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Master of Science HES-SO in Engineering

Orientation : Industrial Technologies (TIN)

Master Thesis Report :

Analog LTE-M / NB-IoT Watch

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Abbreviations

TM

- **GNSS**[1] : General term that encompasses any satellite constellation providing PNT services on a global or regional basis. Including BeiDou-BDS (China), Galileo (Europe), GLONASS (Russia), IRNSS-NavIC (India) and QZSS (Japan)
- **GPS**[2] : Global Positioning System ; U.S. proprietary PNT utility divided in three segments, the Space segment (U.S. Space Force), the Control segment (U.S. Space Force) and the User segment
- **LCD** : Liquid Crystal Display
- **MIP** : Memory In Pixel
- **NLOS**[3] : Non-Line Of Sight ; Partial or complete obstruction of RF's path of propagation by an obstacle, such as buildings, trees, landscapes or high-voltage power conductors that can reflect or absorb the signal and thus limit the transmission efficiency.
- **PNT**[2] : Positioning, Navigation and Timing
- **QI** : *QI* is an open wireless power transfer interface standard using inductive charging.
- **RF** : Radio Frequency
- **RHCP**[4] : Right Handed Circular Polarization ; Circular polarization signals are transmitted on both horizontal and vertical planes with 90° phase shift, which induce a rotation of the signal wave. Right handed mean that the rotation is in the clockwise or anti-trigonometric.
- **SAW** : Surface Acoustic Wave
- **TTM** : Time to Market
- **WPC** : Wireless Power Consortium is consortium that create and promote wide market adoption of *Qi* interface standards

Abstract

About Nordic Semiconductor[5]

Nordic Semiconductor is a fabless semiconductor company from Norway specialized in wireless communication technologies and more particularly in *Internet of things* (*IoT*). The company is well known for its pioneer role in *ultra low power wireless* solutions development such as *Bluetooth Low Energy* (*BLE*). They later implemented other technologies, such as : *ANT+*, *Thread*, *Zigbee*, Low power and compact *LTE-M/NB-IoT* cellular *IoT* solutions, *Wi-Fi technology*, *GSMA*.

Goal of the project

Nordic Semiconductor has developed the *nRF91* family of *cellular LTE-M/NB-IoT* communication devices. The goal of this Master Thesis is to develop the prototype of an analog wristwatch using a such device. There are many challenges to overcome in this project, to name just the most difficult ones as the mechanical as well the energy consumption constraints.

Main tasks of the project

1. **Specification :** Elaborate the exact specification of the wristwatch (number of hands, battery lifetime, user interface, size, recharging mechanism, case)
2. **Antenna study :** The antenna of this device is particularly delicate. Since the communication is actually using 800 MHz, the antenna can not be as small as one would like it. So there has to be done a study how to solve this problems showing several innovative approaches how to solve this problem. At the conclusion of the study, a solution has to chosen for later implementation.
3. **Hardware conception :**
   - 3.1 Component selection (Cellular communication, motors and so on)
   - 3.2 Schematic and PCB realization of a prototype board
   - 3.3 Fabrication and electrical test of the prototype
4. **Software development** : Design and develop a simple watch application that must implement
   - 4.1 Motorized clock's hands
   - 4.2 Buttons
   - 4.3 LCD screen
   - 4.4 *LTE-M/NB-IoT* data reception and transmission with MQTT
   - 4.5 *GNSS* signal reception for position tracking and smart-watch time accuracy
   - 4.6 Battery monitoring, battery charging configuration and level monitoring
   - 4.7 Accelerometer usage
5. **Prototype validation :** Test of the entire development
6. **Documentation :** Establish a technical report enabling further developments

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1 Introduction

1.1 About Nordic Semiconductor[5]

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1.2 Aim of Study

Nordic Semiconductor has developed the *nRF91* family of *cellular LTE-M/NB-IoT* communication devices. The goal of this Master Thesis is to develop the prototype of an analog wristwatch using a such device. There are many challenges to overcome in this project, to name just the most difficult ones as the mechanical as well the energy consumption constraints.

1.2.1 Description of the project

The project consist in the conception and the realization of a prototype board of a *LTE-M/NB-IoT* and *GNSS hybrid smart-watch*. The project is quiet ambitious and, firstly from its multiple tasks that must be achieved and secondly because it covers a wide range subjects and require multiple skills such as :

- **Research and literature reviewing :**
  - State of art of wearable application and current available solution and technologies.
  - Understanding main constraints of wearable low power applications
  - Understanding basics of low power *cellular LTE-M/NB-IoT* and GNSS technologies
- **Hardware conception :**
  - Decomposition of the system in functional blocs.
  - Component selection with current market's constraints (component shortage, time limits, etc...).
  - Schematic and PCB conception and realization.
  - Powering up and validating the prototype board.
- **Software development :** Understand, use or implement :
  - *nRF Connect for Desktop[8]* development environment
  - *nRF Connect SKD[9]* from Nordic Semi.

- — *nrfx[10]* and *nrfxlib[11]* modules from Nordic Semi.
- — *Zephyr RTOS* from *Zephyr Project[12]*.
- — Motor driver source files from Patrice Rudaz.
- — *Soprod* project source files and librairies from Patrice Rudaz.
- — *nRF91 AT Commands* from Nordic Semi.
- — *LTE-M/NB-IoT* receiver and transmitter.
- — *GNSS* receiver.
- — Multiple peripherals implementation (accelerometer, buttons, LCD screen, etc...).
- — Implement and use a *LTE-M/NB-IoT* server for data collecting and visualization.
- — Develop a small watch application that demonstrate implemented functionality.

— **Test and measure :**

- — Electrical test and validation of the prototype board.
- — Modification or correction of possible conception mistakes.
- — Consumption and performance test.

1.2.2 Objectives of the project

The objectives of the project is to achieve the full conception of a prototype board of a This project expect to achieve the following tasks and objectives :

1. **Specification :** Elaborate the exact specification of the wristwatch (number of hands, battery lifetime, user interface, size, recharging mechanism, case)
2. **Antenna study :** The antenna of this device is particularly delicate. Since the communication is actually using 800 MHz, the antenna can not be as small as one would like it. So there has to be done a study how to solve this problems showing several innovative approaches how to solve this problem. At the conclusion of the study, a solution has to chosen for later implementation.
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   - 4.5 GNSS tracking and timing reception
   - 4.6 Accelerometer usage
5. **Prototype validation :** Test of the entire development
6. **Documentation :** Establish a technical report enabling further developments

1.2.3 Prerequisites

This project requires a wide range of knowledges and skills, such as :

— Electronic engineering (user interface, motors, schematic and PCB)

— A few mechanical knowledge (watch case, 3d printing)

— Embedded software engineering (communication protocols, RTOS, UML, C / C++, watch application)

— Preindustrialisation of consumer electronics

— Radio frequency engineering (antenna)

1.3 Scope and Limitation of Study

LTEWatch project consist in the design and the fabrication of an "hybrid" Smart-Watch. The "hybrid" qualification consist in integration of mechanical watch hands (**H** : **M** : **S**) in a smart connected wearable device.

Since the project deserve a large amount of work, the idea is to first create a prototype board as a Proof Of Concept (*POC*) enabling the design and development of the Smart-Watch application software and also to test and have a better idea of the device consumption and performance.

This project is a Master-Thesis, which involves multiple constraints that partly limit the expected result of the project. Because this is an academic project, it is subject to a relatively limited time constraint and limited resources that require finding solutions that are accessible, available quickly and more secure.

2 Literature Review and Research Proposal

2.1 Wearable and low-power application's constraints considerations

2.1.1 Constraints and challenges of low-power electronics

Small embedded and wearable electronic systems had to overcome several constraints and challenges to become so popular and to take such a prominent place in everyone's daily life.

Challenges and constraints as follows :

- **Mechanical :**
  - Increase portability by reducing internal electronic clutter and optimizing circuit complexity in order to increase component density and reduce weight as much as possible.
  - Improve ergonomics and design by increasing size and accessibility of user interface components like display, touch-screen or buttons.
- **Performance :**
  - Increase systems battery life as much as possible by reducing wasted power such as *quiescent current* (I_q) and component efficiency, also in terms of heat dissipation which must be kept as low as possible in order to maintain a reasonable system temperature with a passive cooling design and does not reduce system performance by thermally throttling ICs or reducing battery cell capacity and efficiency. Each μA should be dedicated to the system performance.
  - Reduce charging time as low as possible by increasing charging current as much as possible and choosing new technologies ; such as *USB-C PD*.
- **Price and availability :**
  - Reduce price of the system and increase the ease of production by reducing the number of components and optimizing the system complexity.

Designing ultra-low-power electronics is a constant trade-off between performance and battery autonomy. A good approach consist in reducing as much as possible all sources of wasted currents and more precisely quiescent current.

Quiescent current (I_Q)

The following description is based on the paper *"Overcoming Low-IQ Challenges in Low-Power Applications"*[13] by **Keith Kunz** and **Stefan Reithmaier** from Texas Instrument Incorporated and *IQ : What it is, what it isn't, and how to use it*[14] by **Chris Glaser** from Texas Instrument Incorporated.

The *quiescent current* (I_Q) is the current drown by an **active** IC when **non-switching** and a **no-load** configuration.

— **Active** means that the IC is enabled and is neither in lockout nor shut-down condition.

— **No-load** means that not any current is drawn by the outputs of the IC. I_Q is therefore all currents travelling inside the IC to the ground.

— **Non-switching** means that the IC is in a *high-impedance* state, with its power stage disconnected from any output.

2.2 System MCU - *nRF9160 SiP*[6] (Nordi Semiconductor)

2.2.1 Overview

The *nRF9160 SiP* product bief : "*nRF9160 cellular IoT System-in-Package*"[6] describe the SiP as follows :

1. Accessible *LTE* lates technology
2. Fully integrated *SiP* with the following modules :
   — application processor ;
   — multimode *LTE-M/NB-IoT/GNSS* modem ;
   — RF front-end (RFFE) ;
   — power management.
3. Most compact solution for cellular *IoT* (*cIoT*) on the market with a $10 \times 16 \times 1.04$mm package size.

The figure 2.1 illustrates *nRF9160 SiP*[6] chip :

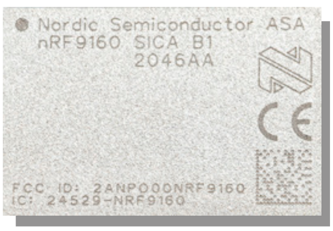


Figure 2.1 – *nRF9160 SiP* chip - Source : Nordic Semi[6]

2.2.2 Application domain

The *nRF9160 SiP*[6] targets asset tracking applications, the *SiP* has a buit-in *nRF Cloud Location Services*[15] that provide built-in *LTE* and *GNSS* location support with :

— Assisted *GPS*

— Predicted *GPS*

— Single-cell and multi-cell location service

The figure 2.2 illustrates an application circuit diagram of the *nRF9160 SiP*[6] :

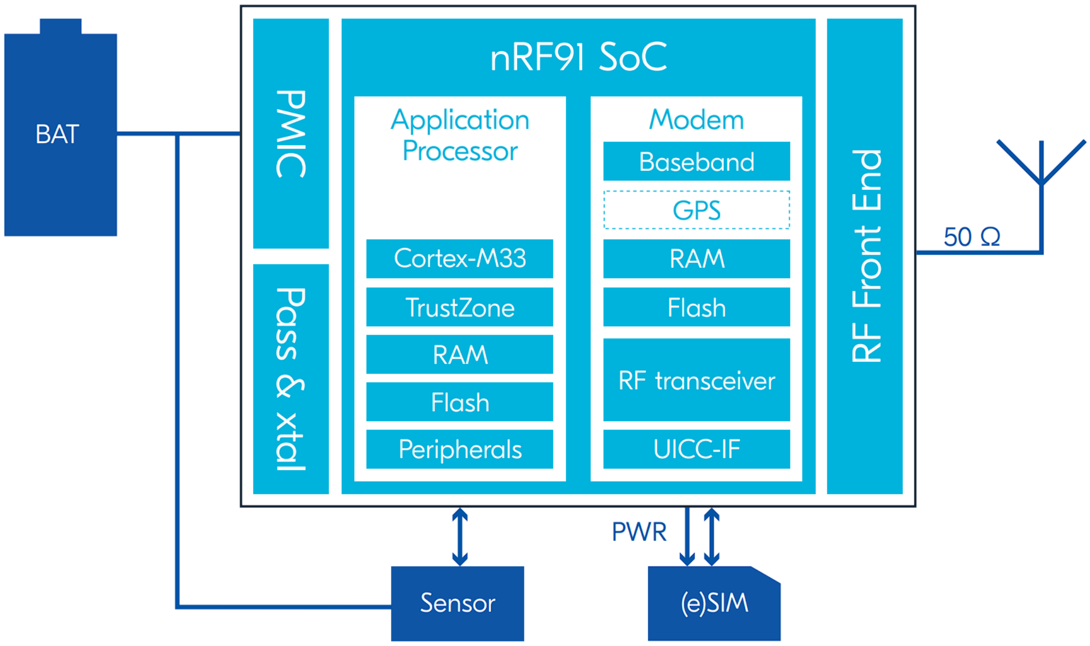


Figure 2.2 – Application Circuit - Source : Nordic Semi[6]

With these characteristics, the *nRF9160 SiP* is oriented towards applications such as :

— Logistics and asset tracking

— Smart city and smart agriculture

— Predictive maintenance and industrial

— Wearables and medical

2.2.3 *nRF9160 SiP* key features

The *nRF9160 SiP* offers good performance and many great features for wearable *IoT*, tracking and connected applications.

LTE-M/NB-IoT modem

The *nRF9160 SiP* modem key data are shown in the table 5.1 :

Frequency range	700 – 2200MHz
Throughput	LTE-M : 300/375 kbps
(DL/UL)	NB-IoT : 30/60 kbps
Output power	Up to 23 dBm
RX sensitivity	• LTE-M : −108 dBm • NB-IoT : −114 dBm • GPS : −155 dBm
Mode	HD-FDD

Table 2.1 – *LTE-M/NB-IoT* modem key data table[6]

Application processor

The *nRF9160 SiP* application processor key data are shown in the table 2.2 :

CPU	64 MHz Arm Cortex-M33 Arm TrustZone
Flash	1 MB
RAM	256 KB
Security	Arm Cryptocell 310
Peripherals	• 4×SPI/UART/TWI • 4×PWM, PDM, I2S • 12bit/200 ksps ADC • 3×TIMER, 2xRTC, WDT

Table 2.2 – Application processor key data table[6]

Current consumption (23 dBm TX power, 3.7 V supply)

The *nRF9160 SiP* consumption key data are shown in the table 5.1 :

PSM floor current	LTE-M : 2.7 µA NB-IoT : 2.7 µA
eDRX, 655 seconds	LTE-M : 6 µA NB-IoT : 9 µA

Table 2.3 – Current consumption key data table[6]

Operating conditions and package

nRF9160 operating conditions and package key data are shown in table 5.1 :

Supply voltage	3.0 – 5.5V
Temperature	−40 to 85 °C
Package	10 × 16 × 1.04 mm *LGA*

Table 2.4 – Operating conditions and package key data table[6]

2.3 Power Supply

The battery cell technology choice is a crucial step in the conception of a smart-watch. In order to make the best choice possible, it is necessary to realize the state-of-the-art of available technologies and solutions on market.

A crucial step consists in the identification of most relevant constraints of the system, which are :

- The autonomy of the smart-watch must be sufficient. Approximately one week (5-7 days) of normal usage.
- The smart-watch must implement a fast charge option. Full charge in 1-2 hours is preferable.
- The size must be minimal. A maximal diameter of 40 mm to 50 mm is desirable.
- Components must be available and price must be as low as possible and as high as necessary.

2.3.1 Lithium Battery Technologies[7]

Lithium-ion, Lithium Polymer and Lithium Iron Phosphate[7]

Currently, lithium is the metal with the highest *energy density* ($\mathrm{W\,h\,kg^{-1}}$) while keeping a very good *power density* ($\mathrm{W\,kg^{-1}}$). This feature still makes lithium the best solution currently available for batteries, especially for small, compact, and lightweight portable applications.

Lithium power source offer interesting advantages if :

- A higher system voltage is required (i.e. 3.0 V to 3.9 V per cell)
- The system weight must be as low as possible
- A long shelf life is required
- The system will be used in a wide range of temperature
- The system reliability is crucial
- The system requires a high energy density
- The system environmental concerns such as temperature, vibration or shock are high
- The application requires a continuous source of power for a long period of time

The main disadvantages of a lithium power source is the price, that is not the cheapest available and the danger of the technologies. Li-Ion and Li-Poly battery doesn't support over charging and over discharging, this can lead to the destruction of the cell with a serious risk of exploding or catching on fire. This is why a battery protection circuit is an obligation while working with that kind of technology.

Lithium Batteries[7]

Lithium batteries are made with lithium metal or lithium compounds as an anode. They are disposable (primary) batteries that can provide voltages from 1.5 V to 3.7 V depending on the design and chemical compounds used. This voltage is over twice the one of an ordinary zinc-carbon battery or alkaline cell battery.

Figure 2.3 – Primary Lithium Battery Pack for Conversion Tracking Device[7]

Lithium-Ion Batteries[7]

Lithium-ion batteries are similar to lithium batteries, except that they are rechargeable. They are common in portable application and consumer electronics because of the following characteristics :

- High energy-to-weight ratio
- No memory effect
- Slow self-discharge when not in use

Figure 2.4 – Lithium-Ion Battery Pack for GPS Tracking Device[7]

Lithium-ion batteries are made of the three primary functional components :

- **Anode :**
  - Is the negative electrode
  - Commercially, is usually made with graphite
- **Cathode :**
  - Is the positive electrode
  - Commercially, is usually made of a layered oxide (such as lithium cobalt oxide), one based on a polyanion (such as lithium iron phosphate), or one based on a spinel (such as lithium manganese oxide), although materials such as TiS2 (titanium disulfide) originally were also used.

— **Electrolyte :**
  — Is a liquid or gel which contains ions and can be decomposed by electrolysis

Lithium-ion batteries' voltage, capacity, life, and safety can change drastically and is dependent to the choice of material for the anode, cathode and the electrolyte.

Lithium-ion battery have the following cycle :

— **Discharge :** During the discharge, lithium ions move from the *anode* to the *cathode*

— **Charge :** During the charge, lithium ions move from the *cathode* to the *anode*

Lithium Polymer (LiPo)[7]

Lithium-ion polymer batteries, polymer lithium-ion, or lithium polymer batteries are also very common rechargeable batteries (secondary cell). They are normally composed of several identical secondary cells in parallel addition to increase the discharge current capability.

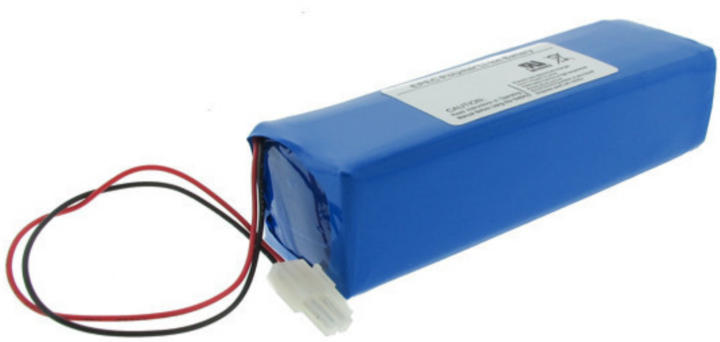


FIGURE 2.5 – Lithium Polymer Battery Pack for Medical Application[7]

Lithium Iron Phosphate (LiFePO4)[7]

Lithium Iron Phosphate batteries better safety characteristics than Lithium-ion technology, this due to the phosphate based technology, which has better thermal and chemical stability. Phosphate chemistry offers a longer cycle life and are less sensitive during charge and discharge and are incombustible in this situation. They are also more stable under overcharge or short circuit conditions, and they can withstand high temperatures without decomposing. Even when the output current is high, the phosphate based cathode material will not burn and is not prone to thermal runaway.

Lithium Ion Cathode Chemistry Comparison table

Cathode Material	Typical Voltage (V)	Energy Density Gravimeric ($\mathrm{W\,h\,kg^{-1}}$)	Energy Density Volumetric ($\mathrm{W\,h\,L^{-1}}$)	Thermal Stability
Cobalt Oxide	3.7	195	560	Poor
Nickel Cobalt Aluminum Oxide (NCA)	3.6	220	600	Fair
Nickel Cobalt Manganese Oxide (NCM)	3.6	205	580	Fair
Manganese Oxide (Spinel)	3.9	150	420	Good
Iron Phosphate (LFP)	3.2	90-130	333	Very Good

Table 2.5 – Lithium Ion Cathode Chemistry Comparison table[7]

Conclusion

Currently, optimal power density and a compact power supply are synonym of lithium battery technology. The Principal advantages and applications constraints of lithium power sources are :

— Offer high output voltage : 3.0 V to 3.9 V per cell

— Have one of the best Gravimetric energy density [Wh/kg] available on market

However, lithium-ion battery always requires a protection circuit to manage its charge and discharge in order to maximize its usage safety. Therefore, a special attention must be given to the battery management circuit and the right choice of battery capacity, charge and discharge current and the system load when implementing a lithium-ion battery.

2.3.2 Battery - State of art

In order to keep a reasonable size for the smart-watch, its diameter must be smaller than 50 mm with an ideal diameter sitting around 45 mm. It has also been decided with Medard Rieder and Patrice Rudaz to choose a circular shape for the design of the smart-watch.

In order to implement the maximum autonomy possible in the system, the best idea seems to select a circular (round) battery cell with a diameter fitting inside the smart-watch's diameter of 45 mm.

After some researches on the market, two solutions seemed to correspond to those needs :

1. Lithium-ion Rechargeable Coin Cell Battery
2. Round LiPo Battery Cells

Lithium Ion Rechargeable Coin Cell Battery

Lithium-ion Rechargeable Coin Cell Battery are small lithium-ion battery package in common button cell and coin cell batteries standards. The package is labeled similarly to the non-rechargeable primary coin/button cell battery. The code consists of two letters, followed by three or four numbers. This standard correspond to the International Electrotechnical Commission (*IEC*). However, there are still coin/button cells that correspond to an older standard which has different naming.

The standard only describes primary batteries. Rechargeable types have a different prefix that is not in the IEC standard, for example ML, RJD and LiR button cells use rechargeable lithium technology.

Battery Type	Shape	Diameter [mm]	Height [mm/10]
LI	R	24	50

Table 2.6 – Coin/Button cell battery IEC standard

The figure 2.6 illustrates lithium-ion rechargeable coin cells with the following label :

— *LI* : Rechargeable lithium-ion technology

— *R* : Round (circular) shaped battery

— 24 : The battery cell diameter is 24.5mm ± 0.50mm

— 50 : The battery cell height is 5 mm tall

Figure 2.6 – Lithium Ion Rechargeable Coin Cell Battery[16]

CDE / Illinois Capacitor RJD provide multiple model of "high capacity" lithium-ion rechargeable coin cell battery. They claim that their batteries offer "a reduced risk of overheating compared to conventional coin-cell batteries."[16].

RJD batteries claims the following characteristics :

— A nominal voltage of 3.7 V (4.2 V to 3.0 V)

— A charging time < 3 h

— High-power rating batteries : graphite anodes and lithium nickel manganese cobalt oxide cathode

— Ideal for memory backup circuits, electronic wearables, and Internet of Things (IoT) devices

The figure 2.7 illustrate the standard coin cell options from RJD :

IC Part Number	Capacity (mAh)		Charging Current (mA)	Discharge Current (mA)		Maximum Internal Resistance (mΩ)	Appox. Weight (g)	Maximum Diameter (D mm)	Thickness (T mm)
	Nom.	Min.		STD	MAX				
RJD2032C1	85	80	40	16	160	700	3.4	20.02	3.5
RJD2048	120	110	55	22	220	700	4.2	20.02	5.0
RJD2430C1	110	104	52	20.8	208	500	4.5	24.5	3.15
RJD2440	150	140	70	28	280	800	5.4	24.5	4.3
RJD2450	200	190	95	38	380	500	6.5	24.5	5.4
RJD3032	200	190	95	38	380	600	7.2	30	3.4
RJD3048	300	290	145	58	580	400	9.3	30	4.9
RJD3555	545	515	257.5	103	1030	200	14.1	35.2	5.7

Figure 2.7 – RJD - Standard Coin Cell Options[17]

The figure 2.8 illustrate corresponding dimensions :

IC Part Number	Fresh Cell				Cycled cell (after 500 cycles)	
	Shipping (Charged)		Full Charge		Full Charge	
	Maximum Diameter (D mm)	Maximum Thickness (T mm)	Maximum Diameter (D mm)	Maximum Thickness (T mm)	Maximum Diameter (D mm)	Maximum Thickness (T mm)
RJD2032C1	20.02	3.5	20.02	3.6	20.02	3.7
RJD2048	20.02	5	20.02	5.2	20.02	5.3
RJD2430C1	24.5	3.15	24.5	3.25	24.5	3.3
RJD2440	24.5	4.3	24.5	4.4	24.5	4.5
RJD2450	24.5	5.4	24.5	5.5	24.5	5.6
RJD3032	30	3.4	30	3.5	30	3.6
RJD3048	30	4.9	30	4.9	30	5.2
RJD3555	35.2	5.7	35.2	5.8	35.2	5.9

Figure 2.8 – RJD - Standard Coin Cell Dimensions[17]

Positive points about RJD Battery :

+ Compatible with coin cell battery socket and standards
+ Available in a wide range of diameter : from 20 mm to 35 mm
+ Available in a wide range of thickness : from 3.5 mm to 5.7 mm
+ Offer multiple choice of capacity : from 85 mA h to 545 mA h
+ Relatively cheap : 100 [mAh] ≈ 6.24 $
+ Easily available (`mouser.ch`,`digikey.com`, etc...)
+ Sufficient discharge current : from 580 mA to 1030 mA (for the two interesting models)

Negative points about RJD Battery :

- Only two interesting models : *RJD3048* (300 [mAh]) and *RJD3555* (545 [mAh])
- Relatively small capacity : maximum capacity of 545 [mAh]
- Require a mounting socket which increase the battery clutter in the system
- Relatively slow recharging time ∼ 3 h

Round LiPo Battery Cells

While LiPo battery have a slightly lower energy density than lithium-ion, it offers many interesting characteristics such as slimmer package and a wider range of shapes sand sizes. LiPo are also widely available and relatively cheap. LiPo battery offers an interesting alternative to lithium-ion rechargeable coin battery.

FIGURE 2.9 – Round LiPo Battery Cells[18]

LiPo battery cells main features :

- Round shape allow a higher energy density with an optimized compact design
- Nominal voltage from 3.6 V to 3.8 V
- If required, PCM, NTC and connector can be easily assembled to the battery
- A wide range of available capacity from 135 mA h to 1500 mA h
- Low self discharge and a longer cell's life

LiPol Battery Co. Ltd ® Round LiPo Battery Cell options :

Part No.	Voltage	Capacity	Size
LPR403535	3.7V	390mAh	4.0x35mm
LPR433736	3.8V	530mAh	4.3x37mm
LPR443535	3.7V	450mAh	4.4x35mm
LPR443735	3.7V	450mAh	4.4x37mm
LPR453535	3.7V	450mAh	4.5x35mm
LPR453535	3.8V	475mAh	4.5x35mm
LPR453535	3.8V	490mAh	4.5x35mm
LPR463535	3.8V	480mAh	4.6x35mm
LPR473736	3.8V	580mAh	4.7x37mm
LPR483535	3.8V	530mAh	4.8x35mm

TABLE 2.7 – Round LiPo Battery Cells Table - Part 1 - Source :[18]

Part No.	Voltage	Capacity	Size
LPR503027	3.7V	300mAh	5.0x30mm
LPR533535	3.8V	560mAh	5.3x35mm
LPR543535	3.8V	610mAh	5.4x35mm
LPR553532	3.8V	600mAh	5.5x35mm
LPR553535	3.7V	580mAh	5.5x35mm
LPR553535	3.7V	600mAh	5.5x35mm
LPR603533	3.7V	630mAh	6.0x35mm
LPR603535	3.8V	650mAh	6.0x35mm
LPR604543	3.7V	1050mAh	6.0x45mm
LPR653027	3.8V	430mAh	6.5x30mm
LPR653929	3.8V	665mAh	6.5x39mm

Table 2.8 – Round LiPo Battery Cells Table - Part 2 - Source :[18]

Selected Battery - 503535 3.8v 580mAh round lipo battery cells

The context of Master thesis requires to find quick and available solution and does not allow ordering custom product. Furthermore, batteries are considerate of hazardous materials and are not very easy to deliver.

Because of this context, the choice available was considerably reduced. A suitable solution is the component "*503535 3.8v 580mAh round lipo battery cells*" available on `https://batteryzone.de/products/503535-580mah-hochspannung-3-8v-runde-polymer-smart-watch-moxibustion-instrument-auto-smart-box-batterie?_pos=1&_sid=59cfd2d74&_ss=r`

The selected battery is illustrated on the figure 2.10.

Figure 2.10 – 503535 3.8v 580mAh round lipo battery cells [19]

Basic Information :

The selected battery is not the most ideal choice, because it is not the thinner model available, but it has a big capacity and a fitting diameter of 35 mm.

The selected battery has the following characteristics :

Cell Thickness	5.0 ± 0.2	[mm]
Cell Diameter	35 ± 0.5	[mm]
Charge voltage	4.35 ± 0.03	[V]
Nominal voltage	3.8	[V]
Nominal capacity	580	[mAh]
Fully charge voltage	4.35	[V]
Ship out voltage	3.9 – 4.2	[V]

Table 2.9 – 503535 3.8V 580mAh round lipo - Basic Information [18]

Battery detailed specification :

Charge current	Standard Charging : 0.2C (116) Rapid charge : 1.0C (580)	[mA]
Charging method	Charge with constant current 0.2C to 4.2 V, then charge with constant voltage 4.2 V till until charge current is less than 0.01C	[-]
Standard discharge current	0.2C (116)	[mA]
Max.discharge current	1C (580)	[mA]
Discharge cut-off voltage	3.0	[V]
Operating environment	Charging : $0 \sim 45$ Discharging : $-20 \sim 60$	[°C]
Storage temperature	less than one month : $-20 \sim 40$ less than half year : $-20 \sim 30$	[°C]
PCB & Wires & connector	Optional	[-]
Cycles	500	[times]
Warranty	12	[months]

Table 2.10 – 503535 3.8 V 580 [mAh] round lipo - Battery specification [18]

2.4 Introduction to *GNSS*

The website `www.gps.gov`[1] describes *GNSS* as a general term describing any satellite constellation providing *PNT* services on a global or regional basis :

1. Positioning *(P)*
2. Navigation *(N)*
3. Timing *(T)*

The most prevalent *GNSS* is **GPS** (*Global Positioning System*) which is the utility owned by the United States with 24 satellites, but it exists several others *PNT* utilities available to provide complementary and independent *PNT* capability.

The mains other *PNT* utilities are :

1. **BeiDou** *Navigation Satellite System (BDS)* : Global *GNSS* owned and operated by the People's Republic of China (*PRC*) with 30 satellites.
2. **Galileo** : Global *GNSS* owned and operated by the European Union (*UE*) with 30 satellites.
3. **GLONASS** *Globalnaya Navigazionnaya Sputnikovaya Sistema* (Global Navigation Satellite System) : Global *GNSS* owned and operated by the Russian Federation with 24 satellites.
4. **IRNSS/NavIC** *Indian Regional Navigation Satellite System / Navigation Indian Constellation* Global *GNSS* owned and operated by the Government of India with 7 satellites. *IRNSS* is an autonomous system designed to cover the Indian region and 1500 km around the Indian mainland.
5. **QZSS** *Quasi-Zenith Satellite System* : Global *GNSS* owned by the Government of Japan and operated by *QZS* System Service Inc. (*QSS*) with 5 satellites.

2.5 Introduction to Cellular IoT

2.5.1 Introduction to *LTE*

Figure 2.11 – *LTE* Logo[20]

Long-Term Evolution (*LTE*[20]) is a wireless broadband communication and data terminals standard for mobile devices. *LTE* is based on the *GSM*/EDGE and the *UMTS*/HSPA standards. Frequencies and bands of *LTE* differ from country to country, which implies that to use *LTE* in all countries where it is supported, it is mandatory to use multi-band receivers.

2.5.2 Description of *LTE-M*

Nordic Semi. provides a good introduction to *LTE-M* on their website[21] :

Figure 2.12 – *LTE-M* Logo[20]

Low-power application required a mode fitting alternative to regular *LTE*, *LTE-M* that is also known as *Cat-M1* is specifically design for medium throughput requirement and low-power application. *LTE-M* has a bandwidth of 1.4 MHz, which significantly narrower than regular *LTE* with 20 MHz. This gives a longer range to *LTE-M* by sacrificing throughput providing approximately 100 kbps application throughput running IP with the following performances :

— **Uplink** : 375 kbps

— **Downlink** : 300 kbps

Main advantages of *LTE-M* :

1. Suitable for *TCP*/TLS end-to-end secure connections.
2. Fully supports mobility by using the same cell handover features as regular *LTE*.
3. Roaming is currently available, meaning it is suitable for multiple regions operating applications.
4. Suitable for time-critical applications offering real-time communication with latency in the millisecond range.
5. Suitable for applications requiring : medium-throughput, low power, low latency and mobility.
6. Perfect for applications, such as : asset tracking, wearable, medical, *POS* and home security.

2.5.3 Description of *NB-IoT*

Nordic Semi. provides a good introduction to *NB-IoT* on their website[21] :

Figure 2.13 – *NB-IoT* Logo[21]

Applications with even lower throughput requirement needs a solution more fitting than *LTE-M* in order to reduce power consumption. *NB-IoT* that is also known as *Cat-NB1* was specially design for that kind of applications. It has a drastically narrower bandwidth of 200 kHz providing longer range and lower throughput compared to *LTE-M* and regular *LTE* with the following performances :

- **Uplink** : 60 kbps
- **Downlink** : 30 kbps

NB-IoT technology standard that does not use a traditional *LTE* physical layer but is designed to operate in or around *LTE* bands and coexist with other *LTE* devices.

Main advantages of *NB-IoT* :

1. Suitable for : static, low throughput applications requiring low power and long-range.
2. Perfect for applications, such as : smart metering, smart agriculture and smart city applications.
3. It also provides better penetration in confined environments, like cellars and parking garages, compared to *LTE-M*.
4. If the network supports it and with *Cat-NB2* in *3GPP* release 14 a better throughput can be achieved :
   - **Uplink** : 169 kbps
   - **Downlink** : 127 kbps

2.6 MQ Telemetry Transport (*MQTT*) Protocol

2.6.1 Description of *MQTT*

Figure 2.14 – *MQTT* Logo[22]

MQ Telemetry Transport (*MQTT*[22]) is a lightweight machine to machine network protocol, using *publish–subscribe* messaging pattern and intended for *message queue* and *message queuing* service. The *MQTT* protocol is designed for connections to remote locations hosting constrained resources or limited network bandwidth devices. This protocol must run over a transport protocol that provides ordered, lossless and bidirectional connections, like *TCP/IP*. *MQTT* is very common and is an open *OASIS* standard and an *ISO* recommendation (*ISO/IEC 20922*).

2.6.2 Overview

The *MQTT* protocol defines two types of network entities (src.[22]) :

1. **Broker :** Server receiving all messages from the clients and then routes the messages to the registered clients
2. **Client :** Device running *MQTT* and connected to a broker over a network

The main advantages of *MQTT* broker usage are (src.[22]) :

1. Can eliminate vulnerable and insecure client connections.
2. Can easily be scaled from a single device to many.
3. Can manage and tracks all client connection states, including security credentials and certificates.
4. Can reduce network strain without compromising the security.

2.6.3 Protocol Working Principle

Working principle of *MQTT* protocol is the following (src.[22]) :

1. **Data are stored and organized in a defined hierarchy of topics**.
2. **If a publisher wants to distribute a new item of data :**
   - Publisher sends a control message containing the data to a broker's topic.
   - Broker then distributes the information to any clients that have subscribed to the concerned topic.
   - Publisher does not need to know anything about the number or locations of subscribers.
   - Subscribers do not need to know anything about publishers.
3. **If a broker receives a message on a topic with no subscribers :**
   - It will discard the message unless the publisher of the message designated the message as a retained message.
4. **Retained message :**
   - Is a normal *MQTT* message with the retained flag set to true.
   - Broker stores last retained message and *QoS* for the selected topic.
   - Each client that subscribes to a topic pattern that matches the topic of the retained message receives it immediately after they subscribe.
   - This allows new subscribers to a topic to receive the latest value rather than waiting for a next update from a publisher.
   - The broker can only store a single retained message per topic.
5. **When a publishing client connects for the first time to a broker :**
   - It can set up a default message to be sent to subscribers if the broker detects an unexpected disconnection of the publishing client from it.

6. **Clients only interact with a broker :**
   — A system can contain several broker servers that exchange data based on their current subscribers' topics.
7. **Control message :**
   — A control message can be as little as two bytes of data.
   — If needed, a control message can carry nearly 256 megabytes of data.
8. ***MQTT* uses fourteen defined message types :**
   — To connect and disconnect a client from a broker
   — To publish data
   — To acknowledge the reception of data
   — To supervise the connection between client and server
9. **Data transmission protocol :**
   — Relies on the *TCP* protocol for data transmission.
   — A variant, *MQTT-SN*, is used over other transports such as *UDP* or *Bluetooth*.
10. **Security :**
    — Does not include any measures for security or authentication, and connection credentials are in plain text format.
    — Can use *TLS* to encrypt and protect the transferred information against interception, modification or forgery.
    — The default unencrypted port is 1883.
    — The default encrypted port is 8883.

2.6.4 Message Types

Figure 2.15 illustrates an example of *MQTT* connection (*QoS* 0) with connect, publish/subscribe and disconnect from client *A*, and also storing of retain messages from the client *B* :

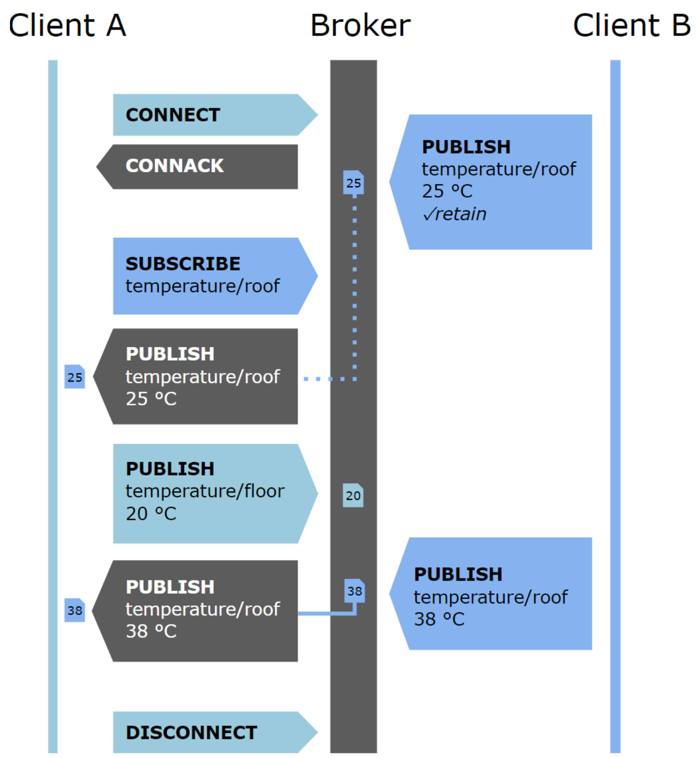


FIGURE 2.15 – Example of an MQTT connection - Source : [22]

Figure 2.15 illustrates the three message types described below :

- **Connect :** Waits establishment of a connection with the server and creates a link between the nodes.
- **Disconnect :** Waits for the end of any current work of the *MQTT* client, and for disconnection of the *TCP/IP* session.
- **Publish :** Immediately returns to the application thread after the request is passed to the *MQTT* client.

