Master degree in Electronics Engineering

Project Technical Report
ECG Sensor

Electronic Systems Engineering
2023-2024

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Contents

1 Project Specification

The project focuses on the design of an ECG sensor embedded in a chest band, a wearable device that can be easily worn to support the user during sports activity.
The main objective is to provide users with real-time monitoring of their heart rate. Thanks to a BLE communication for fitness monitoring, the data collected by the sensor can easily be displayed on a connected device.
The device is low power, easily rechargeable via a USB connector, and equipped with LEDs for both charge monitoring and during operation.

1.1 Device Specification

- Low power device
- Low cost
- Portable device
- Rechargeable battery via USB connector
- Long battery duration ($\approx 40\,\text{h}$)
- BLE communication to a connected device
- Operating conditions: performance specifications are guaranteed in the range of 0°C to 70°C, but the device is designed to function operationally in a wider temperature range of -40°C to +85°C

2 Design Flow

This section outlines the key steps undertaken in designing the system.

1. Project name and specifications
2. Component selection and analysis
3. Project presentation (creating PowerPoint presentation)
4. Component library and schematic design using OrCAD Capture CIS
5. Designing padstack for components using the OrCAD padStack editor
6. Designing footprint for components using the OrCAD Allegro PCB editor
7. PCB design using OrCAD Allegro

3 Block Diagram

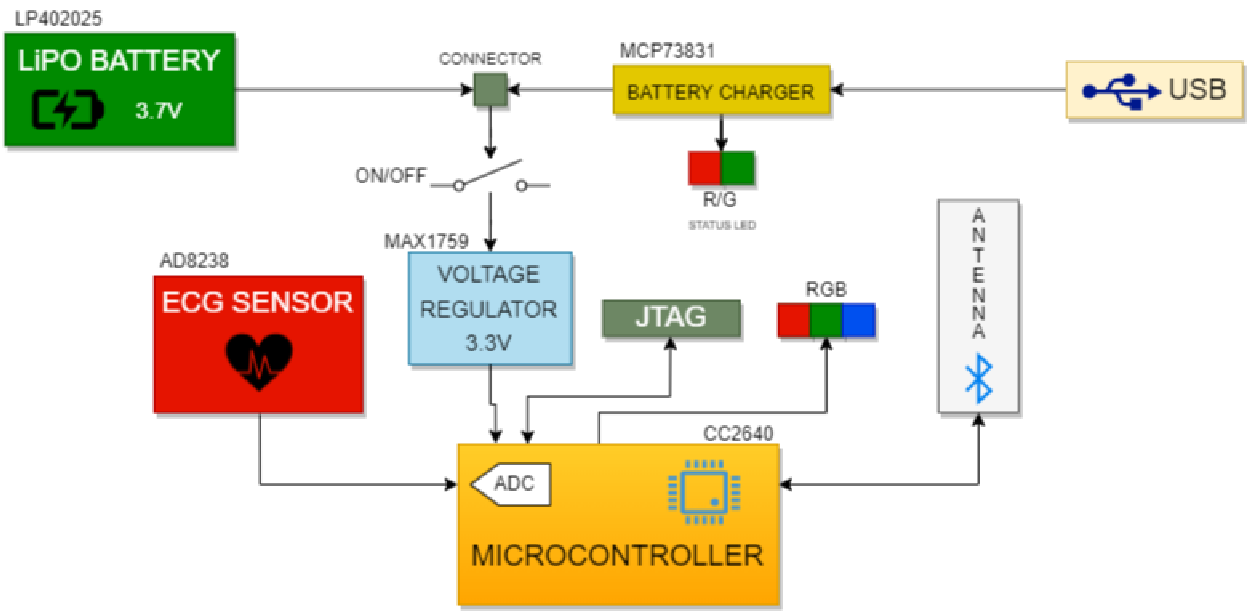


Figure 1: High-level Block Diagram of the entire system

Fig. 1 depicts the block diagram of the entire designed system. The main components are listed below.

- **Microcontroller**: it is the main processing unit, complemented by essential components, such as decoupling capacitors and crystals.
- **ECG sensor**: it is an ECG signal detector, along with signal conditioning components, such as resistors and capacitors. The chosen design focuses on a circuit for heart rate measurement next to heart, enhancing the strength of the cardiac signal while minimizing interference from muscle artifacts. Due to limited space in this setup, the circuit is optimized for size and it includes few external components as possible.
- **Voltage regulator**: the circuitry is designed to adapt the battery voltage to match the necessary supply voltage of 3.3V.
- **Antenna**: 2.4 GHz patch Antenna.
- **LiPo Battery**: it is the main power supply of the entire system (3.7 V).
- **JTAG Connector**: it is used to interface the device with a computer and program, debug, and test it.

- **Battery Connector**: it enables the connection of the LiPo battery to the battery charger.
- **Battery charger**: it is a USB charger.
- **USB connector**: it is needed to recharge the device battery.
- **ON/OFF switch**: it, along with its debouncing circuit, is employed to activate and deactivate the system.
- **LED (Red and Green)**: they are used to signal the charging status of the device (red LED for in charge status, green LED for full charge).
- **RGB LEDs**: they are used to indicate the operating status of the device.

4 Components

4.1 ECG Sensor: AD8232

Figure 2: ECG Sensor - AD8232

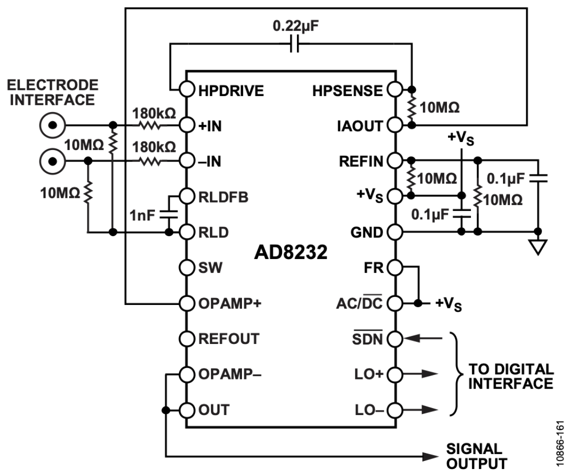


Figure 3: Circuit for heart rate measurement next to heart

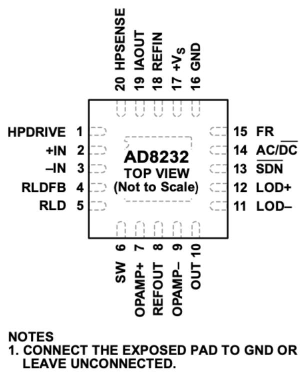


Figure 4: ECG Sensor - PIN Configuration

Pin No.	Mnemonic	Description
1	HPDRIVE	High-Pass Driver Output. Connect HPDRIVE to the capacitor in the first high-pass filter. The AD8232 drives this pin to keep HPSENSE at the same level as the reference voltage.
2	+IN	Instrumentation Amplifier Positive Input. +IN is typically connected to the left arm (LA) electrode.
3	−IN	Instrumentation Amplifier Negative Input. −IN is typically connected to the right arm (RA) electrode.
4	RLDFB	Right Leg Drive Feedback Input. RLDFB is the feedback terminal for the right leg drive circuit.
5	RLD	Right Leg Drive Output. Connect the driven electrode (typically, right leg) to the RLD pin.
6	SW	Fast Restore Switch Terminal. Connect this terminal to the output of the second high-pass filter.
7	OPAMP+	Operational Amplifier Noninverting Input.
8	REFOUT	Reference Buffer Output. The instrumentation amplifier output is referenced to this potential. Use REFOUT as a virtual ground for any point in the circuit that needs a signal reference.
9	OPAMP−	Operational Amplifier Inverting Input.
10	OUT	Operational Amplifier Output. The fully conditioned heart rate signal is present at this output. OUT can be connected to the input of an ADC.
11	LOD−	Leads Off Comparator Output. In dc leads off detection mode, LOD− is high when the electrode to −IN is disconnected, and it is low when connected. In ac leads off detection mode, LOD− is always low.
12	LOD+	Leads Off Comparator Output. In dc leads off detection mode, LOD+ is high when the +IN electrode is disconnected, and it is low when connected. In ac leads off detection mode, LOD+ is high when either the −IN or +IN electrode is disconnected, and it is low when both electrodes are connected.
13	$\overline{\text{SDN}}$	Shutdown Control Input. Drive $\overline{\text{SDN}}$ low to enter the low power shutdown mode.
14	AC/$\overline{\text{DC}}$	Leads Off Mode Control Input. Drive the AC/$\overline{\text{DC}}$ pin low for dc leads off mode. Drive the AC/$\overline{\text{DC}}$ pin high for ac leads off mode.
15	FR	Fast Restore Control Input. Drive FR high to enable fast recovery mode; otherwise, drive it low.
16	GND	Power Supply Ground.
17	$+V_S$	Power Supply Terminal.
18	REFIN	Reference Buffer Input. Use REFIN, a high impedance input terminal, to set the level of the reference buffer.
19	IAOUT	Instrumentation Amplifier Output Terminal.
20	HPSENSE	High-Pass Sense Input for Instrumentation Amplifier. Connect HPSENSE to the junction of R and C that sets the corner frequency of the dc blocking circuit.
	EP	Exposed Pad. Connect the exposed pad to GND or leave it unconnected.

Figure 5: ECG Sensor - PIN functions description

The AD8232 functions as an integrated signal conditioning unit tailored for ECG and other biopotential measurements. Its purpose is to capture, strengthen, and refine weak biopotential signals in perturbated environments, like those induced by movement. It can be configured for various applications, including *Heart Rate Measurement Next to Heart*, *Heart Rate Measured at Hands*, *ECG Waveform Monitoring*, *Low Power Portable Cardiac Monitor*.
The first mode has been selected, also because of the lower number of resistors needed. The reference circuit is depicted in Fig. 3. A shorter distance from the AD8232 to the heart makes this application less vulnerable to common-mode interference. Moreover, the strength of the cardiac signal is maximized and interference from muscle artifacts is strongly reduced.
The analog output signal emitted by the `OUT` pin is directly connected to the internal ADC of the CC2640, without any buffer in the connection to condition the signal. In fact, as specified in the datasheet, no buffer is needed in case of simple connection with no particular added external noise.

- Low supply current: 170 µA
- Shutdown current: 40 nA
- Supply voltage range: 2.0 V to 3.5 V
- CMRR: 80 dB
- High signal gain: G=100
- Integrated Right Led Drive Amplifier improves signal quality

- Package: 20-lead, 4 mm × 4 mm LFCSP

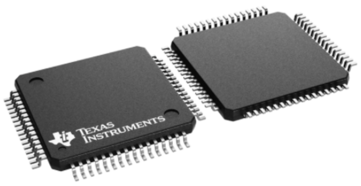
Fig. 6 shows the absolute maximum ratings of ECG sensor.

Parameter	Rating
Supply Voltage	3.6 V
Output Short-Circuit Current Duration	Indefinite
Maximum Voltage, Any Terminal[1]	$+V_S$ + 0.3 V
Minimum Voltage, Any Terminal[1]	−0.3 V
Storage Temperature Range	−65°C to +125°C
Operating Temperature Range	
AD8232ACPZ	−40°C to +85°C
AD8232WACSZ	−40°C to +105°C
Maximum Junction Temperature	140°C
θ_{JA} Thermal Impedance[2]	48°C/W
θ_{JC} Thermal Impedance	4.4°C/W
ESD Rating	
Human Body Model (HBM)	8 kV
Charged Device Model (FICDM)	1.25 kV
Machine Model (MM)	200 V

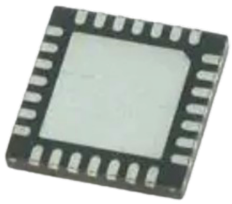
[1] This level or the maximum specified supply voltage, whichever is the lesser, indicates the superior voltage limit for any terminal. If input voltages beyond the specified minimum or maximum voltages are expected, place resistors in series with the inputs to limit the current to less than 5 mA.
[2] θ_{JA} is specified for a device in free air on a 4-layer JEDEC board.

Figure 6: Absolute Maximum Ratings

4.1.1 Alternative ECG Sensors



(a) ADS1194 - TEXAS INSTRUMENTS



(b) MAX30003 - ANALOG DEVICES

Figure 7: Alternative ECG Sensors

Before choosing the AD8232, the two alternatives below were also considered.

ADS1194
TEXAS INSTRUMENTS

- Higher supply voltage
- Higher supply current
- Integrated ADC
- High complexity

MAX30003
ANALOG DEVICES

- High quality
- Very high cost
- Low voltage (2V)
- High ADC resolution

4.1.2 Electrodes

For the detection of the ECG signal, dry electrodes must be connected to the sensor. Dry electrodes shows some advantages over traditional gel-based electrodes (wet), because they eliminate the need for conductive gel and ensure a quicker and cleaner application process. They are more suitable for wearable device.
Some possible choices are stainless steel or gold-plated electrodes. Comparing the options, there are several reasons behind choosing gold-plated electrodes: Gold ensures a better transmission of the electrical signal between skin and the electrode, it has higher biocompatibility, it is resistant to wear, and chemically inert, thus it does not oxidise easily. Therefore, they are suitable to be exposed electrodes, ensuring overall durability and good performance even after prolonged use.

Since the ECG signal is in the range of a few millivolts, it is essential to carefully evaluate the connection between sensors and PCB to prevent signal loss resulting from noise introduced by contacts. We explored different possible solutions.

- **DIN connector**. Electrodes con be connected to snap lead wires, which are sufficiently short and equipped with DIN connector with a 1.5 mm diameter pin. DIN 42802 is a standard for touch-proof connector for electromedical applications. Despite the optimal performance of these cables in detecting ECG signals, the option was dismissed due to the high costs of the connectors in proportion to the overall PCB cost, and because we aim to avoid a wired setup.

- **Jack connector**. A more cost-effective solution involves the use of a jack connector. However, this type of cable requires the connection of three electrodes (left arm, right arm, right leg). As explained in the previous section, we have opted to utilize the AD8232 ECG sensor in the *Next To Heart* configuration, which is more suitable for a chest strap designed for heart rate monitoring. This configuration involves the use of only two electrodes, positioned on the user's chest. Additionally, we prefer avoiding wired solutions. For these reasons, even if this is the cheapest option, it has also been rejected.

