
24	R2, R3, R11, R12, R13, R14	10 kΩ	6
25	R7, R8, R9	47 kΩ	3
26	R10	2 kΩ	1
27	R35	4.02 MΩ	1
28	R36	2.43 MOhms	1
29	R37	6.04 MOhms	1
30	R38	1.82 MOhms	1
31	R39	10 MOhms	1
32	R40	5.9 MOhms	1
33	R41	6.49 MOhms	1
34	R42	4.32 MOhms	1
35	R43	3.65 MOhms	1
36	R44	5.76 MOhms	1
37	R45	28.7 kΩ	1
38	SW1, SW2	7914J-1-032E	2
39	TP1	Test Point	1
40	U1	STM32L4R5ZIT6	1
41	U2	BALF-SPI2-01D3	1
42	U3	BQ25504RGTR	1
43	X1, X2, X3, X4, X5, X6, X7, X8, X11, X12	68000-102HLF	10
44	X9	67996-108HLF	1
45	X10	68000-103HLF	1
46	Y1	32.768kHz	1
47	Y2	32MHz	1
48	Y3	25MHz	1

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