3 Result and Solution Proposal

One of the main task of this Master thesis consists in the conception and fabrication of a prototype board allowing to implement main features of a GNSS and LTE-M hybrid smart-watch. From now on, the Prototype board of the smart-watch will be referred as "**LTEWatch**".

3.1 Specification

LTEWatch must allow the implementation of the following features :

1. Power supply :
    1.1 LTEWatch must be powered by a battery
    1.2 LTEWatch must be rechargeable by USB-C connection and WPC (Wireless)
    1.3 LTEWatch must have battery life of at least one day (24 h)
2. Data display :
    2.1 Time or other information must be displayed with three clock hands and this by driving three mini stepper motors that are provide by the project supervisor Medard Rieder
    2.2 An LCD screen must be implemented to display complementary data or information
3. User interface :
    3.1 The user interface must be done with four push-buttons
    3.2 An embedded accelerometer can be added
4. Computing unit (MCU) :
    4.1 The MCU of LTEWatch must be the **nRF9160** from Nordic Semi
5. Radio frequency communication (RF) :
    5.1 LTEWatch must implement a GNSS receiver
    5.2 LTEWatch must implement a LTE-M / NB-IoT transceiver
    5.3 LTEWatch must have on-board antenna for both GNSS and LTE-M
    5.4 LTEWatch must also have SMA connectors for external antenna connection for both GNSS and LTE-M (allowing custom antenna design)
6. Mechanical specifications :
    6.1 As the time only allow to build a prototype board, LTEWatch will not represent the final design of the watch
    6.2 As the time does not allow to cover everything, the case design and fabrication will not be covered in this project

3.2 System Functional decomposition

Once the list of specifications and features have been chosen, a good methodological approach is to split the system in functional decomposition blocks. Each bloc must answer at least one point of the specification listed above.

Following the specification list, the system functional decomposition is :

1. *Power Supply* Block
2. *User Interface* Block
3. *Data Display* Block
4. *User Interface* Block
5. *RF Communication* Block
6. *MCU and Programming* Block

3.2.1 Power Supply Block Diagram

The *Power Supply* block is a very crucial part of any wearable device. Wearable imply to be powered by an embedded battery, which in this case is a LiPo battery.

Figure 3.1 illustrates the functional block diagram of the power supply block :

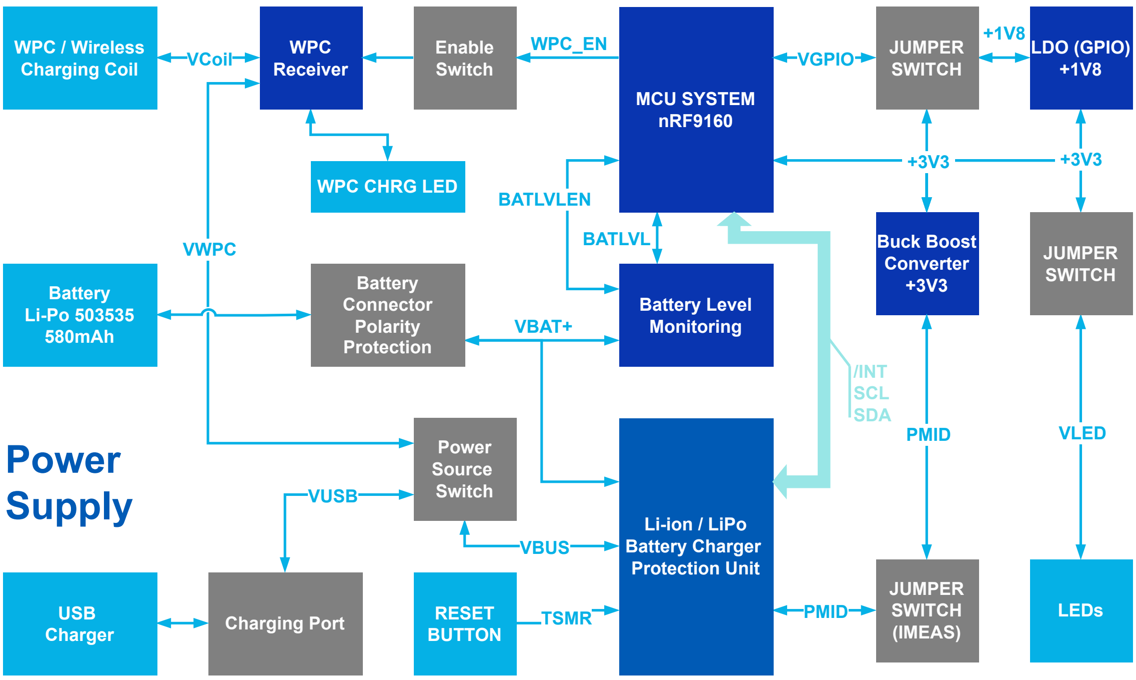


FIGURE 3.1 – Power Supply Block Diagram

The *Power Supply* block (figure 3.1) implement the following features :

Battery Power Supply :
- Battery connector with ESD and polarity protection circuit
- Li-ion/Lipo battery charger and protection unit
- Battery level monitoring circuit

Charging Power Supply :
- Wireless power coil input with a *WPC* receiver unit
- USB-C port to charge the battery and power the system

System Power Supply :
- 3.3 V buck boost converter to power the system
- 1.8 V LDO regulator that can be used to power the GPIO of the system

User Interface :
- Leds to indicate if the board is ON and if the WPC charge is ON
- A master reset push button
- A power system jumper to measure the current consumption of the system

3.2.2 User Interface Block Diagram

The *User Interface* block is a pretty simple, it consists of four push-buttons that will be the only user input available on the smart-watch and also an accelerometer that can be useful to add more functionality to the device. Accelerometer can be use to set a specific profile (normal, sport, etc...), it can also be used to wake-up the system or as a user input.

Figure 3.2 illustrates the *User Interface* block :

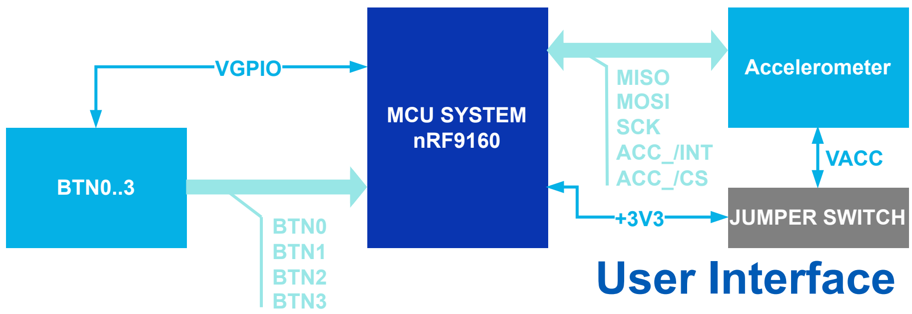


Figure 3.2 – User Interface Block Diagram

The *User Interface* block (figure 3.1) implement the following features :

***BTN* module :**
- Four push-buttons that are directly connected to the *nRF9160* (MCU)

***Accelerometer* module :**
- Accelerometer that is connected to the *nRF9160* with a SPI bus
- Jumper to enable/disable the power supply of the accelerometer to reduce consumption if not implemented.

3.3 Data Display Block Diagram

The *Data Display* block contains all the "graphical" user interface (*GUI*). Information such as the time is displayed on a clock with three hands ($h : m : s$). This clock is driven by three miniaturized stepper motors. A small LCD screen is also implemented to display more complex information, such as network reception status, date, battery level or charging status, as well as text.

Figure 3.3 illustrates the *Data Display* block diagram :

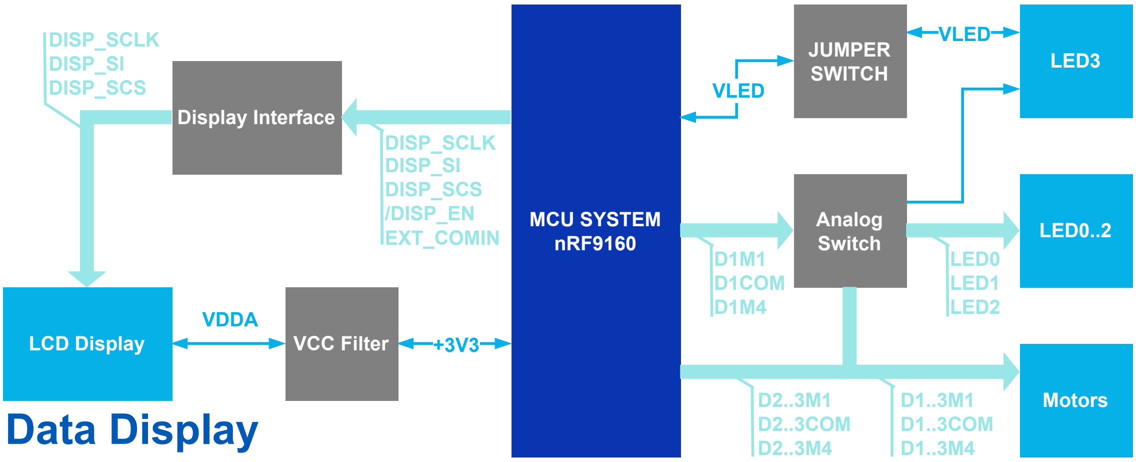


Figure 3.3 – Data Display Block Diagram

The *Data Display* block shown in figure 3.3 includes the following features :

***LCD Display* module** :

- The LCD is driven by the system MCU (*nRF9160*) through the display interface circuit
- The *Sharp Memory In Pixel* LCD module is sensitive to noise on the power supply that is why a *VCC Filter* circuit is required.

***Motors* module** : Used to display the time with three miniaturized stepper motors. One stepper motor is dedicated to the *hours*, one to the *minutes* and the last one to the *seconds*. The position of each stepper motor is driven by two coils which require three command signals :

1. DxM1 : Independent side of coil A
2. DxCOM : Common side between the two coils A and B
3. DxM4 : Independent side of coil B

***LED* modules :** : To make debugging easier, the three command signal of motor D1 can be redirected on three leds (*LED0*, *LED1* ,*LED2*) *LED3* indicate if debugging leds are used or not :

1. ***LED3*** is **ON** if debbugging leds are used.
2. ***LED3*** is **OFF** if motor D1 is used.

3.3.1 RF Communication Block Diagram

The *RF Communication* block is very important because it contains the main features of the *LTEWatch* which are *LTE-M/NB-IoT* reception and transmission (*MQTT*) and GNSS signal reception for position tracking and smart-watch time accuracy.

The *nRF9160* System-in-Package (SiP) is available with and without an integrated *GNSS* receiver module. The SiP with integrated *GNSS* module allows the use of software libraries directly from Nordic Semi which facilitates its implementation. The biggest disadvantage of this solution is that the modem of the *nRF9160* cannot simultaneously use the integrated *GNSS* module and the *LTE-M/NB-IoT* module. This is a significant constraint that reduces system performance.

For this reason, the choice was made to use the SiP without an integrated *GNSS* module and to implement an external one that interfaces with the MCU system (*nRF9160*) using a serial bus.

To speed up the development, the *LTE-M/NB-IoT* reception and transmission line is identical to the *nRF9160DK* (development kit) and uses the same antenna.

Both *GNSS* and *LTE-M/NB-IoT* can be connected to on-board antenna and external antenna with SMA connectors.

Figure 3.4 illustrates the *RF Communication* block diagram :

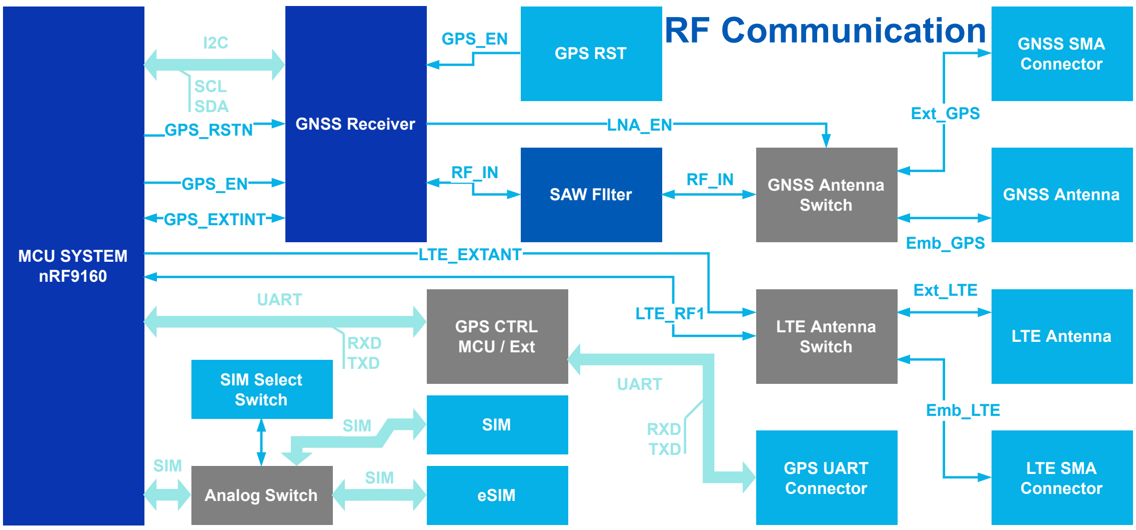


Figure 3.4 – RF Communication Block Diagram

The *RF Communication* block illustrated in figure 3.4 includes the following features :

***GNSS* reception line with :**

- A *GNSS* receiver that communicates with the system MCU by *I2C*. The MCU send three command signals to the *GNSS* receiver :
  1. *GPS_RSTN* : *GNSS* receiver reset
  2. *GPS_EN* : *GNSS* receiver power supply enable
  3. *GPS_EXTINT* : *GNSS* receiver external interruption
- An antenna switch to connect the *GNSS* line to on-board antenna or external antenna. This switch is commanded by the *GNSS* receiver *LNA_EN* output.
- A SMA connector to connect an external antenna to the board.
- The *GNSS* receiver can also be interfaced with *UART* bus. This bus can either be connected to system MCU or to an external source by a *UART* bus connector.

***LTE-M/NB-IoT* reception and transmission line with :**

- An antenna switch to connect the *LTE-M/NB-IoT* line to on-board antenna or external antenna. The switch is commanded by *LTE_EXTANT* signal from system MCU.
- A SMA connector to connect an external antenna to the board.

***SIM* and *eSIM* card interface :**

- The *SIM* card interface automatically select the which card to connect to the system MCU. This interface is identical to the *nRF9160* one.

3.3.2 MCU Programming Block Diagram

The *MCU Programming* block contains all the module required to flash and debug the system MCU *nRF9160*.

Figure 3.5 illustrates the *MCU Programming* block :

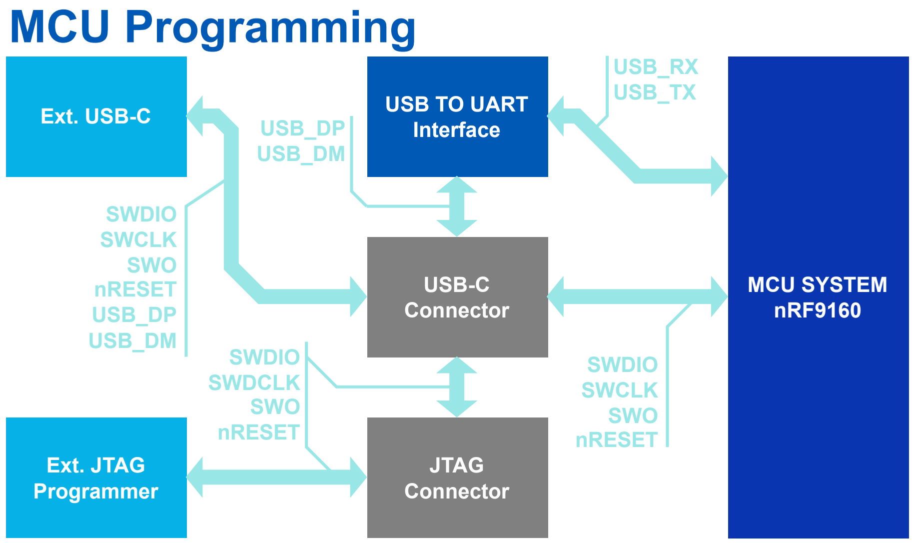


Figure 3.5 – MCU Programming Block Diagram

The *MCU Programming* block illustrated in figure 3.5 includes :

***USB-C* module :**

— Connector to interface system MCU to a programmer with a USB-C programmer. The USB-C programmer was developed for the project *Greg-Tracker* from the HEI (Hes-so Wallis).

***Ext. JTAG Programmer* module :**

— Connector to interface system MCU with a *Segger J-Link JTAG* Programmer or directly to the *nRF9160DK* (development kit) *JTAG* output.

3.4 LTEWatch Functional Architecture Diagram

The *LTEWatch* system is an assembly of all blocks described in the system breakdown, which are : The *Power Supply* block, the *User Interface* block, the *Data Display* block, the *User Interface* block, the *RF Communication* block and the *MCU Programming* block.

The *LTEWatch* overall system functional architecture diagram is illustrated in figure 3.6 :

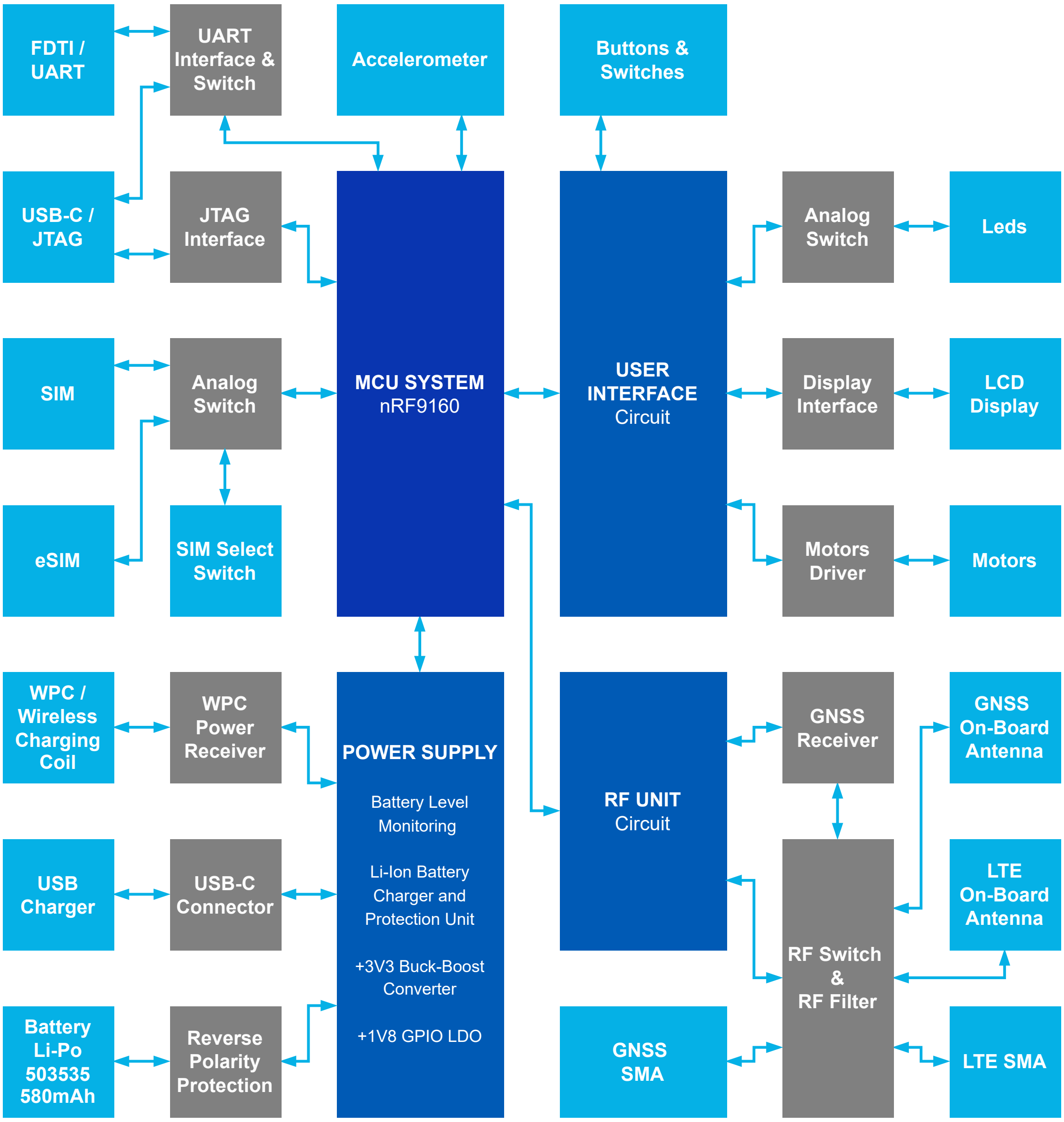


Figure 3.6 – LTEWatch Block Diagram

3.5 LTEWatch Prototype board (PCB) structure

The prototype board of *LTEWatch* must allow to validate the implementation of each block described in the system decomposition and must also make it possible to measure and test the performance of the system, i.e. device consumption, an approximation of the system autonomy, the precision of *GPS* tracking as well as the reliability of LTE-M/NB-IoT. This board should also allow experimentation and creation of custom antennas for the *GNSS* receiver and the *LTE* modem.

In order to fulfill these conditions, the board must allow to use certain functionality or not, using switch or configurable jumpers, the board must also allow to select the type of antenna used (on-board or external).

Figure 3.7 illustrates the prototype board (PCB) structure :

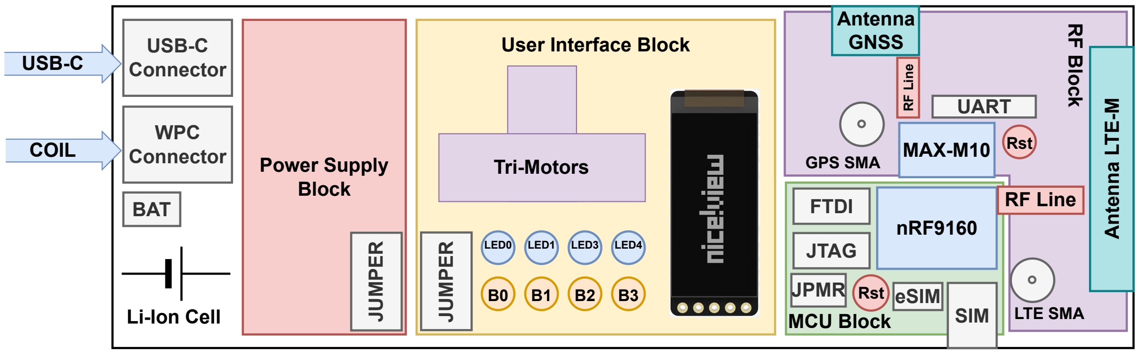


Figure 3.7 – Prototype Board PCB Diagram

As seen in figure 3.7, the board contains the following blocks :

1. Power supply connectors :
   — USB-C connector with *UART* enable jumper and *FTDI* USB to UART module
   — Wireless power coil (WPC) connector
   — Battery cell connector
2. Power supply block :
   — Battery reverse polarity protection circuit
   — Battery charger module
   — System power supply regulator (+3V3 buck-boost converter and +1V8 LDO regulator)
   — System current consumption measure jumper
   — Board led power supply enable jumper
   — System *VGPIO* (3.3 V or 1.8 V) configuration jumper

3. User interface block :
   — Programmable leds and buttons
   — Motors connector
   — Display connector (*nice !view* 5 pins or *FFC* 10 pins)
   — Display configuration jumpers
4. System MCU block :
   — *nRF9061* SiP
   — MCU reset button
   — *JTAG* connector
   — *SIM* and *eSIM* connectors
   — Serial *I2C* and *SPI* jumpers
5. RF block :
   — *LTE* RF line switch and *SMA* connector for external antenna
   — *GNSS* receiver SiP with reset button
   — *GNSS* RF line switch and *SMA* connector for external antenna

3.6 Component Selection

Once the functional decomposition of *LTEWatch* is complete, the next task is to find suitable components to fulfill each block previously described.

As *LTEWatch* is a portable device, this implies that the most important system constraints are the autonomy and the compactness of the battery, which translate for the components by consumption and size. Considering those aspects, it seems judicious to focus on fully integrated chip. This has the advantage of drastically reducing the clutter of the circuit, it also reduce circuit complexity and conception time which reduce time to market (*TTM*) or in this case : time to prototype.

The most obvious drawback of a fully integrated chip is that such components are usually more expensive. A less obvious disadvantage is that it increases the system's dependence on very specific components and manufacturers, making the circuit very susceptible to component shortages or cancellations, which may require circuitry redesign that may lead to complications. Risk can be minimized by paying attention to the availability of components and the amount of equivalent alternatives that share similar characteristics, footprints, and pinouts or that can be easily adapted.

Considering both pros and cons, this solution seems reasonable, especially given the relatively limited time available for the project, which imply that the second most significant criteria for component selection is their availability.

This section is not a detailed description of every components of the system, it focuses more on mains functional blocks of *LTEWatch*, which are the following :

1. **System MCU** : *nRF9160*
2. **Li-ion/LiPo Battery management unit** : *BQ25180*
3. **Buck Boost Converter (+3V3)** : *TPS63036*
4. **LDO Regulator (+1V8)** : *TPS7A03*
5. **Wireless Power (WPC/QI) Receiver** : *BQ51013B*
6. **LCD Display** : *LS011B7DH03*
7. **GNSS Receiver** : *u-blox MAX-M10S*
8. **FTDI USB To UART Interface :** *FT234XD* (USB to BASIC UART IC)
9. **GNSS Antenna** : *DUO mXTENDTM (NN03-320)*
10. **LTE-M/NB-IOT Antenna** : **P822602** (Universal Broadband FR4 Embedded LTE/LPWA Antenna)
11. **Clock Motors** : *TITAN T901A/T902A*

3.6.1 Li-ion/LiPo Battery management unit - BQ25180

Description :

As describe in its datasheet, the *BQ25180*[23] is a single cell Li-ion/Lipo battery charger in a very small *DSBGA* package (1.6 mm × 1.1 mm), a low quiescent current, up to 1 A charging and up to 2.5 A system loads.

Typical Application Diagram :

Figure 3.8 illustrates the simplified schematic of *BQ25180* battery charger :

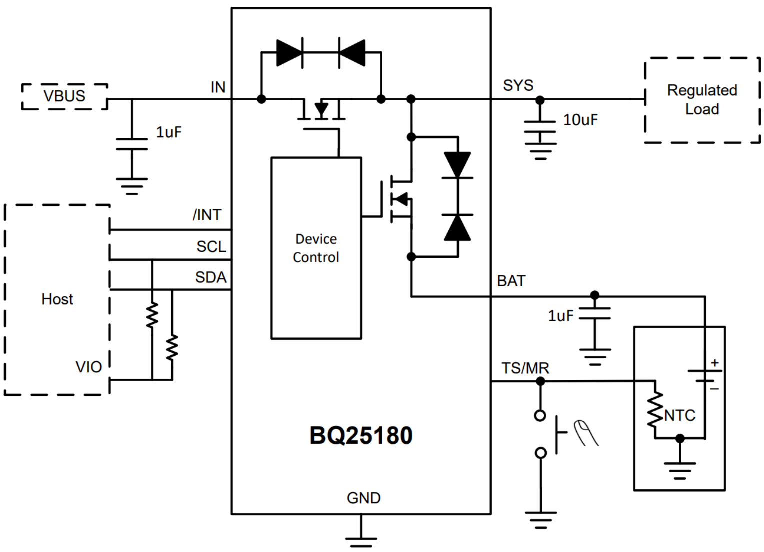


Figure 3.8 – Simplified Schematic - Source : *BQ25180*[23]

The typical application diagram shown in figure 3.8 shows that the implementation of *BQ25180* is very simple and really limits the number of external components needed. This is very positive with regard to the size constraints of wearable devices. Fully programmable settings allow for greater system flexibility and easy battery changes. The downside of programmable settings is extra work during software development as it requires to implement an *I2C* bus and a compatible driver to interface with *BQ25180*.

Features :

The *BQ25180*[23] battery charger main features are the following :

- **Settings :** fully programmable by *I2C* serial bus
- One push-button wake-up and reset input
- **Consumption :**
  - Ultra low quiescent current modes :
    - 15 nA *Shutdown* mode
    - 3.2 µA *Ship* mode with button press wake
    - 3 µA in *Battery Only* mode
    - 30 µA input adapter *Iq* in *Sleep* mode
- **Battery protection :**
  - Integrated Power Path (FET) to disconnect the battery
  - Battery under voltage protection (*UVP*)
  - Battery over voltage protection (*OVP*)
  - Battery short protection
  - Charge and discharge current limitation
  - Battery thermal fault protection
- **System protection :**
  - Thermal regulation and thermal shutdown
  - Watchdog and safety timer fault
  - Input over-voltage protection
  - System short protection
  - System over-voltage protection
- **Size :** 8-pin chip in *DSBGA* package (1.6 mm × 1.1 mm)

The biggest advantage of the *BQ25180* battery charger is the integrated power path, which means that external MOSFETs for battery protection are not required and the management of system powering and battery charging is already implemented. This greatly reduces circuit complexity and component count. The *BQ25180* also has a very low consumption with a quiescent current of only 3 µA when in *Battery Only* mode.

Absolute Maximum Ratings :

The table 3.1 shows the absolute maximum ratings of the *BQ25180* :

		MIN	MAX	UNIT
Input Voltage	IN	-0.3	25	V
Voltage	All other pins	-0.3	5.5	V
Input Current (DC)	IN		1.1	A
SYS Discharge Current (DC)	SYS		1.5	A
SYS Discharge Curr. ($t_{pulse} < 20\,\text{ms}$)	SYS		2.5	A
Output Sink Current	/INT		20	mA
T_J	Junction temp.	-40	150	°C
T_{stg}	Storage temp.	-65	150	°C

Table 3.1 – Absolute Maximum Ratings - Source : *BQ25180*[23]

Recommended Operating Conditions :

The table 3.2 shows the recommended operation conditions of the *BQ25180* :

ID	Description	MIN	MAX	UNIT
VBAT	Battery Voltage Range	2.2	4.6	V
VIN	Input Voltage Range	2.7	5.5	V
IIN	Input Current Range (IN to SYS)		1.1	A
IBAT	Battery Discharge Current (BAT to SYS)		1.5	A
TJ	Operating Junction Temperature Range	-40	125	°C

Table 3.2 – Recommended operating conditions - Source : *BQ25180*[23]

Design Recommendations :

The *BQ25180* implementation is relatively easy, however the datasheet provides some design recommendations that are important to have in mind.

According to the datasheet[23] :

1. **Input decoupling (IN/SYS) Capacitors :**
   — Prefer low *ESR* ceramic capacitors such as *X7R* or *X5R*.
   — Must be placed as close as possible to *VCC* and *groundGND* pins.
   — It is recommended to use 25 V rated capacitors due to their derating voltage.
   — The minimum capacitance after derating must by higher than 1 µF.
2. **TS :** The *GND* connection of the *NTC* should be as close as possible to the *GND* pin of the *BQ25180* or thermally connected to it. This is to minimize any error in TS measurement due to temperature drop in the ground plane of the board.

3. **Recommended Passive Components :**
   The recommended values of the passive components are given in table 3.3 :

ID	*Description*	**MIN**	**NOM**	**MAX**	**UNIT**
C_{SYS}	Capacitance on SYS pin	1	10	100	µF
C_{BAT}	Capacitance on BAT pin	1	1	-	µF
C_{IN}	IN input bypass capacitance	1	1	10	µF

Table 3.3 – Recommended Passive Components - Source : *BQ25180*[23]

3.6.2 Buck Boost Converter (+3V3) - TPS63036

The *MCU* system and all device peripherals need 3.3 V power, so this component is a critical module in the system. There are many voltage regulator solutions available in the market, but the buck-boost converter has the big advantage of being able to step down and step up the supply voltage to 3.3 V. This means that with a buck-boost, it is possible to continue using the battery when its voltage is lower than 3.3 V.

To protect the battery, the over-discharge protection unit must disconnect the battery from the system to prevent its voltage from dropping below 3.0 V. This value depends on the specific characteristics of each battery, but 3.0 V is a safe value for most Li-ion cells. Thus, with a buck-boost converter solution, the battery voltage range between 3.0 V and 3.3 V can still be used to power the system, this represents a valuable additional autonomy.

Typical Application Diagram :

Figure 3.9 illustrates typical application schematic of *TPS63036* :

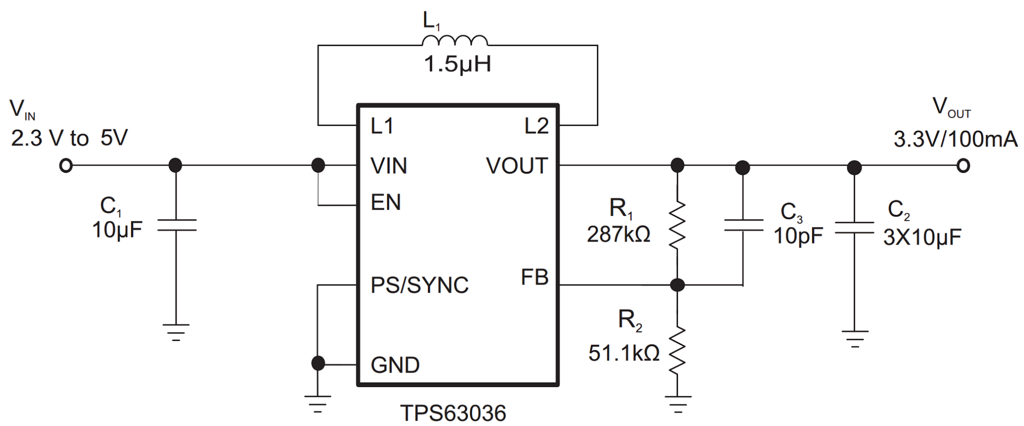


Figure 3.9 – Typical application schematic - Source : *TPS63036*[24]

Description :

As describe in its datasheet, the *TPS63036*[24] is non-inverting buck-boost converter based on a fixed frequency (*PWM*) controller using synchronous rectification to increase efficiency. The high efficiency is also maintain over a wide load current range by entering in power save mode when the load current is low. The maximum output current is limited to a typical value of 1 A. The output voltage is programmable using external resistor divider. To minimize battery drain, the converter can also be disable and the load is disconnected from the supply during shutdown.

Features :

According to the datasheet of the *TPS63036*[24] converter :

- **Performances :**
  - Input voltage from 1.8 V to 5.5 V
  - Adjustable output voltage from 1.2 V to 5.5 V
  - High efficiency over entire load range
- **Consumption**
  - Low operating quiescent current : 25 µA
  - Power save mode available
- **Safety and protection features :**
  - Over-temperature protection
  - Over-voltage protection
  - Load disconnect during shutdown
- **Size :** 8-pin chip in *WCSP* package (1.814 mm × 1.076 mm)

Efficiency vs Output Current :

Figure 3.9 illustrates the graph of efficiency vs output current of the *TPS63036* :

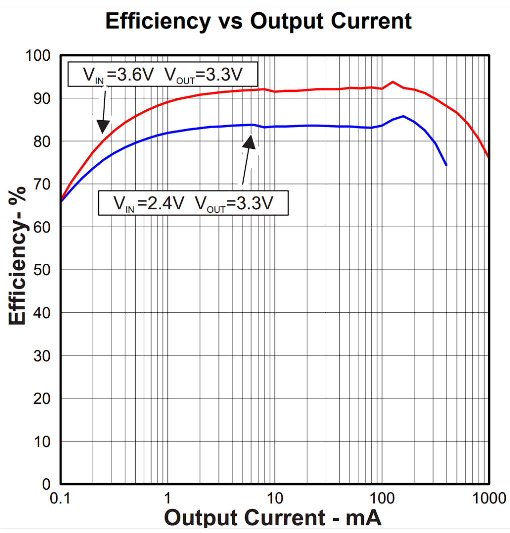


Figure 3.10 – Efficiency vs Output Current Graph - Source : *TPS63036*[24]

Figure 3.10 shows that the *TPS63036* [24] maintains relatively good performance over a wide range of load current consumption :

$$\eta = \begin{cases} > 90\,\% & : \quad 1.5\,\text{mA} < I_{Load} < 1.5\,\text{mA} \\ > 80\,\% & : \quad 250\,\mu\text{A} < I_{Load} < 800\,\text{mA} \end{cases}$$

Absolute Maximum Ratings :

The table 3.4 shows the absolute maximum ratings given by the datasheet of the *TPS63036* [24] :

Description	MIN	MAX	UNIT
Input voltage on VIN, $L1$, $L2$, $VOUT$, $PS/SYNC$, EN, FB	−0.3	7	V
Operating virtual junction temperature, T_J	−40	150	°C
Storage temperature, T_{stg}	−65	150	°C

TABLE 3.4 – Absolute Maximum Ratings - Source : *TPS63036* [24]

Recommended Operating Conditions :

The table 3.5 shows recommended operating conditions according to the datasheet of the *TPS63036* [24] :

Description	MIN	MAX	UNIT
Supply voltage at VIN	1.8	5.5	V
Operating free air temperature, T_A	−40	85	°C
Operating virtual junction temperature, T_J, T_{stg}	−40	125	°C

TABLE 3.5 – Recommended Operating Conditions - Source : *TPS63036* [24]

Design Recommendations :

The datasheet of the *TPS63036* [24] provides design guideline for external components selection. The next sections will follow this guideline for the *LTEWatch* application. For more detailed information, refers to the datasheet of the *TPS63036* [24].

Output Filter Recommendations :

Buck-boost converter have a very noisy output that need to be smoothed with an output filter in order to provide a usable power supply for the load system. Therefore, this filter must be compatible with the internal loop compensation of the *TPS63036*. The datasheet provide the following recommendations :

1. The external filter should be a $L - C$ filter.
2. Low limit condition for the inductor is : $\underline{\underline{L \geq 1\,\mu\text{F}}}$. Below this limit, subharmonic oscillation can appear.