- **Integrated electrode and cable soldering**. We have opted for a solution where a cable is soldered to 2.54mm 2 pin male header on the PCB and electrodes, all enclosed within a package. Only the electrodes will be exposed. We can select a type of electrodes with screw attachments, which are specifically cut to be soldered to the cable. Despite the need to consider additional labor costs, this approach proves the most effective for our device. In fact, there are no exposed wires, impedance is very low, the cost of the cables is reduced, while maintaining good signal quality. It is a good trade-off in terms of cost and performance.

4.2 Microcontroller: CC2460

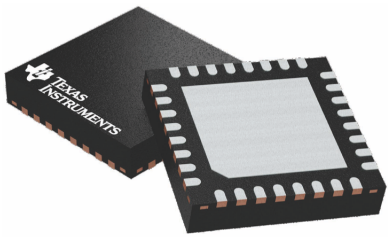


Figure 8: Microcontroller CC2460

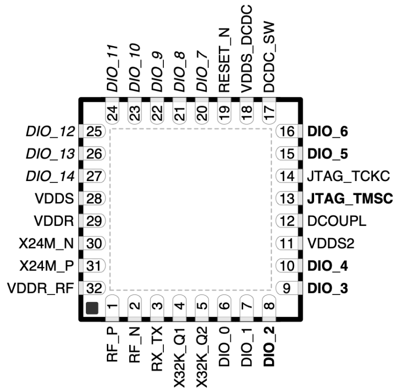


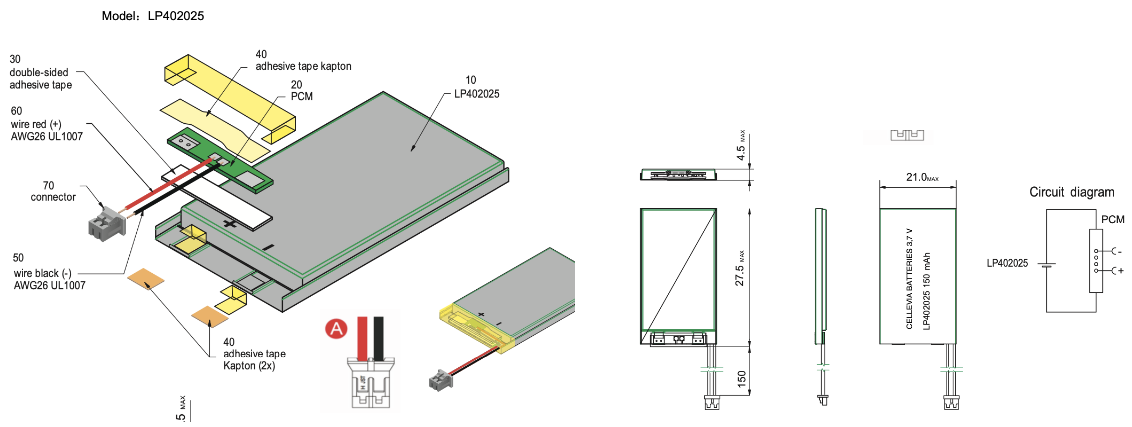
Figure 9: CC2460 - Pins. I/O pins marked in bold have high drive capabilities. I/O pins marked in italics have analog capabilities.

The microcontroller utilized is the CC2640 in RHB format, with dimensions of 5 mm x 5 mm, chosen to optimize the area of the designed system. It is a cost-effective, ultra-low power, 2.4-GHz RF device. The CC2640 is well-suited for our project due to its ideal features for a wide range of applications, including long battery lifetime, small form factor, and ease of use.

- The CC2640 device contains a 32-bit ARM Cortex-M3 processor that runs at 48 MHz as the main processor and a rich peripheral feature set that includes a ultralow power sensor controller. 32-bit ARM Cortex-M3 architecture is optimized for small-footprint embedded applications.
- Low Energy Bluetooth compatibility: the BLE controller is embedded into ROM and runs partly on an ARM Cortex-M0 processor. This architecture improves overall system performance and power consumption and frees up flash memory for the application.
- Memory: the flash memory provides nonvolatile storage for code and data; the SRAM can be used for both storage of data and execution of code execution, offering power-efficient standby retention control; the ROM holds preprogrammed essential software components and BLE controller.
- The on-chip debug and test support is done through a dedicated JTAG interface.
- Power Consumption Summary:
  - Wide supply voltage range: 1.8V to 3.8V for normal operation and 1.7V to 1.95V for external regulator mode
  - Standby current: 1 μA

  - Shutdown current: 100 nA
  - Active-mode RX: 5.9 mA
  - Active-mode TX at 0dBm: 6.1 mA
  - Active-mode TX at +5dBm: 9.1 mAù
  - Active-mode MCU: 61 µA/MHz
  - Active-mode Sensor Controller: 8.2 µA/MHz
- Support I2C, UART and I2S

4.3 LiPo Battery: LP402025



(a) (b)

Figure 10: LiPo Battery

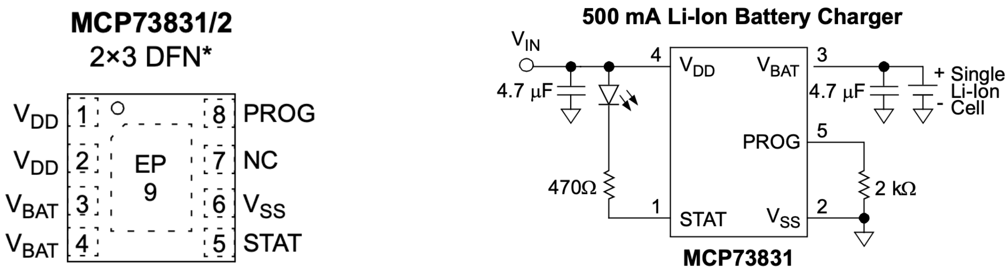
The LiPo battery inserted in our project has the following features:

- Nominal voltage: 3.7V
- Maximum current: 150mAh (nominal capacity)
- Maximum charge current: 155mA
- Operation temperature range:
  - charge: 0 to 45 °C
  - discharge: −20 °C to 60 °C
- Assemblage Dimension:
  - Length: 27.5mm Max
  - Width: 21.0mm Max

- Thickness: 4.5mm Max

- Cell Dimension: 25.5mm x 21.0mm x 4.5mm
- Cell Weight: 5g (approx)
- LiPo battery is connected to the system through battery connector described in Section 4.8.

4.4 Battery charger: MCP73831



(a) Package type. It includes Exposed Thermal Pad (EP) (b) Typical operating circuit

Figure 11: USB charger - MCP7831T-2ACI/OT

Pin No.		Symbol	Function
DFN	SOT-23-5		
1	4	V_{DD}	Battery Management Input Supply
2	—	V_{DD}	Battery Management Input Supply
3	3	V_{BAT}	Battery Charge Control Output
4	—	V_{BAT}	Battery Charge Control Output
5	1	STAT	Charge Status Output
6	2	V_{SS}	Battery Management 0V Reference
7	—	NC	No Connection
8	5	PROG	Current Regulation Set and Charge Control Enable
9	—	EP	Exposed Thermal Pad (EP); must be connected to V_{SS}.

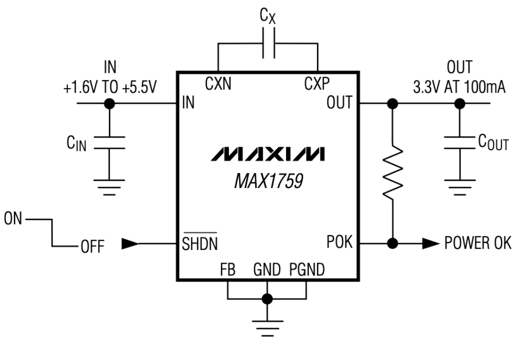
Figure 12: MCP7831 - PIN function table

MCP73831 is the selected USB charger for this project. Due to its compact physical size and minimal external component requirements, it is well-suited for portable applications. The main specifications are listed below.

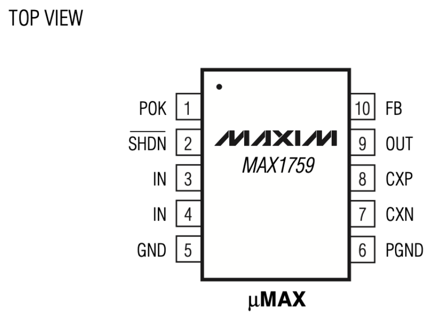
- A constant-current/constant-voltage charge algorithm with selectable preconditioning and charge termination is employed. There are four voltage regulation options (4.20V, 4.35V, 4.40V, 4.50V), while the programmable charge current ranges from 15mA to 500mA.
- Thermal regulation optimizes the charge cycle time while maintaining device reliability.

- Temperature range: $-40\,^{\circ}\mathrm{C}$ to $85\,^{\circ}\mathrm{C}$
- Packaging: 8-Lead, 2 mm x 3 mm DFN

4.5 Voltage Regulator: MAX1759EUB



(a) Typical operating circuit



(b) Pin configuration

Figure 13: MAX1759

PIN	NAME	FUNCTION
1	POK	Open-Drain Power-OK Output. POK is high impedance when output voltage is in regulation. POK sinks current when V_{FB} falls below 1.1V. Connect a 10kΩ to 1MΩ pull-up resistor from POK to V_{OUT} for a logic signal. Ground POK or leave unconnected if not used. POK is high impedance in shutdown.
2	$\overline{\text{SHDN}}$	Shutdown Input. Drive high for normal operation; drive low for shutdown mode. OUT is high impedance in shutdown.
3, 4	IN	Input Supply. Connect both pins together and bypass to GND with a ceramic capacitor (see *Capacitor Selection* section).
5	GND	Ground. Connect GND to PGND with a short trace.
6	PGND	Power Ground. Charge-pump current flows through this pin.
7	CXN	Negative Terminal of the Charge-Pump Transfer Capacitor
8	CXP	Positive Terminal of the Charge-Pump Transfer Capacitor
9	OUT	Power Output. Bypass to GND with an output filter capacitor.
10	FB	Dual-Mode Feedback. Connect FB to GND for 3.3V output. Connect to an external resistor divider to adjust the output voltage from 2.5V to 5.5V.

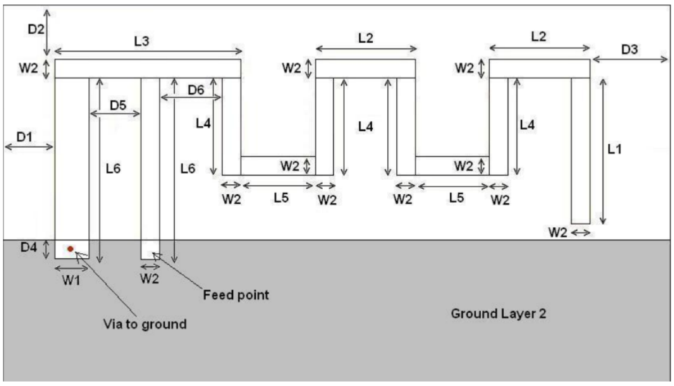
Figure 14: MAX1759 PIN Description

The MAX1759 is a charge pump buck/boost voltage converter designed to generate a regulated output voltage from a single lithium-ion (Li+) cell, or two or three NiMH or alkaline cells. In particular, in the designed system it serves to adapt the output voltage of the battery to 3.3 V. This device is suitable for small portable battery-powered devices. Its main features are listed below.

- Operating input voltage range: +1.6V to +5.5V
- Regulated output voltage range: fixed 3.3V or adjustable 2.5V to 5.5V
- Operating frequency: 1.5MHz (high)

- Quiescent supply current: 50 µA (it is maintained low although the high operating frequency)
- Guaranteed output current: 100 mA (min output current from a +2.5 V input)
- The MAX1759 is available in a space-saving 10-pin µMAX package that is 1.09 mm high
- Shutdown mode: 1 µA
- Temperature range: −40 °C to 85 °C

4.6 Antenna



(a)

L1	3.94 mm
L2	2.70 mm
L3	5.00 mm
L4	2.64 mm
L5	2.00 mm
L6	4.90 mm
W1	0.90 mm
W2	0.50 mm
D1	0.50 mm
D2	0.30 mm
D3	0.30 mm
D4	0.50 mm
D5	1.40mm
D6	1.70 mm

(b)

Figure 15: Antenna Dimensions

This is a 2.4GHz antenna with a characteristic impedance of 50 Ω. Its dimensions are shown in Fig. 15.

4.7 USB Connector: UJC-HP-3-SMT-TR

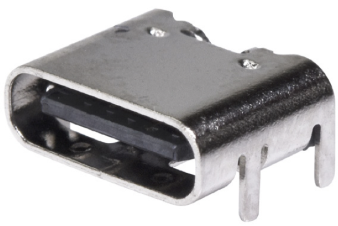


Figure 16: USB connector UJC-HP-3-SMT-TR

The USB connector enables the battery to be recharged via an external USB cable. The selected USB connector is the UJC-HP-3-SMT-TR, and its main features are listed below.

- Max. Rated voltage: 20Vdc
- Max. Rated current: 3A for power/GND pins collectively (A9, A12, B9, B12), 1.5A for power/GND pins individually (A9, A12, B9, B12), 0.25A for all other pins
- Temperature range: $-40\,^{\circ}\mathrm{C}$ to $80\,^{\circ}\mathrm{C}$

4.8 Battery Connector: B2B-PH-K-S

Figure 17: Battery Connector (B2B-PH-K-S)

The battery connector enables the connection of the LiPo battery to the battery charger. The B2B-PH-K-S is an STM connector, known for its compact design, high reliability, and low cost.

- Current rating: 2A AC/DC
- Voltage rating: 100V AC/DC
- Temperature range: $-25\,^{\circ}\mathrm{C}$ to $80\,^{\circ}\mathrm{C}$

4.9 RGB LED

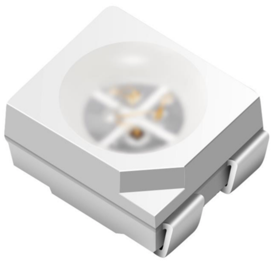


Figure 18: 3D of the RGB LED

Their function can be defined while programming the Microcontroller firmware. The chosen RGB LED is *XZM2CRKM2DGFBB45SCCB* from *SunLED*.
The reasons behind this choice are multiples:

- Common Anode : easier to connect the pin to GND rather than VCC
- Relative Low Voltage : since they are going to be powered at 3.3V, green and blue LEDs could be limited with such low voltages
- Relative high luminous intensity at low current (around 100 mcd at 4mA).

In Fig. 19, Fig. 20 and Fig. 21 a graph representing the characteristics of all the LEDs is shown. Since it is directly powered from the CC2640 microcontroller pins without any driver, the available current is limited. In particular, pins 8, 9, and 10 (`DIO_2`, `DIO_3`, `DIO_4` respectively) have been chosen to control the pins because they have higher driving capabilities than normal GPIO pins (8mA max instead of 2mA), with a driving current of around 4mA it is reasonable.

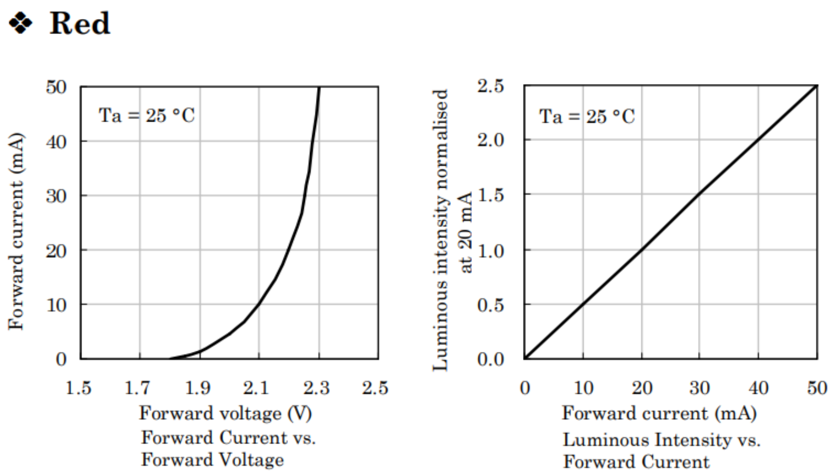


Figure 19: Red LED characteristics

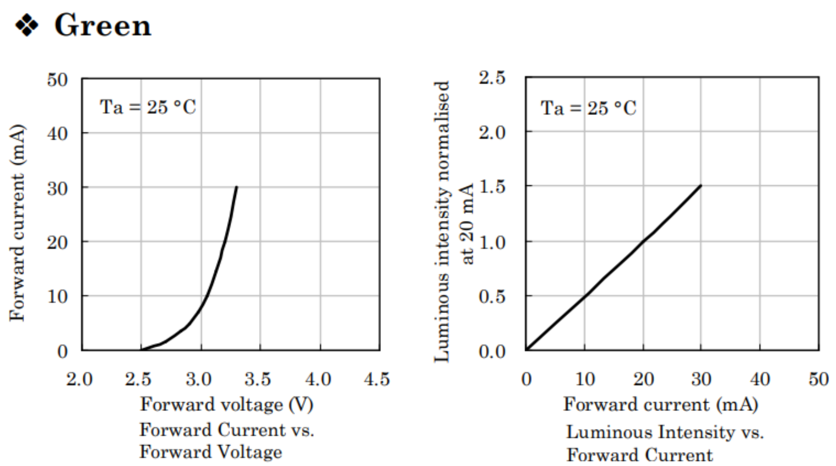


Figure 20: Green LED characteristics

❖ **Blue**

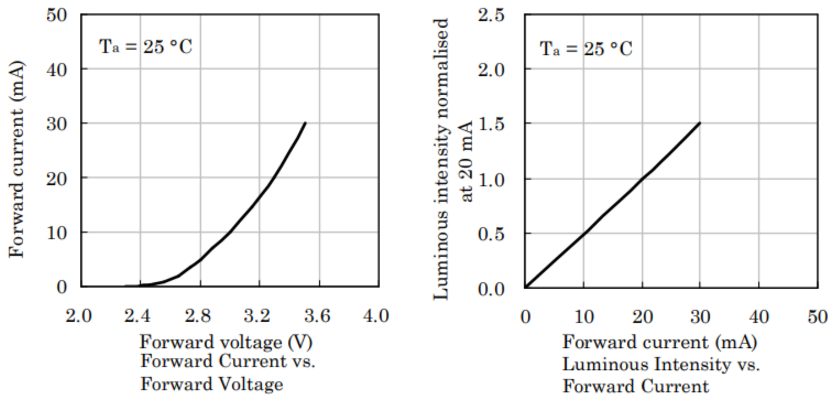


Figure 21: Blue LED characteristics

- Emitting materials, wavelength of peak emission, and spectral line full width:
  - Red: AlGaInP ($\lambda = 640\,\text{nm}$, $\Delta\lambda = 20\,\text{nm}$)
  - Green: InGaN ($\lambda = 520\,\text{nm}$, $\Delta\lambda = 35\,\text{nm}$)
  - Blue: InGaN ($\lambda = 465\,\text{nm}$, $\Delta\lambda = 22\,\text{nm}$)
- Operating temperature: $-40\,^{\circ}\text{C}$ to $85\,^{\circ}\text{C}$

4.10 LEDs (Red and Green)

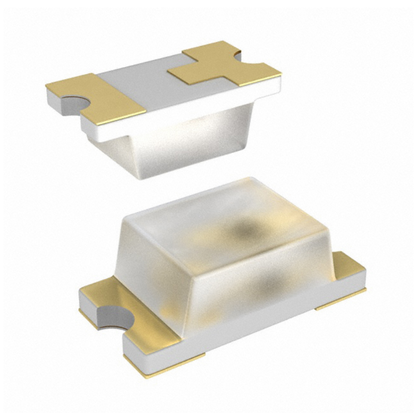


Figure 22: LTST-C191KRKT LED (Lite-On Inc.)

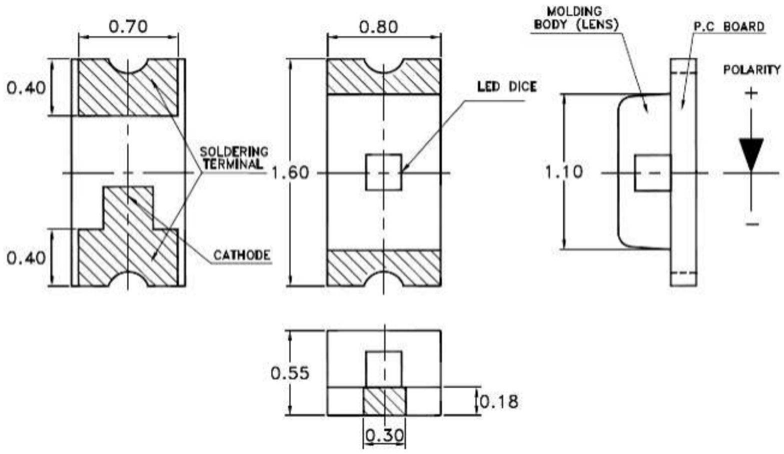


Figure 23: LED - Packaging and dimensions

Red (LTST-C191KRKT) and green (LTST-C191KGKT) LEDs are employed to indicate the device's charging status. Their function can be defined while programming the Microcontroller firmware.

- Emitting material: AlInGaP
  - Green (Peak Emission Wavelength and Spectral Line Half-Width): $\lambda = 574\,\mathrm{nm}, \Delta\lambda = 15\,\mathrm{nm}$
  - Red (Peak Emission Wavelength and Spectral Line Half-Width): $\lambda = 639\,\mathrm{nm}, \Delta\lambda = 20\,\mathrm{nm}$
- Power dissipation: 75mW
- Peak Forward Current (1/10 Duty Cycle, 0.1ms Pulse Width): 80mA
- DC forward current: 30mA
- Reverse current: $10\,\mu\mathrm{A}$
- Forward voltage: 2.0V (Test condition: IF=20mA)
- Operating temperature: $-30\,^{\circ}\mathrm{C}$ to $85\,^{\circ}\mathrm{C}$

4.11 ON/OFF Switch: AYZ0102AGRLC

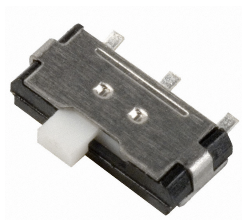
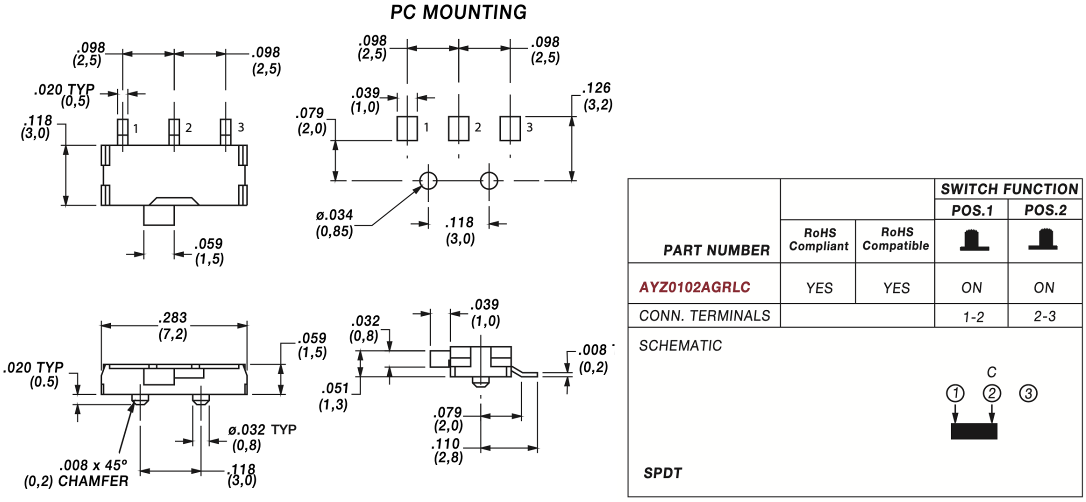


Figure 24: Switch Slide SPDT (AYZ0102AGRLC)



(a) (b)

Figure 25: Switch Slide SPDT

Mechanical switch is used to switch on/off the system. This type of switch is preferred over a SPDT switch placed vertically, to enhance the device's user experience.

- Max Switching Voltage: 12Vdc
- Max Switchin Current: 100mA
- Contact Resistance: $< 80\,\mathrm{m\Omega}$
- Insulation Resistance: $>100\,\mathrm{M\Omega}$
- Operating Temperature: $-40\,^{\circ}\mathrm{C}$ to $85\,^{\circ}\mathrm{C}$

4.12 JTAG Connector

Figure 26: JTAG Connector

4x2 2.54 mm SMD pin header connector is used as JTAG connector.

4.13 Button: FSM2JSMA

Figure 27: Push Button (FSM2JSMA)

The FSM2JSMA has been slected as the reset button. It is a vertical push button, with the following specifications.

- Max. contact rating: 50mA @24V DC
- Min. contact rating: 10 µA
- Operating temperature: −40 °C to 85 °C

5 Schematic

5.1 Power Section

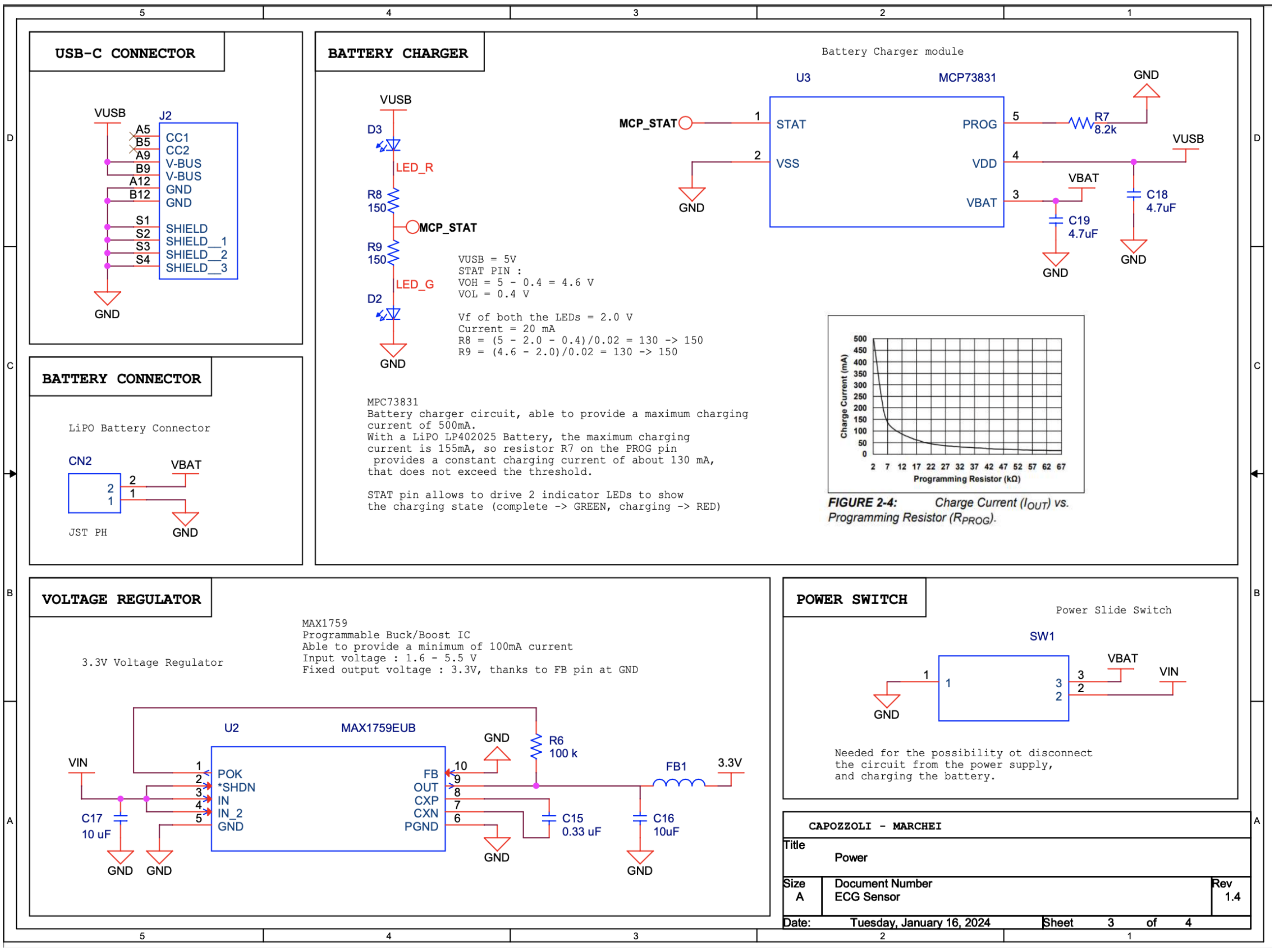


Figure 28: Power Schematic

For the single green and red LEDs, there are no limiting constraints on currents since that is provided directly from the MCP73831 `STAT` pin.
It is specifically designed to drive indicator LEDs in order to signal charging and charging complete state, its specifications are shown in Fig. 29.