The table 3.11 provide possible L and C value combinations :

INDUCTOR VALUE [µH][1]	OUTPUT CAPACITOR VALUE [µF][2]		
	30	44	66
1.0	√	√	√
1.5	√[3]	√	√
2.2			√

(1) Inductor tolerance and current de-rating is anticipated. The effective inductance can vary by 20% and –30%.
(2) Capacitance tolerance and bias voltage de-rating is anticipated. The effective capacitance can vary by 20% and –50%.
(3) Typical application. Other check mark indicates recommended filter combinations

Figure 3.11 – Output Filter Selection (Current up to 1 A) - Source : *TPS63036* [24]

Inductor Selection :

1. Select inductor with a low DC resistance to minimize conduction loss
2. Avoid saturation of the inductor by calculating the peak current in steady-state operation (eq. 3.1) :

$$\boxed{\begin{aligned} &\text{Duty Cycle Boost :} \quad D = \frac{V_{out} - V_{in}}{V_{out}} \\ &\text{Peak current :} \quad I_{PEAK} = I_{SW\_MAX} + \frac{V_{in} \cdot D}{2 \cdot f \cdot L} \end{aligned}} \tag{3.1}$$

Where :

D : Duty cycle in boost mode
f : Converter switching frequency (typ. 2 MHz)
L : Selected inductor value
η : Estimated converter efficiency (typ. 80 %)
I_{SW_MAX} : Maximum average input current
V_{out} : Output voltage
V_{in} : Minimum input voltage

The *LTEWatch* application uses *Li-Ion/Li-Po* battery as power supply, therefore the worst case is equivalent to a nearly empty battery. To keep some headroom, we can use the extreme value :

$$V_{in} = V_{BAT,EMPTY} = \underline{\underline{3.0\text{V}}}$$

The maximum average input current correspond to the maximal discharge current of the battery. To stay safe for most 500 mA h to 1000 mA h lithium battery, we can use a maximum discharge current :

$$I_{BAT,DCHRG} = I_{SW\_MAX} = \underline{\underline{500\text{mA}}}$$

LTEWatch boost duty cycle :

$$D = \frac{V_{out} - V_{BAT,EMPTY}}{V_{out}} = \frac{3.3 - 3.0}{3.3} = \underline{\underline{9.\overline{09}\%}}$$

LTEWatch peak current with recommanded inductors from the table 3.11 :

$$I_{PEAK} = I_{BAT,DCHRG} + \frac{V_{BAT,EMPTY} \cdot D}{2 \cdot f \cdot L} = 0.5 + \frac{3.0 \cdot 0.\overline{09}}{1 \cdot 2 \cdot 10^6 \cdot L}$$

$$\begin{aligned} &\rightarrow\ L = 1\text{µH} &&\Rightarrow\ I_{PEAK} = \underline{\underline{568\text{mA}}} \\ &\rightarrow\ L = 2.2\text{µH} &&\Rightarrow\ I_{PEAK} = \underline{\underline{531\text{mA}}} \end{aligned}$$

We can see that both inductors generate a very similar peak current around 550 mA, therefore the selected inductor specification should be :

- 1 µH $< L <$ 2.2 µH
- $I_{L,SAT} >$ 600 mA

3. The inductor can affect the stability of the feedback loop. Texas Instrument recommends to keep $f_{RHPZ} >$ 400kHz (eq. 3.2)

$$\boxed{f_{RHPZ} = \frac{(1-D)^2 \cdot V_{out}}{2\pi \cdot i_{out} \cdot L} \quad D:\ \text{Duty cycle in boost mode}} \tag{3.2}$$

For the *LTEWatch* :

$$\rightarrow\ L = 1\text{µH} \quad \Rightarrow\ f_{RHPZ} = \frac{(1-0.\overline{09})^2 \cdot 4.5}{2\pi \cdot 0.5 \cdot 1 \cdot 10^{-6}} = \underline{\underline{1.183\text{MHz}}}$$

$$\rightarrow\ L = 2.2\text{µH} \quad \Rightarrow\ f_{RHPZ} = \frac{(1-0.\overline{09})^2 \cdot 4.5}{2\pi \cdot 0.5 \cdot 2.2 \cdot 10^{-6}} = \underline{\underline{538\text{kHz}}}$$

We can see that both inductors satisfy the recommended condition for f_{RHPZ}.

Input Capacitor Selection :

The datasheet recommends at least a 10 µF ceramic capacitor plassed as close as possible to the *VIN* and *GND* pins of the IC. This capacitor improve the transient behavior of the regulator and *EMI* protection.

Output Capacitor Selection :

The datasheet recommends multiple stage of output capacitors starting with a small ceramic capacitor placed as close as possible to the *VOUT* and *GND* pins of the IC followed by a bigger one. The typical output total capacitor value is 30 µF but there is no upper limit. If it is necessary to reduce output voltage ripple and dropout, it is possible to increase the output capacitor value.

Setting the Output Voltage :

The *TPS63036* converter require an external resistor divider connected between *VOUT*, *FB* and *GND* to set the output voltage. The resistor divider can be calculated with the equation 3.3.

$$\boxed{R_1 = R_2 \cdot \left(\frac{V_{OUT}}{V_{FB}} - 1\right) \quad \rightarrow \quad \text{with :} \begin{cases} V_{FB} = 500\text{mV (typ.)} \\ R_2 \leq 100\,\text{k}\Omega \end{cases}} \tag{3.3}$$

For *LTEWatch* application with $R_2 = 100\text{k}\Omega$ and $V_{OUT} = 3.3\text{V}$:

$$R_1 = R_2 \cdot \left(\frac{V_{OUT}}{V_{FB}} - 1\right) = 100 \cdot 10^3 \cdot \left(\frac{3.3}{0.5} - 1\right) = \underline{\underline{560\text{k}\Omega}}$$

Current Limit :

The *TPS63036* internally limit the average input current to protect the device and the IC. The current limit depends on the input voltage and can be calculated with the equations 3.4 :

$$\boxed{\begin{array}{ll} \text{Duty Cycle Boost} & D = \dfrac{V_{OUT} - V_{IN,BOOST}}{V_{OUT}} \\ \text{Maximum Output Current Boost :} & I_{OUT} = \eta \cdot I_{SW} \cdot (1 - D) \\ \text{Duty Cycle Buck :} & D = \dfrac{V_{OUT}}{V_{IN,BUCK}} \\ \text{Maximum Output Current Buck :} & I_{OUT} = \dfrac{\eta \cdot I_{SW}}{D} \end{array}} \tag{3.4}$$

Where :

η : Estimated converter efficiency (typ. 80 %)
f : Converter switching frequency (typ. 2 MHz)
L : Selected inductor value
I_{SW_MAX} : Maximum average input current
$V_{IN,BOOST}$: Minimum input voltage
$V_{IN,BUCK}$: Maximum input voltage

For *LTEWatch* application :

$$D_{BOOST} = \frac{3.3 - 3.0}{3.3} = 0.\overline{09} \quad \Rightarrow \quad I_{OUT,BST} = 0.8 \cdot 0.5 \cdot (1 - 0.09) = \underline{\underline{728\,\text{mA}}}$$

$$D_{BUCK} = \frac{3.3}{4.5} = 0.7\overline{33} \quad \Rightarrow \quad I_{OUT,BUCK} = \frac{0.8 \cdot 0.5}{0.7\overline{33}} = \underline{\underline{1.09\,\text{A}}}$$

NORDIC SEMI recommended to use a power supply that can withstand at least 500 mA for the *nRF9160* SiP. We can see that the maximum output current of the *TPS63036* is higher than 500 mA which is perfect.

3.6.3 LDO Regulator (+1V8) - TPS7A03

This component is added to give more flexibility to the prototype board by allowing the possibility to set the voltage of the *GPIOs* of the device to 1.8 V or 3.3 V, with a jumper. This component is not very critical and should only be able to deliver sufficient current to the *GPIOs*.

Description :

As described in the datasheet, the *TPS7A03*[25] is an ultra-small, ultra-low quiescent current low dropout linear regulator (LDO) with an output range of 0.8 V to 5.0 V and an output current of 200 mA. This component is specifically design for compact wearable device like :

- Wearables electronics
- Thermostats, smoke and heat detectors
- Gas, heat, and water meters
- Blood glucose monitors and pulse oximeters
- Residential circuit breakers and fault indicators
- Building security and video surveillance devices
- *EPOS* card readers

Features :

- **Consumption :**
  - Ultra-low I_Q : 200 nA (typ. even in dropout)
  - Shutdown I_Q : 3 nA (typ.)
- **Performances :**
  - Excellent transient response (1 mA to 50 mA) :
    - $<$ 10 µs settling time
    - 80 mV undershoot
  - Input voltage range : 1.5 V to 6.0 V
  - Output voltage range :0.8 V to 5.0 V (fixed)
  - Output accuracy : 1.5 % over temperature
  - Smart enable with integrated pulldown (*LDO* disabled even when the EN pin is left floating)
  - Very low dropout : 270 mV (max) at 270 mA ($V_{OUT} = 3.3$ V)
  - Stable with a 1 µF or larger capacitor
- **Size and available packages :**
  - *X2SON* : 1.0 mm × 1.0 mm
  - *DSBGA* : 0.64 mm × 0.64 mm
  - *SOT23-5*

Typical Application Diagram :

Figure 3.12 illustrates a typical application circuit for the *TPS7A03* :

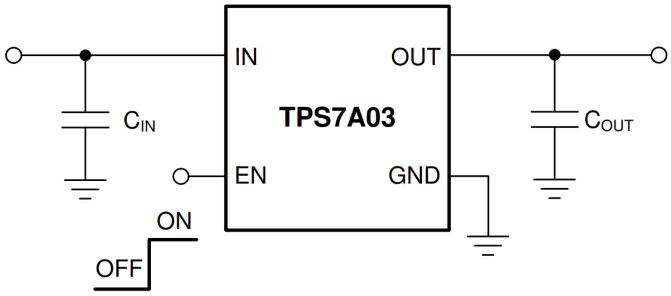


Figure 3.12 – Typical application schematic - Source : *TPS7A03*[25]

Absolute Maximum Ratings :

The table 3.6 shows the absolute maximum ratings provided by the datasheet of the *TPS7A03* :

ID	Description	MIN	MAX	UNIT
Voltage	V_{IN}	-0.3	6.5	V
Voltage	V_{EN}	-0.3	6.5	V
Voltage	V_{OUT}	-0.3	$V_{IN} + 0.3$ or 5.5	V
Current	Max output	Inter. lim.	Internally limited	A
Temperature	Operating junction, T_J	-40	150	°C
Temperature	Stroage T_{stg}	-65	150	°C

Table 3.6 – Absolute Maximum Ratings - Source : *TPS7A03*[25]

Recommended Operating Conditions :

The recommended operating conditions are given in table 3.7 :

ID	*Description*	MIN	NOM	MAX	UNIT
V_{IN}	Input voltage	1.5	-	6.0	V
V_{EN}	Enable voltage	0	-	6.0	V
V_{OUT}	Output voltage	0.8	-	5.0	V
I_{OUT}	Output current	0	-	200	mA
C_{IN}	Input capacitor	-	1	-	µF
C_{OUT}	Output capacitor	1	1	22	µF
F_{EN}	*EN* toggle frequency	-	-	10	kHz
T_J	Operating junction temperature	-40	-	125	°C

Table 3.7 – Recommended Operating Conditions - Source : *TPS7A03*[25]

Design Recommendations :

Figure 3.13 illustrates a recommended implementation schematic for application power from a battery input supply :

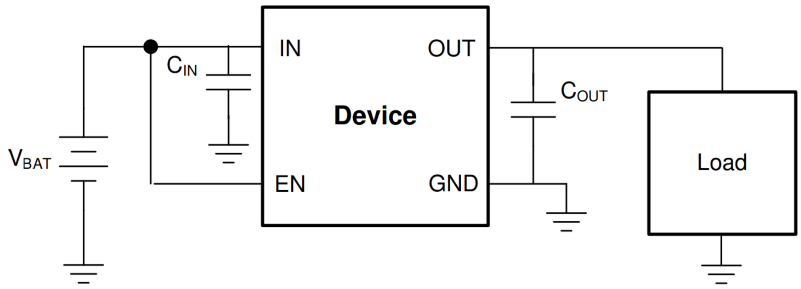


Figure 3.13 – Recommended Implementation Schematic - Source : TPS7A03[25]

1. **Input and output capacitors selection :**

   The implementation of the **TPS7A03** is straightforward and only require to add input and output ceramic capacitors :

   $$\boxed{C_{IN} = 1\,\mu F} \qquad \boxed{C_{OUT} = 1\,\mu F}$$

2. **Temperature effect :**

   Temperature has a significant effect on the **TPS7A03** performances. Figure 3.14 illustrate the current efficiency against the output current and the temperature :

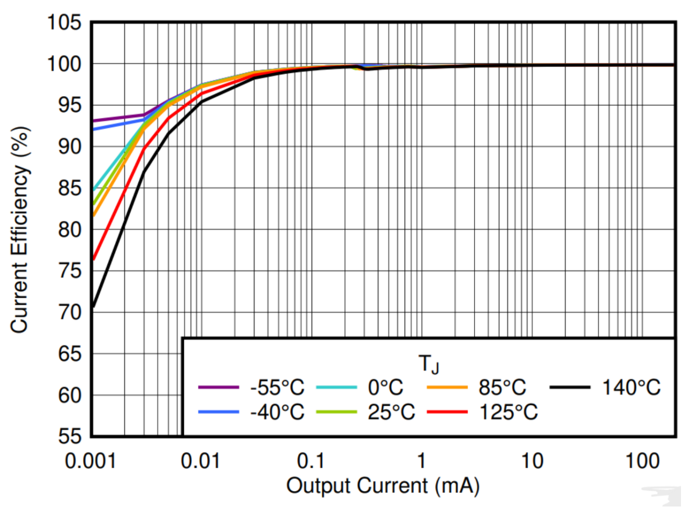


Figure 3.14 – Current Efficiency vs I_{OUT} and Temperature - Source : TPS7A03[25]

3. **Power Supply Recommendations :**

   — Power supply output voltage range of 1.5 V to 6.0 V

   — Power supply must regulated and free of spurious noise

   — To ensure good performances, V_{IN} must be at least $V_{OUT(nom)} + 0.5\,V$

3.6.4 WPC Receiver - BQ51013B

Wireless charging became more and more usual in wearable device, therefore it was decided to include a wireless power receiver (*WPC*) on the device.

Description :

The datasheet[26] describes the *BQ51013B* as a single chip, advanced and flexible secondary side for wireless power transfer up to 5 W for portable applications. The chip provides a receiver with *AC-to-DC* power conversion and regulation and fully integrates the digital control required to comply with the *Wireless Power Consortium (WPC) Qi v1.2* communication protocol.

The *BQ51013B* also integrates a low-resistance synchronous rectifier, a *LDO*, digital control, and accurate voltage and current loops for a high efficiency and low power dissipation module.

The *BQ51013B* is design for portable applications, such as :
- *WPC v1.2* compliant receivers
- Cell phones and smart phones
- Headsets
- Digital cameras
- Portable media players
- Handheld devices

Typical Application Diagram :

Figure 3.15 illustrates the simplified schematic of *BQ51013B* :

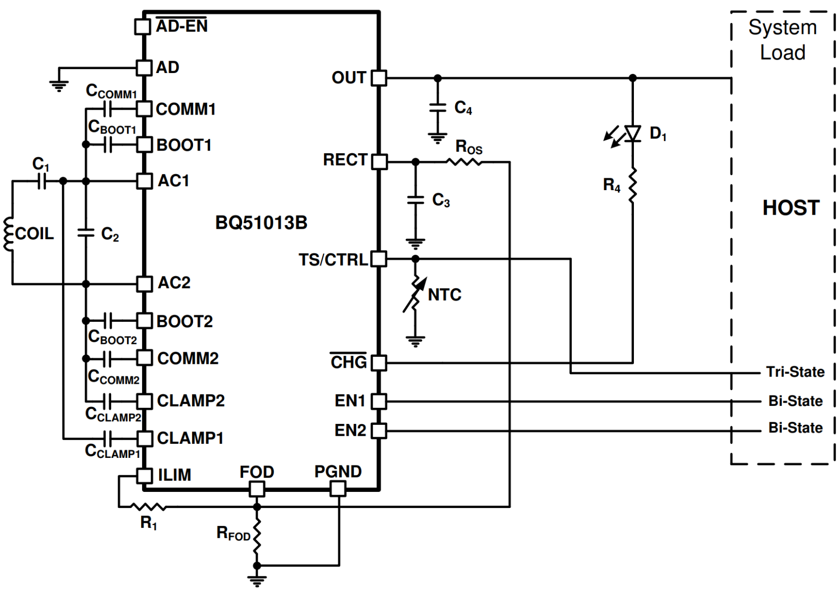


FIGURE 3.15 – Simplified Schematic - Source : *BQ51013B*[26]

Features :

- **Specification and performances :**
  - 93 % Overall peak *AC-DC* efficiency
  - *WPC v1.2* compliant communication control
  - Output voltage conditioning
  - for Improved load transient response by dynamic rectifier control
  - Optimization of performance by dynamic efficiency scaling
  - Supports input up to 20 V
- **Control and safety features :**
  - Rectifier over-voltage clamp with low-power dissipation ($V_{OVP} = 15\,\text{V}$)
  - Thermal shutdown protection
  - Control pin for temperature monitoring, charge complete, and fault host check
  - Multifunction *NTC*
- **Size and package :**
  - VQFN 20-Pin : 4.5 mm × 3.5 mm
  - DSBGA 28-Pin : 3.0 mm × 1.9 mm

Absolute Maximum Ratings :

The table 3.8 shows the absolute maximum ratings of the *BQ51013B* :

<table>
<tr><th>ID</th><th>Description</th><th>MIN</th><th>MAX</th><th>UNIT</th></tr>
<tr><td rowspan="5">Input voltage</td><td>AC1, AC2</td><td>-0.8</td><td>20</td><td rowspan="5">V</td></tr>
<tr><td>RECT, COMM1, COMM2, OUT, $\overline{\text{CHG}}$, CLAMP1, CLAMP2</td><td>-0.3</td><td>20</td></tr>
<tr><td>AD, $\overline{\text{AD-EN}}$</td><td>-0.3</td><td>30</td></tr>
<tr><td>BOOT1, BOOT2</td><td>-0.3</td><td>26</td></tr>
<tr><td>EN1, EN2, FOD, TS/C-TRL, ILIM</td><td>-0.3</td><td>7</td></tr>
<tr><td>Input current</td><td>AC1, AC2</td><td>-</td><td>2</td><td>A(RMS)</td></tr>
<tr><td>Output current</td><td>OUT</td><td>-</td><td>1.5</td><td>A</td></tr>
<tr><td rowspan="2">Output sink current</td><td>$\overline{\text{CHG}}$</td><td>-</td><td>1500</td><td rowspan="2">A</td></tr>
<tr><td>COMM1, COMM2</td><td>-</td><td>1</td></tr>
<tr><td>Junction temperature</td><td>T_J</td><td>-40</td><td>150</td><td>°C</td></tr>
<tr><td>Storage temperature</td><td>T_{stg}</td><td>-65</td><td>150</td><td>°C</td></tr>
</table>

Table 3.8 – Absolute maximum ratings - Source : *BQ51013B*[26]

Recommended Operating Conditions :

The table 3.9 shows the recommended operation conditions of the *BQ51013B* :

ID	Description	Pin	MIN	MAX	UNIT
V_{RECT}	Voltage	RECT	4	10	V
I_{RECT}	Current through internal rectifier	RECT	-	1.5	A
I_{OUT}	Output current	OUT	-	1.5	A
V_{AD}	Adapter voltage	AD		15	V
I_{AD-EN}	Sink current	$\overline{\text{AD-EN}}$	-	1	mA
I_{COMM}	COMMx sink current	COMM1, COMM2	-	500	mA
T_J	Junction Temperature		0	125	°C

TABLE 3.9 – Recommended operating conditions - Source : *BQ51013B*[26]

Design Recommendations :

Concerning the implementation of the *WPC* receiver, model chosen was the "*Dual Power Path : Wireless Power and DC Input*" solution from the datasheet of the *BQ51013B*[26] and the schematic of the *bq51013xEVM-764* evaluation module (*EVM*) from TEXAS INSTRUMENT.

Figure 3.16 illustrates "*Dual Power Path : Wireless Power and DC Input*" solution schematic for the *BQ51013B* wireless power receiver :

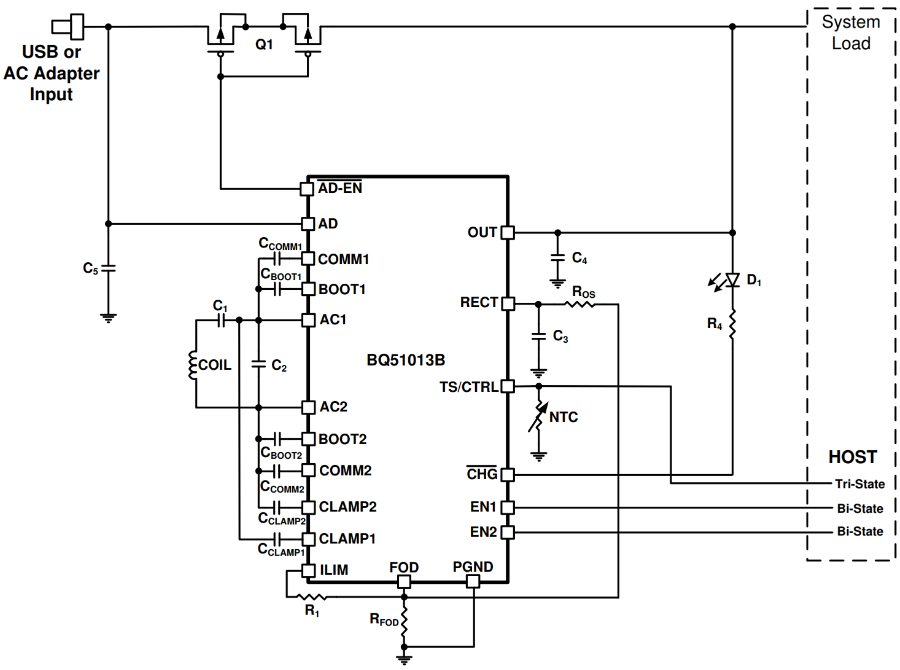


FIGURE 3.16 – Wireless Power Receiver and Power Supply for System Loads With Adapter Power-Path Multiplexing - Source : *BQ51013B*[26]

Series and Parallel Resonant Capacitor Selection

Following the figure 3.17 from the datasheet of the *BQ51013B*[26], the series capacitors C_1 and parallel capacitors C_2 creates a dual resonant circuit with the receiver coil, therefore these two capacitors must be sized correctly according to the *WPV v1.2* specification.

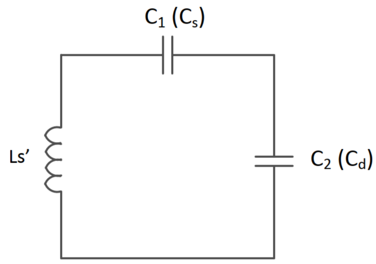


FIGURE 3.17 – Dual Resonant Circuit With the Receiver Coil - Source : *BQ51013B*[26]

The two capacitors can be calculated with the equations 3.5 :

$$\boxed{C_1 = \left[\left(f_S \cdot 2\pi\right)^2 \cdot L'_S\right]^{-1}} \qquad \boxed{C_2 = \left[\left(f_D \cdot 2\pi\right)^2 \cdot L_S - \frac{1}{C_1}\right]^{-1}} \tag{3.5}$$

Where :

$$\underline{\underline{f_S = 100\,\text{kHz} + 5/-10\,\%}} \qquad \underline{\underline{f_D = 1\,\text{MHz} \pm 10\,\%}}$$

Note : C_1 must be chosen prior to calculating C_2.

According to the datasheet, the quality factor must be : $\underline{\underline{Q > 77}}$ and is determined with the equation 3.6 :

$$\boxed{Q = \frac{2\pi \cdot f_D \cdot L_S}{R}} \qquad \text{Where, } R : \text{DC resistance of the receiver coil} \tag{3.6}$$

Following the solution from the datasheet, the selected inductance for the application gives :

$$\underline{\underline{L_S = 11\,\mu\text{H}}} \qquad \underline{\underline{L'_S = 16\,\mu\text{H}}} \qquad \underline{\underline{R = 191\,\text{m}\Omega}}$$

Using the equation 3.5 :

$$C_1 = \left[\left(100 \cdot 10^3 \cdot 2\pi\right)^2 \cdot 16 \cdot 10^{-6}\right]^{-1} = \underline{\underline{158.3\,\text{nF}}}$$

With f_S $(+5/-10\%)$, the range of C_1 is : $\underline{\underline{144\,\text{nF} \leq C_1 \leq 175\,\text{nF}}}$

For an optimal solution of three parallel capacitors, the selected values are :

$$\boxed{C_{1a} = 68\,\mathrm{nF},\ C_{1b} = 47\,\mathrm{nF},\ C_{1c} = 39\,\mathrm{nF} \quad \Rightarrow \quad C_{1tot} = \underline{\underline{154\,\mathrm{nF}}}}$$

With C_1 defined, it is possible to calculate C_2 (eq. 3.5) :

$$C_2 = \left[\left(1 \cdot 10^6 \cdot 2\pi\right)^2 \cdot 11 \cdot 10^{-6} - \frac{1}{154 \cdot 10^{-9}}\right]^{-1} = \underline{\underline{2.3\,\mathrm{nF}}}$$

An easy solution of two capacitors is :

$$\boxed{C_{2a} = 2.2\,\mathrm{nF},\ C_{2b} = 100\,\mathrm{pF} \quad \Rightarrow \quad C_{2tot} = \underline{\underline{2.3\,\mathrm{nF}}}}$$

Now, the quality factor condition can be tested (eq. 3.6) :

$$Q = \frac{2\pi \cdot 10^6 \cdot 11 \cdot 10^{-6}}{191 \cdot 10^{-3}} = \underline{\underline{361.86 > 77}} \checkmark$$

Those values of capacitors are totally dependent to the used coil and must be adapted to the used coil specification. The datasheet also recommend to use ceramic capacitors with a **minimum voltage range** of $\underline{\underline{25\,\mathrm{V}}}$.

COMM, CLAMP, and BOOT Capacitors Selection

COMM, CLAMP and BOOT capacitors values from the *BQ51013BEVM-764* evaluation module of the *BQ51013B* can be used for most application :

$$\boxed{\begin{array}{lllll} C_{BOOT1} & = & C_{BOOT2} & = & \underline{\underline{10\,\mathrm{nF}}} \\ C_{CLAMP1} & = & C_{CLAMP2} & = & \underline{\underline{470\,\mathrm{nF}}} \\ C_{COMM1} & = & C_{COMM2} & = & \underline{\underline{22\,\mathrm{nF}}} \end{array}}$$

Note : All capacitors must have a **minimum voltage range** of $\underline{\underline{25\,\mathrm{V}}}$.

Control Pins and $\overline{\textbf{CHG}}$ external components selection

The **TS/CTRL** pin can be used as a temperature sensor with an external *NTC* of $10\,\mathrm{k\Omega}$. Even with a *NTC* connected, this pin can still be used as system controller. In this case de *GPIO* will be in high impedance for normal temperature sense control.

The $\overline{\textbf{CHG}}$ can be used as a power transfer indicator by connecting a forward bias LED and a current limiting series resistor.

Current Limit and FOD External Components Selection

The *BQ51013B* also have a current limit and foreign object (*FOD*) functions. Those two functions are related :

- $R_1 + R_{FOD}$ set the current limit
- *FOD* calibration determines R_{FOD} and R_{OS}, default value :

$$\boxed{R_{FOD} = 196\,\mathrm{k\Omega}} \qquad \boxed{R_{OS} = 20\,\mathrm{k\Omega}}$$

The equations 3.7 are used to determine the value of R_1 and R_{FOD} :

$$\boxed{\begin{aligned} R_{ILIM} &= \frac{K_{IMAX}}{I_{MAX}} & R_{ILIM} &= R_1 + R_{FOD} \\ I_{ILIM} &= 1.2 \cdot I_{MAX} = \frac{K_{ILIM}}{R_{ILIM}} \end{aligned}} \tag{3.7}$$

Where :

- I_{MAX} : Expected maximum output current during normal operation
- I_{ILIM} : Hardware over-current limit

For the *LTEWatch* device :

$$I_{MAX} = 1\,\mathrm{A} \qquad R_{FOD} = 196\,\Omega \quad K_{IMAX} = 262\,\mathrm{A}\,\Omega \qquad K_{ILIM} = 314\,\mathrm{A}\,\Omega$$

The resistance R_1 can be determined with equations 3.7 :

$$I_{ILIM} = 1.2 \cdot I_{MAX} = 1.2 \cdot 1 = \underline{\underline{1.2\,\mathrm{A}}} \;\rightarrow\; R_{ILIM} = \frac{K_{ILIM}}{I_{ILIM}} = \frac{314}{1.2} = \underline{\underline{262\,\Omega}}$$

$$\boxed{\Rightarrow\; R_1 = R_{ILIM} - R_{FOD} = \underline{\underline{66\,\Omega}}}$$

RECT and OUT Capacitance Selection

A capacitor is connected to RECT to smooth th *AC-to-DC* conversion and prevent minor current transient from passing to OUT. The datasheet recommends to use two 10 µF capacitors followed by one 100 nF for $I_{MAX} = 1\,\mathrm{A}$. The capacitors must be rated to at least 16 V.

A capacitor connected on OUT is used to smooth any ripple from minor load transients. A single 10 µF capacitors followed by a single 100 nF is enough.

Dual Power Path Blocking FET Selection

In dual power path solution, an external blocking FET is required. The datasheet of the *BQ51013B* recommends the *CSD75207W15*, which is *WCSP* package integrated a *P-Channel*, 20 V, 3.9 A FET pair.

As the *CSD75207W15* component was not available, another model with similar specification was used. The selected component is the *CSD75208W1015*, a *P-Channel*, 20 V, 1.6 A FET pair, which is enough for the *LTEWatch* application.

EN1 and EN2 Inputs

EN1 and EN2 are used to enable/disable the wireless/wired charging (tab. 3.10) :

EN1	EN2	Description
0	0	Wireless charging is enabled
0	1	Dynamic communication current limit disabled
1	0	Wireless charging disabled
1	1	Wireless charging disabled

Table 3.10 – Recommended operating conditions - Source : *BQ51013B*[26]

3.6.5 Accelerometer - MC3635

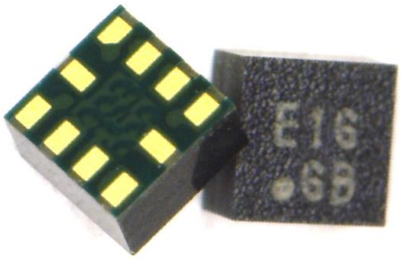


Figure 3.18 – MC3635 3-Axis Accelerometer from mCube - Source : *MC3635* [27]

Description :

The *MC3635* [27] is described in its datasheet as an ultra-low power, low-noise, integrated digital output 3-axis accelerometer optimized for wearable applications and *IoT* devices.

Features :

- **Range, Sampling and Power :**
  - ±2, 4, 8, 12 or 16 g ranges
  - 8, 10 or 12 bit resolution with *FIFO* or 14 bit single samples
  - Sample rate from 14 to 1300 sample/s that can be triggered via :
    - Internal oscillator
    - Clock pin
    - Software command
  - *Sniff* and *Wake* modes :
    - 0.4 µA *Sniff* current at 6 Hz
    - Separate or combined *Sniff* / *Wake*
  - Ultra-Low Power with 32 sample *FIFO* :
    - 0.9 µA typical current at 25 Hz
    - 1.6 µA typical current at 50 Hz
    - 2.8 µA typical current at 100 Hz
    - 36 µA typical current at 1.3 kHz
- **System Integration :**
  - *I2C* interface up to 1 MHz
  - *SPI* Interface up to 4 MHz
  - 1.6 × 1.6 × 0.94 mm 10 Pin package
  - Single-chip *3D silicon MEMS*
  - Low noise to 2.3 mg(RMS)

Typical Application Diagram :

Figure 3.19 illustrates a typical 4-wire *SPI* Application Circuit for the *MC3635* :

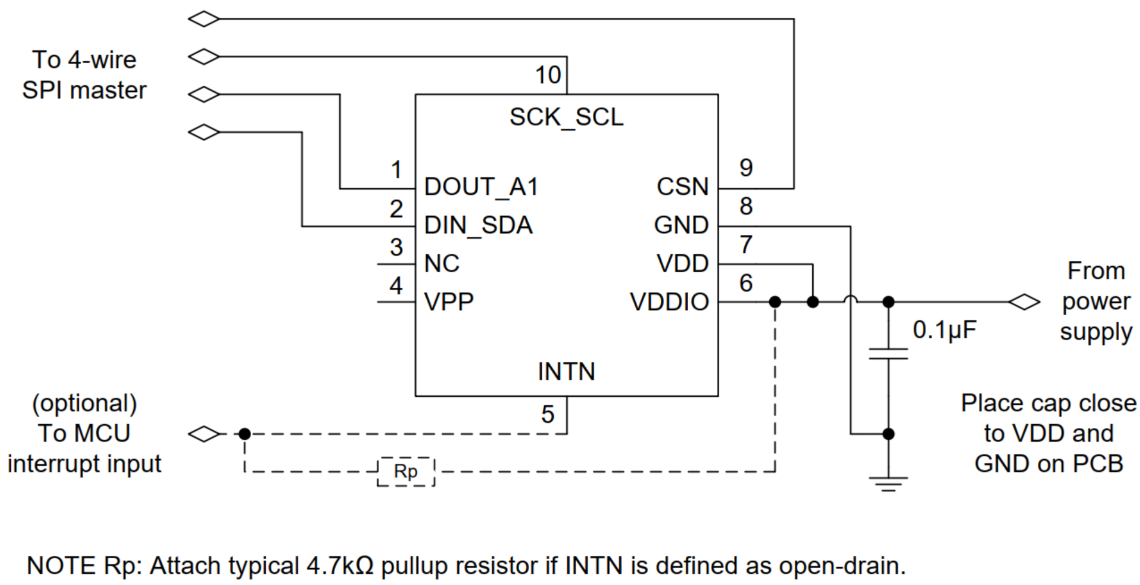


Figure 3.19 – Typical 4-wire SPI Application Circuit - Source : *MC3635*[27]

Absolute Maximum Ratings :

The table 3.11 shows the absolute maximum ratings provided by the datasheet of the *MC3635* :

ID	Symbol	MIN	MAX	UNIT
Supply Voltages	VDD, VDDIO	-0.3	$+3.6$	V
Acceleration, any axis, 100 µs	g_{MAX}	-	10000	g
Ambient operating temperature	T_{OP}	-40	$+85$	°C
Storage temperature	T_{STG}	-40	$+125$	°C
ESD human body model	*HBM*	-2	$+2$	kV
Input voltage to non-power pin	CSN, DIN_SDA, DOUT_A1, INTN, SCK_SCL	-0.3	(VDDIO +0.3) or 3.6	V

Table 3.11 – Absolute Maximum Ratings - Source : *MC3635*[27]

3.6.6 LCD Display - LS011B7DH03

Even if the *LTEWatch* use clock hands to display the time, it is also a connected smart-watch which means that the device require à screen to display more complex information, such as date, connection state, notifications and settings.

Finding a display for the *LTEWatch* is not an easy task despise the fact that smart-watch round format display are widely available. The perfect solution would be a perforated round display to let the clock hands rotor pass through the screen. This kind require custom order and are not available for average customer and require too much time to be a suitable solution for this Master Thesis project. The best compromise solution for the moment is to select a display that is small enough to be placed next to the motors on a 45-50 mm diameter watch.

The next step is to choose the display technology. After many research the selected display is the *LS011B7DH03*[28] from Sharp which is a *Memory In Pixel (MIP) LCD*, a display technology specifically design for outdoor application with battery supply.

Figure 3.20 – Sharp *MIP* Display Technology - Source :[29]

Description :

On Sharp website[29], their *MIP* LCDs are described as, ultra-low power consumption and high readability screen for any ambient lighting ans environment. They exist in 64 colors or high-contrast monochrome solution.

MIP screen are reflective screen, this mean that they do not require back light which can already drastically reduce the consumption of the device. The display driver circuits is also directly integrated into the panel for a easy to implement, lightweight and compact solution.

Sharp Memory-in-Pixel LCDs offer the following features :

- **Product Line-up :**
  - Available in diagonal sizes ranging from 1.08 " to 4.40 " (27.432 mm to 111.785 mm)
- **High readability :**
  - Viewable in any light, from edge-of-vision to bright sunlight.
- **Color solutions :** Available in 64 colors or Monochrome solution
- **Operating Temperature :**
  - Wide operating temperatures for the most extreme environments
- **View Angle :**
  - Wide, symmetrical viewing angles, typically 120 ° × 120 °
- **Ultra-low Power Consumption :**
  - Consumption of only 1.25 % to 2.5 % of a *STN* LCD's and approximately 0.1 % of an *AM-TFT* LCD's
  - Excellent reflective display performance without the need for a backlight
  - TFT glass with monolithic embedded driver and peripheral circuits. Each pixel contains 1 bit *SRAM* memory to stores graphic data, therefore still image does not require continuous refresh. Moreover, refresh require less power than with traditional graphic displays :

Model	128 × 128	400 × 240
Static Image	12 µW	50 µW
1 Hz **Dynamic Update**	50 µW	175 µW

Table 3.12 – Power Consumption for 1.28 " and 2.7 " Memory *LCDs*

- **Interface :**
  - Easy implementation with a 3 wires *SPI* serial interface (*SI*, *SCS*, *SCK*)
- **Fast Image Refresh Time :**
  - *MIP LCDs* have fast response times for scrolling text and moving images, way better performances than *Cholesteric*, *STN*, and *E-Ink* displays.

Data Refresh Rate	20 Hz (typ.)
***LCD* Response time** (Black to White/White to Black	10 µs/20 µs

Table 3.13 – Refresh Rate and Time Performances Of Memory *LCDs*

Memory-in-Pixel (*MIP*) LCDs from Sharp seems to be a suitable solution for *LTEWatch*. Based on this choice, the best fitting model is the *LS011B7DH03*. The following sections are based on the datasheet of the *LS011B7DH03*[28].

Features :

The *LS011B7DH03 MIP LCD* from SHARP have the following features :

- **Performances and Image Quality :**
  - Reflective *TFT-LCD* active-matrix with slightly transmissive panel of white and black
  - Screen with 1.08 ” diagonal and 160 × 68 resolution for a total strip array of 10 880 pixels
  - Screen with an anti-glare *AG* front polarized surface
  - High image refresh rate range up to 70 Hz
- **Controls and Interfaces** :
  - Mounted with a 10-Pin flat cable compatible with *FPC* type connector
  - Simple 3-wire *SPI* serial data signal communication up to 1 MHz
  - Panel with integrated data storage of 1 bit per pixel
  - Arbitrary line data renewable mode
- **Mechanical Properties :**

  Monolithic construction for a compact, thin and lightweight panel with an outline dimension of 32 mm×14 mm×0.745 mm (W×H×D)
- **Power Consumption**
  1. Hold Mode (no display data update with all black pattern) :
     a) 15 µW (typ.)
     b) 50 µW (max)
  2. Data update mode (1 Hz with vertical stripe pattern) :
     a) 25 µW (typ.)
     b) 100 µW (max)

Mechanical Specification

Mechanical specification of the *LS011B7DH03* is presented in table 3.14

ID	Specification	Unit
Screen size	1.8 ”	inch
Active area (H×V)	25.28 × 10.744	mm
Dot configuration (H×V)	160 × 68	Dot (Pixel)
Pixel array	square	-
Display mode	Normally White	-
Outline dimension (W×H×D)	32.000 × 14.000 × 0.745	mm
Mass (max)	0.73	g
Surface hardness	3H	Pencil Hardness
Surface treatment	Anti-Glare (*AG*)	-

TABLE 3.14 – Mechanical specification of the *LS011B7DH03* - Source : datasheet[28]

Absolute Maximum Ratings :

Absolute maximum ratings of the *LS011B7DH03* are presented in table 3.15 :

ID	**Symbol**	**MIN**	**MAX**	**Unit**
Power Supply Voltage	VDDA	-0.3	$+3.6$	V
	VDD	-0.3	$+3.6$	V
Input Signal Voltage (*Hi*)	VHI	-	VDD	V
Input Signal Voltage (*Low*)	VLI	-0.3	VDD	V
Storage Temperature	T_{stg}	-30	$+80$	°C
Operating Temperature	T_{opr}	-20	$+70$	°C

Table 3.15 – Absolute Maximum Ratings - Source : *LS011B7DH03*[28]

Recommended Operating Conditions :

Recommended operating conditions of the *LS011B7DH03* are presented in table 3.16 :

ID	**Symbol**	**MIN**	TYP	**MAX**	**Unit**
Power Supply Voltage	VDDA	$+2.7$	$+3.0$	$+3.3$	V
	VDD	$+2.7$	$+3.0$	$+3.3$	V
Input Signal Voltage (*Hi*)	VHI	VDD-0.1	VDD	VDD	V
Input Signal Voltage (*Low*)	VLI	VSS	VSS	VSS$+0.1$	V

Table 3.16 – Recommended Operating Conditions - Source : *LS011B7DH03*[28]

Design Recommendations :

Figure 3.21 illustrates the typical application schematic for the *LS011B7DH03* :

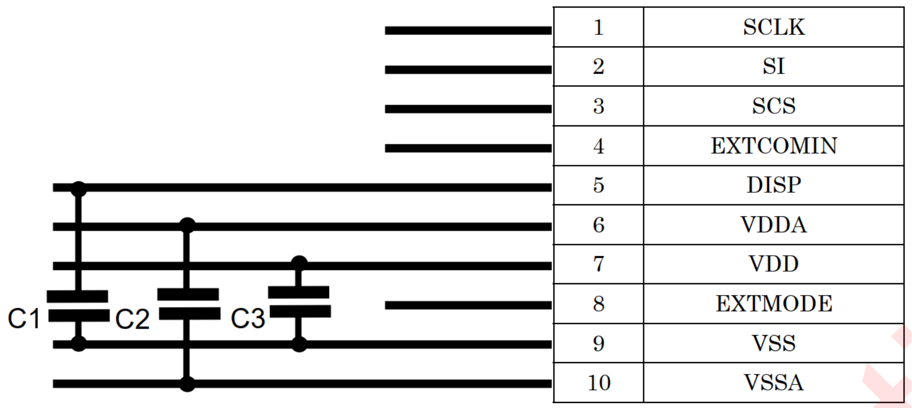


Figure 3.21 – Typical Application Circuit - Source : *LS011B7DH03*[28]

The *LS011B7DH03* have a very simple integration process and only requires three external capacitor ceramic capacitors ; C_1 C_2 and C_3, to filter power supply lines of the panel. The recommended capacitors are listed in table 3.17.

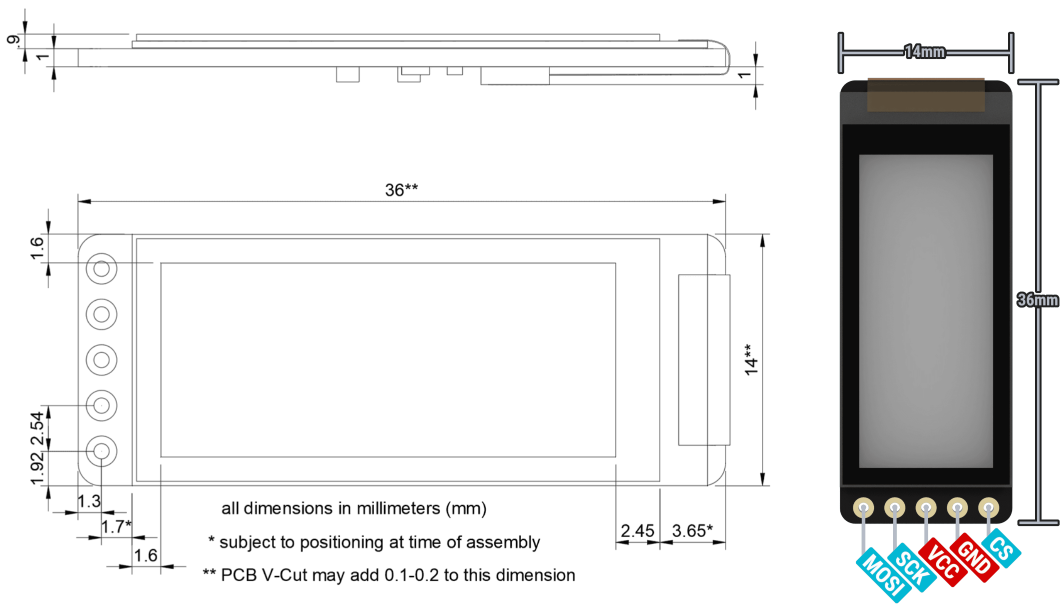
ID	Specification	Value	Unit
C_1	Rank B ceramic capacitor	$560^{(1)}$	pF
C_2	Rank B ceramic capacitor	1.0	µF
C_3	Rank B ceramic capacitor	1.0	µF

(1) : Must be adjusted to respect *DISP* rise time limit (50 ns)

Table 3.17 – External Capacitor Recommendation - Source : *LS011B7DH03*[28]

nice !view breakout board for *LS011B7DH03*

Nice Technologies LLC sells breakout board for the *LS011B7DH03* : *nice !view*. This has the advantage of making the display easier to order but it also guaranty to have an easy to implement solution for a prototype board. Mechanical characteristics and pinout are illustrated in the figure 3.22 :



(a) Dimensions (b) Pinout

Figure 3.22 – *nice !view* Breakout Board for *LS011B7DH03* - Source : [30]

Nice Technologies LLC also provides an open source schematic of the textitnice !view breakout board for *LS011B7DH03* illustrated in figures 3.23 to 3.24 :

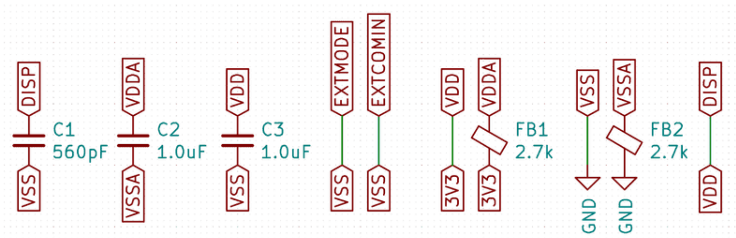


Figure 3.23 – *nice !view* Electrical Schematic (Part 1) - Source : [30]

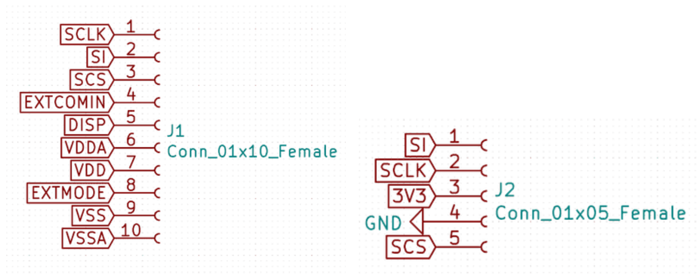


Figure 3.24 – *nice !view* Electrical Schematic (Part 2) - Source : [30]

3.6.7 GNSS Receiver - MAX-M10S

Figure 3.25 illustrate the *MAX-M10S* module from u-blox :

Figure 3.25 – Module *MAX-M10S* from u-blox - Source : [31]

As mentioned in the system decomposition, the choice was made to integrate an external *GNSS* receiver to the device. After researches for suitable solutions, the most interesting solution seamed to be the last *M10* series from *u-blox*.

Introduction to u-blox *M10* series :

The *M10*[32] series is the tenth generation of standard precision *GNSS* technology platform form u-blox. The *M10* series offers ultra-low-power positioning in an ultra-compact form factor with solid accuracy and good availability. This series is advertised to consume less than 15 mW in continuous tracking mode and high RF sensitivity which guarantees a short time to establish a position. The *M10* platform was specifically designed for small battery-powered wearable applications.

The *M10* series form u-blox is ideal for compact product design and smartwatches by providing interesting features, such as :

- **RF interference mitigation (*RIM*)** : Technique to protect *GNSS* receivers from interference and jamming without compromising final position, velocity and timing accuracy [33]. *RIM* gives protection against :
  - **Advanced jamming** : Intentional and deliberate interference by radiation of electromagnetic signals at *GNSS* frequencies [34].
  - **Spoofing** : Malicious and deliberate practice of altering a user's *GNSS* measurements, making positioning unreliable [35].
- **Super-S technology :** Boost performance in weak signal environments or when used with small antennas.

Description :

Following the datasheet[31] of the *MAX-M10S GNSS* receiver module from U-BLOX, here is an overview of the module :

— The *MAX-M10S* is built on the ultra low power U-BLOX *M10 GNSS* platform and provide extremely good performances for all *L1 GNSS* systems.

— Power consumption lower than 25 mW in continuous tracking mode, which allows great for all battery-operated devices.

— Supports concurrent reception of four *GNSS* (*GPS, GLONASS, Galileo, and BeiDou*) for maximum position availability by selection of best available signal. This gives better reliability in challenging conditions like urban environment.

— U-BLOX *Super-S* technology offers excellent sensitivity with small antennas and is claiming to be able to improve the dynamic position accuracy by up to 25 % in a a non-line-of-sight scenario.

— The module integrates an *LNA* and a *SAW* filter in the RF path to improve sensitivity for design with passive antenna.

— Provides advanced spoofing and jamming detection

— Offer backwards pin-to-pin compatibility with previous U-BLOX generations which is interesting for design upgrade.

— Compact module : 10.1 mm × 9.7 mm

Performance :

The general performance of the *MAX-M10S* module is described in table 3.18 :

Parameter	Specification	Value
Receiver type		u-blox M10 receiver
Accuracy of time pulse signal	RMS	30 ns
	99%	60 ns
Frequency of time pulse signal		Default 1PPS (0.25 Hz to 10 MHz configurable)
Operational limits[1]	Dynamics	≤ 4 g
	Altitude	80,000 m
	Velocity	500 m/s
Velocity accuracy[2]		0.05 m/s
Dynamic heading accuracy[2]		0.3 deg

TABLE 3.18 – *MAX-M10S* - General Performance - Source : [31]

The typical performance in multi-constellation *GNSS* modes of the *MAX-M10S* module is presented in table 3.19 :

Parameter		GPS+GAL	GPS+GAL +GLO	GPS+GAL +BDS B1I	GPS+GAL +BDS B1C	GPS+GAL +BDS B1C +GLO
Maximum navigation update rate[3]		10 Hz	10 Hz	10 Hz	10 Hz	5 Hz
Position accuracy (CEP)[4, 5]		1.5 m	1.5 m	1.5 m	1.5 m	1.5 m
Time To First Fix (TTFF)[4, 6, 7]	Cold start	28 s	23 s	27 s	28 s	23 s
	Hot start	1 s	1 s	1 s	1 s	1 s
	AssistNow Online[8]	1 s	1 s	1 s	1 s	1 s
	AssistNow Offline[9]	2 s	2 s	3 s	2 s	2 s
	AssistNow Autonomous[10]	3 s	4 s	4 s	4 s	4 s
Sensitivity[11]	Tracking and nav.	-167 dBm	-167 dBm	-167 dBm	-167 dBm	-167 dBm
	Reacquisition	-160 dBm	-160 dBm	-160 dBm	-160 dBm	-160 dBm
	Cold Start	-148 dBm	-148 dBm	-148 dBm	-148 dBm	-148 dBm
	Hot start[6]	-159 dBm	-159 dBm	-159 dBm	-159 dBm	-159 dBm

1 Assuming Airborne 4 g platform
2 50% at 30 m/s for dynamic operation
3 For high navigation update rates, increase the communication baud rate and reduce the number of enabled messages.
4 GPS is always in combination with SBAS and QZSS.
5 CEP, 50%, 24 hours static, -130 dBm, > 6 SVs for each GNSS system

Table 3.19 – Typical Performance in Multi-constellation Modes - Source : [31]

The typical typical performance in single-*GNSS* mode of the *MAX-M10S* module is presented in table 3.19 :

Parameter		GPS	GLONASS	BDS B1I	GALILEO	BDS B1C
Maximum navigation update rate		18 Hz	18 Hz	18 Hz	18 Hz	18 Hz
Position accuracy (CEP)[4, 5]		1.5 m	4 m	2 m	3 m	2 m
Time To First Fix (TTFF)[4, 6, 7]	Cold start	29 s	27 s	30 s	41 s	56 s
	Hot start	1 s	1 s	1 s	1 s	1 s
	AssistNow Online[8]	1 s	1 s	1 s	5 s	TBD
Sensitivity[11]	Tracking and nav.	-167 dBm	-166 dBm	-160 dBm	-161 dBm	-163 dBm
	Reacquisition	-160 dBm	-158 dBm	-158 dBm	-154 dBm	-156 dBm
	Cold Start	-148 dBm	-147 dBm	-146 dBm	-141 dBm	-136 dBm
	Hot start[6]	-159 dBm	-159 dBm	-159 dBm	-155 dBm	-157 dBm

Table 3.20 – Typical Performance in Single-*GNSS* Mode - Source : [31]

Supported *GNSS* Constellations :

As mentioned earlier, the *MAX-M10S* is a concurrent *GNSS* receiver and can receive and track multiple *GNSS* systems. The concurrent reception of multiple *GNSS* constellations are enabled by the single RF front-end architecture. It is possible to achieve lower power consumption by configuring the *GNSS* receiver for a subset of constellations. **By default**, the configuration of the *MAX-M10S* is concurrent reception of ***GPS***, ***Galileo***, and ***BeiDou B1I*** with ***QZSS*** and ***SBAS*** enabled.

Supported *GNSS* and signals on *MAX-M10S* are listed in table 3.21 :

System	Signals
GPS / QZSS	L1C/A (1575.42 MHz)
Galileo	E1-B/C (1575.42 MHz)
GLONASS	L1OF (1602 MHz + k*562.5 kHz, k = –7,..., 5, 6)
BeiDou[12]	B1I (1561.098 MHz), B1C (1575.42 MHz)

6 Commanded starts.
7 All satellites at -130 dBm. Measured at room temperature.
8 Dependent on the speed and latency of the aiding data connection, commanded starts.
9 Using seven days old AsisstNow Offline data.
10 Using two days old orbital predicted data.
11 Demonstrated with a good external LNA. Measured at room temperature.

TABLE 3.21 – Supported *GNSS* and Signals on *MAX-M10S* - Source : [31]

Supported Assisted (*A-GNSS*) service on *MAX-M10S* are listed in table 3.22 :

Service	Support
AssistNow™ Online	GPS L1C/A, QZSS L1C/A, Galileo E1, GLONASS L1OF, BeiDou B1I
AssistNow™ Offline	GPS L1C/A, GLONASS L1OF
AssistNow™ Autonomous	GPS L1C/A, QZSS L1C/A, Galileo E1, GLONASS L1OF, BeiDou B1I

TABLE 3.22 – *MAX-M10S* - Supported Assisted *A-GNSS* service - Source : [31]

Supported augmentation systems on *MAX-M10S* are listed in table 3.23 :

System	Support
SBAS	EGNOS, GAGAN, MSAS and WAAS
QZSS	L1S (SLAS)

TABLE 3.23 – *MAX-M10S* - Supported Augmentation Systems - Source : [31]

Note :

→ The augmentation systems *SBAS* and *QZSS* can be enabled only if *GPS* operation is also enabled.

Supported Protocols :

Supported protocols on *MAX-M10S* are listed in table 3.24 :

Protocol	Type
UBX	Input/output, binary, u-blox proprietary
NMEA versions 2.1, 2.3, 4.0, 4.10 and 4.11 (default).	Input/output, ASCII

Table 3.24 – *MAX-M10S* - Supported Protocols - Source : [31]

Firmware Features :

The detailed description of firmware features offered on the *MAX-M10S* are listed in table 3.25 :

Feature	Description
Antenna supervisor[13]	Antenna supervisor for active antenna control and short detection
CloudLocate GNSS	Extends the life of energy-constrained IoT applications. Small payload messages supported.
Assisted GNSS	AssistNow Online, AssistNow Offline and AssistNow Autonomous
Backup modes	Hardware backup mode and software standby mode
Power save modes[14]	On/off, cyclic tracking
Super-S	Improved dynamic position accuracy with small antennas
Protection level	Real-time position accuracy estimate with 95% confidence level
Galileo return link messages	Galileo search and rescue (SAR) return link messages (RLM) via Galileo satellite signal
Data batching	Autonomous tracking up to 10 minutes at 1 Hz
Odometer	Measure traveled distance with support for different user profiles

12 BeiDou B1I cannot be enabled simultaneously with BeiDou B1C or GLONASS L1OF
13 External components required, some pins need to be reconfigured.
14 The power save modes are not available if BeiDou B1C is enabled.

Table 3.25 – *MAX-M10S* - Firmware Features - Source : [31]

The security features offered by the *MAX-M10S* are listed in table 3.25 :

Feature	Description
Anti-jamming	RF interference and jamming detection and reporting
Anti-spoofing	Spoofing detection and reporting
Configuration lockdown	Receiver configuration can be locked by command
Message integrity	All messages are cryptographically signed
Secure boot	Only signed firmware images executed

Table 3.26 – *MAX-M10S* - Security Features - Source : [31]

Block Diagram :

Figure 3.26 illustrate the block diagram of the *MAX-M10S GNSS* receiver :

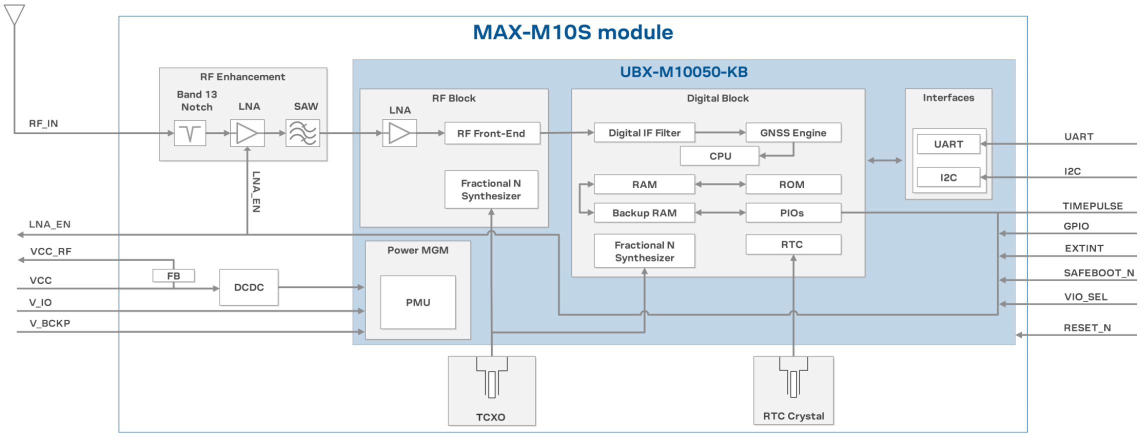


Figure 3.26 – *MAX-M10S* - Block Diagram - Source : [31]

The most notable blocks of the *MAX-M10S* shown in figure 3.26 are :

- **RF Enhancement Block :**
  The internal line of the module integrates a *Band 13 Notch* filter, an *LNA* and a *SAW* filter.
- **Power Management Block :**
  A power management unit is integrated in the module.
- **TCXO Block :** The module possesses a temperature controlled crystal oscillator that are more precise compared to regular crystal oscillator. This features improve the tracking accuracy.
- **RTC Crystal Block :**
  The module also integrates a *RTC* which allows to keep a correct timing value even if the *GNSS* reception is lost. This is true as long as the module is powered by a back-up battery.
- **Interface Block :**
  The module integrates both *UART* and *I2C* serial bus interface

Pin Definition :

The pinout of the *MAX-M10S* is illustrated in the figure 3.27

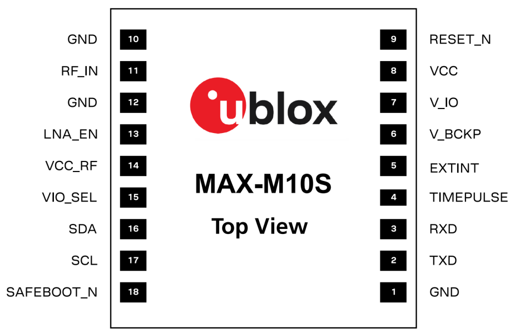


Figure 3.27 – *MAX-M10S* - Pin Assignment - Source : [31]

The pin assignment and their function is described in table 3.27 :

Pin no.	Name	PIO no.	I/O	Description
1	GND	-	-	Connect to GND
2	TXD	1	O	UART TX
3	RXD	0	I	UART RX
4	TIMEPULSE	4	O	Time pulse signal (shared with SAFEBOOT_N pin)[15]
5	EXTINT	5	I	External interrupt
6	V_BCKP	-	I	Backup voltage supply
7	V_IO	-	I	IO voltage supply
8	VCC	-	I	Main voltage supply
9	RESET_N	-	I	System reset (active low). Has to be low for at least 1 ms to trigger a reset.
10	GND	-	-	Connect to GND
11	RF_IN	-	I	GNSS signal input
12	GND	-	-	Connect to GND
13	LNA_EN	-	O	On/Off external LNA or active antenna
14	VCC_RF	-	O	Output voltage RF section
15	VIO_SEL	-	I	Voltage selector for V_IO supply. Connect to GND for 1.8 V supply, or leave open for 3.3 V supply.
16	SDA	2	I/O	I2C data
17	SCL	3	I	I2C clock
18	SAFEBOOT_N	-	I	Safeboot mode (leave open)[15]

Table 3.27 – *MAX-M10S* - Pin Assignment Table - Source : [31]

The description of pins state of the *MAX-M10S* is presented in table 3.28 :

PIO no.	Pin no.	Default function	Continuous mode	Software standby mode	Safe boot mode
0	3	RXD	Input pull-up	Input pull-up	Input pull-up
1	2	TXD	Output	Input pull-up	High Z
2	16	SDA	Input pull-up	Input pull-up	Input pull-up
3	17	SCL	Input pull-up	Input pull-up	Input pull-up
4	18	SAFEBOOT_N	Output	Input pull-down	High Z
	4	TIMEPULSE	Output	Input pull-down	High Z

Table 3.28 – *MAX-M10S* - Pins State - Source : [31]

Note :

→ In reset mode (RESET_N = *low*), all PIOs are config. as input pull-up.

→ In hardware backup mode (VCC = 0 V and V_IO = 0 V), PIOs must not be driven.

Absolute Maximum Ratings :

Absolute maximum ratings for the *MAX-M10S* are listed in table 3.29 :

Symbol	Parameter	Min	Max	Unit
VCC	Main supply voltage	–0.3	3.6	V
	Voltage ramp on VCC[16]	25	35000	µs/V
V_IO	IO supply voltage	–0.3	VCC + 0.3 (max 3.6)	V
	Voltage ramp on V_IO[16]	25	35000	µs/V
V_BCKP	Backup supply voltage	–0.3	3.6	V
V_PIO	Input voltage on RESET_N and digital pins. VIO_SEL = GND.	–0.3	V_IO + 0.3 (max 1.98)	V
	Input voltage on RESET_N and digital pins. VIO_SEL = open.	–0.3	V_IO + 0.3 (max 3.6)	V
I_PIO	Max source / sink current, digital pins[17]	-10	10	mA
ICC_RF	Max source current, VCC_RF		100	mA
P_{rfin}	RF input power on RF_IN[18]		0	dBm
T_{amb}	Ambient temperature	–40	+85	°C
T_s	Storage temperature	–40	+85	°C

TABLE 3.29 – *MAX-M10S* - Absolute Maximum Ratings - Source : [31]

Note :

→ V_{IO} supply voltage must not be higher than $V_{CC} + 0.3\,\text{V}$.

→ The product is not protected against over-voltage or reversed voltages. Voltage spikes exceeding the power supply voltage specification, given in table above, must be limited to values within the specified boundaries by using appropriate protection diodes.

Recommended Operating Conditions :

Recommended operating conditions for the *MAX-M10S* are listed in table 3.30 :

Symbol	Parameter	Min	Typical	Max	Units
VCC	Main supply voltage	1.76	1.8, 3.3	3.6	V
V_IO	IO supply voltage, VIO_SEL = GND	1.76	1.8	VCC (max 1.98)	V
	IO supply voltage, VIO_SEL = open	2.7	3.3	VCC (max 3.6)	V
V_BCKP	Supply voltage, backup domain	1.65		3.6	V
V_IO_{SWITCH}	V_IO voltage threshold to switch an internal supply for the backup domain from V_IO to V_BCKP		1.45		V
VCC_RF	VCC_RF output voltage		VCC - 0.1		V
ICC_RF	VCC_RF output current			50	mA
NF_{tot}	Receiver chain noise figure		1.5		dB
Ext_gain[19]	External gain at RF_IN, low gain mode (default)			30	dB
	External gain at RF_IN, bypass mode	10		40	dB
T_{opr}	Operating temperature	-40		+85	°C

TABLE 3.30 – *MAX-M10S* - General Operating Conditions - Source : [31]

Recommended digital IO conditions for the *MAX-M10S* are listed in table 3.31 :

Symbol	Parameter	Min	Typical	Max	Units
V_{in}	Input pin voltage range	0		V_IO	V
V_{il}	Low-level input voltage			0.63	V
V_{ih}	High-level input voltage	0.68 x V_IO			V
V_{ol}	Low-level output voltage, Iout = -2 mA [20]			0.4	V
V_{oh}	High-level output voltage, Iout = 2 mA [20]	V_IO - 0.4			V
$R_{pu, IO}$	Pull-up resistance, Digital IO[21]. VIO_SEL = GND	6	17	72	kΩ
$R_{pu, IO}$	Pull-up resistance, Digital IO[21]. VIO_SEL = open	8	18	40	kΩ
$R_{pd, IO}$	Pull-down resistance, Digital IO	21	80	180	kΩ
$R_{pu, SAFEBOOT\_N}$	Pull-up resistance, SAFEBOOT_N[22]	6	17	72	kΩ
$R_{pu, RESET\_N}$	Pull-up resistance, RESET_N	7	10	13	kΩ

19 The internal LNA gain is configurable.
20 TIMEPULSE (PIO4) has 4 mA current drive/sink capability.
21 TXD, RXD, TIMEPULSE, EXTINT, SCL, SDA, and LNA_EN.
22 The SAFEBOOT_N pin has an additional 1 kΩ series resistor.

Table 3.31 – *MAX-M10S* - Digital IO - Source : [31]

Indicative power requirements :

Indicative typ. power requirements for the *MAX-M10S* are listed in table 3.32 :

Symbol (Parameter)	Conditions	GPS	GPS+GAL	GPS+GAL +GLO	GPS+GAL +BDS B1I (default)	GPS+GAL +BDS B1C	GPS+GAL +BDS B1C +GLO	Unit
I_{VCC}[23] (Current at VCC)	Acquisition[24]	8	10	12	11.5	11	13	mA
	Tracking (Continuous mode)	7.5	8	9	9.5	8.5	10	mA
	Tracking (Power save mode)[25]	4.5	5	5	5	-	-	mA
I_{V_IO} (Current at V_IO)	Acquisition and Tracking (Continuous mode)	2.1	2.2	2.3	2.3	2.2	2.3	mA
	Tracking (Power save mode)[25]	2	2	2	2	-	-	mA

Table 3.32 – Typical Currents for 3.0 V Supply at V_{CC} and V_{IO} - Source : [31]

Backup current consumption of the *MAX-M10S* is listed in table 3.33 :

Symbol	Parameter	Conditions	Typ.	Unit
I_{V_BCKP}[26]	Total current in hardware backup mode	V_BCKP = 3.3 V, V_IO = VCC = 0 V	32	µA
$I_{VCC} + I_{V\_IO}$	Total current in software standby mode	V_IO = 1.8 V, VCC = 1.8 V	37	µA
		V_IO = 3.3 V, VCC = 3.3 V	46	µA

23 Internal LNA set to low gain. Simulated signal using power levels of -130 dBm.
24 Average current from start-up until the first fix.
25 Power save mode in cyclic tracking operation, 1-second update period. GNSS configurations that include BeiDou B1C do not support this mode.
26 I_{V_BCKP} current in normal operation (V_BCKP = 3.3 V, V_IO = VCC = 3.3 V) is ~3 µA.

Table 3.33 – *MAX-M10S* - Backup Currents - Source : [31]

Communication interfaces :

The specification of the communication interface of the *MAX-M10S* is described in table 3.34 :

Interface	Settings
UART	• 9600 baud, 8 bits, no parity bit, 1 stop bit. • Input messages: NMEA and UBX. • Output messages: NMEA GGA, GLL, GSA, GSV[29], RMC, VTG and TXT.
I2C	• 7-bit I2C address (0x42). • Input messages: NMEA and UBX. • Output messages: NMEA GGA, GLL, GSA, GSV[29], RMC, VTG and TXT.

27 I2C is a registered trademark of Philips/NXP.
28 External pull-up resistors may be needed to achieve 400 kbit/s communication speed, as the internal pull-up resistance can be very large.
29 In the default configuration, the NMEA-GSV messages are sent at 5-second intervals to avoid overflow in the TX buffer.

Table 3.34 – *MAX-M10S* - Default Interface Settings - Source : [31]

Design Recommendations :

All information about design recommendation are presented in the document "*Standard precision GNSS module - Integration manual*"[36] from u-blox.

Design Recommendations - RF interference :

The biggest concern with *GNSS* is that signal power received to antenna is extremely low compared to other wireless communication signals. In fact, the nominal strength of *GNSS* signal is $-130\,\mathrm{dBm}$, which is bellow thermal noise floor, making *GNSS* receiver very susceptible to interference from nearby RF sources.

For comparison, cellar applications signals strength is approximately $30\,\mathrm{dBm}$ comparing to *GNSS* signals strength value, it is clear that interference issues must be seriously took in consideration during the design phase.

RF front-end of *GNSS* receiver is essential to eliminate out-of-band interference from sources such as GSM, CDMA, WCDMA, LTE, Wi-Fi, or Bluetooth. The goal of the RF front-end design is to let pass the inband signal with minimum loss and adding minimum noise while suppressing the out-of-band interference.

The *MAX-M10S* integrates a RF front-end block design to keep the highest sensitivity possible. The front-end is also matched to $50\,\Omega$, it also includes a built-in *DC* block, an *LTE Band 13 notch* filter, an *LNA*, and an *SAW* filter.

The integration manual still recommends to add an external *SAW* filter to improve the immunity against RF interference if the application integrates other radio systems. Which is the case for the *LTEWatch* that also integrates a *LTE-M/NB-IoT* modem and antenna. The external *SAW* filter must be selected for an optimal trade-off between sensitivity and immunity.

Design Recommendations - Power Supply :

The *MAX-M10S* module power supply must be provided by the VCC and V_IO pins that can either be connected together or supplied independently by the system. V_BCKP is optional and can be use to enable the hardware backup mode that is active when V_IO supply or both V_IO and VCC supplies are not supplied.

1. **VCC Pin :**
   — Provides power to the core and RF domains and constantly need to be supplied to start-up the receiver or for any operation in continuous mode. The VCC pin is connected to an internal *DCDC* converter that reduce power consumption. The pin is also connected to the RF domain through a ferrit bead.

   — **Note :** The supply line must not be connected with series resistance greater than 0.2 Ω to avoid voltage ripple due to the dynamic conditions of the current.

   — The output voltage at VCC_RF pin is derived from VCC. If supply on VCC is removed, VCC_RF supply is interrupted.

2. **V_IO Pin :**
   — All the digital IOs, clock and backup domain are supplied by V_IO, therefore the current drawn at this pin depends on the loading and activity of the *PIOs* in addition to the *TCXO* consumption.

   — Be aware that a power interruption on this pin will erase the battery-backed RAM (BBR) unless hardware backup is enable (V_BCKP powered).

   — V_IO can be supplied with two voltage ranges, 1.8 V or 3.3 V. This option is configured with VIO_SEL pin : Short to *GND* for 1.8 V designs and left open for 3.3 V designs.

   — **Note :** V_IO supply voltage must never be higher than VCC+0.3 V

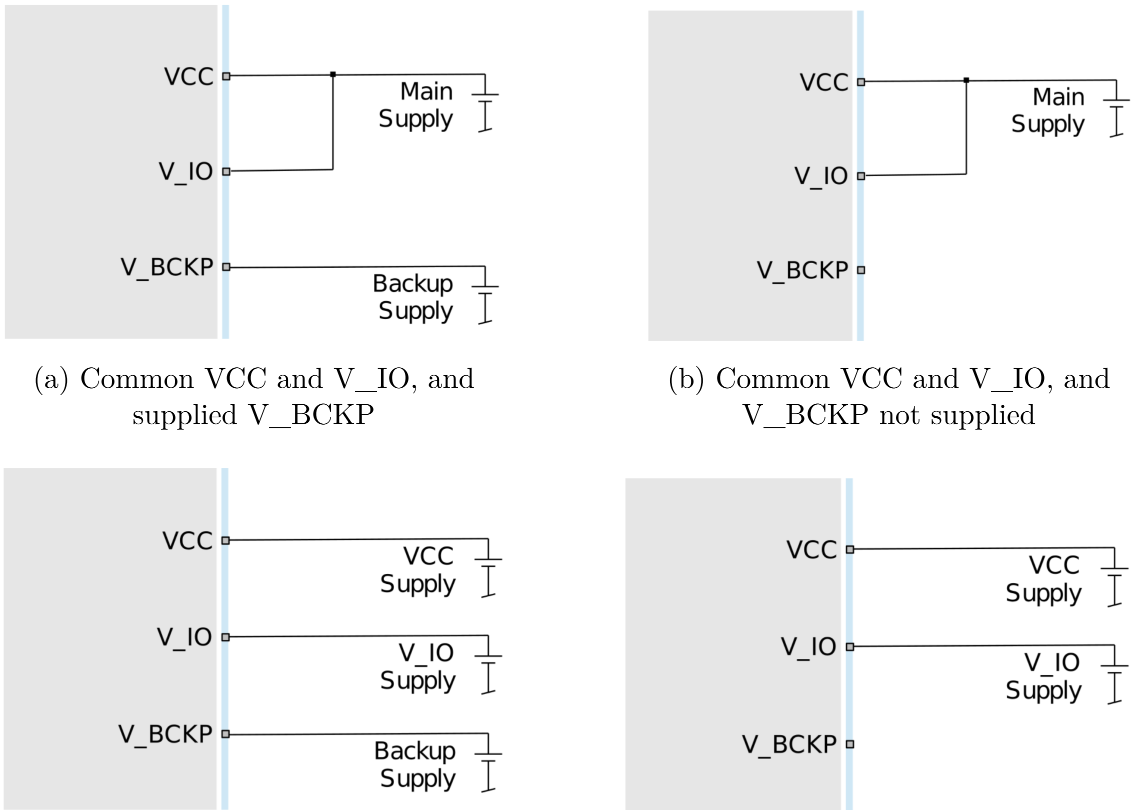
3. **V_BCKP :**
   — Powering this pin is option and is used to enable the hardware backup mode.

   — In this mode, the *RTC* TIME AND THE *gnss orbit* data in the *BBR* are maintained.

   — Valid time and *GNSS orbit* data at startup improves positioning performance by enabling hot starts, warm starts, and *AssistNow* Autonomous. This ensures faster time to first fix *(TTFF)* when V_IO is supplied again.

   — To make these features available, simply power the V_BCKP with an independent source to ensure backup domain supply when V_IO is not supplied.

4. **Supply Design Examples :**
   The *integration manual* from U-BLOX provide voltage supply design examples that are illustrated in figure 3.28 :



(a) Common VCC and V_IO, and supplied V_BCKP

(b) Common VCC and V_IO, and V_BCKP not supplied

(c) Separate VCC and V_IO, and supplied V_BCKP

(d) Separate VCC and V_IO, and V_BCKP not supplied

FIGURE 3.28 – *MAX-M10S* - Voltage Supply Design Examples - Source : [31]

Design Recommendations - Internal LNA modes :

The *MAX-M10S* integrated *LNA* can be configured in three operating modes :

1. **Normal Gain :** Not recommended for *MAX-M10S* because the already sufficient gain provided by the integrated *LNA*.
2. **Low Gain :** Default configuration of the *MAX-M10S* for optimized sensitivity and immunity against RF interference.
3. **Bypass Mode :** Recommended to improve immunity for RF front-end designs with 10 dB to 15 dB or higher total external gain. This mode also slightly reduces power consumption.

Note : The internal *LNA* mode can be configured at run time in *BBR* and *RAM* of the layers *MAX-M10S* using the configuration item CFG-HW-RF_LNA_MODE follow by a **reset**.

3.6.8 Clock Motors : (TITAN T901A/T902A)

The *LTEWatch* must display time with stepper motors. Those motors were already selected and were provided by the project supervisor Medard Rieder. The next sections presents the specifications and hardware consideration concerning those motors. For more details, full datasheets are in appendix 10.2 and 10.3.

Technical Data For TITAN (Bi-Directional) - *T901A* :

The first motor model is the *T901A*,which is a bi-direction single shaft stepper motor design to drive a single clock hand. Figure 3.29 illustrates the technical data of the *T901A* stepper motor :

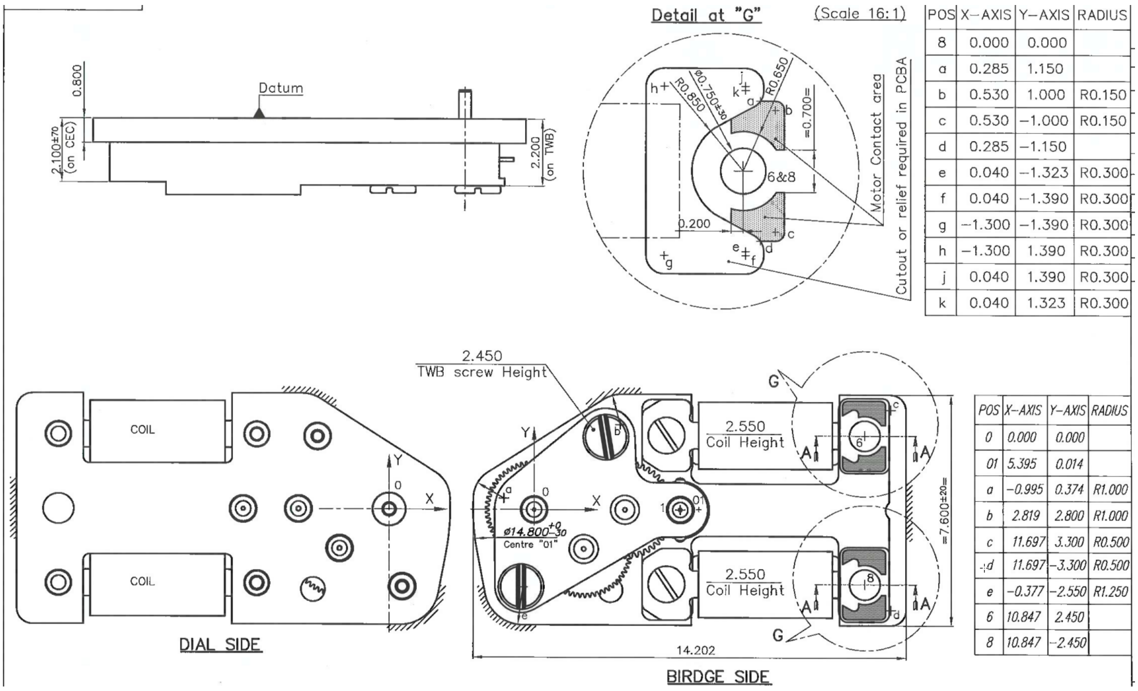


Figure 3.29 – *T901A* - Technical Data For TITAN (Bi-Directional) - Source : [37]

Motor Driving Parameters - *T901A* :

Table 3.35 describes the *T901A* stepper motor driving parameters :

SL	Description	Unit	Nominal Voltage (V)	
			2.10	3.00
01	Pulse Width	ms	4.5	3.0
02	Duty Cycle	%	100%	100%
03	Current consumption @ 64Hz	µA	335(Typ)~385(Max)	335(Typ)~385(Max)
04	Current Consumption @ 1Hz	µA	5.1(Typ)~5.3(Max)	4.9(Typ)~5.4(Max)
05	Driving torque (typ)	µNm	36 (Min)	36 (Min)
06	Voltage Range	V	1.6 ~ 2.5	1.8 ~ 4.0

Table 3.35 – *T901A* - Motor Driving Parameters - Source : [37]

Motor Control Wave Forms - *T901A* :

Figure 3.30 illustrates wave forms specification for driving the *T901A* motor :

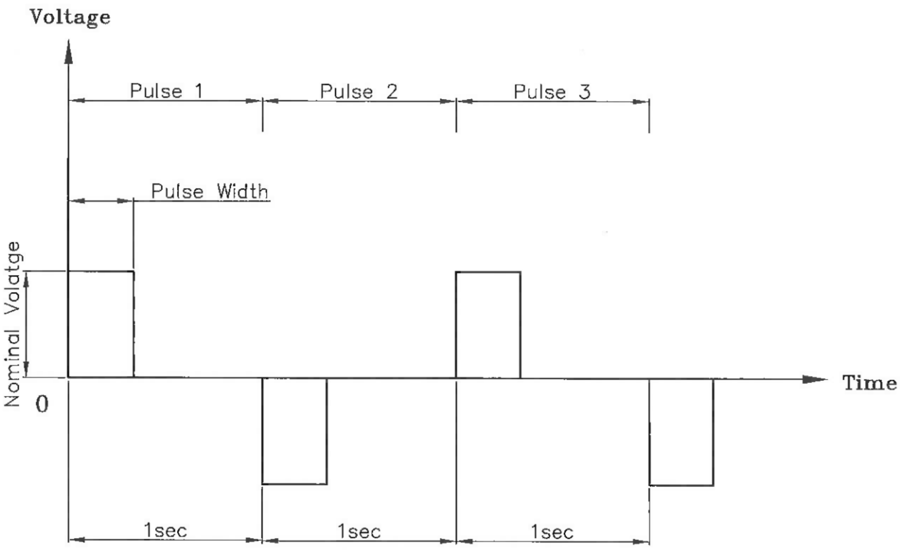


Figure 3.30 – *T901A* - Wave Forms - Source : [37]

Technical Data For TITAN (Bi-Directional) - *T902A* :

The second motor model is the *T902A*, which is a bi-direction dual shaft stepper motor design to drive two clock hands.