Status Indicator – STAT						
Sink Current	I_{SINK}	—	—	25	mA	
Low Output Voltage	V_{OL}	—	0.4	1	V	I_{SINK} = 4 mA
Source Current	I_{SOURCE}	—	—	35	mA	
High Output Voltage	V_{OH}	—	V_{DD}-0.4	V_{DD} - 1	V	I_{SOURCE} = 4 mA (MCP73831)
Input Leakage Current	I_{LK}	—	0.03	1	µA	High-Impedance

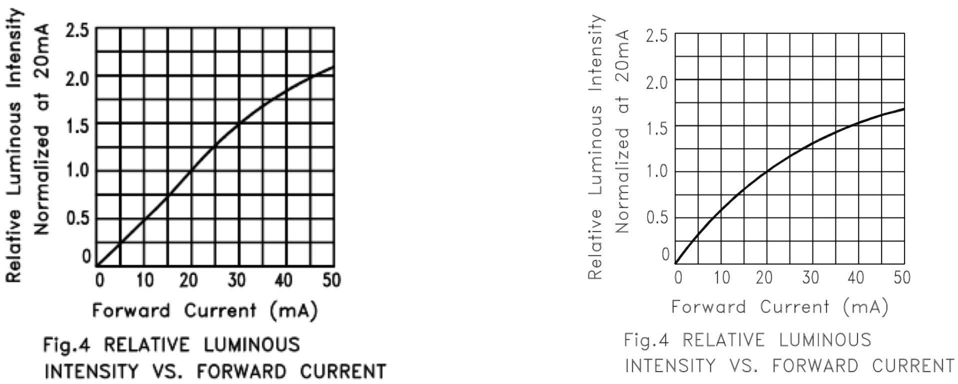
Figure 29: MCP73831 STAT pin specifications

As it can be observed, to compute the resistances to limit the current on the LEDs, the following formula has been used:

$$R_{RED} = \frac{V_{BUS} - V_f - V_{OL}}{I} = 130\,\Omega$$

$$R_{GREEN} = \frac{V_{OH} - V_f}{I} = 130\,\Omega$$

V_{BUS} is the power from the MicroUSB (5V), V_{OL} is the output voltage when `STAT` is low (0.4V), V_{OH} is the output voltage when $STAT$ is high (5 - 0.4 = 4.6V), I is the LED current (20mA).
To prevent the current being too high (although the maximum current sink of `STAT` is 25mA), the $150\,\Omega$ value have been chosen to use an E12 series resistor.
Fig. 30 shows how relative luminous intensity varies with respect to forward current for red and greed LEDs.



(a) Red LED (b) Green LED

Figure 30: Relative Luminous Intensity vs Forward Current

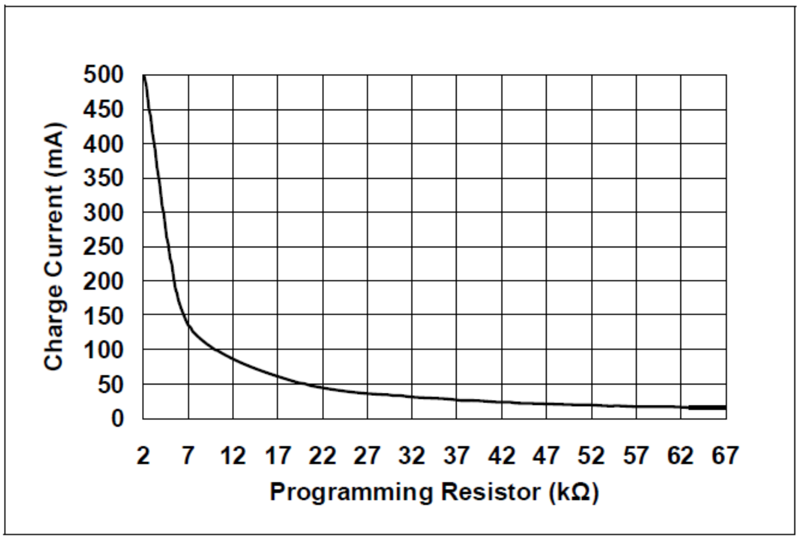


Figure 31: Charging current characteristics as function of R_{PROG}

3. Ratings

3.1. Nominal Capacity[at 0.2C]:	155mAh (min); 165mAh (typical)
3.2. Nominal Voltage:	3.7V (average voltage at 0.2C discharge)
3.3. Charging Voltage:	4.20 ±0.05V
3.4. Max. Charging Current:	155mA

Figure 32: LiPo battery Ratings

The curve in Fig. 31 allows you to choose the resistor according to the desired charge current. The LiPo battery selected for this project can have a maximum charging current of 155 mA, as reported in Fig. 32. The selected values are 130 mA for the charge current and 8.2 kΩ for the programming resistor R_{PROG}, to kept the current under the threshold value and protecting the battery in case of overcurrents.
Therefore, the time taken by the device to charge is

$$\frac{150\,\mathrm{mAh}}{130\,\mathrm{mA}} \simeq 1.15\,\mathrm{h} \simeq 69\,\mathrm{min}$$

5.2 Microcontroller Section

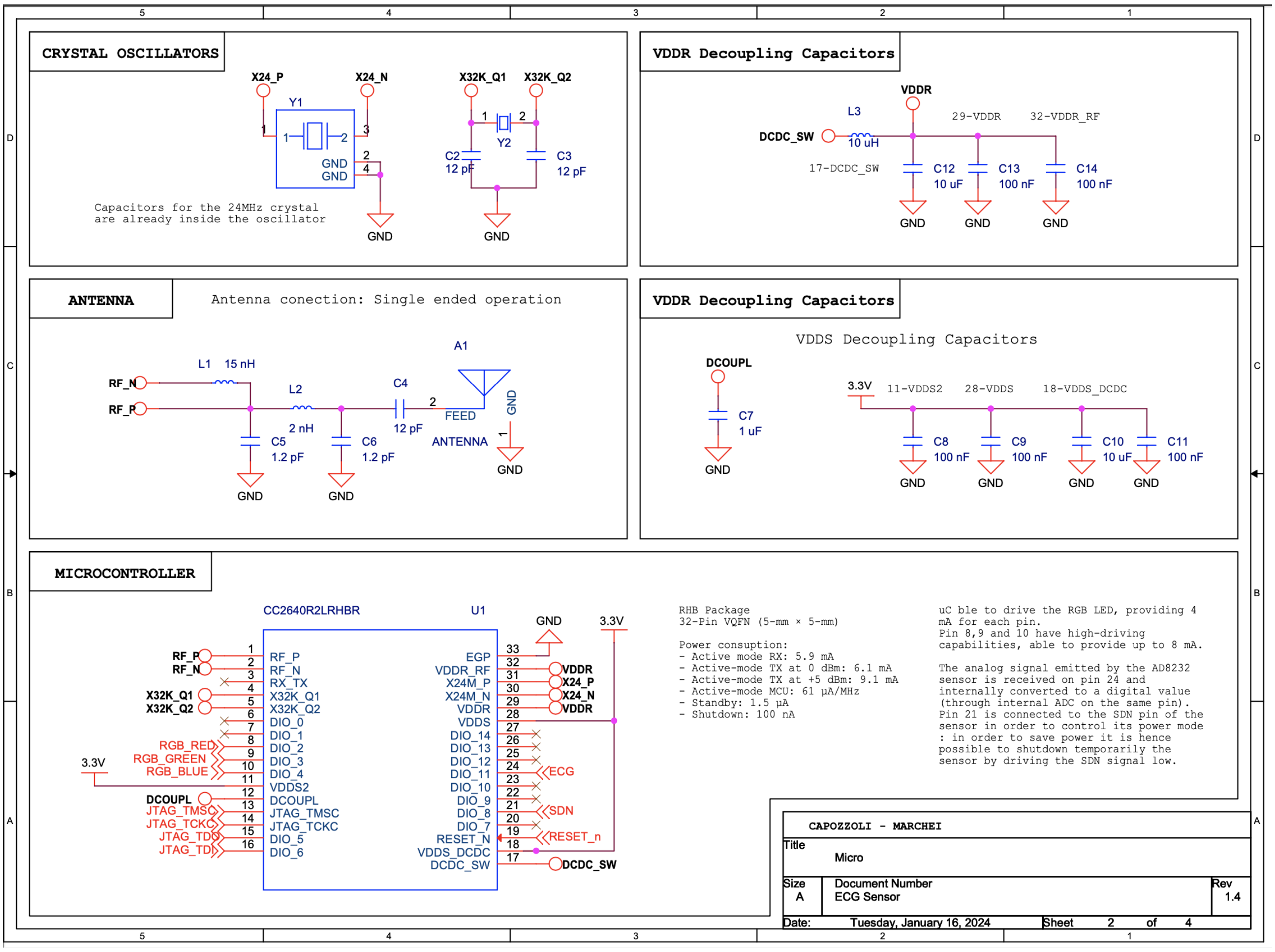


Figure 33: Microcontroller Schematic

In the schematic in Fig. 33 all the passive elements have been selected according to datasheet specifications.
Antenna is configured for single ended operations.
Pins `DIO_2`, `DIO_3`, `DIO_4` are used to control RGB LED for their higher driving capabilities, as specified in section 4.9. `JTAG_TMSC`, `JTAG_TCKC`, `DIO_5`, `DIO_6` are used for JTAG connections. `DIO_11` receives the analog signal emitted by the AD8232 sensor, and the internal ADC on the same pin converts it to a digital value. `DIO_8` is connected to the `SDN` pin of the AD8232 sensor to control its power mode. By driving SDN signal low, it is possible to shutdown temporarily the ECG sensor, saving power. `RESET_N` is sent to JTAG Connector and to the Reset button, that is used to reset microcontroller and its debouncing circuit.

5.3 Sensor Section

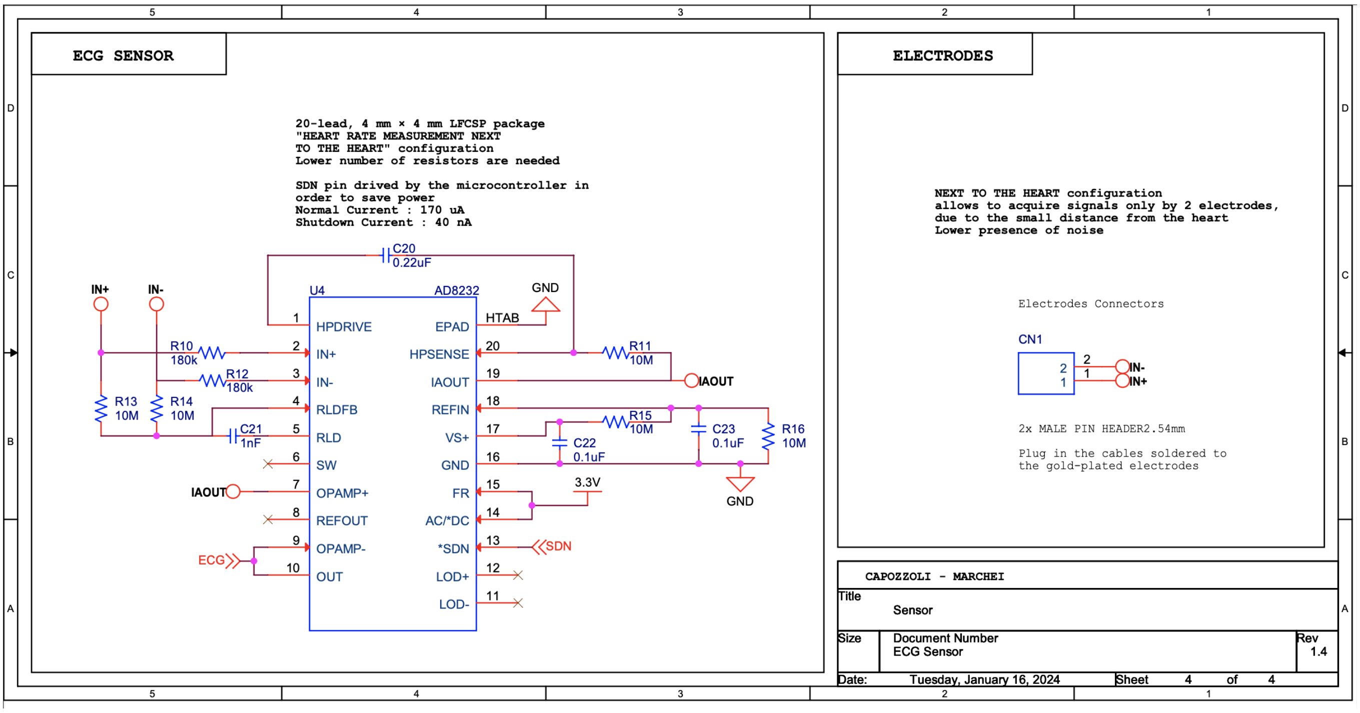


Figure 34: Sensor Schematic

Sensor scheme has been designed according to datasheet specifications for the *NextTo-Heart* configuration (Fig. 3). Specifically, in the component schematic, the goal was arranging resistors and capacitors in the most favorable way to enhance the overall circuit readability. Fig. 34 depicts an optimal solution. The primary challenge lay in the proximity of the pins to which these components needed to be connected. To maintain the pin order unchanged, they were spaced apart during the schematic design phase.
`SDN` pin is driven by microcontroller in order to save power: by drving SDN signal low, the sensor is temporarily shutdown. In particular, normal current is 170 μA, while shutdown current is 40 μA.