Figure 3.31 illustrates the technical data of the *T902A* motor :

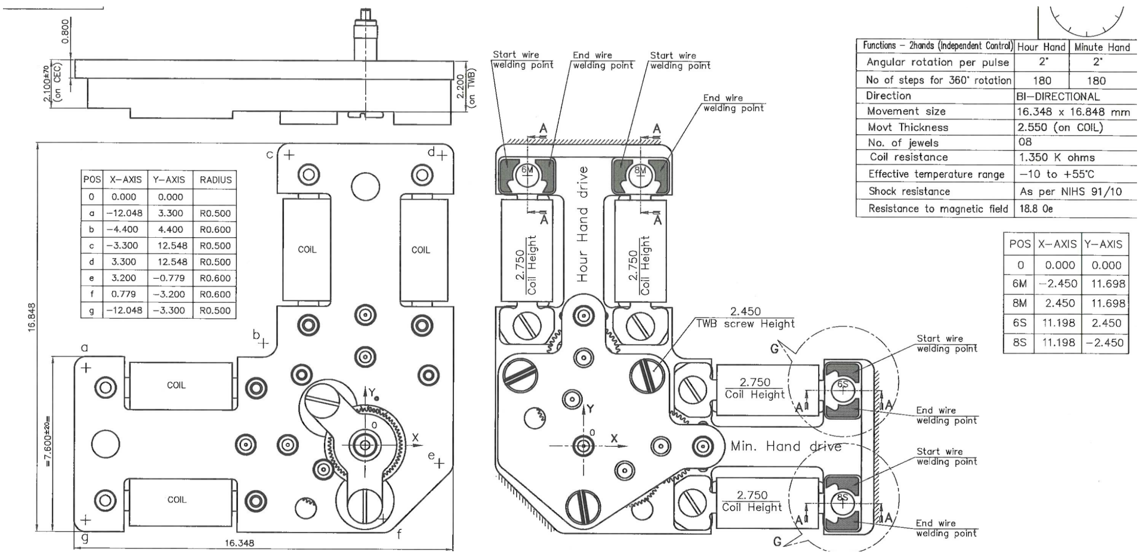


Figure 3.31 – *T902A* - Technical Data For TITAN (Bi-Directional) - Source : [38]

Motor Driving Parameters - *T902A* :

Table 3.36 describes the *T902A* stepper motor driving parameters :

SL	Description	Unit	Nominal Voltage (V)	
			2.10	3.00
01	Pulse Width	ms	4.5	3.0
02	Duty Cycle	%	100%	100%
03	Current consumption @ 64Hz	µA	335(Typ)~385(Max)	335(Typ)~385(Max)
04	Current Consumption @ 1Hz	µA	5.1(Typ)~5.3(Max)	4.9(Typ)~5.4(Max)
05	Driving torque (typ)	µNm	36 (Min)	36 (Min)
06	Voltage Range	V	1.6 ~ 2.5	1.8 ~ 4.0

Table 3.36 – *T902A* - Motor Driving Parameters - Source : [38]

Motor Control Wave Forms - *T902A* :

Figure 3.32 illustrates wave forms specification for driving the *T902A* stepper motor :

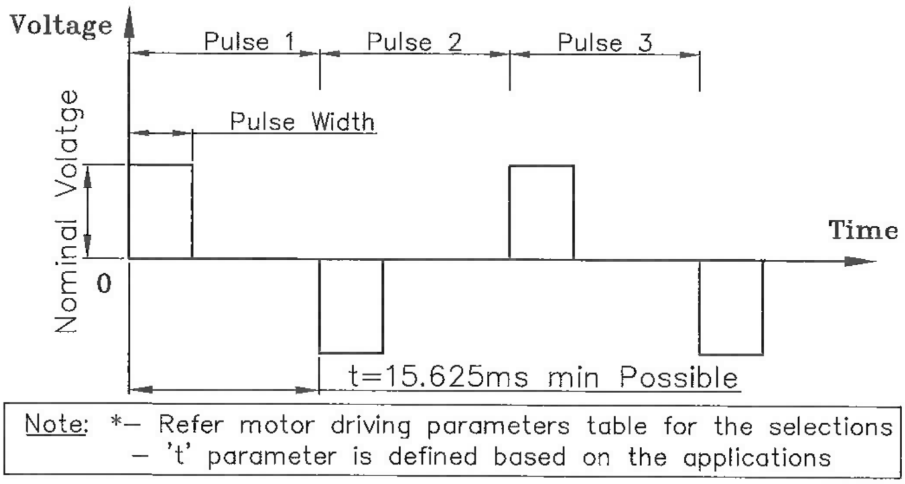


Figure 3.32 – *T902A* - Wave Forms - Source : [38]

3.6.9 FTDI USB To UART Interface - FT234XD-R

In order to add more flexibility to the software development and connectivity of the *LTEWatch* the choice was made to add a *FTDI USB To UART* Interface. The datasheet of the *FT234XD-R*[39], describes the component as a *USB* to serial *UART* interface with size optimized for compact applications.

Typical Application Diagram :

Figure 3.33, illustrate typical USB bus power configuration for the *FT234XD-R* :

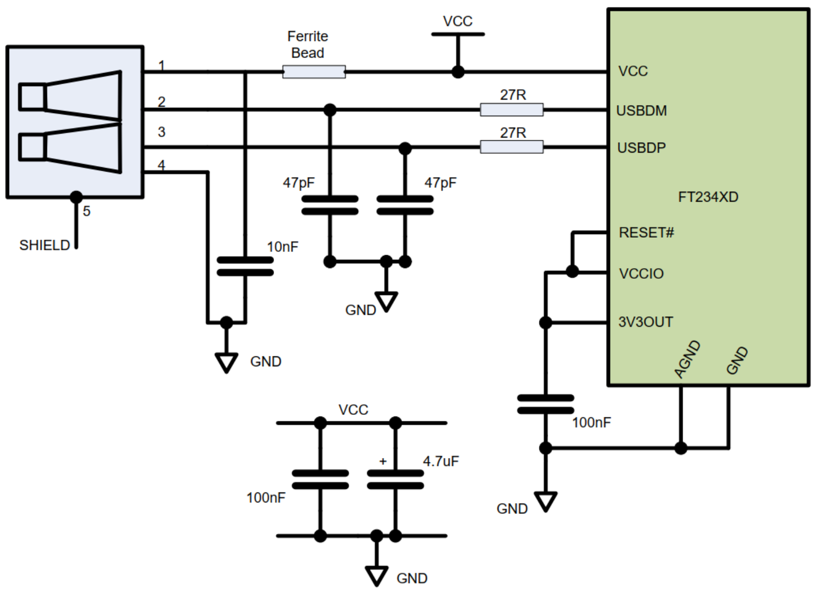


Figure 3.33 – USB Bus Powered Configuration - Source : [39]

Recommended Operating Conditions :

Recommended conditions for the *FT234XD-R* are presented in table 3.37 :

Parameter	Conditions	ID	MIN	TYP	MAX	UNIT
VCC Operating Supply Voltag	Normal Operation	VCC	2.97	5	5.5	V
VCCIO Operating Supply Voltage	-	VCC2	1.62	-	3.63	V
Operating Supply Current	Normal Operation	Icc1	6.5	8	8.3	mA
Operating Supply Current	USB Suspend	Icc2	-	125	-	µA
3V3 regulator output	-	3V3	2.97	3.3	3.63	V

Table 3.37 – Recommended Operating Conditions - Source : *FT234XD-R*[39]

Absolute Maximum Ratings :

Absolute maximum ratings for the *FT234XD-R* are presented in table 3.38 :

Parameter	**MIN**	**MAX**	**UNIT**
Storage Temperature	−65	150	°C
Ambient Operating Temperature (Power Applied)	−40	85	°C
VCC Supply Voltage	−0.3	+5.5	V
VCCIO IO Voltage	−0.3	+4.0	V
DC Input Voltage – USBDP and USBDM	−0.5	+3.63	V
DC Input Voltage – High Impedance Bi-directional (powered from VCCIO)	−0.3	+5.8	V
DC Output Current – Outputs	-	22	mA

Table 3.38 – Absolute maximum ratings - Source : *FT234XD-R*[39]

Features :

The datasheet of the *FT234XD-R*[39] *USB* to *BASIC UART* IC provides the following features :

- **Overview :**
  - Single chip data interface from *USB* to asynchronous data transfer
  - The chip handles entire *USB* protocol and does not require any specific firmware programming
  - Fully integrated 2048 byte multi-timeprogrammable (MTP) memory, storing device descriptors and CBUS I/O configuration specific firmware programming required
  - Fully integrated clock generation with no external crystal required
- **Performances :**
  - Data transfer rates from 300 baud baud to 3 Mbaud (*RS422*, *RS485*, and *RS232*) at TTL levels
  - 512 byte receive buffer and 512 byte transmit buffer
- **Complementary features :**
  - FTDI's royalty-free Virtual Com Port (*VCP*) and Direct (*D2XX*) drivers
  - Configurable *CBUS* I/O pin
  - *TX* and *RX* LED drive signals
  - *UART* interface support for 7 or 8 data bits, 1 or 2 stop bits and *odd* / *even* / *mark* / *space* / *no parity*
  - USB Battery Charging Detection
  - Device supplied pre-programmed with unique *USB* serial number
  - USB Power Configurations :
    - bus-powered
    - self-powered
    - bus-powered with power switching
  - Integrated 3.3 V level converter for *USB I/O*
  - Integrated *power-on-reset* circuit
- **Size and package :** *DFN* 12 pin package (3 mm × 3 mm)

Design Recommendations :

Because the *FT234XD-R* is a *USB* to *UART* interface, basic rules for USB bus power devices must be respected. Those basic rules are provided in the datasheet of the *FT234XD-R*[39] and are as follows :

1. On *USB* plug-in, the device should draw no more current than 100 mA
2. In *USB* Suspend mode the device should draw no more than 2.5 mA
3. A bus powered high power *USB* device (one that draws more than 100 mA) should use the *CBUS* pin configured as *PWREN#* and use it to keep the current below 100 mA on plug-in and 2.5 mA on *USB* suspend
4. A device that consumes more than 100 mA cannot be plugged into a *USB* bus powered hub
5. No device can draw more than 500 mA from the *USB* bus

3.6.10 Components Package Type and Size Selection

The prototype board integrates the *nRF9160 SiP* from Nordic Semi.. This *SiP* is only available as a *LGA* package, which is not easy to assemble. To ensure the correct assembly of the prototype *PCBs*, it was agreed with the project manager Rieder Medard to order them fully assembled in-house by Euro Circuits. As assembly is no longer a constraint, it is possible to select tiny package type such as *BGA* in order to design a compact device. That's why many components have been selected in tiny difficult to assemble packages.

Concerning all passive components like resistors, capacitors or inductors, the opposite approach was chosen. The *LTEWatch* board is a prototype, it is reasonable to expect that modifications will probably be necessary. To ensure easier modification of the passive components, it was decided to select these components in **0603** size packages. This package size is the smallest size that I've always been comfortable replacing and soldering without too much difficulty. This components can easily be replaced by **0402** size packages for the final round version of the *LTEWatch*.

4 Hardware Part

4.1 Electrical Schematic

Once the system decomposition is complete as well as the selection of the components, the next step is design of the electrical schematic of the system.

In this section, the electrical schematic will be decomposed in blocks similar to those describe in the system decomposition (page 24).

4.1.1 Power Supply

Starting with the power supply block which is composed the following parts :

1. Battery Connector and Polarity Protection
2. Battery Level Monitoring
3. Li-Ion Battery Charger and Protection Unit
4. $+3V3$ Buck-Boost Converter
5. $+1V8$ GPIO LDO
6. Wireless Power Receiver (WPC/QI)

Battery Connector and Polarity Protection

Figure 4.1 illustrates the electrical schematic of the battery connection and polarity protection circuit from the power supply block of the *LTEWatch* :

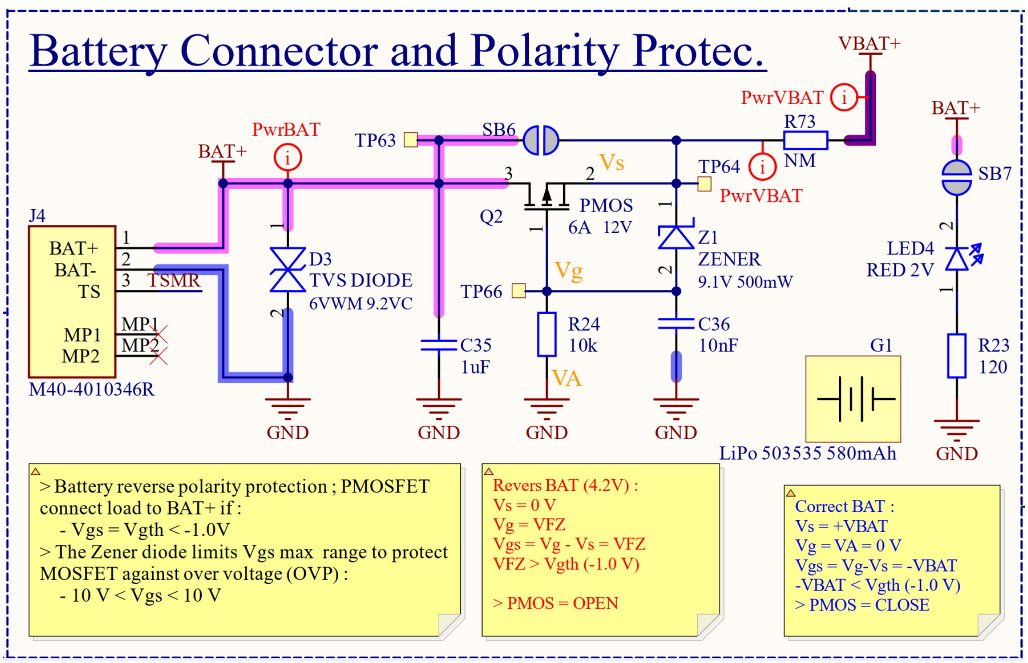


Figure 4.1 – Power Supply : Battery Connector and Polarity Protection

As the device is powered by battery, there is a risk of connecting the cell in reverse polarity which could seriously damage the circuit and in the worst case the battery if the reverse polarity connection results in a short circuit. The battery is connected with a 3-pin connector with a *TS* line for battery thermal regulation.

The reverse polarity protection is achieved with a *P-Chanel* MOSFET that act as a low loss reverse battery protection diode :

— $VBat > 0 : V_{gs} < V_{gth} \rightarrow$ PMOS is **ON**

— $VBat < 0 : V_{gs} > V_{gth} \rightarrow$ PMOS is **OFF**

The zener diode is used to limit the voltage range on the PMOS. The TVS diode is implemented for ESD protection. For direct revers battery indication, a red LED can be connected to +VBAT.

The *P-Channel* MOSFET is the *SSM3J332R*[40] from Toshiba, which has the following specification :

— Gate threshold voltage : $V_{gth} = -1.2\,\text{V}$ (max)

— Drain–source on resistance : $R_{DS(ON)} = 50\,\text{m}\Omega$ ($V_{GS} = 4.5\,\text{V}$)

— Gate-Source voltage range : $V_{GSS} = \pm 12\,\text{V}$

— Drain current max : $I_D = -6\,\text{A}$

— Power dissipation : $P_D = 1\,\text{W}$

Battery Level Monitoring

Battery level monitoring is mandatory in portable and wearable application. The simple battery level monitoring circuit of *LTEWatch* is illustrated in figure 4.2 :

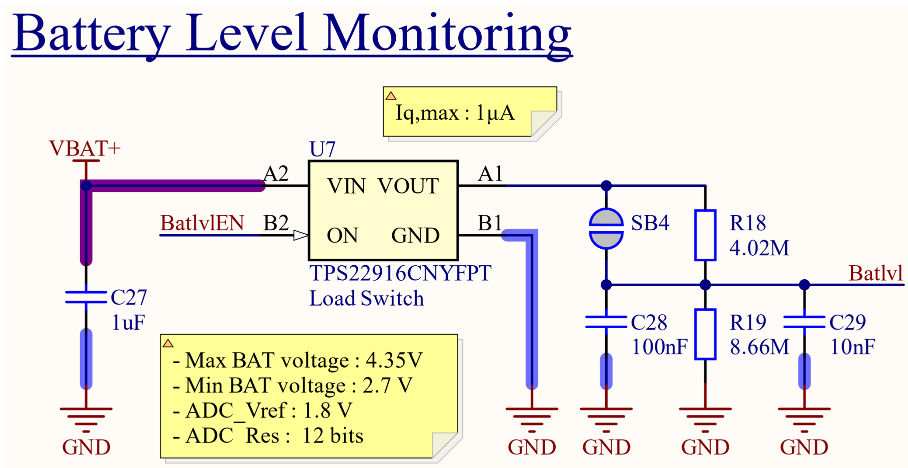


Figure 4.2 – Power Supply : Battery Level Monitoring

Battery level monitoring is directly measured by an ADC input of the *nRF9160*. The measured battery voltage is adapted to the ADC range with a simple restive voltage divider :

$$V_{meas} = V_{BAT} \cdot \frac{R_{19}}{R_{18} + R_{19}} = \underline{\underline{0.683 \cdot V_{BAT}}}$$

For a battery with $V_{BAT,FULL} = 4.2\,\text{V}$ and $V_{BAT,EMPTY} = 3.0\,\text{V}$:

— $V_{ADC,MAX} = 2.868\,\text{V}$ with $I_{BATLVL,MAX} = 331\,\text{nA}$

— $V_{ADC,MIN} = 2.049\,\text{V}$ with $I_{BATLVL,MIN} = 237\,\text{nA}$

In order to reduce current consumption, a load switch is added to enable or disable the battery level monitoring. The load switch typical current consumption is :

— **ON** state : $I_{BATLVL,MAX} = 500\,\text{nA} > I_{BATLVL,MIN}$

— **OFF** state : $I_{BATLVL,MIN} = 10\,\text{nA} < I_{BATLVL,MIN}$

This means that current consumption is reduced if :

$$\left(\overbrace{\frac{t_h}{t_h + t_l}}^{D}\right) \cdot 500\,\text{nA} + \left(\overbrace{\frac{t_l}{t_h + t_l}}^{1-D}\right) \cdot 10\,\text{nA} < 237\,\text{nA}$$

$$\rightarrow D \cdot 500\,\text{nA} + (1 - D) \cdot 10\,\text{nA} < 237\,\text{nA}$$

$$\rightarrow \quad D \cdot 490\,\text{nA} < 237\,\text{nA} \Rightarrow \quad \underline{\underline{D < 48\,\%}}$$

The load switch effectively reduces the current consumption of battery level monitoring, as long as **ON** state duty cycle is less than 48 %.

Li-Ion Battery Charger and Protection Unit

The battery charger and protection unite implement the *BQ25180* from Texas Instrument. The electrical schematic of the battery charger unit is illustrated in figure 4.3 :

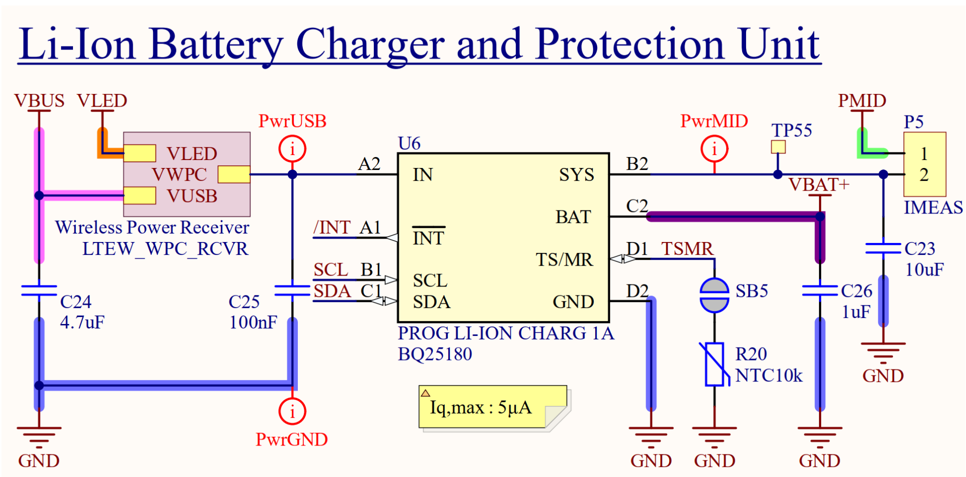


Figure 4.3 – Power Supply : Li-Ion Battery Charger and Protection Unit

The integration of the *BQ25180* is very straightforward, the values of capacitors C_{23}, C_{24}, C_{25} and C_{26} have been chosen following the design recommendation describes on page 35. This unit also contains a $10\,\text{k}\Omega$ *NTC* that can be connected to the *BQ25180* with a solder bridge and *"IMEAS"* jumper that can be unplug to measure the current consumption of the system.

+3V3 Buck-Boost Converter

Figure 4.4 illustrates the electrical schematic of the *+3V3 Buck-Boost* unit :

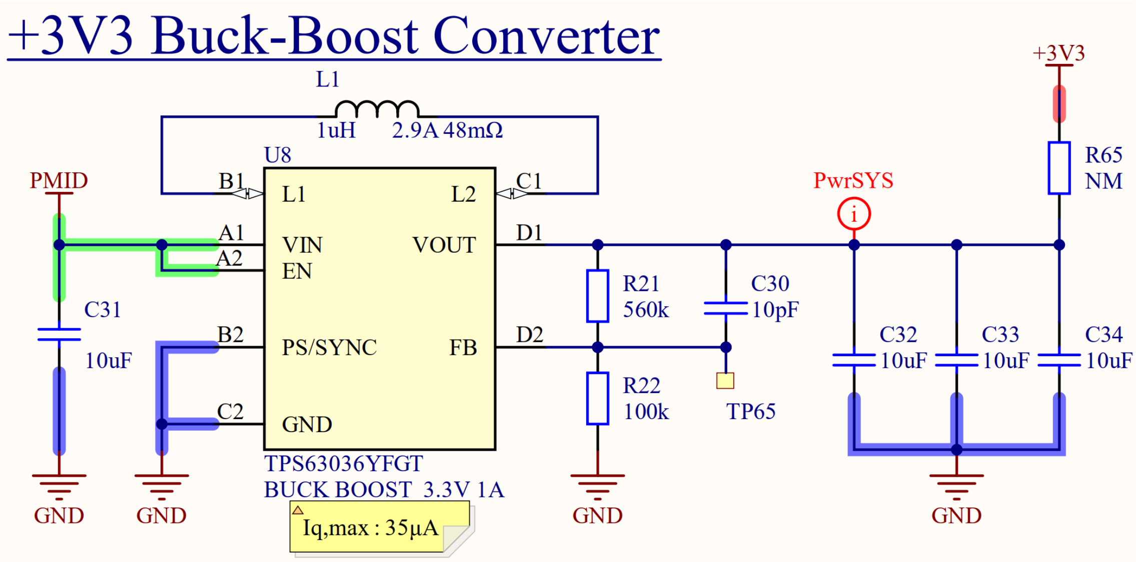


Figure 4.4 – Power Supply : +3V3 Buck-Boost Converter

The most critical components of the circuit illustrated in figure 4.4 are the inductor L_1 and the voltage divider resistances R_{21} and R_{22}. Their value were determined using the design recommendation of the *TPS63036* describes on page 38.

+1V8 GPIO LDO

Figure 4.5 illustrates the electrical schematic of the *+1V8 GPIO LDO* unit :

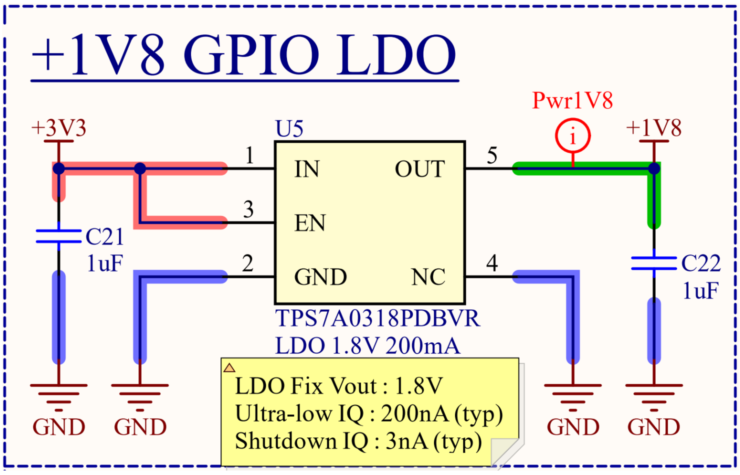


Figure 4.5 – Power Supply : +1V8 GPIO LDO

This circuit only integrates the *TPS7A03* 1.8 V *LDO* regulator. We can see that the schematic of the figure 4.5 is very simple. The only external component required are the coupling capacitors C_{21} and C_{22}. Their values correspond to those of the design recommendation described on page 44.

Wireless Power Receiver (WPC/QI)

The *Wireless Power Receiver (WPC/QI)* unit integrates the *BQ51013B* from Texas Instrument. The schematic of this unit is shown in figures 4.6 to 4.7 :

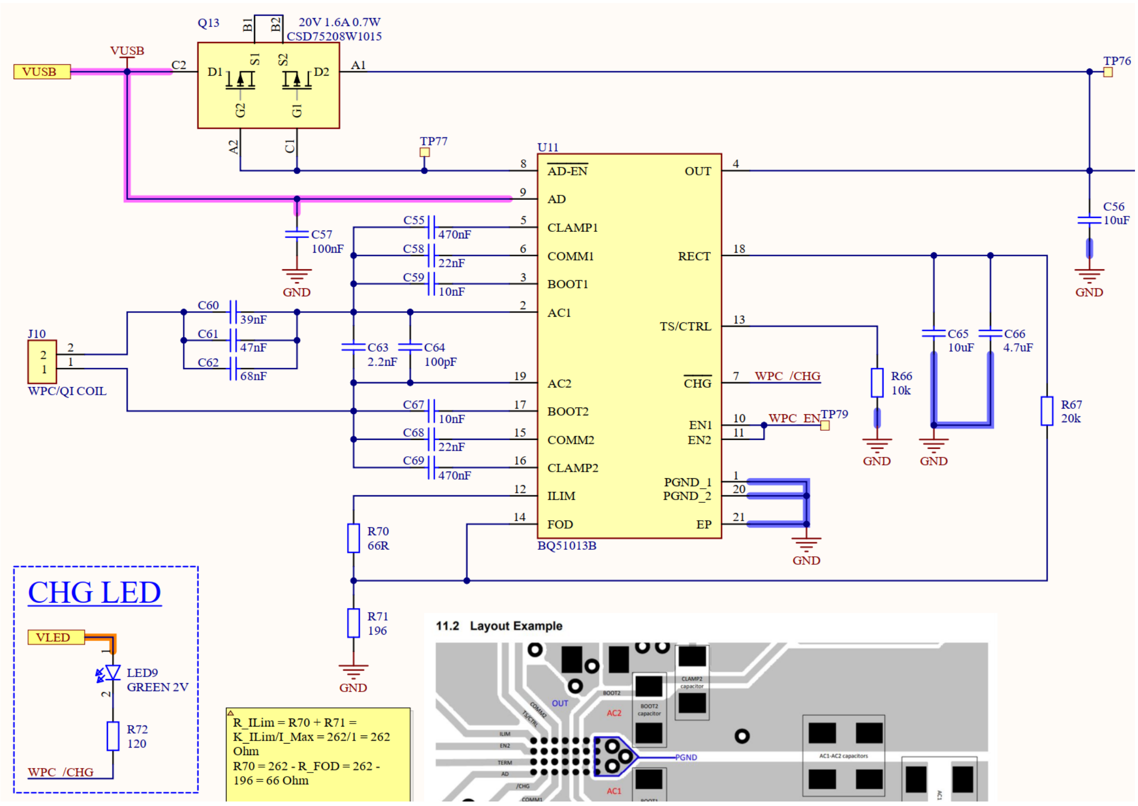


Figure 4.6 – Power Supply : Wireless Power Receiver (WPC/QI)

Figure 4.6 illustrates the electrical schematic of the *BQ51013B*.

The integration of the (*WPC/QI*) power receiver is less trivial than units previously described. The schematic is decomposed in the following blocks :

1. Power Receiver (*WPC/QI*) chip (*BQ51013B*)
2. Power supply blocking *FET* (*CSD75208W1015*)
3. Charging state indicator (*LED9*)
4. Power Receiver (*WPC/QI*) enable circuit (R_{68}, R_{69} and Q_{14})

The integration process of the *BQ51013B* is describes in detail in the design recommendation of the component on page 47. The most critical part of the implementation of the *BQ51013B* is the the determination of receiver coil dual resonant circuit series capacitors C_{60}, C_{61}, C_{62}, and parallel capacitors C_{63} and C_{64}. The guideline to calculate those component is also described on page 47.

The second block is the power supply block *FET* (*CSD75208W1015*), this component is a *P-Channel FET* pair. When the *USB* bus is supplied ($V_{BUS} = 5\,\mathrm{V}$), the pin *AD* is set 'high' and the pin $\overline{\text{AD-EN}}$ is set to 'low'. In this state, the blocking *FET* lets pass the power supply from VUSB. Conversely, when VBUS is not supplied ($V_{BUS} = 0\,\mathrm{V}$) the blocking *FET* disconnect VBUS line from the load system.

The third block is the charging state indicator, which is simply a LED in series with a resistance to limit current. The calculation of the value of R_{72} is described in the design recommendations on page 47.

The last block is the *WPC* enable control circuit, which is simply an inverting *N-Channel* MOSFET switch. The schematic of this block is illustrated in figure 4.7 :

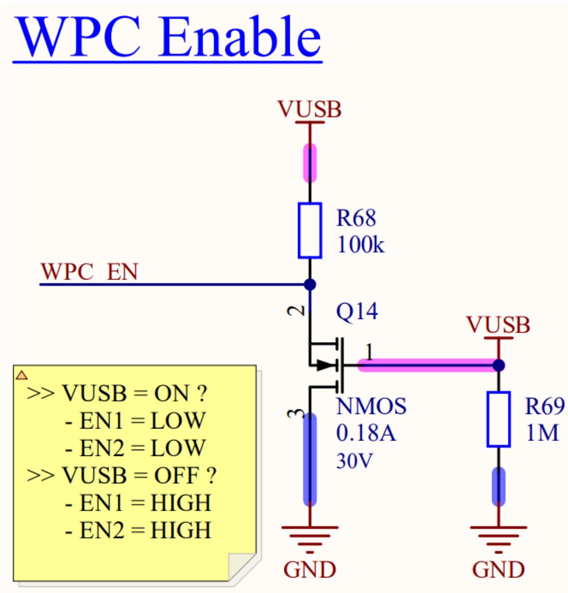


Figure 4.7 – Power Supply : Wireless Power Receiver (WPC/QI) Enable

4.1.2 MCU System (*nRF9160*)

The *MCU* System block contains all units relative to the *nRF9160*, which are decomposed as follow :

1. *nRF9160* SiP
2. FTDI-UART *USB-to-UART* interface
3. USB-C and JTAG connectors
4. GPS EXTINT : +1V8 MAGPIO to +3V3 GNSS EXT INT level shifter
5. SIM and eSIM connectors

nRF9160 SiP

The electrical schematic of the *nRF9160* SiP is illustrated in figure 4.8 :

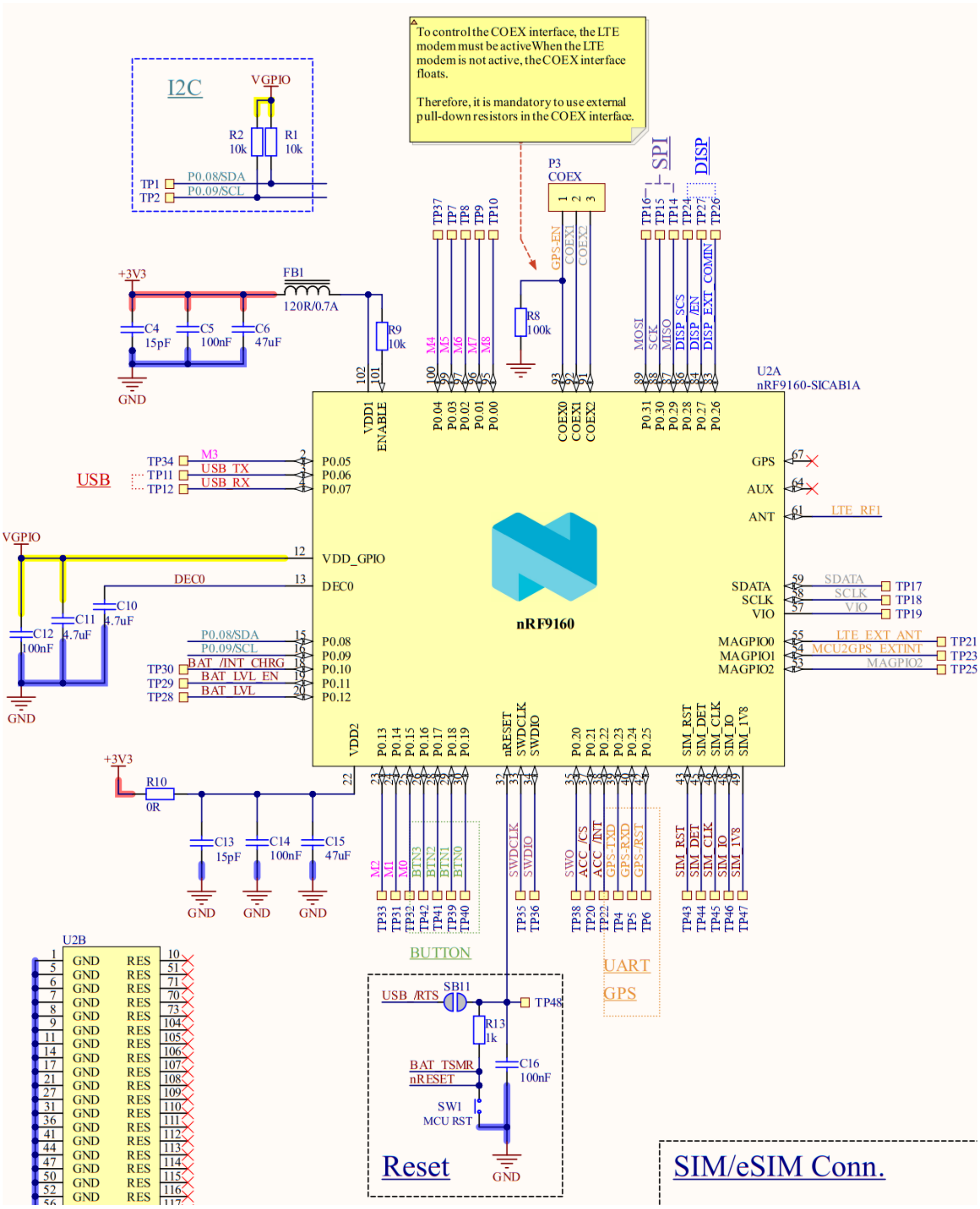


Figure 4.8 – nRF9160 : nRF9160

The integration shown in figure 4.8 is based on the board schematic of the *nRF9160DK*[41], the pin assignment varies, but the values of external components are identical. A noticeable difference is the *nRESET* pin which is connected to a push button like the *nRF9160DK* board, but is also connected to the battery charger *TSMR* pin which is also used as a /RESET pin.

We can see from the schematic that the *MCU* is well populated and almost all the pins are used. Even COEX0 is used as *GPS-EN* output, MAGPIO0 and MAGPIO1 are used, respectively for external LTE antenna configuration (*LTE_EXT_ANT*) and as GNSS interrupt output (*MCU2GPS_EXTINT*).

The reason the *MCU* is cluttered is that I'm adding lots of options and extra configuration to keep the prototype board versatile and to keep back-up plans in case of mistakes while designing the board or unfortunate discoveries during the software development.

FTDI - UART

Figure 4.9 illustrates the electrical schematic of the FTDI-UART *USB-to-UART* interface circuit :

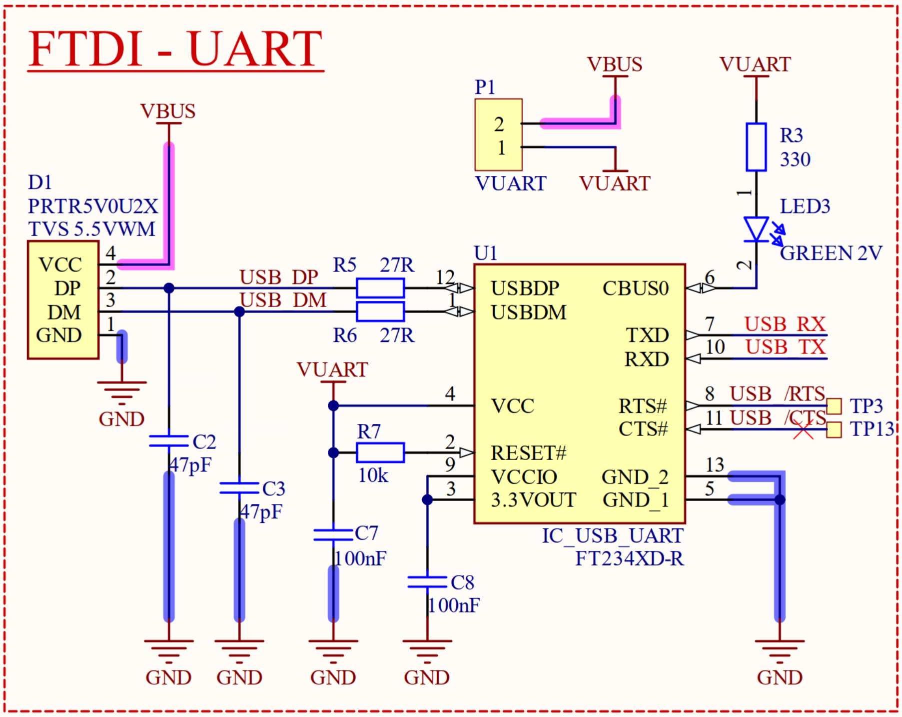


Figure 4.9 – nRF9160 : FTDI-UART

As shown in figure 4.9, the FTDI-UART interface module is the *FT234XD-R*. This implementation is based on the *typical USB bus power configuration* described on page 73.