5.4 IO Section

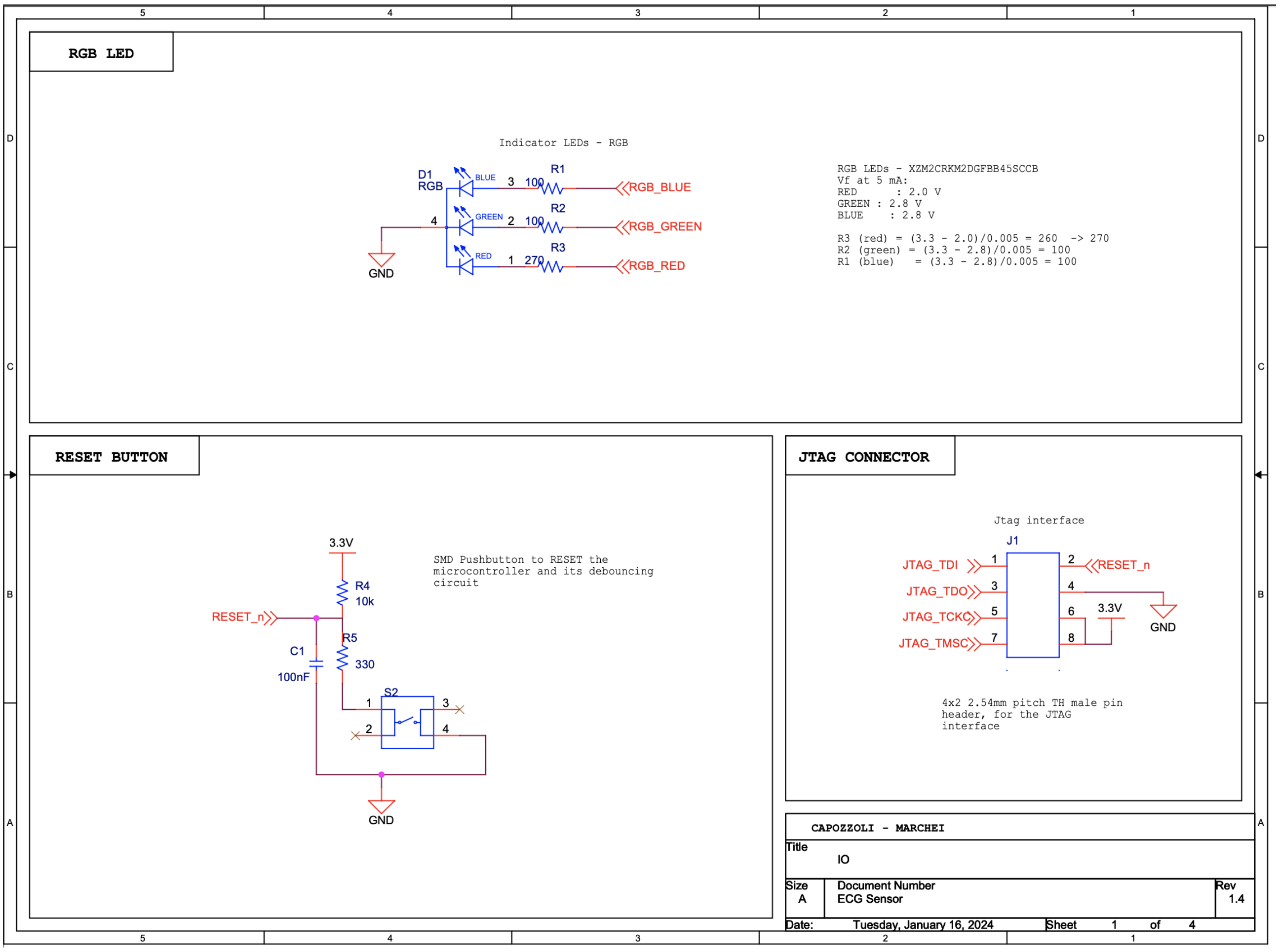


Figure 35: I/O Schematic

A standard debouncing circuit has been incorporated to filter out potential disturbances generated during button presses. The resistances for the RGB LED were calculated based on the following formula.

$$R = \frac{V_s - V_f}{I}$$

V_s is the micro supply voltage (3.3V), V_f is the forward voltage (2.0V for red, 2.8V for green, 2.8V for blue), I is the current (4mA).
This computation resulted in a 100 Ω resistance for green LED, 100 Ω for blue LED, and a 260 Ω resistance for the red LED. The E12 series values of 100 Ω (for blue), 100 Ω (for green),270 Ω (for red) have been chosen.

6 PCB Layout

The complete PCB is shown below in Fig. 36, as seen in the Orcad Allegro.

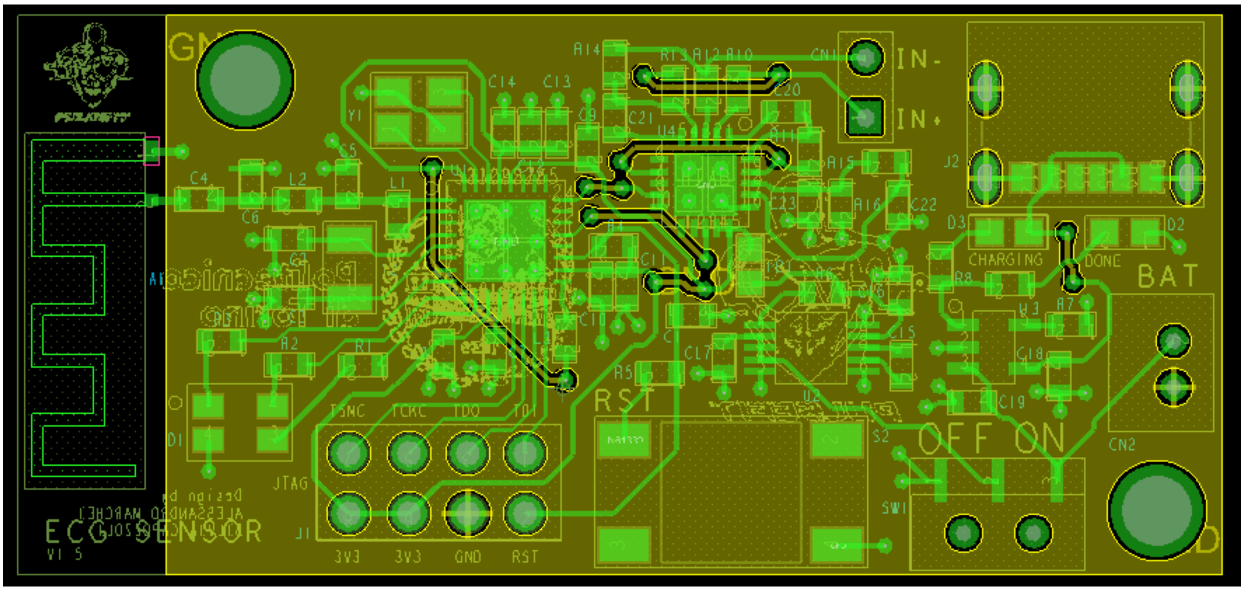


Figure 36: PCB

6.1 Component arrangement

The first approach to come up with a valid positioning was based on a sort of individual priority that each item requires. They tipically consisted of :

- Operating frequency
- Noise rejection needs
- Component dimensons
- Power source.

Since the patch antenna is clearly the most vulnerable component it has been positioned on the left edge and its feed is rigorously straight in order to optimize its behaviour at high frequency (2.4GHz), easily affected by eventual geometrical non-idealities, and bad design strategies.
After that, the integrated circuit such as the microcontroller and the AD8232 ECG sensor have been placed in such a way to create the shortest path possible to carry the analog signal on the ECG pin of the schematic. In fact it is a low-range signal susceptible to noise, that feeds the internal ADC of the microcontroller and hence a short distance is optimal to provide the best digital conversion.
The position of the 2 male pins to connect the soldered electrodes' signal has been placed at the top border of the board because the injected disturbances from the antenna on the

left and from the pushbutton and switches on the bottom could fatally reduce the quality of their signal which, at this pre-amplification stage, has a very low dyanmic range of about 5 mV. Although the reset pushbutton is small, its mechanical structure containing the electrical connection is frequently creating small frictions that are not optimal in this environment.
On the right part of the PCB the power modules has been placed, to group them together in a small area and able to expose the VCC and GROUND signals in an easy manner.

6.2 Traces and Routing

After the proper component placement, the routing has been carried out with fixed trace dimension of 0.25 mm, which, with respect of a 0.127 mm standard width is much lower in impedance, optimal for the environment subject to noise. Furthermore, the minimum spacing between components in the whole board result in a class 5C classification by Eurocircuit, thanks to the *Allegro PCB Editor*'s spatial constraints set to 0.175 mm for the minimum distance.
The width of the traces is always over than 2.0 mm, in order to reduce the overall impedance of each connection. This value is limited by the pad width of the CC2640 microcontroller which is exactly equal to 2.0 mm, and to not exceed the value with the trace all the nets connected to its pin are all adapted (Fig. 37).

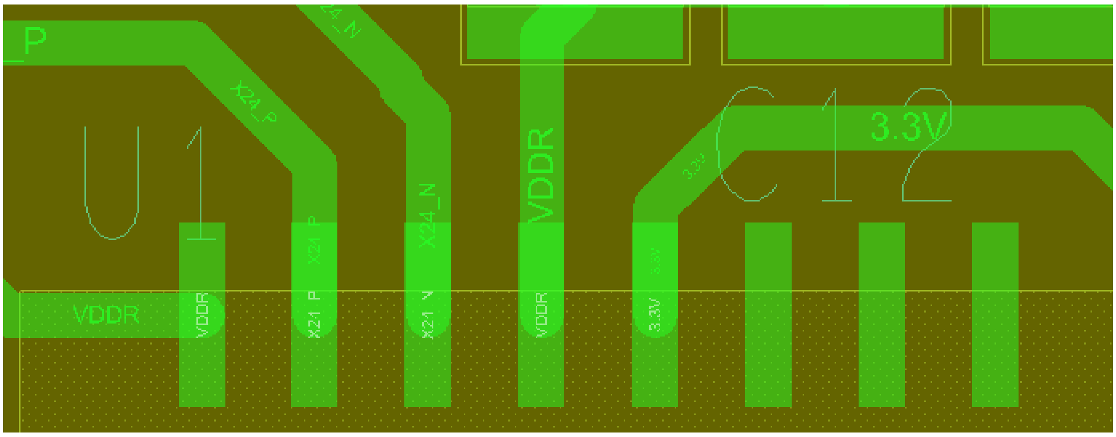


Figure 37: CC2640 pad witdh

As specified by the Fig. 38 in the vendor datasheet, it is optimal to enlarge the nets of the antenna to the maximum possible of 0.6 mm, optimizing the input impedance of the module.

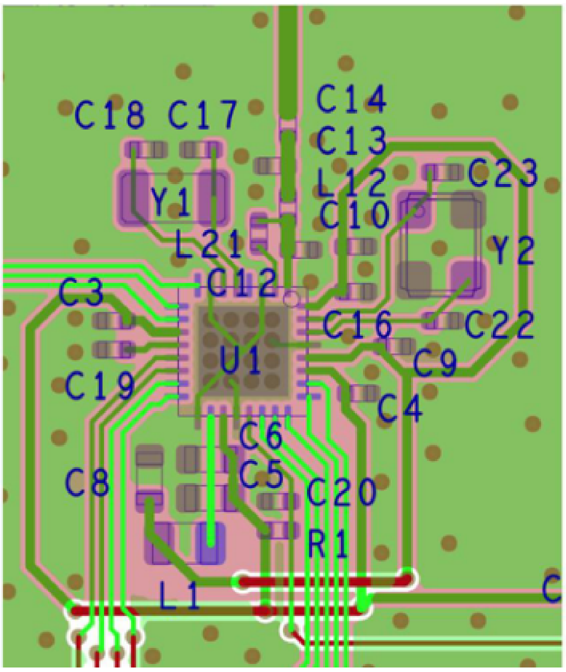


Figure 7-6. 4 × 4 External Single-ended (4XS) Layout

Figure 38: Antenna connection specified by the CC2640 datasheet

6.3 Board dimensions

Due to the application of the device that has to be placed on the user chest in order to monitor the cardiac activity, one of the main constraint of our board has been the total dimension. It is crucial to create the smallest area possible, so that the complete device could be realistically used. In our case, the board is 5.1 x 2.39 cm, which is perfectly suited to be held on the chest.

To fix the board into the device case a couple of mounting holes has been placed at the top-left and at the bottom-right. The drill diameter is 3.0mm , which is a standard size that fits most of the screws (M3).

6.4 VIAs and Ground Plane

In order to fit into the 5C Eurocircuits class, standard VIAs have been modified many times until the final dimensions have been chosen : 0.3 mm drill diameter and 0.7 mm pad diameter.

The addition of a ground plane is almost always adopted to facilitate the routing of all the traces that are connected back to the GROUND signal. In this case the plane consisted of almost all the area of the board except the part under the antenna, which, for obvious reasons of signal integrity, has been left with no plane.

The ECG sensor AD8232 instead, does not have this type of issue, and the ground plane has been place beneath it as well. In fact, as specified by the vendor in the layout recommentations in the datasheet (Fig. 39), the ground plane highly benefits the noise rejection capability of the system.

LAYOUT RECOMMENDATIONS

It is important to follow good layout practices to optimize system performance. In low power applications, most resistors are of a high value to minimize additional supply current. The challenge of using high value resistors is that high impedance nodes become even more susceptible to noise pickup and board parasitics, such as capacitance and surface leakages. Keep all of the connections between high impedance nodes as short as possible to avoid introducing additional noise and errors from corrupting the signal.

To maintain high CMRR over frequency, keep the input traces symmetrical and length matched. Place safety and input bias resistors in the same position relative to each input. In addition, the use of a ground plane significantly improves the noise rejection of the system.

Figure 39: AD8232 layout recommentations

7 Gerber Files

Below is shown the full list of gerber files analyzed by Eurocircuits, with the relative description.