Due to the limited number of pins still available on the *nRF9160*, the *RTS* and *CTS* signals are not connected to the *MCU* and therefore not used. The *FT234XD-R* can drive a *TX/RX* LED indicator on the pin CBUS0. This pin is internally pulled-down.

The component on the left (D1), which is a (*PRTR5V0U2X*[42]), is an ultra low capacitance double rail-to-rail *ESD* protection diode suitable for USB bus.

Concerning the external passive components, the datasheet of the *FT234XD-R*[39] recommended adding small 25 Ω series resistors to the USB bus to limit current. It was also recommended to add a ferrite bead on the VUSB power supply line to reduce *EMI* noise from the *FT234XD* and associated circuitry being radiated down the USB cable to the USB host. The ferrit bead is present on the *USB-C/JTAG* block (fig.4.11). More details are described in the design recommendations of the component on page 75.

GPS EXTINT

Figure 4.10 illustrates the electrical schematic of the *GPS EXTINT* block :

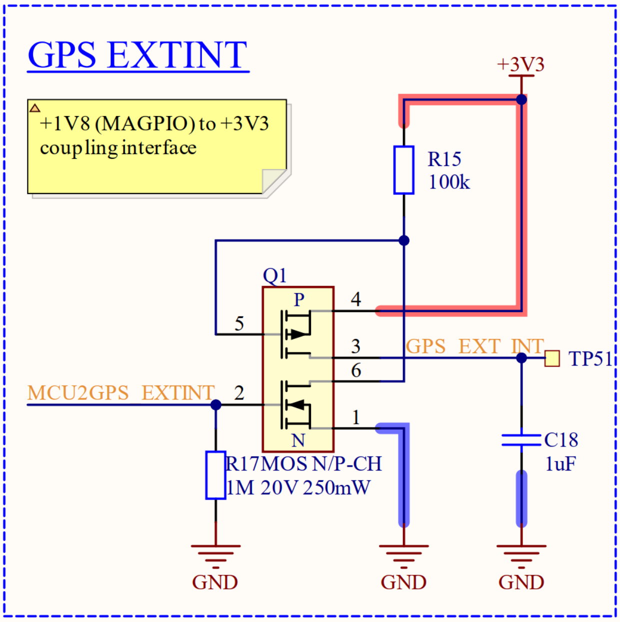


FIGURE 4.10 – nRF9160 : GPS EXTINT

The *GNSS* receiver has an external interrupt (EXT_INT) input that can be used by the *MCU* to send interrupts to the *GNSS* module. Due to the overcrowded *GPIOs* of the *nRF9160*, the only solution to add this signal was to connect it on one of the *MAGPIO* pin of the *nRF9160*. *MAGPIO* is IO port of the modem that is integrated in the *nRF9160*. The problem with this port is the only compatibility with 1.8*V GPIO*. The *GNSS* requiring at least 2.7 V to detect a *'high'*, it is necessary to interface this pin with a level shiffter for 3.0 V designs. The level shifter is simply implemented with a non inverting dual MOSFET switch.

USB-C / JTAG

The *USB-C/JTAG* block contains two connectors :

1. USB-C : This connector provides USB power supply and can also be interfaced with c custom JTAG to USB-C interface that can be developed later.
2. JTAG (SWIO) : Standard connector for *J-Link* programmer from Segger This connector can also be used directly with other *nRF* development Kit from Nordic Semi.

The electrical schematic of the textitUSB-C/JTAG block is illustrated in the figure 4.11 :

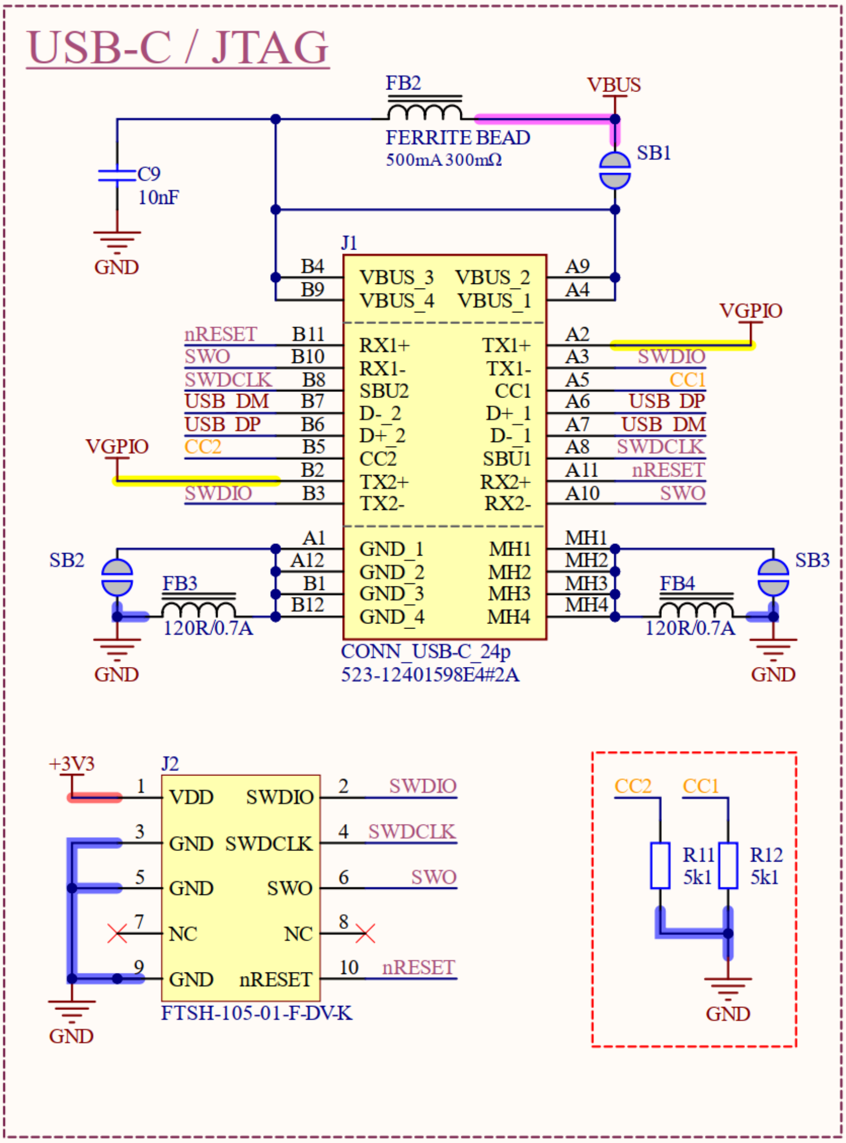


Figure 4.11 – nRF9160 : USB-C / JTAG

As shown on figure 4.11, the USB-C connector uses three ferrite bead filters that can be connected with solder bridge if needed. This filter are used to reduce *EMI* noise from the USB-C host and cable.

SIM/eSIM Connector

This block integrates connectors for both SIM and eSIM cards. The electrical schematic of this block is illustrated in figure 4.12 :

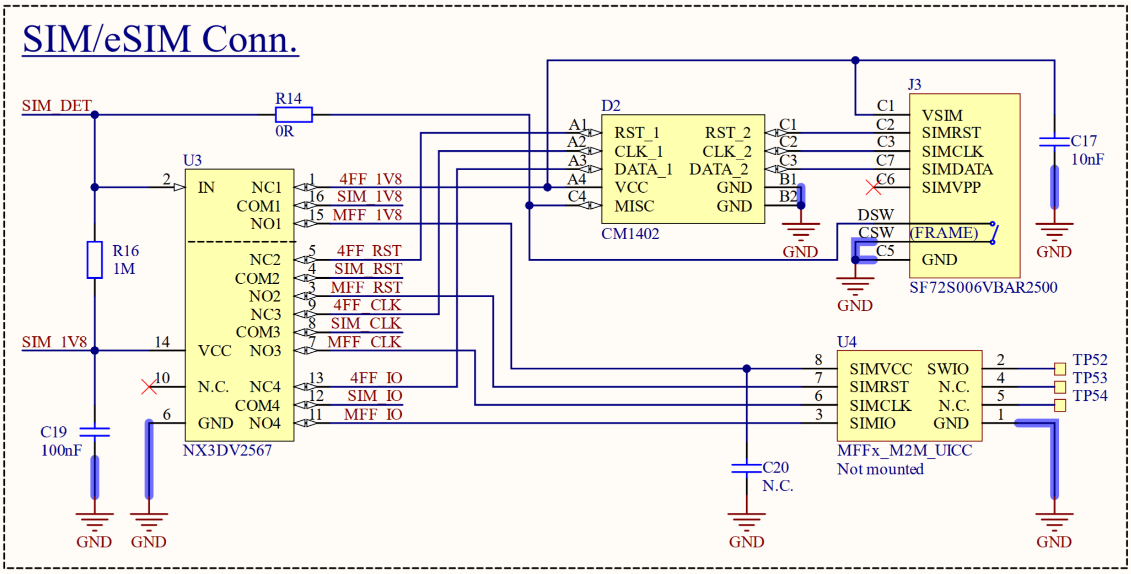


Figure 4.12 – nRF9160 : SIM/eSIM Connector

The schematic shown in figure 4.12 is based on the schematic from the *thingy91* [43] board from Nordic Semi. This schematic also respects Sim card interface recommendations from the *"Product Specification"*[44] of the *nRF9160*, which has the topology shown in figure 4.13 :

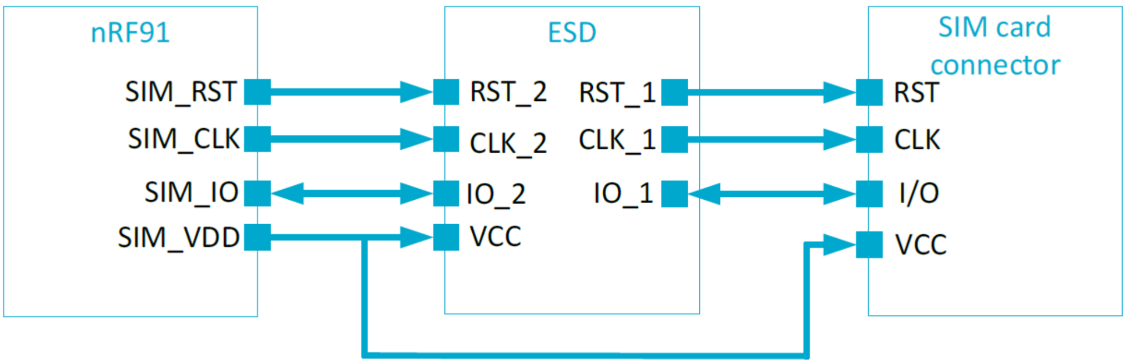


Figure 4.13 – Recommended Sim Card Interface Topology - Source :[44]

The Sim card interface topology form Nordi Semi recommends interfacing the Sim card connector with the *nRF9160* through an *ESD* filter component to protect extremely sensitive inputs of the *LTE* modem.

According to the *"Product Specification"*[44] of the *nRF9160*, the *LTE* modem controls the physical interfaces towards the *UICC* and implements the transport protocol over a four-pin *ISO/IEC 7816-3* interface :

- VCC (power supply) : LTE modem drives this
- CLK (clock signal) : LTE modem drives this
- RST (reset signal) : LTE modem drives this
- I/O (input/output serial data) : Bi-directional

Accelerometer

Figure 4.14 illustrates the electrical schematic of the *MC3635* accelerometer :

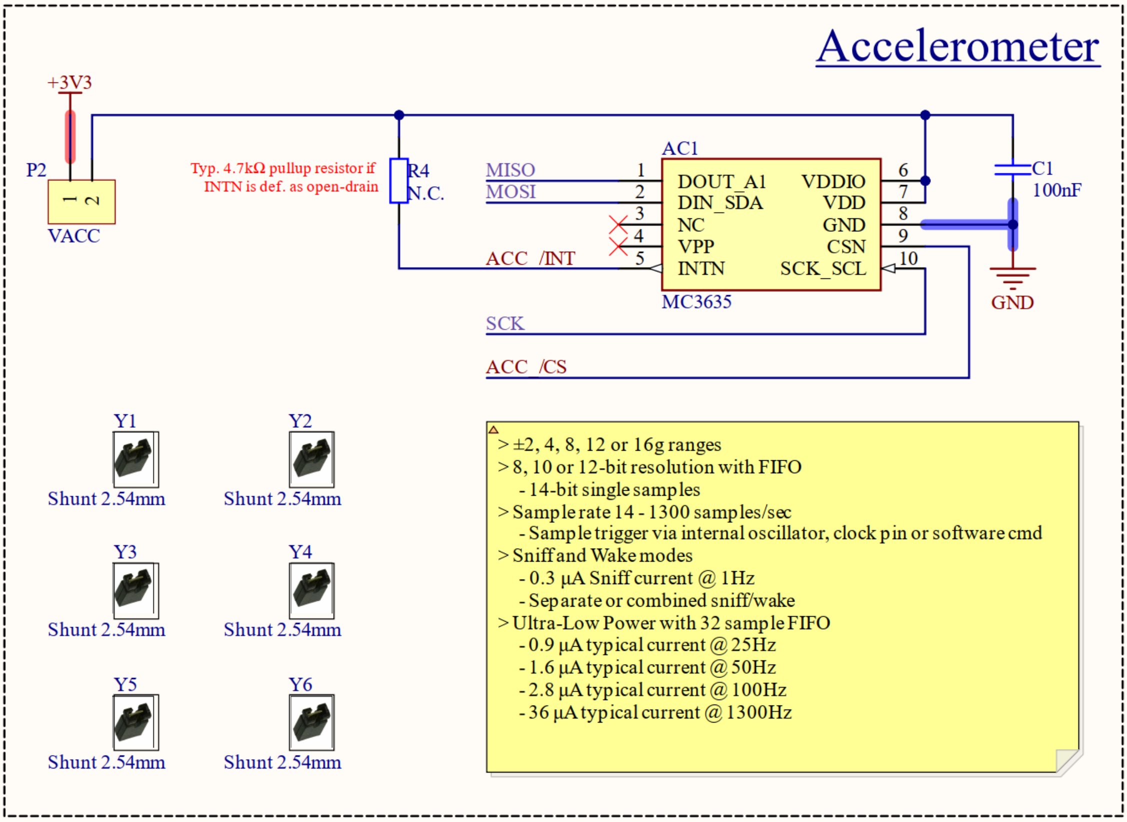


Figure 4.14 – nRF9160 : Accelerometer

The schematic shown in figure 4.14 is based on the typical 4-wire *SPI* application circuit provided in the *MC3635*[27] datasheet. More information about the accelerometer has already been presented on the page 52.

4.1.3 User interface

TThis block concerns all functionality related to the user interface.

Buttons & Switches

Buttons and switch unit presented on the schematic of figure 4.15 is based on the schematic from the *nRF9160DK*[41] board :

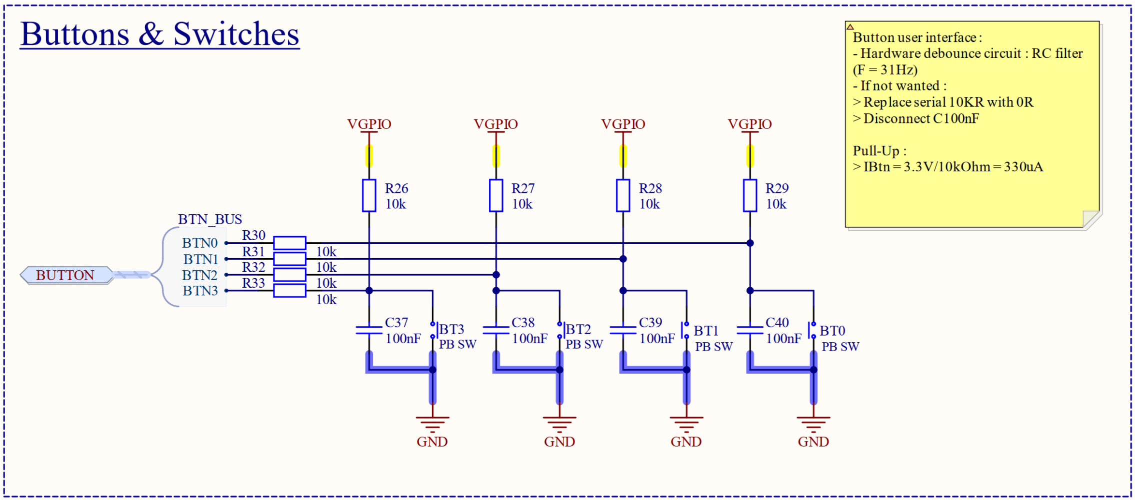


FIGURE 4.15 – User Interface : Buttons & Switches

Leds

Leds unit presented on the schematic of figure 4.16 is based on the schematic from the *nRF9160DK*[41] board :

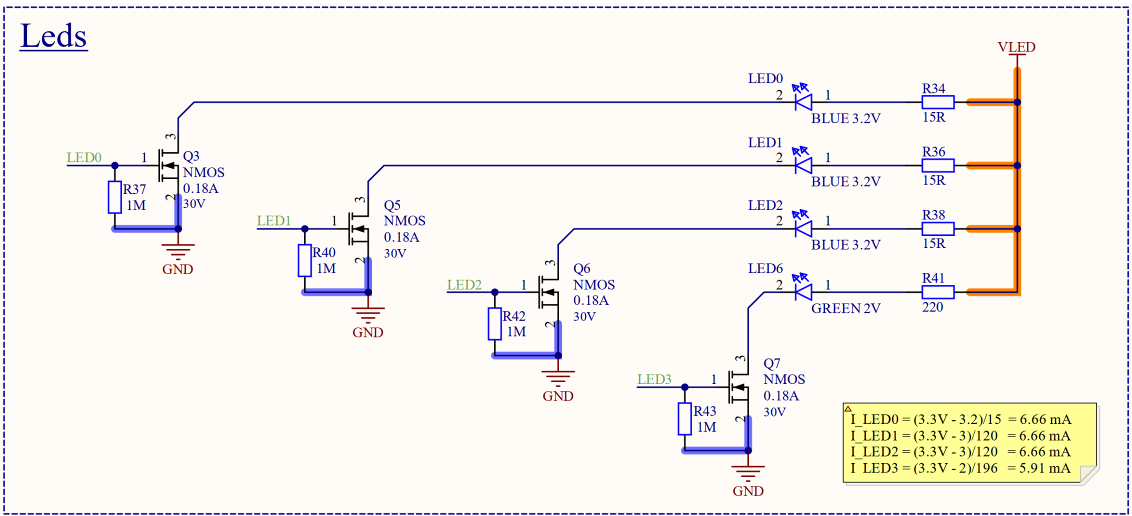


FIGURE 4.16 – User Interface : Leds

Motors Driver

Figure 4.17 illustrates the motor driver interface electrical schematic :

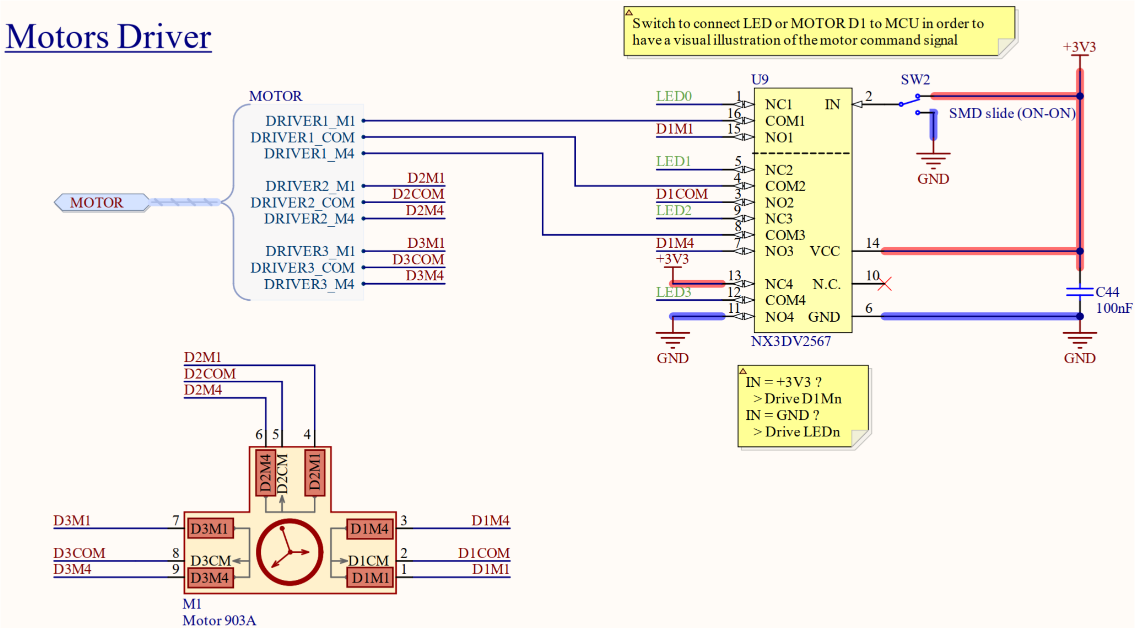


Figure 4.17 – User Interface : Motors Driver

The schematic shown at 4.17 contains the motor drive pin connectors and the parallel switch that allows three signals from the motor driver to be redirected to three external LEDs for debugging purposes.

Display Interface

The electrical schematics relatives to the display interface are shown in figures 4.18 to 4.21 :

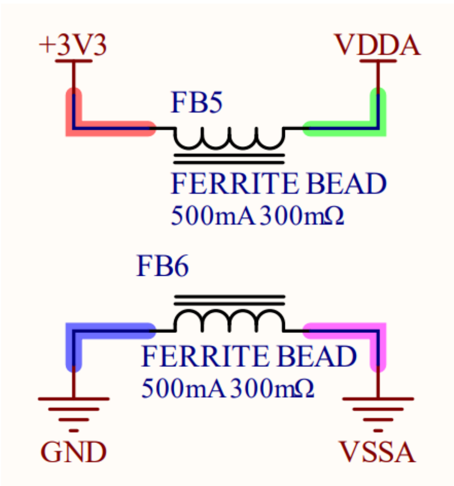


Figure 4.18 – User Interface : Display Interface - Power Supply Filter

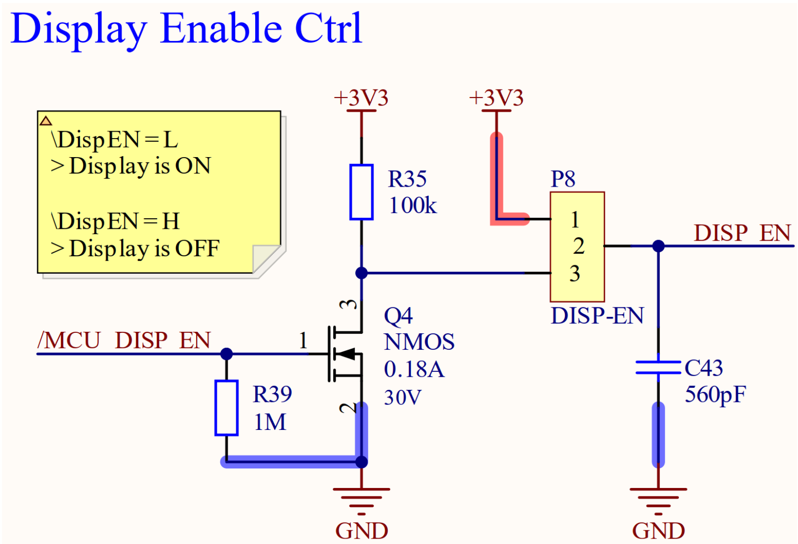


Figure 4.19 – User Interface : Display Interface - Display Enable

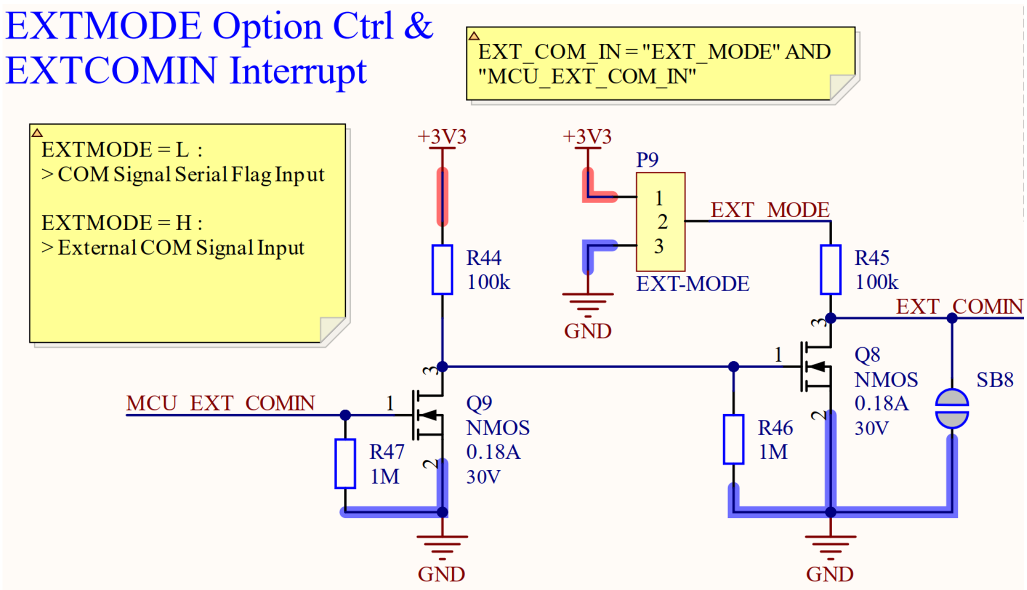


Figure 4.20 – User Interface : Display Interface - EXTMODE Control

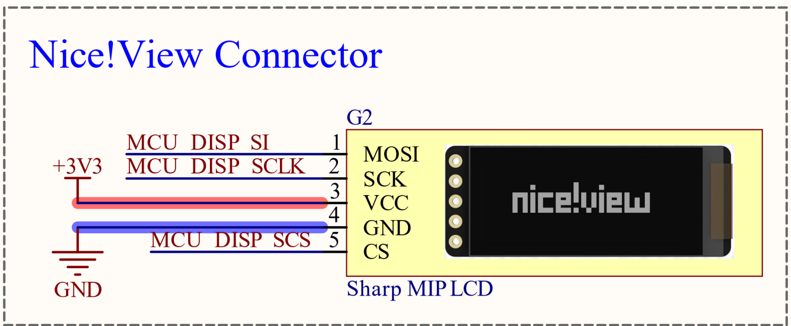


Figure 4.21 – User Interface : Display Interface - *nice !view* Connector

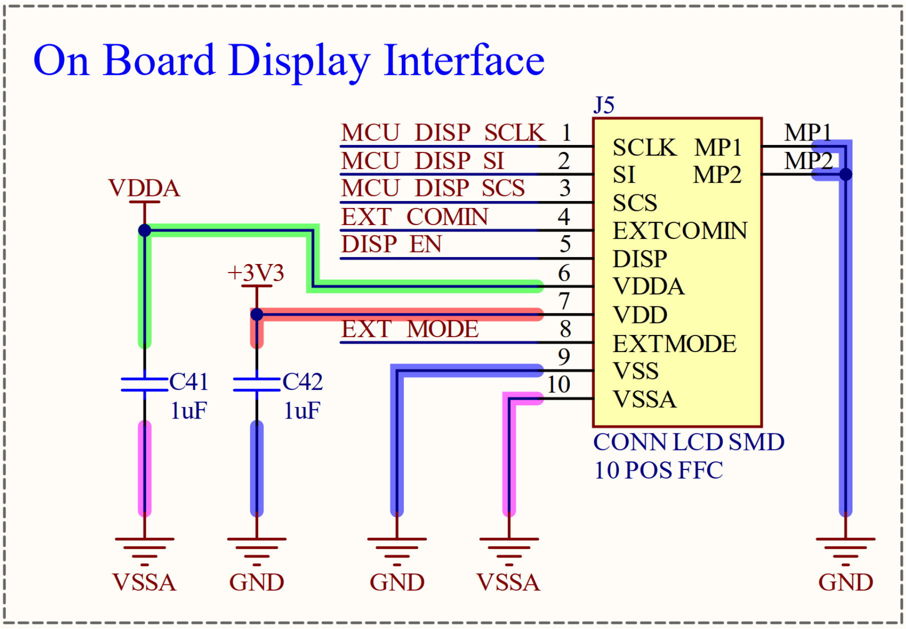


Figure 4.22 – User Interface : Display Interface - Display Interface

4.1.4 RF Unit (Radio Freq)

This contains all units and module relative to RF signals transmission, such as :

- GNSS Receiver
- GNSS Enable
- GNSS RF Transmission Line
- GPS Contolled by MCU or Ext
- LTE RF transmission Line

GNSS Enable

Figure 4.23 illustrates the *GNSS* Enable circuit schematic :

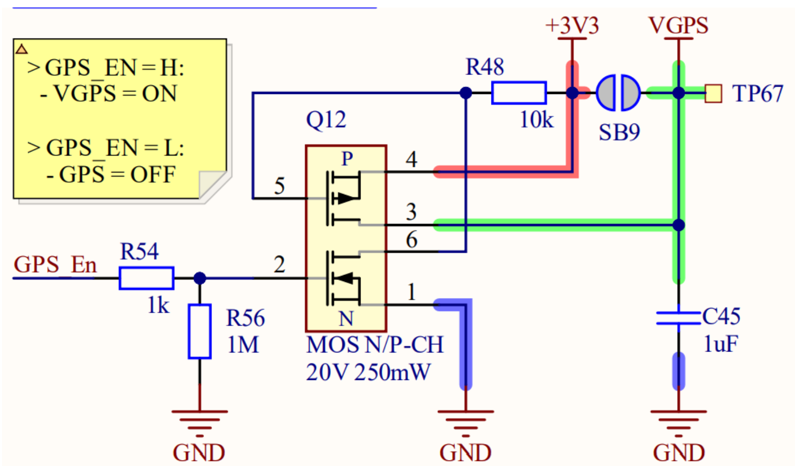


Figure 4.23 – RF Unit : GNSS Enable

GNSS Receiver

Figure 4.24 illustrate the electrical schematic of the integration of the GNSS receiver *MAX-M10S* from u-blox :

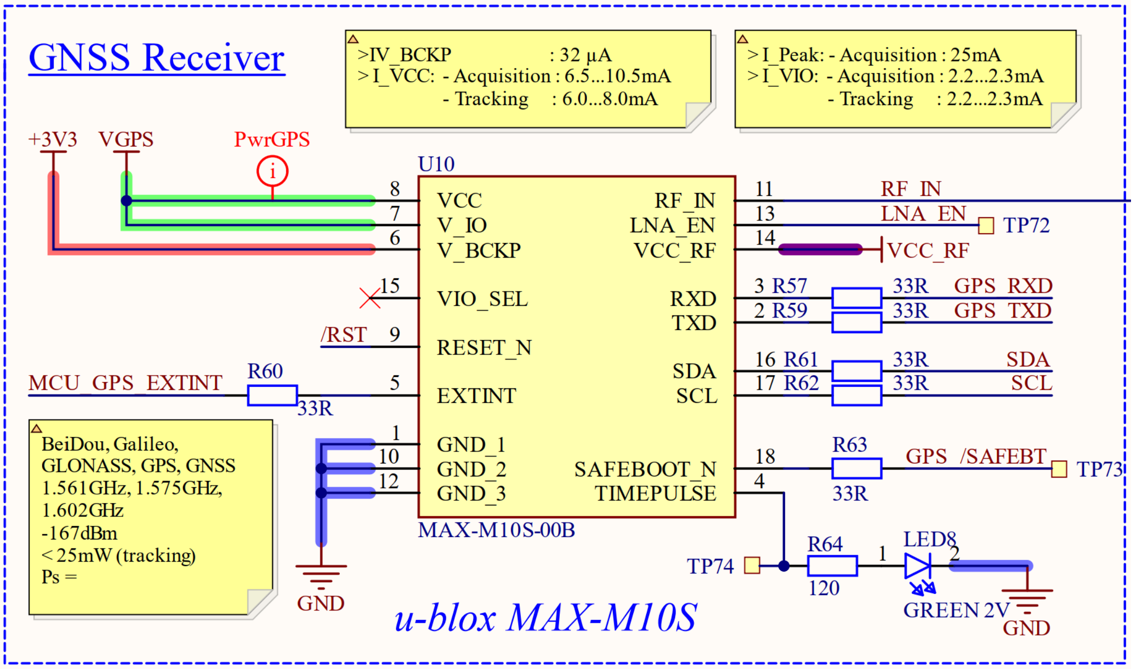


Figure 4.24 – RF Unit : GNSS Receiver *MAX-M10S*

The schematic shown in figure 4.24 is based on the open source schematic of "*GNSS Receiver Breakout - MAX-M10S (Qwiic)*" from Sparkfun : `https://www.sparkfun.com/products/18037`. The main difference is that I added the possibility to either use the *GNSS* receiver with an on-board chip antenna or with an external antenna that can be connected through a *SMA* connector. Except that, the integration is fairly simple with only some series resistors added on each lines to limit currents.

On *the LTEWatch*, the *GNSS* receiver can be power or not in order to keep a better control on system consumption and battery life. The *GNSS* is powered through a dual MOSFET non-inverting switch that connect the *VCC* and *V_IO* pin of the *GNSS* receiver to the board 3.3 V when GOS_En is set *'high'*.

The *V_BCKP* pin of the *GNSS* receiver is directly connected to the 3.3 V to enable the hardware backup mode, which reduces the *TTFF* and consumption of the *GNSS* receiver module.

GNSS RF Transmission Line

Figuer 4.25 illustrates the schematic of the *GNSS* RF line (front-end) :

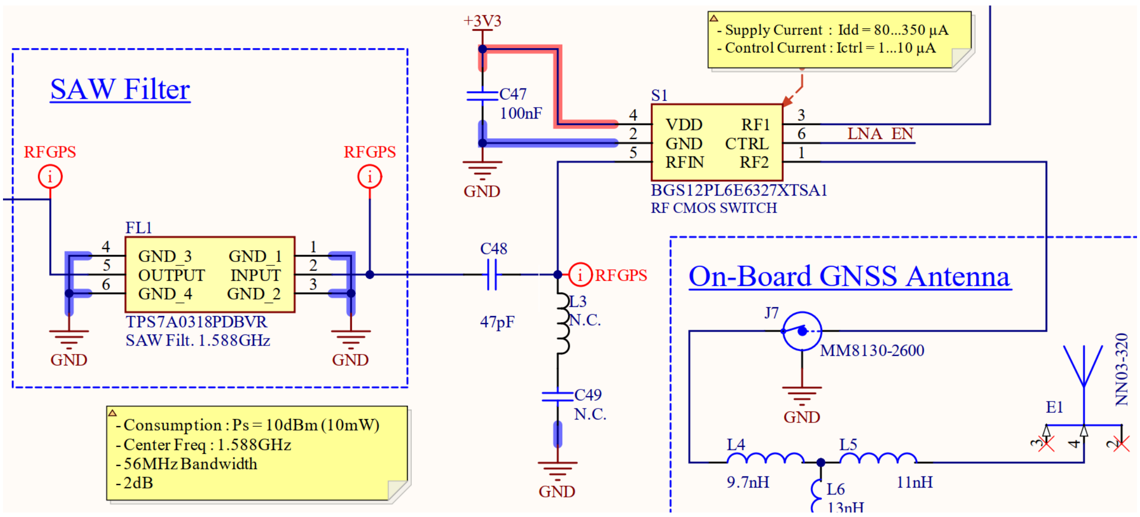


Figure 4.25 – RF Unit : RF Switch with *SAW* Filter

In order to add the possibility to connect the *GNSS* receiver to the on-board chip antenna or to an external active antenna, a RF switch is added. The RF switch is a *BGS12PL6E6327*[45], which is a general purpose RF *CMOS SPDT* switch with the following specifications (src.[45]) :

- 2 high-linearity TRx paths with power handling capability of up to 35 dBm
- All ports are fully symmetrical
- Low insertion loss
- Low harmonic generation
- High port-to-port isolation
- 30 MHz to 4 GHz coverage
- High ESD robustness
- On-chip control logic
- No decoupling capacitors required if no DC applied on RF lines

To add more robustness against interference and following the design recommendations that were presented on page 68, an addition external SAW filter is implemented right before the front-end of the *GNSS* receiver. This seems necessary, due to the presence of both *GNSS* and *LTE* antenna present on the same board.

Figure 4.26 illustrates the schematic of the *GNSS* external antenna power supply supervisor :

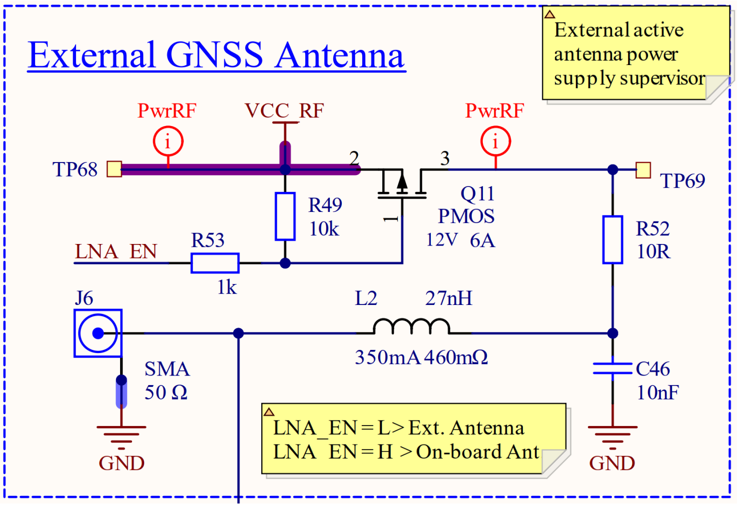


FIGURE 4.26 – RF Unit : External GNSS Antenna

The external *GNSS* antenna power supply supervisor is based on the "*MAX-M10S two-pin antenna supervisor*" application diagram from the integration manual of the *MAX-M10S*[36]. When the LNA_EN signal from the *MAX-M10S* is set 'low' (internal *LNA* mode configuration) the antenna power supply source *VCC_RF* is connected to the RF line and the *SMA* connector to the supply in order to power an external active *GNSS* antenna.

Figure 4.27 illustrates the schematic of the on-board GNSS chip antenna which is the *NN03-320* model from IGNION. The advantage with this company, is that they furnish simulation and component tuning values for custom board for free. To make the design process faster and to try it out, I used the components value that they recommended for my board. The full simulation and documentation from IGNION is in appendix 10.4.