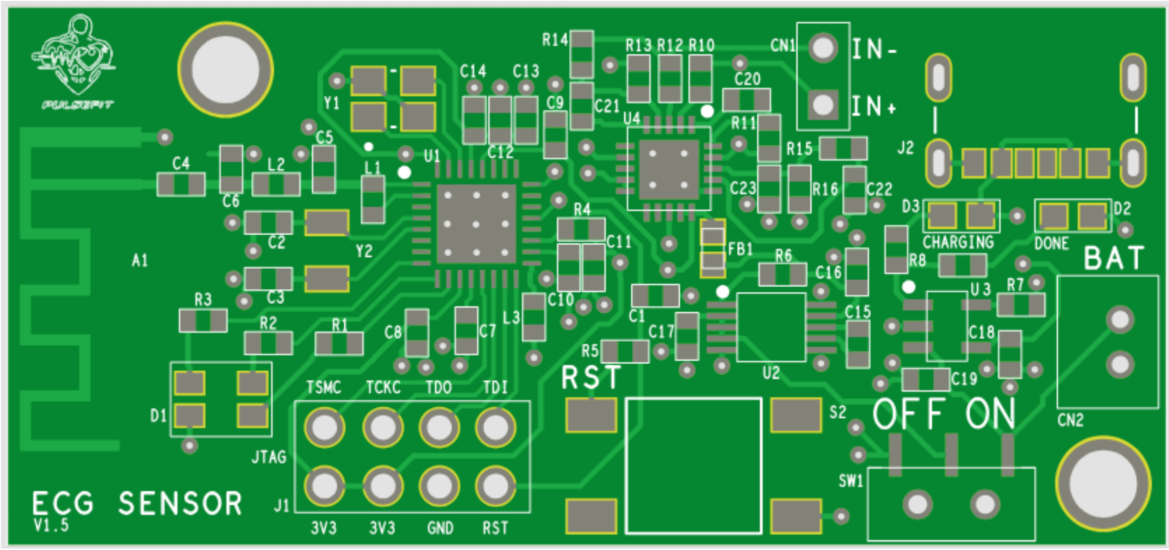


Figure 40: Top view of the PCB

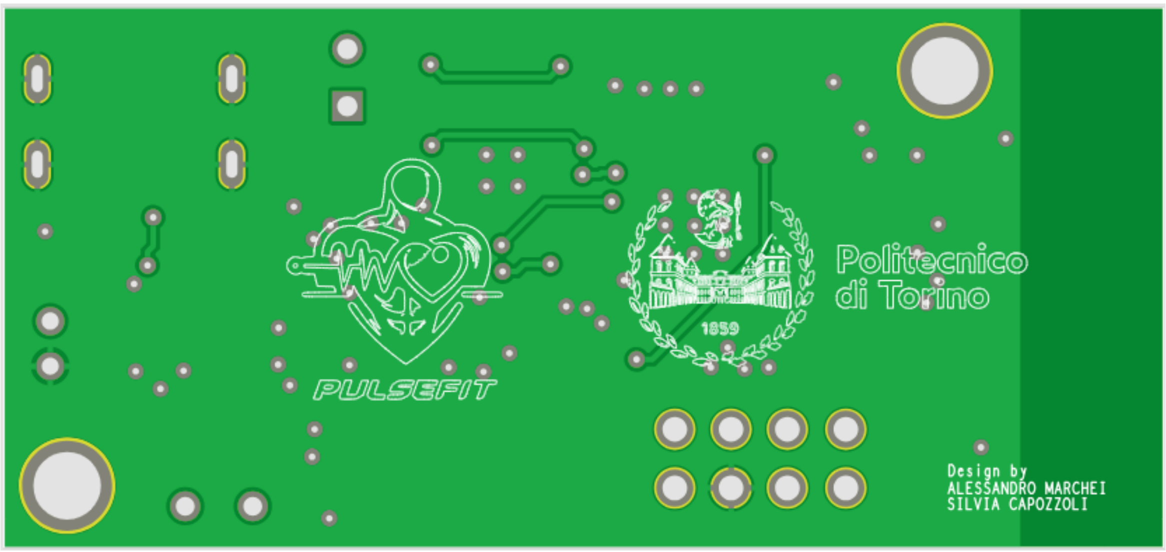


Figure 41: Bottom view of the PCB

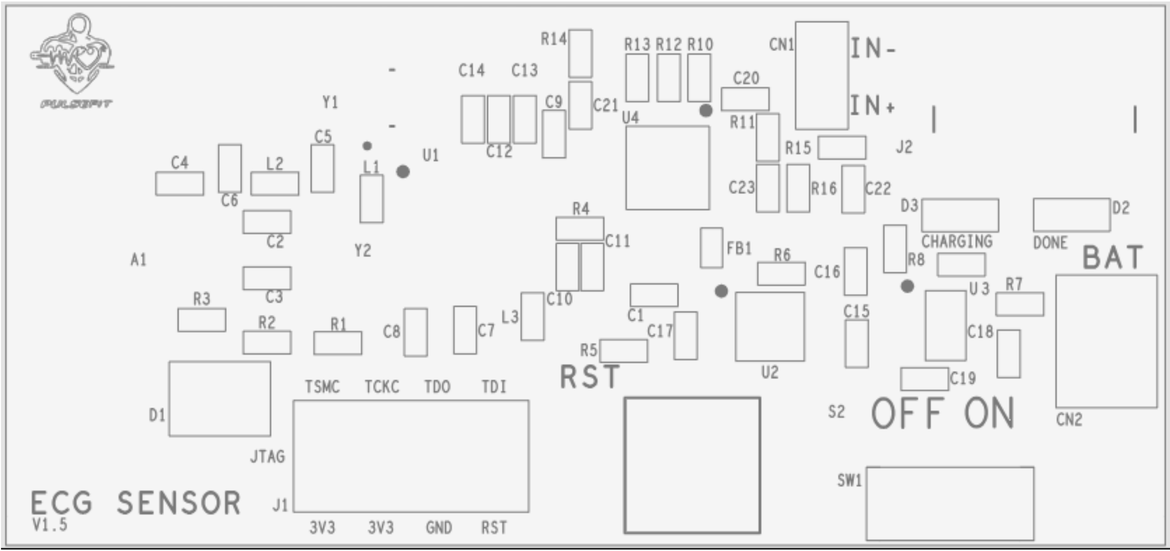


Figure 42: Silksreen Top

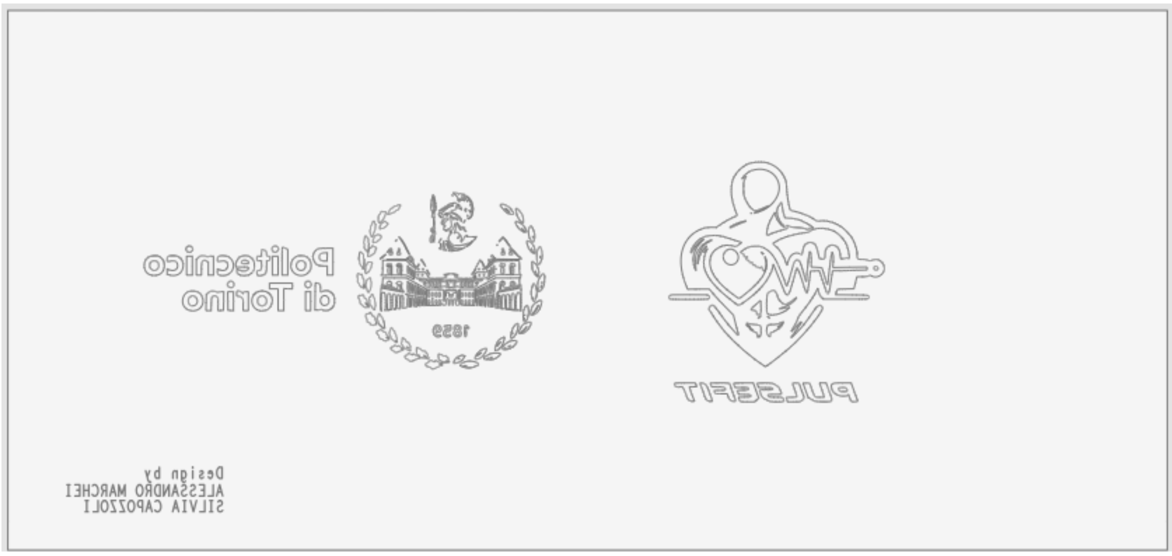


Figure 43: Silksreen Bottom

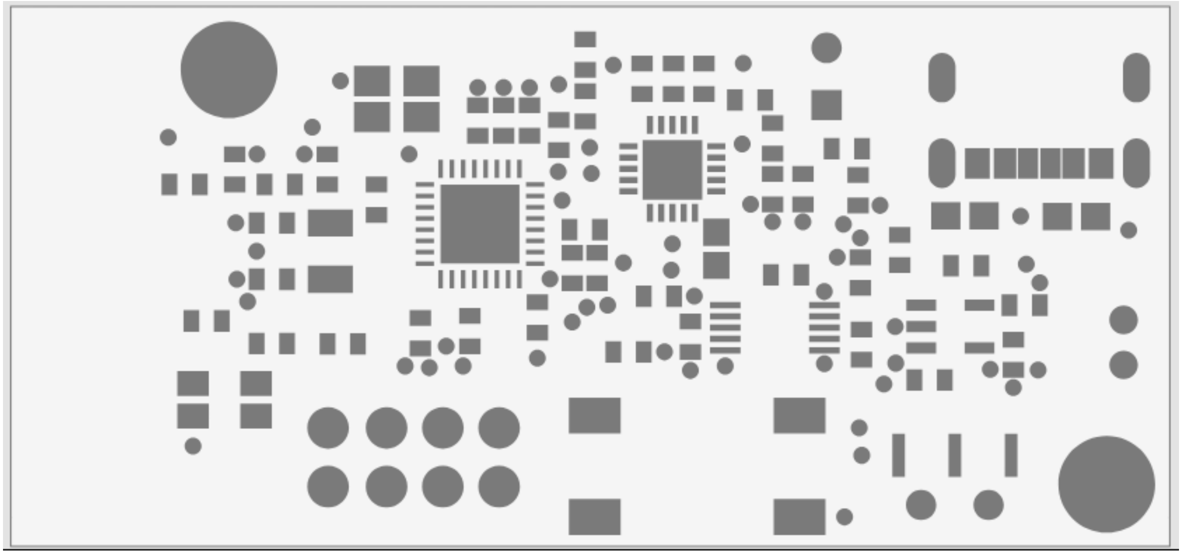


Figure 44: SolderMask Top

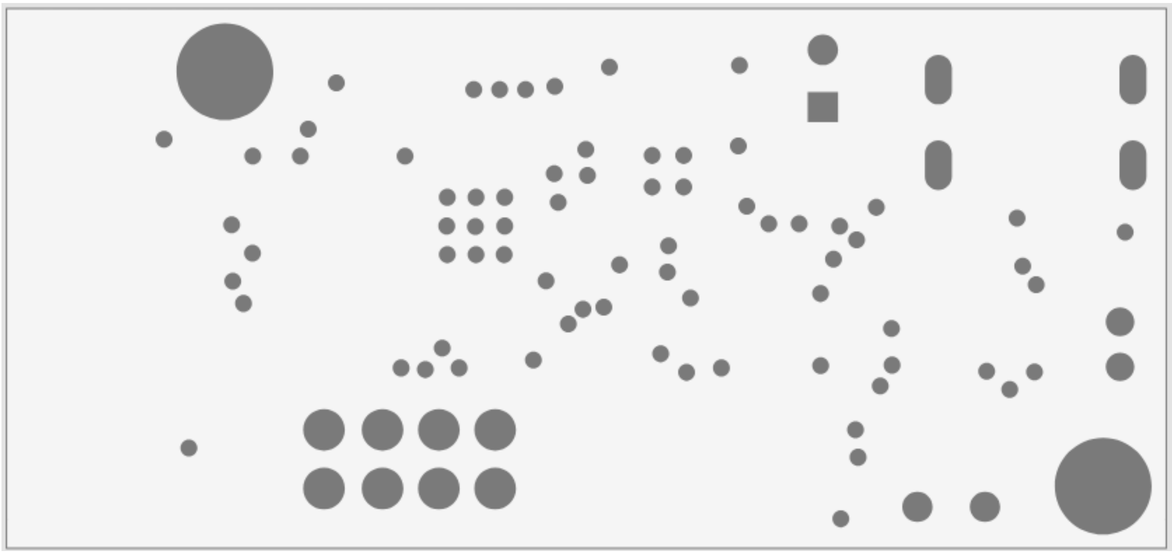


Figure 45: SolderMask Bottom

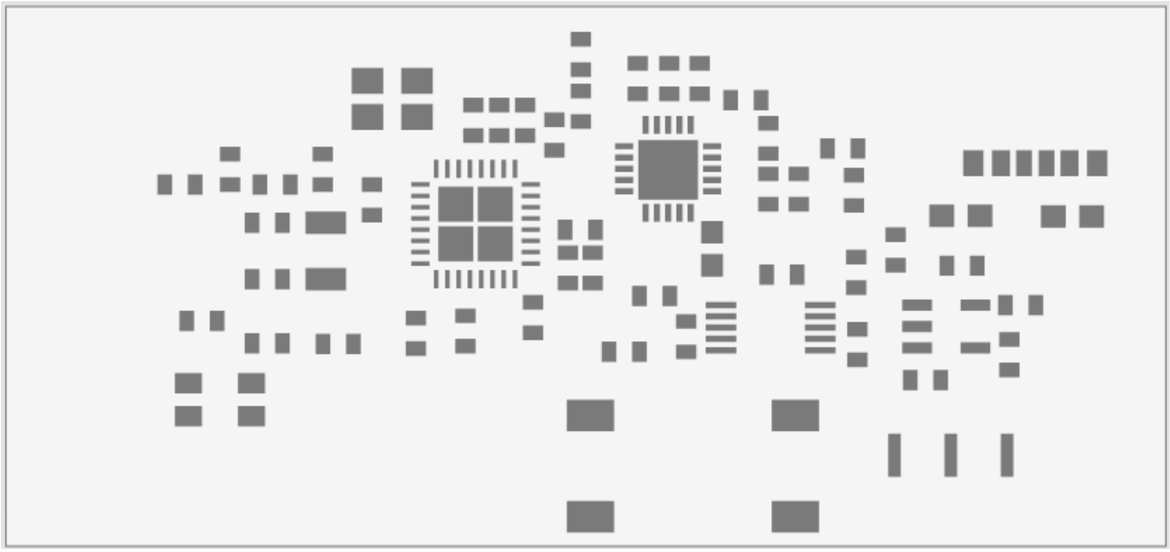


Figure 46: SolderPaste Top

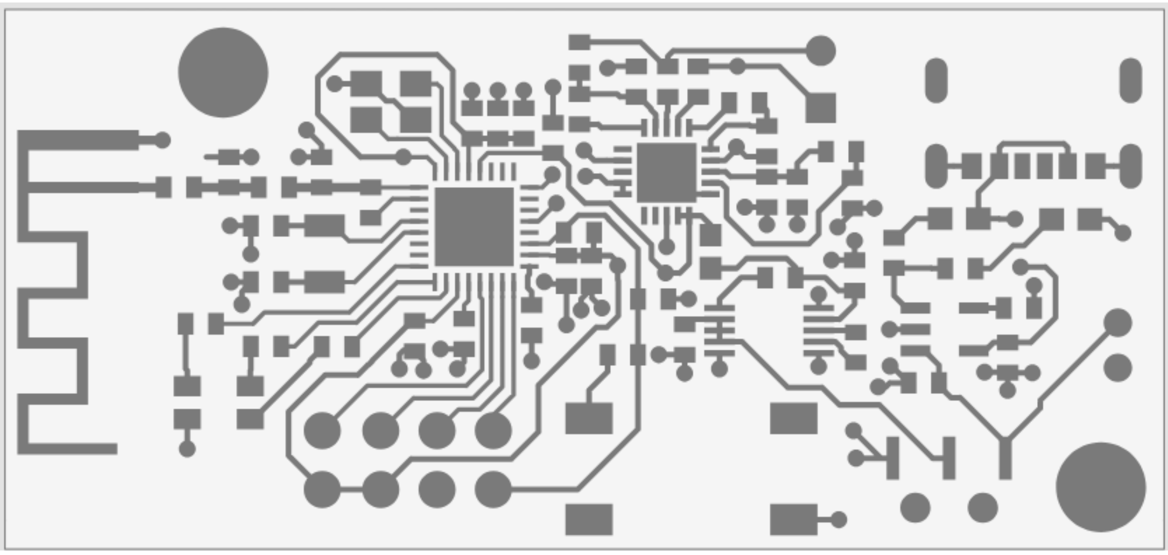


Figure 47: Etching Top

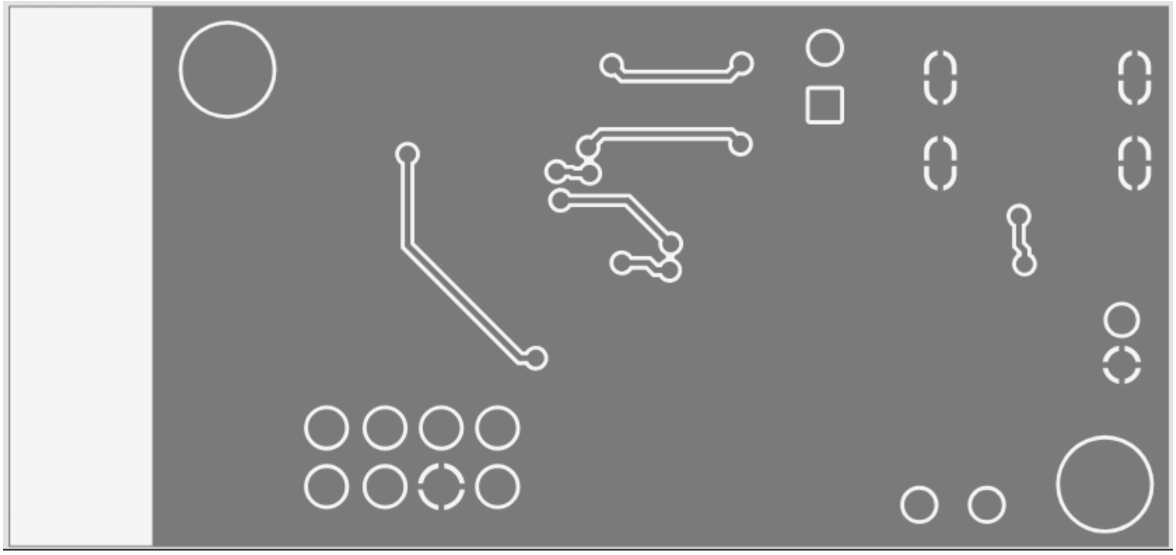


Figure 48: Etching Bottom

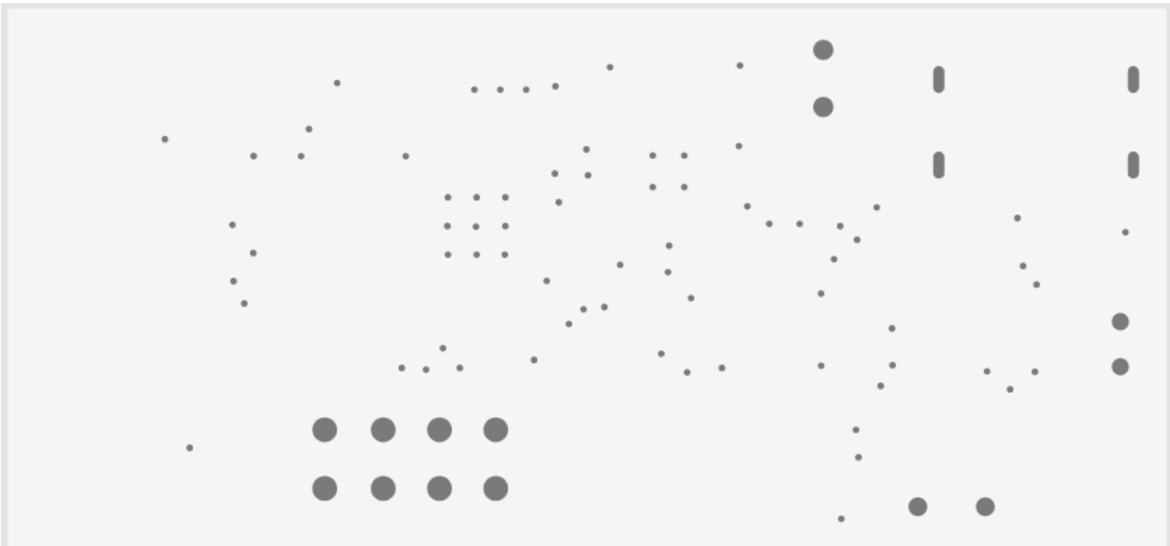


Figure 49: Plated Drill

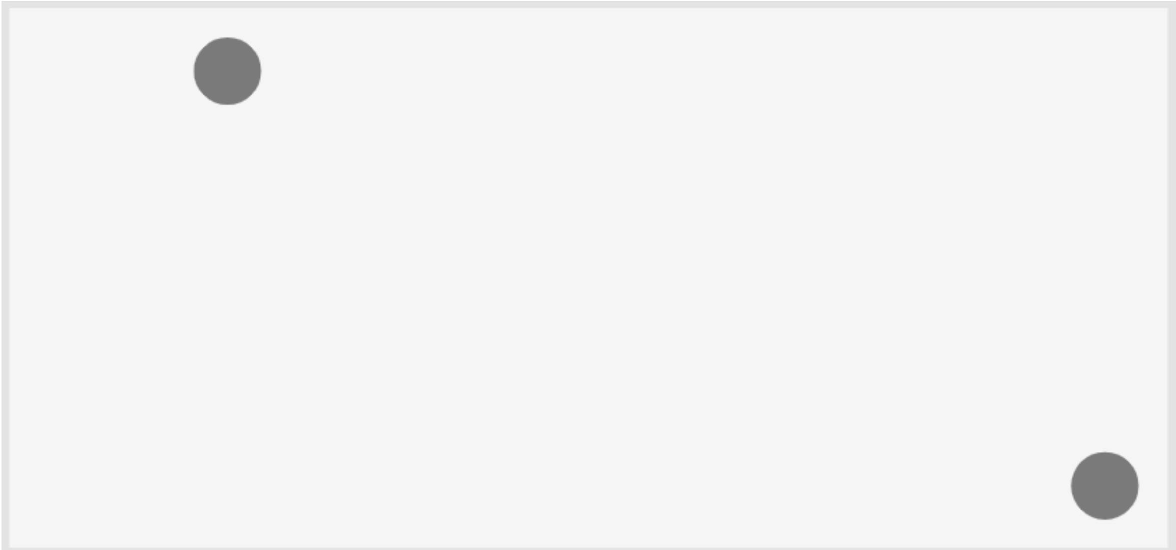


Figure 50: Non Plated Drill

8 Power Consumption

In the projected device the main power contributions are

- Microcontroller (CC2640):
  - Active-Mode: $1.45\,\text{mA} + 31\,\mu\text{A/MHz}$
  - Stand-by-Mode: $1.5\,\mu\text{A}$
  - Transmitting Mode: $9.1\,\text{mA}$
- RGB LEDs:
  - $3 \cdot 5\,\text{mA}$
  - Reverse current: $10\,\mu\text{A}$
- ECG sensor(AD8232):
  - $170\,\mu\text{A}$ in normal conditions

The estimation of the average current consumption relies on knowing the duration of system and components activity. In typical sport activities, where there is a need to monitor cardiovascular activity, predicting the amount of time the device is actively used could be difficult because it varies on the application.

It is reasonable to consider the system always active (needs to sample @ 250 Hz) and transmitting the data via Bluetooth for 10 ms every second. LED blinks for a tenth of a second, for each second.

Microcontroller: $(1.45 + 0.031 \cdot 48)\text{mA} + (0.01 \cdot 9.1)\text{mA} = 3.02\,\text{mA}$
The contributions from the normal mode and transmitting mode are summed according to the assumptions stated above.

ECG sensor: 0.17 mA

RGB LED: $(0.1 \cdot 5)\text{mA} + (0.9 \cdot 0.01)\text{mA} = 0.51\,\text{mA}$
The active mode contribution is considered for 10%, and that of the reverse current for the remaining 90%, as the LED flashes for 0.1 s every second. The active current is assumed to be around 5mA, but it depends on the combination of the 3 colors.

$$Total\ battery\ duration = \frac{150\,\text{mAh}}{3.02\,\text{mA} + 0.17\,\text{mA} + 0.51\,\text{mA}} = 40\,\text{h}$$

9 Bill of Materials (BOM)

ITEM	QTY	REFERENCE	PART	COMPONENT	MOUNTING TYPE	MANUFACTURER	SUPPLIER	UNIT PRICE
1	1	A1	ANTENNA	/			/	
2	1	CN1	2x HEADER	3-644456-2	TH	TE Connectivity AMP Connectors	Digikey	0,1800 €
3	1	CN2	JST-2P	B2B-PH-K-S	TH	JST Sales America Inc.	Digikey	0,1700 €
4	3	C2,C3,C4	12 pF	600S120GT250XT	SMD	Amercian Technical Ceramics	Digikey	1,0500 €
5	2	C5,C6	1.2 pF	QSCP251Q1R2B1GV001T	SMD	Johanson Technology	Digikey	0,2000 €
6	1	C7	1 uF	CL10B105KA8NNNC	SMD	Samsung Electro-Mechanics	Digikey	0,0900 €
7	5	C1,C8,C9,C11,C13,C14	100 nF	CL10B104KA8NNNC	SMD	Samsung Electro-Mechanics	Digikey	0,0900 €
8	3	C10,C12,C16 C17	10 uF	CL10A106MA8NRNC	SMD	Samsung Electro-Mechanics	Digikey	0,2400 €
9	1	C15	0.33 uF	CL10B334KA8VPNC	SMD	Samsung Electro-Mechanics	Digikey	0,1300 €
10	2	C18,C19	4.7uF	CL10A475MA8NQNC	SMD	Samsung Electro-Mechanics	Digikey	0,2500 €
11	1	C20	0.22uF	CC0603KRX7R9BB224	SMD	YAGEO	Digikey	0,2600 €
12	1	C21	1nF	AC0603JRNPO0BN102	SMD	YAGEO	Digikey	0,1500 €
13	2	C22,C23	0.1uF	CC0603MRX7R9BB104	SMD	YAGEO	Digikey	0,0900 €
14	1	D1	RGB	XZM2CRKM2DGFBB45SCCB	SMD	SunLED	Digikey	0,9300 €
15	2	D2,D3	LED	LTST-S270KGKT	SMD	Lite-On Inc.	Digikey	0,2200 €
16	1	J1	4X2 MALE HEADER	61300821121	TH	Würth Elektronik	Digikey	0,6400 €
17	1	J2	USB CONNECTOR	UJC-HP-3-SMT-TR	SMD	CUI Devices	Digikey	0,9100 €
18	1	L1	15 nH	BSPQ0006030415NH00	SMD	Pulse Electronics	Digikey	0,1200 €
19	1	L2	2 nH	L-14W2N0CV4E	SMD	Johanson Technology Inc.	Digikey	0,2100 €
20	1	L3	10 uH	LQM18DH100M70L	SMD	Murata Electronics	Digikey	0,2300 €
21	2	R1,R2	100	RC0603JR-07100RL	SMD	YAGEO	Digikey	0,0900 €
22	1	R3	270	RC0603FR-07270RL	SMD	YAGEO	Digikey	0,0900 €
23	1	R4	10k	RMCF0603FT10K0	SMD	Stackpole Electronics Inc	Digikey	0,0900 €
24	1	R5	330	RC0603JR-13330RL	SMD	YAGEO	Digikey	0,0900 €
25	1	R6	100 k	RMCF0603FT100K	SMD	Stackpole Electronics Inc	Digikey	0,0900 €
26	1	R7	8.2 k	RMCF0603FT8K20	SMD	Stackpole Electronics Inc	Digikey	0,0900 €
27	2	R8,R9	150	RT0603FRE07150RL	SMD	YAGEO	Digikey	0,0900 €
28	2	R10,R12	180k	ERA-8AEB184V	SMD	Panasonic Electronic Components	Digikey	0,5400 €
29	5	R11,R13,R14,R15,R16	10M	RC0603FR-1310ML	SMD	YAGEO	Digikey	0,0900 €
30	1	S1	SPDT	AYZ0102AGRLC	TH	C&K	Digikey	1,1400 €
31	1	S2	BUTTON	FSM2JSMA	SMD	TE Connectivity ALCOSWITCH Switches	Digikey	0,2500 €
32	1	U1	CC2640R2LRHBR	CC2640R2LRHBR	SMD	Texas Instruments	Digikey	4,0100 €
33	1	U2	MAX1759	MAX1759EUB+	SMD	Analog Devices Inc./Maxim Integrated	Digikey	6,8800 €
34	1	U3	MCP73831	MCP73831T-2ACI/OT	SMD	Microchip Technology	Digikey	0,6900 €
35	1	U4	ECG SENSOR	AD8233	SMD	Analog Devices Inc.	Digikey	4,2500 €
36	1	Y1	24 MHz	TSX-3225_240000MF20X-AC1	SMD	Epson	Digikey	0,3500 €
37	1	Y2	32.76 KHz	FC-135R_327680KA-AG1	SMD	Epson	Digikey	0,6400 €
38	1	FB1	1.5 Kohm @ 100 MHz	BLM18HE152SN1D	SMD	Murata Electronics	Digikey	0,1700 €