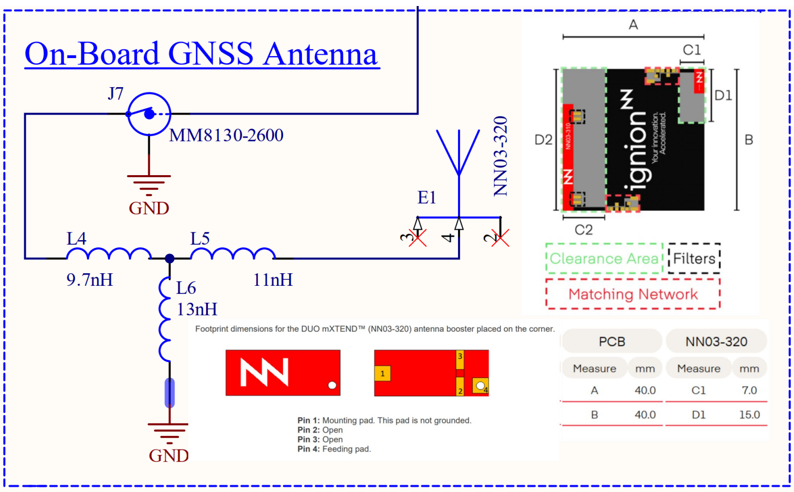


FIGURE 4.27 – RF Unit : On Board GNSS Antenna

GPS Ctrl MCU/Ext

Figure 4.28 illustrate schematic of *GNSS UART* bus configuration :

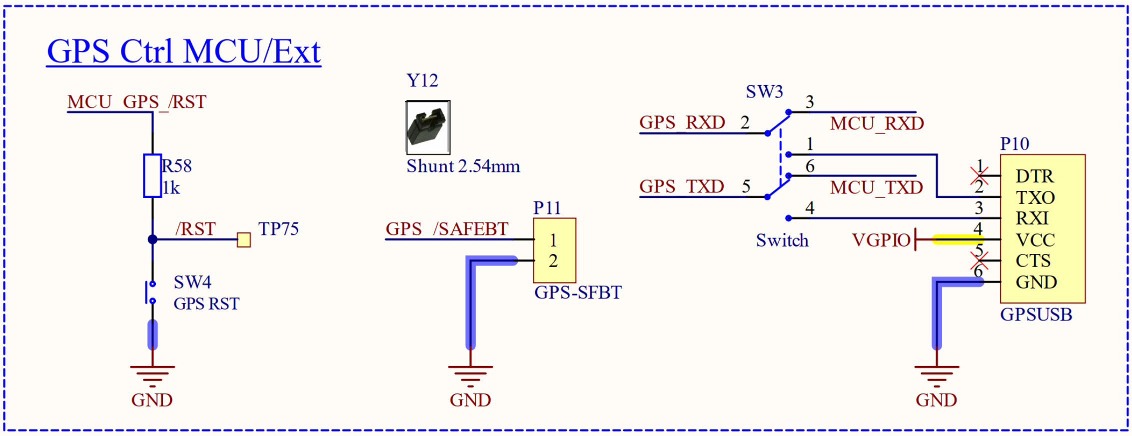


FIGURE 4.28 – RF Unit : GPS External/MCU Control Selection

This unit allows to connect the *UART* of the *GNSS* receiver to an external *UART* interface or to the system *MCU* (nRF9160).

LTE RF Transmission Line

Figure 4.29 illustrated the schematic of the LTE RF transmission line :

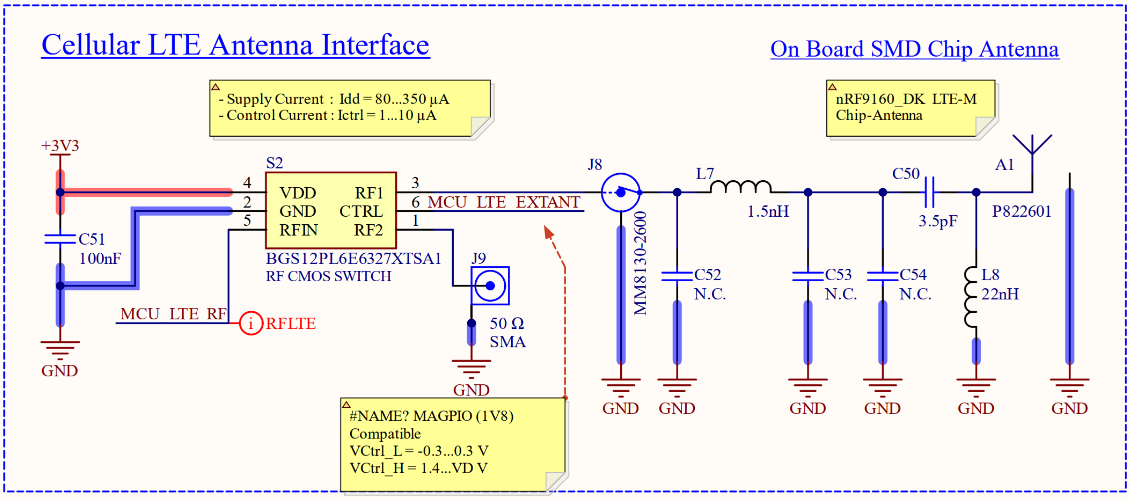


FIGURE 4.29 – RF Unit : Cellular LTE Transmission Line

The schematic of figure 4.29 is based on the one from the *nRF9160DK*[41] board with an aded RF switch and a *SMA* connector to allow the possibility to connect the *LTE* Modem to an external antenna.

4.2 Prototype board (PCB)

Figure 4.30 illustrates rooted PCB of the *LTEWatch* :

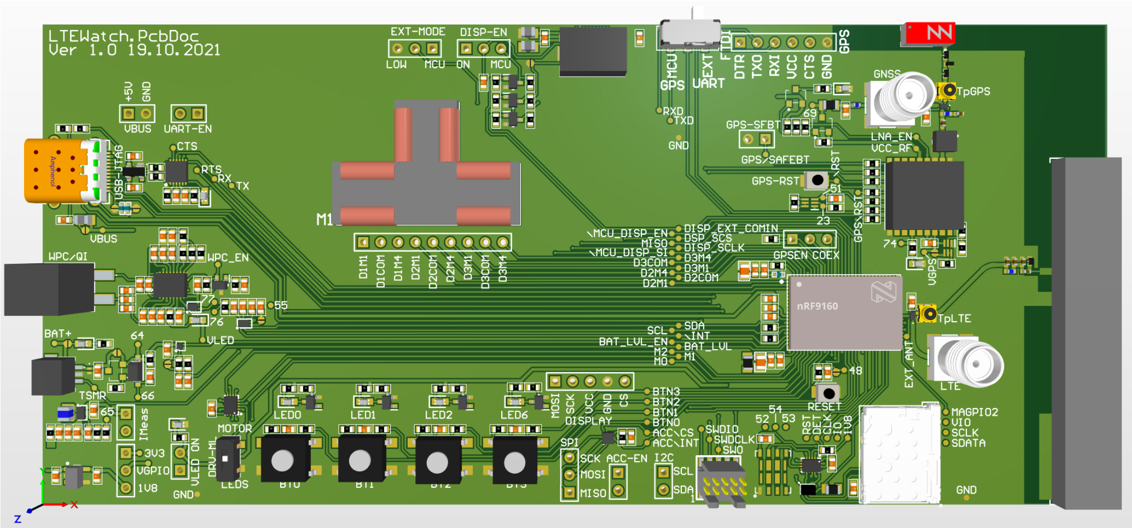


FIGURE 4.30 – Prototype PCB of the *LTEWatch*

Due to time constraints, it was agreed with the project manager RIEDER MEDARD, to let the *PCB* rooting task to Steve Gallay from the HEVS (HES-SO Valais).

The *LTEWatch* prototype board illustrated in figure 4.30 is similar to the one shown in figure 3.7.

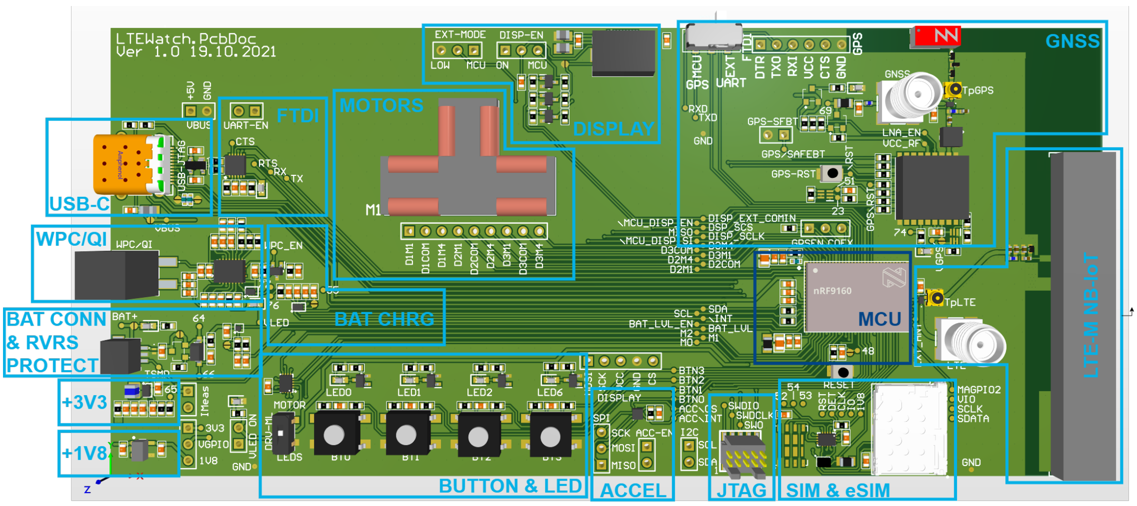


FIGURE 4.31 – Prototype PCB of the *LTEWatch* With Annotations

5 Antenna Part

5.1 *LTE-M/NB-IoT* Antenna

At the start of the project, the idea was to design a custom dipole antenna integrated into the watch strap. The design of a custom *LTE-M/NB-IoT* antenna for the *LTEWatch* was expected to be done but, due to the limited time available for the project and given the amount of work required to other tasks of the project, it was agreed with the project manager Medard Rieder to keep this part for further complementary tasks of this project. This is why this chapter only focuses on the design of the *GNSS* antenna.

5.2 *GNSS* Antenna

The *LTEWatch* project integrates a *GNSS* receiver which requires the implementation of a suitable *GNSS* antenna. RF design applications and antenna integration are complex processes that require special attention. U-BLOX provides several documentations about RF design and antenna integration process. The following sections are based on the following list of documentation and application note from U-BLOX :

1. *"RF design considerations for u-blox GNSS receivers"* (src.[46])
2. *"Antenna integration guidance"* (src.[47])
3. *"Design guide for small, high performance GNSS patch antenna applications"* (src.[48])

5.2.1 Introduction to *GNSS* Antenna Integration

GNSS applications have become very common in wearable and compact embedded applications. Applications that need to be more and more compact while increasing battery life and performance, in addition to an environment crowded with RF signals of all kinds. Due to these constraints, antennas are a critical part of any *GNSS* receiver design that requires special attention. As explained earlier, *GNSS* signals are extremely weak and even an optimal receiver cannot compensate for a bad antenna or in-band interference due to poor RF board design. Therefore, antenna integration plays an important role in the performance of *GNSS* applications.

5.2.2 Antenna basics

General considerations :

In *GNSS* applications, a good sky visibility is crucial, more satellites *GNSS* signal reception by the *GNSS* receiver means more performance and accuracy. Conversely, poor sky visibility environments such as narrow streets, underground parking lots, or any object covering the antenna will cause position drift and a significantly longer

TTFT (*Time To First Fix*), resulting in more power consumption and less battery life. A *GNSS* receiver can only achieve its specified performance if the *average carrier to noise power density ratio* of the strongest satellites reach at least 44 dB Hz. In an optimal RF design, the average of the C/N_0 ratio of high elevation satellites should be in the following range :

$$\boxed{44\,\text{dB Hz} \leq \frac{C}{N_0} \leq 50\,\text{dB Hz}} \quad \frac{C}{N_0} : \textit{Average carrier to noise power density ratio}$$

***GNSS* Antenna Requirements :**

To achieve optimal performance, the *GNSS* antenna should fulfill the following requirements :

1. Use high gain antenna : > 4 dBic
2. With active antenna, use *LNA* with low noise figure : < 2 dB
3. Low level of directivity : As shown in figure 5.1
4. Good sky visibility
5. Good matching between antenna and RF line impedance
6. High gain
7. Filter

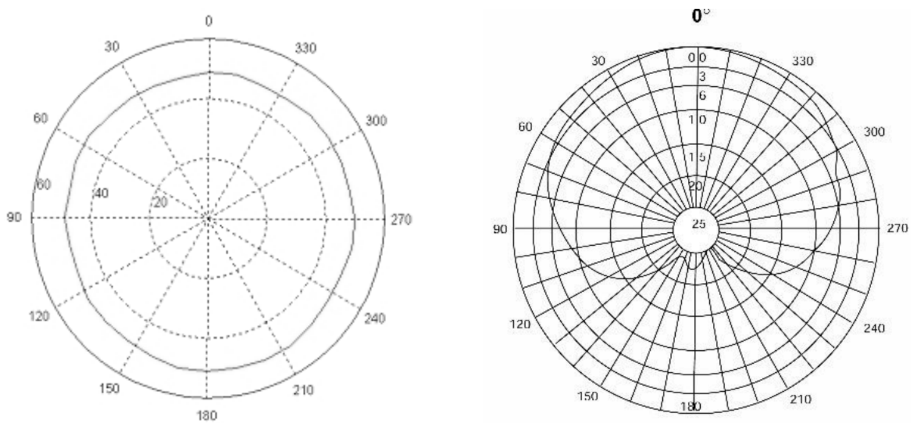


Figure 5.1 – Low directivity (left), high directivity (right) - Source :[46]

5.2.3 Active vs. Passive Antenna

Antennas are available in two main categories :

1. Passive antennas (ceramic patch, helix structure) :
   - Only contain the radiating element
   - Can also contain a 50 Ω line impedance adaptation matching network

2. Active antennas
   - Integrated *LNA* (*Low Noise Amplifier*)
     - Eliminate the line losses after the *LNA* which reduce the overall noise
     - Reduce the overall noise figure of the system resulting in better sensitivity
   - Some receivers require active antenna only
   - Increase power consumption $\boxed{3 \ldots 20\,\text{mA}}$

Active antennas are always advisable if antenna receiver line length exceeds $\boxed{10\,\text{cm}}$. The gain of the *LNA* inside the antenna must not lead to an overload condition at the receiver. For receivers that also work with passive antennas an antenna LNA gain of $\boxed{15\,\text{dB}}$ is usually sufficient, even for cable lengths up to 5 m. There is no need for the antenna *LNA* gain to exceed $\boxed{26\,\text{dB}}$ for use with U-BLOX receivers (at the RF input). With shorter cables and a gain above $\boxed{35\,\text{dB}}$, an overload condition might occur on some receivers.

When comparing the gain figures of active and passive antennas, keep in mind that the gain of an active antenna is composed of two components :

1. **Antenna gain of the passive radiator** : given in dBic
2. ***LNA* power gain** : given in dB

A low antenna gain cannot be compensated by high *LNA* gain. **It is not possible to judge the quality of the antenna if a manufacturer provides only one total gain figure**. Information on the antenna gain (in dBic), the amplifier gain, and the amplifier noise figure is also required.

Active antenna	**Passive antenna**
Needs more power ($10 - 60\,\text{mW}$) than a passive antenna	Does not add anything to the power budget
Is more tolerant to minor impedance miss-match or cable length than a passive antenna	Antenna must be connected with a carefully designed micro strip or strip line of maximum 10 cm to the *GNSS* receiver to ensure good *GNSS* performance
Helps to keep the receiver noise figure low	Jamming signals coupled into the micro-strip or strip line negatively affect the performance
Is less affected by jamming into the antenna cable than a passive antenna (if equipped with filter)	RF design experience is required to properly design a passive antenna

Table 5.1 – Active vs Passive antenna table - Source :[46]

5.2.4 Passive *GNSS* Antennas :

It is important to know that *GNSS* signal is right-hand circuit polarized (RHCP) which result in different needs of antenna style than the well-known *whip* antenna used for linear polarized signals.

For *GNSS* application, the list of available antenna style is the following :

- Patch Antenna
- Helix Antenna
- Monopole Antenna
  - Chip Antenna
  - PCB Antenna
  - Fractal Element Antenna (FEA)
- Dipole antenna
  - Loop antenna
  - Planar Inverted F Antenna (PIFA)
  - High-end GNSS antennas

Patch Antenna :

- Most common antenna for *GNSS* applications
- Flat antenna
- Have a ceramic and metal body mounted on a metal base plate
- Often cast in housing

Figure 5.2 – Example of patch antenna - Source :https://www.inpaq.com.tw/upload/file/20160125020258534235875.png

Advantages :

- Ideal for flat surface mounting
- Very high gain capable
- Low cost
- Huge variation of available size (40×40 mm down to 10×10 mm)

Disadvantages :

- Require a large ground plane for best performance ($70 \times 70\,\text{mm}$)
- A smaller antenna equal a lower overall gain
- Amplifying the signal after the antenna will not improve the *SNR* (*Signal to Noise Ratio*)
- The minimal ground plane size is ($50 \times 50\,\text{mm}$)

Practical values :

1. Patch antennas size $= 25 \times 25\,\text{mm}$:
   - Optimal performance
   - Cost-efficient
2. Patch antennas size $< 17 \times 17\,\text{mm}$:
   - Moderate navigation performance (Unless enhanced by u-blox *Super-Sense technology*)

Performance is highly dependent to the ground plane size

Helix Antenna :

- Geometric size depends on the dielectric that fill the space between the active parts of the antenna
- Air dielectric : Large dimension ($l = 60\,\text{mm}$, $\oslash = 45\,\text{mm}$)
- Ceramic dielectric : Much smaller form factor

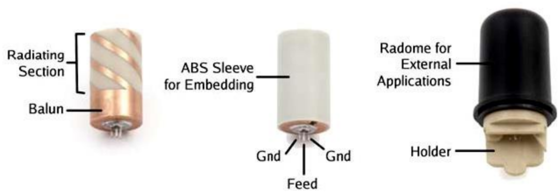


Figure 5.3 – Example of helix antenna - Source :[46]

Advantages :

- Like patch antennas, filling the antenna with a high dielectric constant material can reduce the size of helix antennas
- Antenna size of $l = 18\,\text{mm}$ and $\oslash = 10\,\text{mm}$ are being available on the market

Disadvantages :

- Smaller antenna dimensions $\rightarrow$ tight manufacturing tolerances
- Antenna gain decrease with size of the antenna

Monopole Antenna - Chip Antenna :

- More and more common for compact *GNSS* designs
- Very common smart-phone and *Personal-Navigation-Devices* (*PNDs*) applications

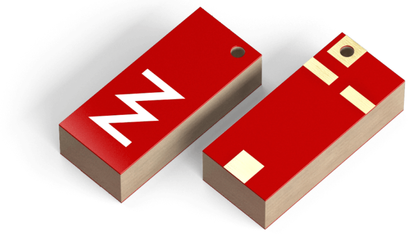


Figure 5.4 – Example of chip antenna - Source : `https://ignion.io`

Advantages :

- Low cost
- Extremely small size available ($3.2 \times 1.6 \times 1.1$ mm)
- High gain
- Omni-directional radiation patterns

Disadvantages :

- A variety of factors influence their performance due to their miniature size
  - Footprint
  - Ground plane size
  - Isolation distance (typ. 5 mm) : The keep-out area can have an important impact on antenna efficiency and *GNSS* performance
- Require more careful RF design
- Respecting all recommendations doesn't guaranty performance due to potential detuning effects created by nearby objects

Practical recommendations :

- Even if the antenna manufacturers claim that a ground plane is not required, the available ground plane has a significant impact on the *GNSS* performance of a chip antenna. Therefore, not only the size of the chip but also the ground plane must be considered in the design. For designs with a sufficiently large ground plane a chip antenna can provide satisfactory *GNSS* performance.
- However, in designs with an inadequate ground plane and device layout their performance is insufficient for *GNSS*.
- Chip antennas have a 3 dB loss compared to helical or patch antennas due to linear polarization and their performance is highly dependent on the size of the ground plane
- Chip antennas are not recommended for use in devices where navigation is an essential feature

Monopole Antenna - PCB Antenna :

Advantages :

- Simple and economical antenna solution
- Cheapest *GNSS* antenna solution
- Usually have a larger bandwidth than chip or patch antennas

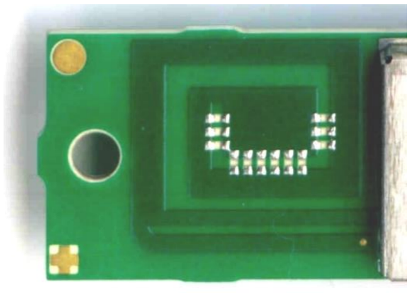


Figure 5.5 – Example of *PCB* antenna - Source :[46]

Disadvantages :

- Significantly weaker signals compared to a patch or helix antennas
- Loss of -3dB due to linear polarization
- Massively in-homogeneous directivity
- Lower overall gain
- Typically bigger than chip antennas
- Requires RF expertise

Dipole Antenna :

Advantages :

- Very cost-effective solution, especially when printed on PCB
- Acceptable performance in indoor environments
- Field independent from any ground plane
- Linear polarization increase *backlog* sensitivity which is useful for indoor reception

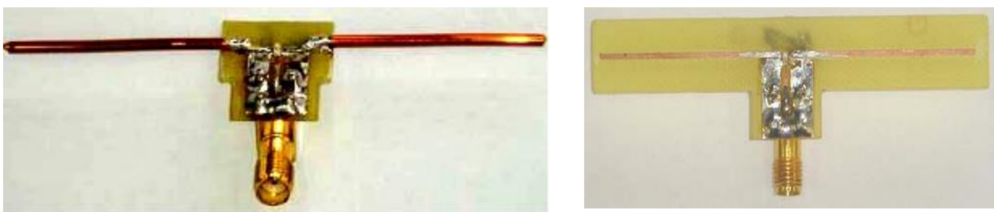


Figure 5.6 – Example of dipole antennas - Source :[46]

Disadvantages :

- Linear polarized antenna : 3 dB loss for *GNSS* in open spaces
- Similar drawbacks as PCB antennas
- Require RF expertise

Practical recommendations :

Warning : Dipole antennas are not recommended for use in devices where navigation is an essential feature

Dipole Antenna - Loop antenna :

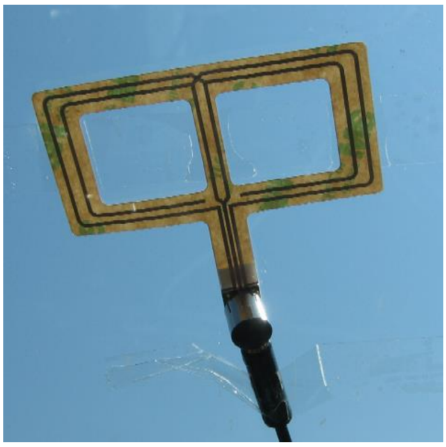


Figure 5.7 – Example of dipole loop antenna - Source :[46]

Advantages :

- Independent from ground plane → not sensitive to objects in the near field
- Good navigation performance when mounted on glass

Disadvantages :

- Not a suitable solution for small embedded system

Dipole Antenna - Planar Inverted F Antenna (PIFA) :

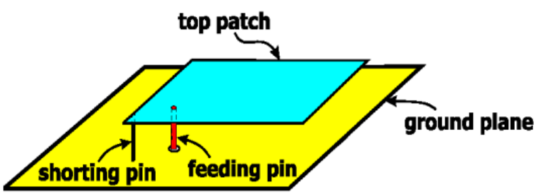


Figure 5.8 – Example of dipole *PIFA* antenna - Source :[46]

Advantages :

- Suitable antenna solution for embedded applications
- Nearly omnidirectional
- Multi-band radiation capability

Disadvantages :

- Linearly polarized : 3 dB loss
- Only moderate efficiency

Practical recommendations :

- Mainly used in cellular phones (*E-911*) applications
- Not recommended for applications where navigation is an essential feature

Dipole Antenna - High-end *GNSS* antennas :

Advantages :

- Highly optimized for multi-path reflected signals suppression (choke ring antennas, multi-path limiting antennas, *MLA*)
- Very accurate antenna phase center determination

Disadvantages :

- Larger size
- Higher power consumption
- Higher price

Practical recommendations :

- Recommended for precision *GNSS* applications with position resolution in the mm range
- For that kind of application, it is required that signals from all elevations satellites meet at exactly the same point inside the antenna
- Receivers with multiple antenna inputs are often required for that kind of precision

5.2.5 *LTEWatch GNSS* Antenna Selection

Considering all points described in previous sections, the best solution for the *LTEWatch GNSS* receiver seems to be a passive chip antenna. After long research on available solution on the market, a suitable solution was found : the *DUO mXTEND (NN03-320)* from IGNION.

***DUO mXTEND (NN03-320)* from ignion :**

Figure 5.9 – *DUO mXTEND (NN03-320)* Antenna from IGNION - Source :[49]

The datasheet of the *DUO mXTEND (NN03-320)*[49] describes the antenna as a versatile product can be used to operate communication services such as, *5G*, *GNSS*, *BT*, *Wi-Fi*, or *UWB* in a *single port* or *multiport* configuration.

The *NN03-320* is designed for application such as :

- *UWB* modules
- Smart Watches
- Air Tags
- Earphones
- Bluetooth modules
- Asset Trackers

Features & Benefits :

- Multipurpose : Multiband *IoT* chip antenna component with multiport (2 independant ports)
- Low power consumption
- High efficiency
- Smallest clearance : No clearance beyond the antenna footprint
- Miniature : Ultra compact form factor of 7.0 mm × 3.0 mm × 2.0 mm
- Best for combining : One or more GNSS, Bluetooth, UWB and 5G applications.
- Versatile : Can be mounted on device center edge or on device corner
- Reliability : *Off-the-Shelf* standard product

Antenna Design Tool from ignion *(Antenna Intelligence Cloud)* :

One of the biggest advantages of anntenna solution from IGNION is that they provides an online antenna design tool *"Antenna Intelligence Cloud"* on their website : `https://ignion.io/antenna-intelligence/`. This tools allow to get a RF design proof of concept in 24 h and also provides a full simulation of a custom design with performance values, electrical schematic and components selection.

***LTEWatch GNSS* Antenna :**

For the *LTEWatch*, I asked for a custom wearable application design using *LTE-M/NB-IoT* and *GNSS* communication standard on a 40 mm × 40 mm board. A document containing a design proposition was received. The full document is available in appendix 10.4 and the main specifications of the proposed solution by Ignion are illustrated in figures 5.10 to 5.12.

Figure 5.10 illustrates the *GNSS* Antenna placement proposition :

PCB		NN03-320		NN03-310	
Measure	mm	Measure	mm	Measure	mm
A	40.0	C1	7.0	C2	12.0
B	40.0	D1	15.0	D2	40.0

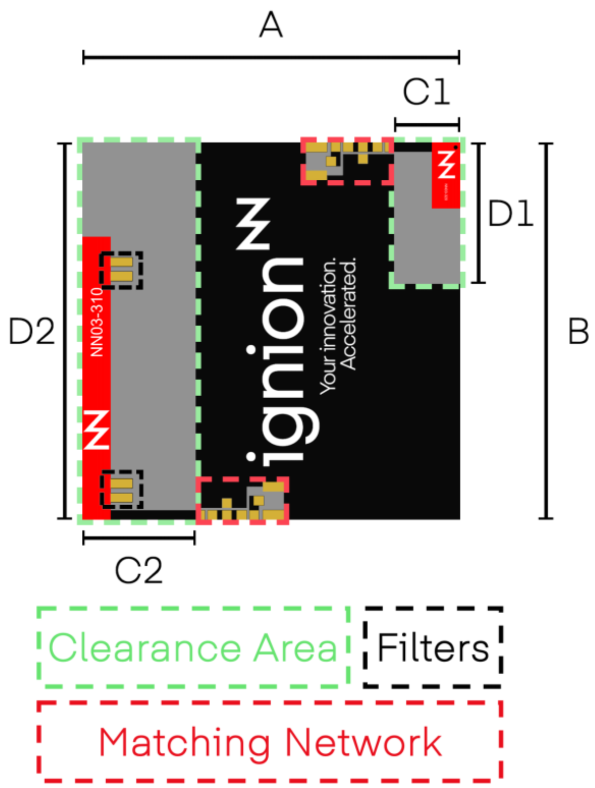
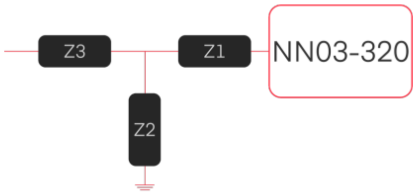


Figure 5.10 – Sketch of the proposed antenna placement and clearance

Figure 5.11 illustrates the *GNSS* antenna matching network topology :



Comm. Standard	Component	Value	Part Number	Manufacturer
GNSS	Z1	11nH	LQW18AN11NG80	Murata
	Z2	13nH	LQW18AN13NG80	Murata
	Z3	9.7nH	LQW15AN9N7G80	Murata

Figure 5.11 – *GNSS* Matching Network topology proposed by Ignion

Figure 5.12 illustrates the expected performance proposed by Ignion :

	DUO mXTEND™ (NN03-320) for GNSS		
Frequency (MHz)	1559	1610	Avg 1559 - 1610
Total efficiency (%)	46.3	46.5	49.2

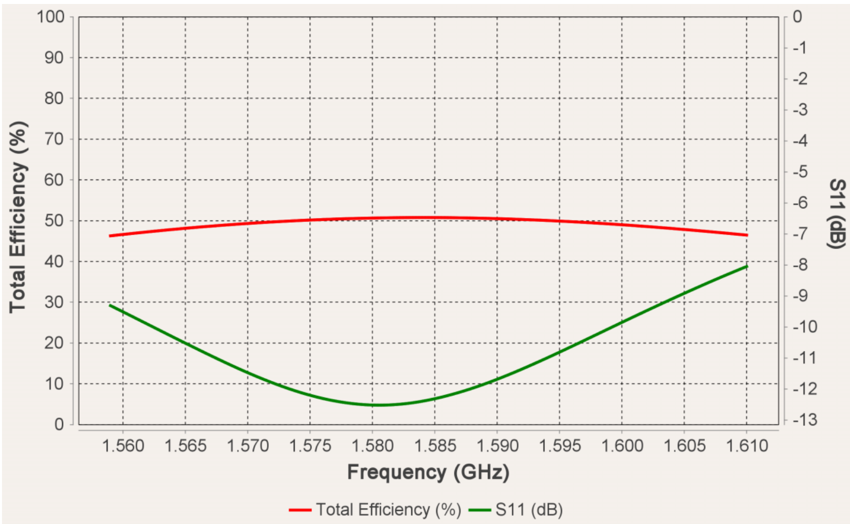


Figure 5.12 – Expected device performance for the proposed design by Ignion

As shown in figure 5.12, the expected performance of the proposed solution is not very impressive but is not that bad considering the very limited size of the ground plane. An efficiency of 50 % is not optimal but still sufficient for a small *GNSS* application. It is also important to mention that the *LTEWatch* prototype board has a much larger size and a much larger ground plane. Ignion specifies in the documentation that an increase 10 mm in board length results in an improvement in total efficiency of 0.5 dB, of this fact, we can expect a significantly higher total efficiency with the *LTEWatch* prototype board.

6 Software Part

6.1 Small Watch Application Development

The second biggest task of of this project is to develop a simple watch application for the prototype board of *LTEWatch*. Due to the limited time available for the project, the objectif is not to develop a definitive and complex smart-watch application but is to implement every functional blocks from the prototype board, because of this, the developed application is name "*PicoWatch*".

Following the system functional decomposition (p. :24), the small watch application (*PicoWatch*), is decomposed in the following functional blocks :

1. **Power Supply** : Relating to battery and charger module
2. **User Interface** : Relating to user-accessible peripherals and sensors
3. **RF & Network** : Relating to *LTE-M/NB-IoT*, *MQTT* and *GNSS*
4. **Debugging** : Relating to VS-Code *IDE* logging

6.2 *LTEWatch* Application Decomposition

6.2.1 Power Supply Block :

Description :

This block integrates the battery charger module and the battery level monitoring unit of the *LTEWatch* prototype board and should implement the features listed below :

1. **Battery Charger :**
   — Set battery charger's configurable registers ; *Battery Voltage Control*, - *Fast Charge Current Control*, - *Charger Control*, - *Input Current Limit Control*, - *TS Control* and others
   — Get charger's interruption flags
   — Read and clear charger's status and fault registers ; *Charger Status*, - *Charger Status and Faults* and - *Charger Flag Registers*
2. **Batter Level Monitoring :**
   — Measure and store battery voltage level value in "mV"
   — Convert and store battery level value to "%"

6.2.2 User Interface Block :

Description :

This block integrates all the peripherals and sensors accessible to the user of the *LTEWatch* prototype board. The *User Interface Block* is the only way users interact with the device, which includes :

- **Output interactions :** "*DEVICE*" → "*USER*", such as :
  - display time using clock hands,
  - display device information using the LCD and LEDs.
- **Input interactions :** "*USER*" → "*DEVICE*", such as :
  - Change modes or settings of the device using buttons and accelerometer.

This block should implement the features listed below :

1. **Buttons :**
   - Get button press and button release action events
   - Filter button events with debounce
   - Convert button events into button action ; *Click*, - *Double Click*, - *Triple Click*, - *Long-Press* and - *Double Long-Press*
2. **LEDs :**
   - Set **ON**/**OFF**,
   - **START**/**STOP** Blinking
3. **Display :**
   - Interface with SHARP *Memory-In-Pixel (MIP)* LCD
   - Display modes ; *Set Motor Position Mode*, - *Set GNSS Antenna Mode*, - *LTEWatch Mode* and *GNSS Tracking Mode*
   - Display device information ; *Date*, - *Current Time*, - *LTE/MQTT Connection State*, - *GNSS Connection State*, - *Current Battery Level* and - *Battery Charging State*
4. **Motorized Clock Hands :**
   - Move stepper motors position
   - Set stepper motors position
   - Get current stepper motors position
   - Display time on stepper motors ; *Hour*, - *Minute*, - *Second*
5. **Accelerometer**[1] **:**
   - Read 3-axis accelerometer values
   - Convert accelerometer acceleration values to speed
   - Add functionality ; *Wake-Up Event*, - *Pedometer*, - *Tracking Refresh-Rate Modification* and others.

1. Optional : Depending on available time

6.2.3 RF & Network Block :

Description :

This block is one of the most important in the device, as it basically defines the name of the project. By integrating the *LTE-M/NB-Iot* modem, the *MQTT* client and the *GNSS* receiver module of the *LTEWatch* prototype board, this block should implement the following features :

1. ***LTE-M/NB-Iot Modem* :**
   - **Connect**/**Disconnect** to/from *LTE-M/NB-Iot* network
   - Set use of on-board or external *LTE* antenna
2. ***MQTT* Client :**
   - **Connect**/**Disconnect** client to *MQTT* broker
   - Publish data on *MQTT* broker topics
   - Subscribe to *MQTT* broker topics [2]
3. ***GNSS* Receiver :**
   - Set *GNSS* receiver module configuration
   - Ask *GNSS* receiver for position
   - Get and store *GNSS* receiver communications (answers)
   - Set use of on-board or external *GNSS* antenna

6.2.4 Debugging Block :

Description :

The *nRF COnnect SDK* development environment for VS-Code allows to transmit logs for debugging purposes. This can be achieved either using *RTT* logging option using the *J-Link* from Segger or eiter using *UART* logging. The difference between the tow options is that *UART* logging require target's log to pass through a *FTDI UART-to-USB* interface. In order to use *UART* logging option, this block should implement the following modules.

1. ***UART* Logging :**
   - Interface with *USB-to-UART FTDI* interface module
   - Send data to *FTDI* interface module
   - Get data from *FTDI* interface module

2. Optional : Depending on available time

6.2.5 Application Functional Decomposition Diagram

In order to have a more visual understanding of the application, it is interesting to decompose the application software in a functional block diagram that illustrates each block with its correspond pin assignment. With this diagram, it is easier to understand which *API*, library and peripherals need to be implemented to integrate each features.

Figure 6.1 illustrates the functional decomposition diagram of *LTEWatch* application software :

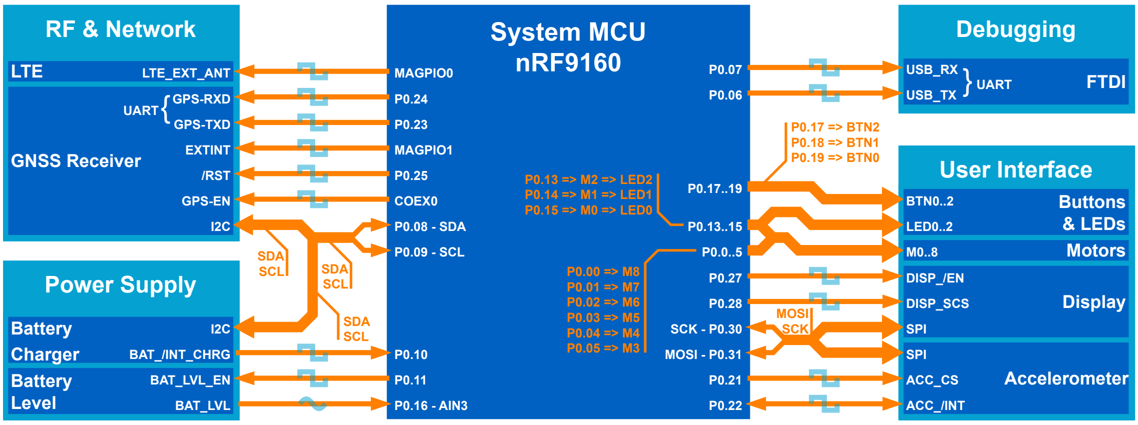


Figure 6.1 – *LTEWatch* Application Functional Decomposition Diagram

As shown in figure 6.1, even if the goal of the firmware development is to implement a small watch application to validate prototype board hardware and features, the *LTEWatch* application (firmware) is already quite complex and requires to implement several peripherals.

The small watch application firmware (*LTEWatch*) require following peripherals to be implemented :

- many digital inputs and outputs for LEDs, motors and command signals,
- several interrupt sensitive digital inputs for external modules and buttons,
- an analog input (*ADC*) for battery level monitoring (AIN3),
- two *UART* serial bus for the *FTDI* interface and the *GNSS* receiver,
- a *I2C* serial bus for the battery charger and the *GNSS* receiver,
- a *SPI* serial bus for the display and the accelerometer,
- and a *LTE Modem* for *LTE-M/NB-IoT* RF communication.