Figure 51: BOM for 1 PCB

ITEM	QTY	REFERENCE	PART	COMPONENT	MOUNTING TYPE	MANUFACTURER	SUPPLIER	UNIT PRICE
1	1	A1	ANTENNA	/			/	
2	1	CN1	2x HEADER	3-644456-2	TH	TE Connectivity AMP Connectors	Digikey	0,1560 €
3	1	CN2	JST-2P	B2B-PH-K-S	TH	JST Sales America Inc.	Digikey	0,1340 €
4	3	C2,C3,C4	12 pF	600S120GT250XT	SMD	Amercian Technical Ceramics	Digikey	0,7880 €
5	2	C5,C6	1.2 pF	QSCP251Q1R2B1GV001T	SMD	Johanson Technology	Digikey	0,1320 €
6	1	C7	1 uF	CL10B105KA8NNNC	SMD	Samsung Electro-Mechanics	Digikey	0,0360 €
7	5	C1,C8,C9,C11,C13,C14	100 nF	CL10B104KA8NNNC	SMD	Samsung Electro-Mechanics	Digikey	0,0220 €
8	3	C10,C12,C16 C17	10 uF	CL10A106MA8NRNC	SMD	Samsung Electro-Mechanics	Digikey	0,1550 €
9	1	C15	0.33 uF	CL10B334KA8VPNC	SMD	Samsung Electro-Mechanics	Digikey	0,0880 €
10	2	C18,C19	4.7uF	CL10A475MA8NQNC	SMD	Samsung Electro-Mechanics	Digikey	0,1610 €
11	1	C20	0.22uF	CC0603KRX7R9BB224	SMD	YAGEO	Digikey	0,1660 €
12	1	C21	1nF	AC0603JRNPO0BN102	SMD	YAGEO	Digikey	0,1010 €
13	2	C22,C23	0.1uF	CC0603MRX7R9BB104	SMD	YAGEO	Digikey	0,0410 €
14	1	D1	RGB	XZM2CRKM2DGFBB45SCCB	SMD	SunLED	Digikey	0,6060 €
15	2	D2,D3	LED	LTST-S270KGKT	SMD	Lite-On Inc.	Digikey	0,1210 €
16	1	J1	4X2 MALE HEADER	61300821121	TH	Würth Elektronik	Digikey	0,5410 €
17	1	J2	USB CONNECTOR	UJC-HP-3-SMT-TR	SMD	CUI Devices	Digikey	0,7610 €
18	1	L1	15 nH	BSPQ0006030415NH00	SMD	Pulse Electronics	Digikey	0,0960 €
19	1	L2	2 nH	L-14W2N0CV4E	SMD	Johanson Technology Inc.	Digikey	0,1670 €
20	1	L3	10 uH	LQM18DH100M70L	SMD	Murata Electronics	Digikey	0,1820 €
21	2	R1,R2	100	RC0603JR-07100RL	SMD	YAGEO	Digikey	0,0140 €
22	1	R3	270	RC0603FR-07270RL	SMD	YAGEO	Digikey	0,0170 €
23	1	R4	10k	RMCF0603FT10K0	SMD	Stackpole Electronics Inc	Digikey	0,0140 €
24	1	R5	330	RC0603JR-13330RL	SMD	YAGEO	Digikey	0,0140 €
25	1	R6	100 k	RMCF0603FT100K	SMD	Stackpole Electronics Inc	Digikey	0,0140 €
26	1	R7	8.2 k	RMCF0603FT8K20	SMD	Stackpole Electronics Inc	Digikey	0,0140 €
27	2	R8,R9	150	RT0603FRE07150RL	SMD	YAGEO	Digikey	0,0490 €
28	2	R10,R12	180k	ERA-8AEB184V	SMD	Panasonic Electronic Components	Digikey	0,3620 €
29	5	R11,R13,R14,R15,R16	10M	RC0603FR-1310ML	SMD	YAGEO	Digikey	0,0170 €
30	1	S1	SPDT	AYZ0102AGRLC	TH	C&K	Digikey	1,1010 €
31	1	S2	BUTTON	FSM2JSMA	SMD	TE Connectivity ALCOSWITCH Switches	Digikey	0,2370 €
32	1	U1	CC2640R2LRHBR	CC2640R2LRHBR	SMD	Texas Instruments	Digikey	3,5790 €
33	1	U2	MAX1759	MAX1759EUB+	SMD	Analog Devices Inc./Maxim Integrated	Digikey	6,2170 €
34	1	U3	MCP73831	MCP73831T-2ACI/OT	SMD	Microchip Technology	Digikey	0,6900 €
35	1	U4	ECG SENSOR	AD8233	SMD	Analog Devices Inc.	Digikey	3,8140 €
36	1	Y1	24 MHz	TSX-3225_240000MF20X-AC1	SMD	Epson	Digikey	0,3230 €
37	1	Y2	32.76 KHz	FC-135R_327680KA-AG1	SMD	Epson	Digikey	0,5300 €
38	1	FB1	1.5 Kohm @ 100 MHz	BLM18HE152SN1D	SMD	Murata Electronics	Digikey	0,1400 €

Figure 52: BOM for 10 PCB

ITEM	QTY	REFERENCE	PART	COMPONENT	MOUNTING TYPE	MANUFACTURER	SUPPLIER	UNIT PRICE
1	1	A1	ANTENNA	/			/	
2	1	CN1	2x HEADER	3-644456-2	TH	TE Connectivity AMP Connectors	Digikey	0,1420 €
3	1	CN2	JST-2P	B2B-PH-K-S	TH	JST Sales America Inc.	Digikey	0,0992 €
4	3	C2,C3,C4	12 pF	600S120GT250XT	SMD	Amercian Technical Ceramics	Digikey	0,5887 €
5	2	C5,C6	1.2 pF	QSCP251Q1R2B1GV001T	SMD	Johanson Technology	Digikey	0,0749 €
6	1	C7	1 uF	CL10B105KA8NNNC	SMD	Samsung Electro-Mechanics	Digikey	0,0160 €
7	5	C1,C8,C9,C11,C13,C14	100 nF	CL10B104KA8NNNC	SMD	Samsung Electro-Mechanics	Digikey	0,0096 €
8	3	C10,C12,C16 C17	10 uF	CL10A106MA8NRNC	SMD	Samsung Electro-Mechanics	Digikey	0,0881 €
9	1	C15	0.33 uF	CL10B334KA8VPNC	SMD	Samsung Electro-Mechanics	Digikey	0,0411 €
10	2	C18,C19	4.7uF	CL10A475MA8NQNC	SMD	Samsung Electro-Mechanics	Digikey	0,0916 €
11	1	C20	0.22uF	CC0603KRX7R9BB224	SMD	YAGEO	Digikey	0,0942 €
12	1	C21	1nF	AC0603JRNPO0BN102	SMD	YAGEO	Digikey	0,0476 €
13	2	C22,C23	0.1uF	CC0603MRX7R9BB104	SMD	YAGEO	Digikey	0,0184 €
14	1	D1	RGB	XZM2CRKM2DGFBB45SCCB	SMD	SunLED	Digikey	0,3971 €
15	2	D2,D3	LED	LTST-S270KGKT	SMD	Lite-On Inc.	Digikey	0,0563 €
16	1	J1	4X2 MALE HEADER	61300821121	TH	Würth Elektronik	Digikey	0,3419 €
17	1	J2	USB CONNECTOR	UJC-HP-3-SMT-TR	SMD	CUI Devices	Digikey	0,6836 €
18	1	L1	15 nH	BSPQ0006030415NH00	SMD	Pulse Electronics	Digikey	0,0676 €
19	1	L2	2 nH	L-14W2N0CV4E	SMD	Johanson Technology Inc.	Digikey	0,1244 €
20	1	L3	10 uH	LQM18DH100M70L	SMD	Murata Electronics	Digikey	0,1362 €
21	2	R1,R2	100	RC0603JR-07100RL	SMD	YAGEO	Digikey	0,0068 €
22	1	R3	270	RC0603FR-07270RL	SMD	YAGEO	Digikey	0,0086 €
23	1	R4	10k	RMCF0603FT10K0	SMD	Stackpole Electronics Inc	Digikey	0,0068 €
24	1	R5	330	RC0603JR-13330RL	SMD	YAGEO	Digikey	0,0068 €
25	1	R6	100 k	RMCF0603FT100K	SMD	Stackpole Electronics Inc	Digikey	0,0068 €
26	1	R7	8.2 k	RMCF0603FT8K20	SMD	Stackpole Electronics Inc	Digikey	0,0068 €
27	2	R8,R9	150	RT0603FRE07150RL	SMD	YAGEO	Digikey	0,0199 €
28	2	R10,R12	180k	ERA-8AEB184V	SMD	Panasonic Electronic Components	Digikey	0,1905 €
29	5	R11,R13,R14,R15,R16	10M	RC0603FR-1310ML	SMD	YAGEO	Digikey	0,0085 €
30	1	S1	SPDT	AYZ0102AGRLC	TH	C&K	Digikey	0,8947 €
31	1	S2	BUTTON	FSM2JSMA	SMD	TE Connectivity ALCOSWITCH Switches	Digikey	0,2032 €
32	1	U1	CC2640R2LRHBR	CC2640R2LRHBR	SMD	Texas Instruments	Digikey	2,9353 €
33	1	U2	MAX1759	MAX1759EUB+	SMD	Analog Devices Inc./Maxim Integrated	Digikey	5,1466 €
34	1	U3	MCP73831	MCP73831T-2ACI/OT	SMD	Microchip Technology	Digikey	0,5584 €
35	1	U4	ECG SENSOR	AD8233	SMD	Analog Devices Inc.	Digikey	3,6050 €
36	1	Y1	24 MHz	TSX-3225_240000MF20X-AC1	SMD	Epson	Digikey	0,2578 €
37	1	Y2	32.76 KHz	FC-135R_327680KA-AG1	SMD	Epson	Digikey	0,4236 €
38	1	FB1	1.5 Kohm @ 100 MHz	BLM18HE152SN1D	SMD	Murata Electronics	Digikey	0,0900 €

Figure 53: BOM for 100 PCB

9.1 Cost Estimation

In addition to the components listed in the BOM, we also need to include gold-plated reusable electrodes (TDE-211B) priced at €4.95 each (VAT included). Additionally, labor costs for soldering these electrodes to the cables are accounted for at a rate of €25 per hour per person (VAT included), with an estimated soldering time of 30 minutes. Therefore, for each PCB, we will add the cost of two electrodes (2 x €4.95) and half an hour of labor (€25 / 2). We can also include the cost of cheap cables and a package for electrodes connection. All these contributions are grouped under the heading "Electrodes", from which VAT has been subtracted to be consistent with the other prices.

In the following estimation cost as function of the bulk quantity, the price does not include the VAT (22%).

In the x100 and x1000 cases, the stencil has been considered since it would help a lot to solder each pad properly and in a fast way. A single stencil for our PCB cost €33.06 so in those cases an estimation of the contribute to the final cost is exactly the cost of a single stencil divided by the number of boards considered.

9.1.1 1 PCB

Component	**Cost**
PCB	€38.83
Components	€30.58
Electrodes	€18.20
TOTAL	€87.61

Table 1: Total price for single PCB

9.2 10 PCB

Component	**Cost**
PCB	€6.84
Components	€24.52
Electrodes	€18.20
TOTAL	€49.56

Table 2: Total price for 1 PCB in case of bulk purchase (10 pieces)

9.3 100 PCB

Component	Cost
PCB	€1.80
Components	€19.38
Electrodes	€18.20
Stencil	€0.33
TOTAL	€39.71

Table 3: Total price for 1 PCB in case of bulk purchase (100 pieces)

9.4 1000 PCB

Component	Cost
PCB	€0.74
Components	€19.38
Electrodes	€18.20
Stencil	€0.033
TOTAL	€38.35

Table 4: Total price for 1 PCB in case of bulk purchase (1000 pieces)

As can be observed by the results of the various cases, the labour cost and the price of the electrodes are the only ones that do not change, accounting in the last high-quantity cases for almost half of the entire cost of a single PCB. However the cost of the electrodes could be reduced in reality since in the majority of purchases are done in very large batches, with a consequent dropping price (instead we considered the price to be constant at around €9)
Instead, reducing the cost of labour would be possible only if some advanced machinery is available during the assembling process, make the soldering process quicker and easier.

10 References

- Components datasheets:
  - Digikey.it
  - Mouser.it
- PCB render and quotation: eurocircuit.com
- Technical report and presentation examples (uploaded on ”Portale della Didattica”):
  - Technical report.pdf
  - ESE_presentation_NOxSensor_Pecorara_Cora_301179_296164.pptx
  - 2019_MOTTA_S251312_ESE_presentation_Dongiovanni_Motta.pdf
  - MOVIE_PECORARA_CORA_NOxSensor.mkv

11 Design History of the Project

11.1 Components Selection

We carefully evaluated three available ECG sensors in the market, ultimately selecting the one that represented the best trade-off in terms of performance and costs. Our choice was driven by the need to achieve reliable performance at a reasonable cost while also maintaining strict control over the overall project expenses. Consistent with this approach, other components were also chosen following the same criterion. Additionally, we took into account size limitations, in order to embed the whole device in a chest strap comfortable to wear.

Reasons behind the main choices of this project are detailed in the relative sections of this report.

11.2 Padstacks

Padstacks have been developed in alignment with Eurocircuits' specifications, ensuring uniform sizes for both pads and solder mask dimensions. In the case of considering alternative manufacturers, it is necessary to adjust the pad designs to meet their specific requirements.

11.3 Versions

The final version of the project is the 1.5.

Intermediate steps that led to the final version are listed below.

1. In the initial phase, schematics of sensor, microcontroler, I/O and Power components have been designed.

2. Passive components (resistors, capacitors, inductors, crystals) have been added according to specifications.

3. Footprints are generated for the components.

4. The next step involves associating real components with their respective schematic symbols. Up to this step, no PCB has been created.

5. Corrections were made to certain schematic symbols and footprints. Schematic's readability has been enhanced. The initial version of the PCB was then generated. In the following, the main differences and improvements made in successive versions are described.

11.3.1 Version 1.1

Version 1.1 is the basic initial version of the PCB. It entails the preliminary arrangement of all components and their respective connections.

To ensure proper integration of the antenna into the design, preventing it from being identified by the OrCAD program as an isolated shape, it is essential to configure flags within the program. This configuration is necessary to establish a short circuit connection between the antenna shape and its corresponding pad on the PCB.

11.3.2 Version 1.2

The power switch has been modified. Instead of being SPDT placed vertically, a slide switch has been chosen. The reset has been retained as a push button.
These decisions were made to enhance the user experience of the final product.

11.3.3 Version 1.3

The device design has been optimized based on the selection of electrodes and their connection to the PCB. For further details, refer to Section 4.1.2.

Moreover, the readability of component labels on the PCB has been enhanced, addressing font size and positioning.

11.3.4 Version 1.4

Spacing between components and hole size on the PCB has been adjusted to lower manufacturing costs.

Finally, logos have been added.

11.3.5 Version 1.5

Mounting holes have been added to make the mechanical connection to the device case solid and stable.