6.3 *LTEWatch* Software Architecture

As seen in the "*LTEWatch Application Decomposition*" section starting at page 109, the developed application is relatively complex and integrates multiple components and features. For better understanding, a visual illustration of the developed firmware architecture is shown in figure 6.2 :

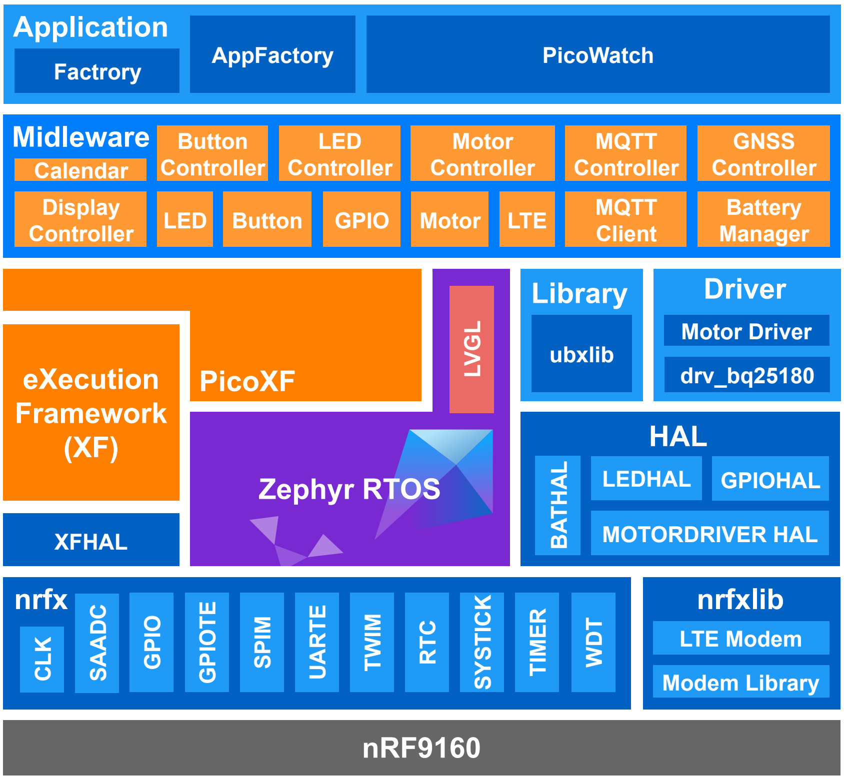


FIGURE 6.2 – *LTEWatch* Software Architecture

As shown in figure 6.2, the application requires the integration of many *APIs* from the NORDIC SEMICONDUCTOR *nrfx* driver set. These *API* are either directly used by the *LTEWatch* application, or required by the *Zephyr RTOS* which is the main component of the software.

The *LTEWatch* firmware is an event-based application. This means that each process is triggered by events such as timeout triggered, *GPIO* triggered or software triggered events. Since the application needs to be as responsive as possible, every submitted event needs to be stored, executed, and disposed of by an event manager unit, also known as an executive framework.

The *Institute of Industrial System* of the *HES-SO Wallis (HEVS)* has developed its own executive framework : ***eXecution Framework*(*XF*)**. This *XF* is used by the *LTEWatch* firmware to implement an event-based application. Besides the integrated *XF*, a more compact and simpler version of external framework *PicoXF* is implemented for reasons that will be covered later.

6.3.1 Introduction to *nRF Connect SDK* from Nordic Semi.

Before diving into the *LTEWatch* firmware, it seems worth having a good understanding of the *nRF Connect SDK* of Nordic Semi.

nRF Connect SDK is an open-source and optimized cellular IoT (*LTE-M/NB-IoT*), *Bluetooth Low Energy*, *Thread*, *Zigbee*, and *Bluetooth mesh stacks* software development kit which includes the *Zephyr* real-time operating system (*RTOS*). The nRF Connect SDK enables to develop application for nRF52, nRF53, and nRF91 Series devices. The *nRF Connect SDK* source code is fully accessible on Nordic Semi.'s *"nrfconnect"* repository : `https://github.com/nrfconnect`.

The *nRF Connect SDK* from Nordic Semi. contains the following modules :

1. **sdk-nrf *(nrfx)* :** Contains applications, samples, libraries, and drivers that are specifically targeted for Nordic Semiconductor devices.
2. **sdk-nrfxlib *(nrfxlib)* :** Contains closed-source libraries and modules in binary format.
3. **sdk-zephyr *(Zephyr RTOS)* :** Contains a fork of the *Zephyr* project, which provides samples, libraries, and drivers for a wide variety of devices, including Nordic Semiconductor devices.
4. **sdk-mcuboot *(mcuboot)* :** Contains a fork of the *MCUboot* project, which provides a secure bootloader application. You can find the fork in bootloader/mcuboot after obtaining the nRF Connect SDK source code.

6.3.2 Nordic Semi. Driver Package (*nrfx*)

Overview :

The replacement of the old *"nRF5 SDK"* from Nordic Semi. with the new *"nRF Connect SDK"* required to export all the drivers from their previous *SDK* to ensure compatibility with previously developed applications, or at leas to facilitate as much as possible port to the new *SDK*.

In the new *nRF Connect SDK*, Nordic Semi.'s SoCs peripherals drivers are contained in *nrfx*. Nordic Semi. also wanted to provide drivers that could be used in various environments without needing to integrate other parts of *SDK*, if unnecessary, that's why they regrouped all drivers in *nrfx*.

More detailed information about *nrfx* is available on their online documentation : `https://developer.nordicsemi.com/nRF_Connect_SDK/doc/latest/nrfx/index.html`.

SoC Driver Compatibility Comparison Table :

Before using any drivers or *APIs* from *nrfx*, it is necessary to understand which drivers are supported by which SoC, in this case the *nRF9160 SiP*.

The comparative overview of drivers compatibility of each SoCs from Nordic Semi. is presented in the following table 6.1 :

Driver	*nRF*51xx	*nRF*52805	*nRF*5281x	*nRF*52820	*nRF*52832	*nRF*52833	*nRF*52840	*nRF*5340	*nRF*9160
AAR	✓	✓	✓	✓	✓	✓	✓	✓	✗
ACL	✗	✗	✗	✓	✗	✓	✓	✓	✗
ADC	✓	✗	✗	✗	✗	✗	✗	✗	✗
BPROT	✗	✓	✓	✗	✓	✗	✗	✗	✗
CACHE	✗	✗	✗	✗	✗	✗	✗	✓	✗
CCM	✓	✓	✓	✓	✓	✓	✓	✓	✗
CLOCK	✓	✓	✓	✓	✓	✓	✓	✓	✓
COMP	✗	✗	✓	✓	✓	✓	✓	✓	✗
DCNF	✗	✗	✗	✗	✗	✗	✗	✓	✗
DPPI	✗	✗	✗	✗	✗	✗	✗	✓	✓
ECB	✓	✓	✓	✓	✓	✓	✓	✓	✗
EGU	✗	✓	✓	✓	✓	✓	✓	✓	✓
FICR	✓	✓	✓	✓	✓	✓	✓	✓	✓
FPU	✗	✗	✗	✗	✗	✗	✗	✓	✗
GPIO	✓	✓	✓	✓	✓	✓	✓	✓	✓
GPIOTE	✓	✓	✓	✓	✓	✓	✓	✓	✓
I2S	✗	✗	✗	✗	✓	✓	✓	✓	✓
IPC	✗	✗	✗	✗	✗	✗	✗	✓	✓
KMU	✗	✗	✗	✗	✗	✗	✗	✓	✓
LPCOMP	✓	✗	✗	✗	✓	✓	✓	✓	✗
MPU	✓	✗	✗	✗	✗	✗	✗	✗	✗
MUTEX	✗	✗	✗	✗	✗	✗	✗	✓	✗
MWU	✗	✗	✗	✗	✓	✓	✓	✗	✗
NFCT	✗	✗	✗	✗	✓	✓	✓	✓	✗
NVMC	✓	✓	✓	✓	✓	✓	✓	✓	✓
PDM	✗	✗	✓	✗	✓	✓	✓	✓	✓
POWER	✓	✓	✓	✓	✓	✓	✓	✓	✓
PPI	✓	✓	✓	✓	✓	✓	✓	✗	✗
PWM	✗	✗	✓	✗	✓	✓	✓	✓	✓
QDEC	✓	✓	✓	✓	✓	✓	✓	✓	✗
QSPI	✗	✗	✗	✗	✗	✗	✓	✓	✗
RADIO	✓	✓	✓	✓	✓	✓	✓	✓	✗
RNG	✓	✓	✓	✓	✓	✓	✓	✓	✗
RTC	✓	✓	✓	✓	✓	✓	✓	✓	✓
SAADC	✗	✓	✓	✗	✓	✓	✓	✓	✓
SPI	✓	✓	✓	✓	✓	✓	✓	✗	✗
SPIM	✗	✓	✓	✓	✓	✓	✓	✓	✓
SPIS	✓	✓	✓	✓	✓	✓	✓	✓	✓
SPU	✗	✗	✗	✗	✗	✗	✗	✓	✓
SYSTICK	✗	✓	✓	✓	✓	✓	✓	✓	✓
TEMP	✓	✓	✓	✓	✓	✓	✓	✓	✗
TIMER	✓	✓	✓	✓	✓	✓	✓	✓	✓
TWI	✓	✓	✓	✓	✓	✓	✓	✗	✗
TWIM	✗	✓	✓	✓	✓	✓	✓	✓	✓
TWIS	✗	✓	✓	✓	✓	✓	✓	✓	✓
UART	✓	✓	✓	✓	✓	✓	✓	✗	✗
UARTE	✗	✓	✓	✓	✓	✓	✓	✓	✓
USBD	✗	✗	✗	✓	✗	✓	✓	✓	✗
VMC	✗	✗	✗	✗	✗	✗	✗	✓	✓
WDT	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 6.1 – SoC Driver Compatibility Comparison Table - Source :[10]

LTEWatch application require several drivers that are listed in table 6.1. Using the list of supported drivers for the *nRF9160* SoC and the function block decomposition it is possible to list all necessary drivers required for *LTEWatch* application using *nRF9160* SoC.

The list of drivers required by the *LTEWatch* application is the following :

1. **Buttons, LEDs and other DI/O :**
   - GPIO : *Hardware access layer* for managing the GPIO peripheral
   - GPIOTE : *GPIO Task Event* peripheral driver
2. **Display & Accelerometer :**
   - SPIM : *Serial Peripheral Interface Master* with *EasyDMA* driver
   - SPIS : *Serial Peripheral Interface Slave* with *EasyDMA* driver
3. **Motors :**
   - RTC : *Real Timer Counter* peripheral driver
4. **Battery Manager & *GNSS* Controller :**
   - SAADC : *Successive Approximation ADC* peripheral driver
   - TWIM : *Two Wire Interface Master* with *EasyDMA* peripheral driver
   - TWIS : *Two Wire Interface Slave* with *EasyDMA* peripheral driver
5. **Debug & Logging**
   - UARTE : *UART Task Event* peripheral driver
6. **Events, Timers and Timeouts Based Application :**
   - CLOCK : Clock peripheral driver
   - SYSTICK : ARM(R) driver to configure *SysTick* as a free-running timer used to generate delays and pool for short timeouts ($\leq 250\,\mu s$)
   - TIMER : *Timer* peripheral driver
7. **LTE Modem :**
   - PDM : *Pulse Density Modulation* peripheral driver
8. **Zephyr RTOS :**
   - DPPI : *Distributed Programmable Peripheral Interconnect* allocator
   - EGU : *Event Generator Unit* peripheral driver
   - FICR : *HAL* to get *Factory Information Configuration Registers*
   - IPC : *Interprocessor Communication* peripheral driver.
   - KMU : *HAL* for managing the *Key Management Unit* peripheral
   - NVMC : *Non-Volatile Memory Controller* peripheral driver
   - POWER : Set of drivers for managing POWER peripherals
   - SPU : *HAL* for managing the *System Protection Unit* peripheral.
   - VMC : *HAL* for managing the *Volatile Memory Controller* peripheral
   - WDT : *Watchdog Timer* peripheral driver

6.3.3 *Zephyr* Real Time Operating System (*RTOS*)

Zephyr RTOS is an open-source real time operating system with a small-footprint that is specially designed for resource constrained and embedded applications. Compact embedded portable applications such as simple environmental sensors and LED oriented wearables but also more complex and sophisticated portable applications, like smart-watches, embedded controllers and *IoT* wireless applications.

6.3.4 Nordic Semi. Libraries & Modules (*nrfxlib*)

As described on Nordic Semi.'s online documentation[11], *nrfxlib* contains *RTOS*-independent libraries and modules for Nordic Semi. SoCs such as the *Modem Library* that is required by the *LTEWatch* firmware to implement *LTE-M/NB-IoT* and *MQTT* applications.

nrfxlib Modem library :

The *Modem Library* is an interface provided by Nordic Semi. that is used for :

— operating the *nRF9160* modem,

— establishing the *LTE-M* and *NB-IoT* connections,

— and receiving the position data (GPS).

In the case of the *LTEWatch* application, this library is used to operate the *nRF9160* modem and to establish the *LTE-M/NB-IoT* connections. Features relatives to *GNSS* is not requiered because *LTEWatch* uses an external *GNSS* receiver that only necessitates to implement a serial *I2C* bus communication to configure the receiver and to get position data.

6.4 External Library

The *LTEWatch* application implement a display and an external *GNSS* receiver. Both modules requires drivers and libraries to be reconfigured and operated.

The application implement the two following external libraries :

1. **LVGL** : An open-source, graphics library that is already integrated in *Zephyr*
2. **ubxlib** : An open-source library for u-blox products and services

6.4.1 Light and Versatile Graphics Library (*LVGL*)

LVGL Overview (source :[50]) :

LVGL is very popular, free and open-source embedded graphics library compatible with any *MCU*, *MPU*, and display type that is supported by many vendors and project such as Arm, STM32, NXP, Espressif, Nuvoton, Arduino, RT-Thread, Zephyr, NuttX, Adafruit and many more.

The *LVGL* library provides all necessary features to create all king of *GUIs* with over 30 built-in widgets, style system, web inspired layout manager, typography system supporting many languages.

The library implementation only requires the following specifications :

1. 32 kB of *RAM*
2. 128 kB of *Flash*
3. A *C* compiler
4. A frame buffer
5. At least an 1/10 screen sized buffer for rendering

LVGL Features :

The *LVGL* library provides the following interesting features (src.[50]) :

- **Free and Portable :**
  - A fully portable C (C++ compatible) library with no external dependencies.
  - Can be compiled to any MCU or MPU, with any (RT)OS.
  - Supports monochrome, ePaper, OLED or TFT displays, or even monitors. Porting Guide
  - Distributed under the MIT licence, so you can easily use it in commercial projects too.
  - Needs only 32 kB *RAM* and 128 kB *Flash*, a frame buffer, and at least an 1/10 screen sized buffer for rendering.
  - OS, External memory and *GPU* are supported but not required.
- **Widgets, Styles, Layouts and more :**
  - 30+ built-in Widgets : Button, Label, Slider, Chart, Keyboard, Meter, Arc, Table and many more.
  - Flexible Style system with $\approx$ 100 style properties to customize any part of the widgets in any state.
  - *Flexbox* and *Grid*-like layouts engines to automatically size and position the widgets in a responsive way.
  - Texts are rendered with *UTF-8* encoding supporting CJK, Thai, Hindi, Arabic, Persian writing systems.
  - Word wrapping, kerning, text scrolling, sub-pixel rendering, Pinyin-IME Chinese input, Emojis in texts.
  - Rendering engine supporting animations, anti-aliasing, opacity, smooth scrolling, shadows, image transformation, etc
  - Supports Mouse, Touchpad, Keypad, Keyboard, External buttons, Encoder Input devices.
  - Multiple display support.

LVGL Installation and Integration Process :

The *LVGL* library is directly integrated in the *Zephyr RTOS*, which makes its implementation fairly easy.

The installation and integration process is as follow :

1. In the application configuration file (*Kconfig*) :
   - 1.1 Enable *Zephyr* display driver and library with : CONFIG_DISPLAY=y
   - 1.2 Enable the *LVGL* library with : CONFIG_LVGL=y
   - 1.3 If required, it is possible to configure custom memory for the *LVGL* with :
     - CONFIG_LV_MEM_CUSTOM=y
     - CONFIG_LV_Z_MEM_POOL_NUMBER_BLOCKS=16
   - 1.4 Enable the driver for *SHARP MIP LCD LS0XX* with :
     - CONFIG_LS0XX=y
   - 1.5 If required, configure *LVGL* specific proprieties :
     - Enable *label* type widget : CONFIG_LV_USE_LABEL=y
     - Enable *image* type widget : CONFIG_LV_USE_IMG=y
     - Set display color depth : CONFIG_LV_COLOR_DEPTH_1=y
     - Set text font style and size : CONFIG_LV_FONT_DEFAULT_MONTSERRAT_16=y
     - Set text format : CONFIG_LV_TXT_ENC_UTF8=y

2. In the application *Devicetree* overlay :
   - 2.1 Enable the *SHARP MIP LCD LS0XX* driver binding with :

```
chosen {
    zephyr,display = &ls0xx;
  };
```

3. Include lvgl.h in each *C/C++* application file that uses *LVGL* library

More detailed information about *LVGL* library configuration and implementation is available on *LVGL* online documentation : `https://docs.lvgl.io/master/index.html`.

6.4.2 u-blox Host Library (*ubxlib*)

ubxlib Overview :

The following description is sourced from the *ubxlib* GitHub repository[51].

The *ubxlib* contains add-on for building embedded applications with u-blox products and services on *MCU* and *RTOS SDKs*. The *ubxlib* repository provides portable *C* libraries APIs and many examples and sample code for an easier implementation process.

The *ubxlib* library main features are :

- Supports the following u-blox modules :
  - Cellular modules (*2G/3G/4G*)
  - Short-range modules (*Bluetooth* and *Wifi*)
  - *GNSS* positioning modules
- Provides high level *C APIs* for customer applications such as connection to a network, *TCP* socket opening, location establishment, and many others)
- Compatibility with *ARM MCUs* and *Zephyr* project

Figure 6.4 illustrates the *ubxlib* library integration diagram :

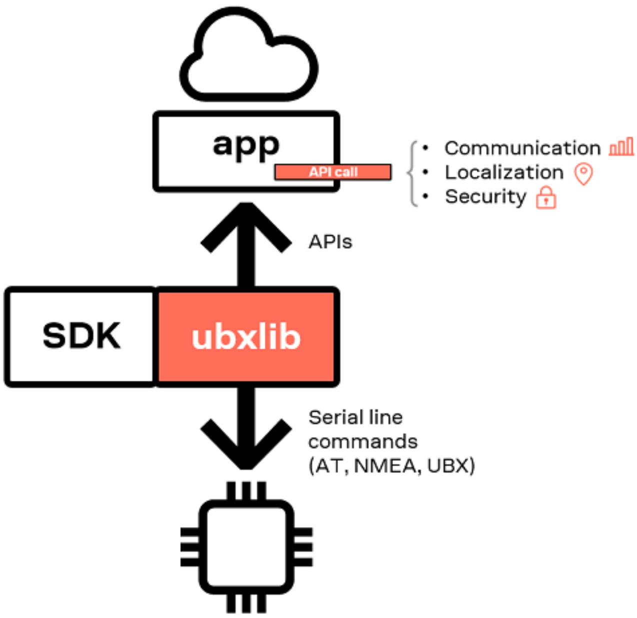


Figure 6.3 – *ubxlib* Library Integration Diagram - Source :[51]

Description of *ubxlib APIs*

The *ubxlib* repository[51] provides a visual illustration of the different *APIs* contained in the library as well as their relationships with each other. This diagram is illustrated in figure 6.4 :

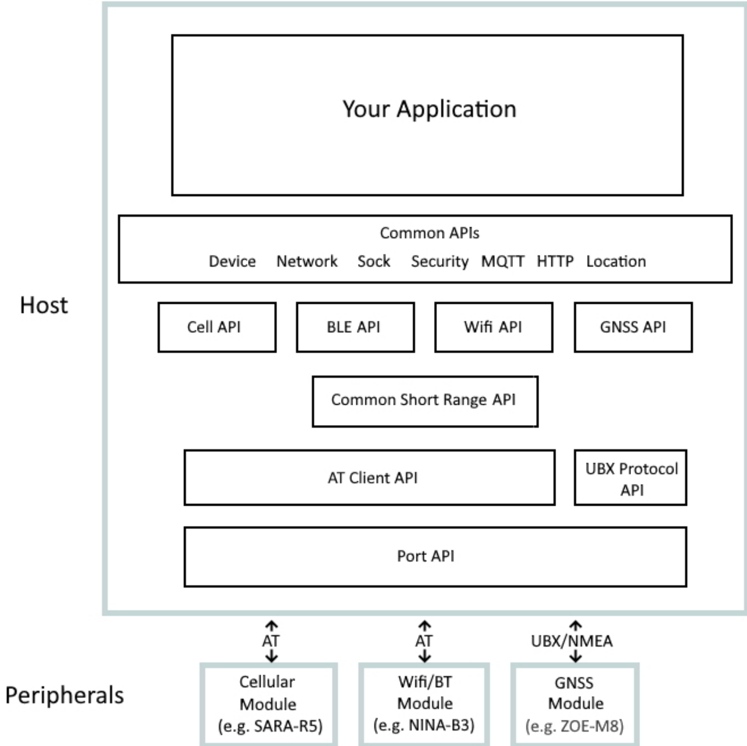


Figure 6.4 – *ubxlib* Library *APIs* Diagram - Source :[51]

The *ubxlib* repository[51] also gives information about which *APIs* to use for which application. The *ubxlib* library usage recommendations are the following(src.[51]) :

— *Common Device* and *network APIs* : Used to quickly bring up a device/network such as *cellular*, *BLE/Wifi* or *GNSS*
— *Common Sock API* : Used for application requiring a socket over the network
— *Common Security API* : Used for network that require security functionality
— *Common MQTT (mqtt_client) API* : Used for *MQTT* applications
— *Common HTTP (http_client) API* : Used for HTTP applications
— *Common Location API* : Used for application requiring location fixes
— *Cell, Ble, Wifi, GNSS APIs* : Used for finer control and configuration
— *GNSS API* : Used for application requiring a specific *GNSS* configuration
— *Common Short Range API* : Used for short range applications (*BLE* or *Wifi*)
— *AT Client API* : Used by *Cell* and *Short Range APIs* to talk to AT-based u-blox modules
— *Port API* : Permits all of the above *APIs* to run on different hosts

Installation and Integration Process :

The *ubxlib* library is not integrated in *Zephyr* project or *nRF Connect SDK*, which imply, that the library must be linked to the application using the project *CMake* linker file.

The installation and integration process of *ubxlib* library is as follow :

1. Clone the *ubxlib* GitHub repository in your local computer either in your *Zephyr* root directory or either on a custom location with the shortest path possible : `https://github.com/u-blox/ubxlib`
2. In the application linker file *CMakeLists.txt* :
   2.1 Add the library to your project as an external module of *Zephyr* using the list(APPEND ZEPHYR_EXTRA_MODULES ...) command :
   ```
   list(APPEND ZEPHYR_EXTRA_MODULES "${<my_ubxlib_repo_path>/ubxlib")
   ```
3. In the application configuration file (*Kconfig*) :
   3.1 Enable the *ubxlib* library with : CONFIG_UBXLIB=y
4. For the *LTEWatch* application, the following additional configuration is necessary :
   4.1 Enable *ubxlib GNSS API* : CONFIG_UBXLIB_GNSS=y
   4.2 Enable *ubxlib Cell API* (not used but is required by *GNSS API* dependencies) : CONFIG_UBXLIB_CELL=y
   4.3 Disable *Test API* to reduce extra module size : CONFIG_UBXLIB_TEST=n
5. Include necessary *ubxlib* header files in each *C/C++* application files that use u-blox modules or *APIs*

6.5 *LTEWatch* Hardware Description

Once the firmware is decomposed in functional block and before looking at the application software, it is necessary to clearly defines the target device hardware, the application configuration and the project management file.

This section covers hardware description process in *Zephyr* environment, starting by system hardware description and configuration using *Devicetree*, project source files management and external library integration using *CMakeLists.txt* and finally application configuration using *Kconfig* file (*conf.prj*).

6.5.1 Pin Assignment of *LTEWatch* Prototype Board

The table 6.2 describes the pin assignment of the *LTEWatch* prototype board :

PIN	I/O	CFG	SIGNAL	DESCRIPTION
P0.00	DO [3]	-	M8	Stepper Motor driving output *D3M4*
P0.01	DO	-	M7	Stepper Motor driving output *D3COM*
P0.02	DO	-	M6	Stepper Motor driving output *D3M1*
P0.03	DO	-	M5	Stepper Motor driving output *D2M4*
P0.04	DO	-	M4	Stepper Motor driving output *D2MCOM*
P0.05	DO	-	M3	Stepper Motor driving output *D2M1*
P0.06	SO [4]	UART	USB_TX	*TX* signal of the *USB-to-UART* interface
P0.07	SI [5]	UART	USB_RX	*RX* signal of the *USB-to-UART* interface
P0.08	SIO	I2C	SDA	Data line of *I2C* Bus
P0.09	CLK	I2C	SCL	Clock line of *I2C* Bus
P0.10	DI	Pull-up	BAT_/INT_CHRG	Battery charger interrupt line
P0.11	DO	-	BAT_LVL_EN	Battery level monitoring enable
P0.13	DO	-	M2	Stepper Motor driving output *D1M4*
P0.14	DO	-	M1	Stepper Motor driving output *D1COM*
P0.15	DO	-	M0	Stepper Motor driving output *D1M1*
P0.16/AIN3	AI [6]	No Pull	BAT_LVL	Battery level
P0.17	DI [7]	No Pull	BTN2	Push button *BT2*
P0.18	DI	No Pull	BTN1	Push button *BT1*
P0.19	DI	No Pull	BTN0	Push button *BT0*
P0.20	SO	JTAG	SWO	Serial Wire Output (SWO) line
P0.21	DO	SPI	ACC_CS	Accelerometer *Chip Select* (SPI)
P0.22	DI/O [8]	-	ACC_/INT	Accelerometer interrupt line
P0.23	SO	UART	GPS-TXD	GNSS *uART* TX line
P0.24	SI	UART	GPS-RXD	GNSS *uART* RX line
P0.25	DO	-	GPS-/RST	GNSS reset
P0.26	SO	-	DISP_EXT_COMIN	Display EXT_COMIN serial line
P0.27	DO	-	DISP_/EN	Display power enable
P0.28	DO	SPI	DISP_SCS	Display *Chip Select*
P0.29	SI	SPI	MISO	Serial data input signal
P0.30	CLK	SPI	SCK	Serial clock signal
P0.31	SO	SPI	MOSI	Serial data output signal
COEX0	DO	-	GPS-EN	GNSS power enable
MAGPIO0	DO	-	LTE_EXT_ANT	*LTE* external antenna enable
MAGPIO1	DO	-	MCU2GPS_EXTINT	*GNSS* receiver external interrupt

Table 6.2 – *LTEWatch* - Pin Assignment Table

6.5.2 Board Description in *Zephyr RTOS* - (Devicetree)

The section if based on the online documentation "Introduction to devicetree"[?] from Nordi Semi.

Overview :

A specific aspect of developing with *Zephyr RTOS* is that the hardware is fully described *Devicetree*, which is a hierarchical data structure. Zephyr uses *Devicetree* to describe hardware to the *Device Driver Model* as well as the initial configuration of that hardware.

Devicetree can be described using two type of input files :

1. *devicetree sources* : Actual description of the *devicetree* itself
2. *devicetree bindings* : Description of contents and data types of *devicetree*

Those two files are combined by *build system* to produce a generated C header that is abstracted by the devicetree.h *API*. Simplified diagram of the *devicetree* build process is illustrated in figure 6.5 :

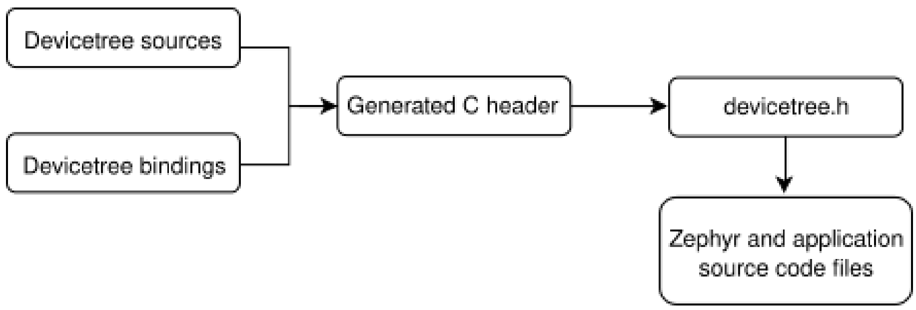


Figure 6.5 – Simplified *Devicetree* build flow - Source :[52]

> **Warning** : It is necessary to include *devicetree.h* in any *Zephyr* and application source code that need to access or use the *devicetree*

Syntax and structure :

The human-readable text of the *Devicetree* is called *Device Tree Source DTS*. An example *DTS* file is illustrated in the listing 6.1 :

```
/{
  a-node {
          subnode_nodelabel: a-sub-node {
              foo = <3>;
          };
  };
};
```

Listing 6.1 – Example *DTS* File - Source:[52]

The structure of *devicetree* is composed of three nodes :

1. A root node : /
2. A node named a-node, which is a child of the root node
3. A node named a-sub-node, which is a child of a-node

Aliases and chosen nodes :

It possible to refer to a specific node without specifying its entire path using aliases or chosen nodse. An example of *DTS* using both methods is illustrated in listing 6.2 :

```
/ {
  chosen {
        zephyr,console = &uart0;
  };
  aliases {
        my-uart = &uart0;
  };
  soc {
      uart0: serial@12340000 {
                      ...
      };
  };
};
```

Listing 6.2 – Example *DTS* File using *chosen* and *aliases* nodes - Source:[53]

zephyr,user **node :**

The zephyr,user node is a very useful node that can be used to describe essentially arbitrary properties that can be retrieve without requiring binding files. It can be compared to a convenient container to store few simple properties.

The zephyr,user node can store three types of properties :

1. **Simple values :** numeric or array values that are configurate at build time via *devicetree*
2. **Devices :** phandles that allows to reconfigure which devices the application uses in simple cases using devicetree overlays
3. **GPIOs :** Application-specific *GPIOs* that can be reconfigured with a *devicetree* overlay

The three types of properties are illustrated in listings 6.3 to 6.5 :

```
/ {
     zephyr,user {
             boolean;
             bytes = [81 82 83];
             number = <23>;
             numbers = <1>, <2>, <3>;
             string = "text";
             strings = "a", "b", "c";
     };
};
```

Listing 6.3 – Example *zephyr,user* Node - Simple Value Properties - Source:[53]

```
/ {
    zephyr,user {
        handle = <&gpio0>;
        handles = <&gpio0>, <&gpio1>;
    };
};
```

Listing 6.4 – Example *zephyr,user* Node - Devices Properties

```
#include <zephyr/dt-bindings/gpio/gpio.h>

/ {
    zephyr,user {
        signal-gpios = <&gpio0 1 GPIO_ACTIVE_HIGH>;
    };
};
```

Listing 6.5 – Example *zephyr,user* Node - *GPIOs* Properties - Source:[53]

Listings 6.6 to 6.8 illustrates how to retrieve property values from zephyr,user node in application *C/C++* files :

```
#define ZEPHYR_USER_NODE DT_PATH(zephyr_user)
DT_PROP(ZEPHYR_USER_NODE, boolean) // 1
DT_PROP(ZEPHYR_USER_NODE, bytes)   // {0x81, 0x82, 0x83}
DT_PROP(ZEPHYR_USER_NODE, number)  // 23
DT_PROP(ZEPHYR_USER_NODE, numbers) // {1, 2, 3}
DT_PROP(ZEPHYR_USER_NODE, string)  // "text"
DT_PROP(ZEPHYR_USER_NODE, strings) // {"a", "b", "c"}
```

Listing 6.6 – Example *zephyr,user* Node - *GPIOs* Properties - Source:[53]

```
/*
 * Same thing as:
 *
 * ... my_dev = DEVICE_DT_GET(DT_NODELABEL(gpio0));
 */
const struct device *my_device = DEVICE_DT_GET(DT_PROP(ZEPHYR_USER_NODE, handle));
#define PHANDLE_TO_DEVICE(node_id, prop, idx) \
    DEVICE_DT_GET(DT_PHANDLE_BY_IDX(node_id, prop, idx)),
/*
 * Same thing as:
 *
 * ... *my_devices[] = {
 *         DEVICE_DT_GET(DT_NODELABEL(gpio0)),
 *         DEVICE_DT_GET(DT_NODELABEL(gpio1)),
 * };
 */
const struct device *my_devices[] = {
    DT_FOREACH_PROP_ELEM(ZEPHYR_USER_NODE, handles, PHANDLE_TO_DEVICE)
};
```

Listing 6.7 – Example *zephyr,user* Node - *GPIOs* Properties - Source:[53]

```
#include <zephyr/drivers/gpio.h>

#define ZEPHYR_USER_NODE DT_PATH(zephyr_user)

const struct gpio_dt_spec signal =
        GPIO_DT_SPEC_GET(ZEPHYR_USER_NODE, signal_gpios);

/* Configure the pin */
gpio_pin_configure_dt(&signal, GPIO_OUTPUT_INACTIVE);

/* Set the pin to its active level */
gpio_pin_set_dt(&signal, 1);
```

Listing 6.8 – Example *zephyr,user* Node - *GPIOs* Properties - Source:[53]

Custom Board Creation Process :

Using the pin assignment of the *LTEWatch* prototype board (table 6.2), a custom devicetree board "ltewatch_nrf9160_ns" was created. The process used to create the custom board is described in Nordic Semi. tutorial video "*Getting started with custom development in nRF Connect SDK*" : `https://www.youtube.com/watch?v=KSivO9Cf1TE`.

The custom board creation process presented in the tutorial is fairly simple :

1. Duplicate an already existing board with identical SoC. For *LTEWatch*, the *nrf9160dk* development board description, "nrf9160dk_nrf9160_ns", was used.
2. In the duplicate folder, rename each mention of the previous board with the new name of the board. Be careful to rename everything correctly.
3. After renaming, remove any unnecessary definitions or descriptions and adapt the remaining ones to suit the new board hardware.

6.5.3 Devicetree overlays :

In *Zephyr*, *devicetree* overlays are used to reconfigure proprieties defined in *DTS*. The overlay is only used in the application environment and must be described in the root (*src*) directory of the project. To reconfigure a node in the *DT* overlay, à "&" symbol must be added in front of the node label. Listing 6.9 illustrates an example of *DT* overlay :

```
&i2c0 {
        temp: temperature-sensor@76 {
                compatible = "vnd,some-sensor";
                reg = <0x76>;
        };
};
```

Listing 6.9 – *DT* Overlay Example

The propriety described in listing 6.9 can be accessed in the *C/C++* application using the macro : DT_ON_BUS(DT_NODELABEL(temp), i2c).

6.6 *LTEWatch* Application Firmware

This section describes the *LTEWatch* application firmware that was developed for the prototype board.

6.6.1 Application System Configuration :

The first steps of the firmware development are the application configuration using the project *Kconfig* file and the hardware description using the project's board *Devicetree* overlay file.

Kconfig :

The *LTEWatch* application uses multiple drivers and libraries that require to enable *C* and *C++* library from *Zephyr*. The configuration of *C/C++* library is illustrated in the listing 6.10 :

```
# ****************************************** #
# C Library                                  #
# ****************************************** #
CONFIG_NEWLIB_LIBC=y
CONFIG_NEWLIB_LIBC_NANO=n
CONFIG_NEWLIB_LIBC_FLOAT_PRINTF=y

# ****************************************** #
# C++                                        #
# ****************************************** #
CONFIG_CPLUSPLUS=y
CONFIG_LIB_CPLUSPLUS=y
```

Listing 6.10 – Application *C* library Configuration

In order to avoid unexpected comportment during the development state of the firmware, the build optimization is disabled and reset on fatal error is enabled. To use certain drivers, the *C++* library and more particularly *POO*, *Zephyr* requires to enable *C++* exceptions.

```
# ****************************************** #
# Compiler Optimization                      #
# ****************************************** #
CONFIG_NO_OPTIMIZATIONS=y

# ****************************************** #
# Exception                                  #
# ****************************************** #
CONFIG_EXCEPTIONS=y

# ****************************************** #
# FATAL ERROR Management                     #
# ****************************************** #
CONFIG_RESET_ON_FATAL_ERROR=y
```

Listing 6.11 – Application System Configuration

Zephyr RTOS and *XF* requires multiple kind of queues and memory allocation process. For this reason the application memory allocation must be configured. To be more precise, the size of following memory blocks must be configured :

- Application Main Stack : Main stack memory allocated for static elements of the application
- AT Monitor Heap : Heap memory used by the *LTE* Modem to queue dynamic elements
- Heap Memory Pool : Heap memory used by the executive framework and the *RTOS* for dynamic elements handling, such as events and threads management
- System Work-queue Stack : Memory allocated to the main system work-queue from *Zephyr*

Memory allocation of the *LTEWatch* firmware is described in the listing 6.12 :

```
# ********************************************** #
# Heap and stacks                                #
# ********************************************** #
CONFIG_MAIN_STACK_SIZE=12288
CONFIG_AT_MONITOR_HEAP_SIZE=512
CONFIG_HEAP_MEM_POOL_SIZE=8192
#stack size of system k_work queue
CONFIG_SYSTEM_WORKQUEUE_STACK_SIZE=8192
```

Listing 6.12 – Application Memory Configuration

6.6.2 Digital I/O - *GPIO* :

As mentioned in multiple times, the *LTEWatch* application used several *GPIOs* of the *nRF9160 SiP*. In *Zephyr*, *GPIOs* must be described in the application *Devicetree* and must be enabled in the *Kconfig* file.

Devicetree :

To use *GPIOs* in *Zephyr RTOS*, it is simply necessary to enable the *GPIO HAL API* and the *GPIOTE HAL API* in the application *DTS* or *DT* overlay. The *DT* overlay description of *GPIOs* is illustrated in listing 6.13 :

```
&gpiote {
  status = "okay";
};

&gpio0 {
    status = "okay";
};
```

Listing 6.13 – *DT GPIOs* Description

To fully benefit from the *Devicetree* provided by *Zephyr*, some macros are defined using the zephyr,user node. Macros description using zephyr,user node is illustrated in the listing 6.14 :

```
/ {
  zephyr,user {
    // Led
    led-max-number  = <3>;
    // Button
    button-max-number  = <3>;
   };
};
```

Listing 6.14 – *DT GPIOs* Proprieties Description

Kconfig :

Once *GPIOs* are described in the application *Devicetree* it is still necessary to enable *GPIOs* in the application *Kconfig* as shown in listing 6.15 :

```
# ********************************************* #
# GPIO                                          #
# ********************************************* #
CONFIG_GPIO=y
```

Listing 6.15 – Application *GPIOs* Configuration

6.6.3 Analog Input - *ADC* :

To use the *ADC*, the process is very similar to that of the *GPIOs*, namely description in the application *Devicetree* and activation of the *API* in the application *Kconfig* .

Devicetree :

For the *LTEWatch* application, the *ADC* input *AIN3* with the configuration shown in the listing 6.16 :

```
&adc {
  #address-cells = <1>;
  #size-cells = <0>;
    status = "okay";

  channel@0 {
    reg = <0>;
    zephyr,gain = "ADC_GAIN_1_5";
    zephyr,reference = "ADC_REF_INTERNAL";
    zephyr,acquisition-time = <ADC_ACQ_TIME_DEFAULT>;
    zephyr,input-positive = <NRF_SAADC_AIN3>;  // P0.16 = AIN3
    zephyr,resolution = <12>;
  };
};
```

Listing 6.16 – *DT ADC* Description

As before, some macros are defined in the application *Devicetree* using the zephyr,user node as shown in listing 6.17 :

```
/ {
  zephyr,user {
    io-channels = <&adc 3>; // P0.16 = AIN3
    // Display
    // Battery Manager
    bat-lvl-gpios  = <&gpio0 12 GPIO_ACTIVE_HIGH>;
    batlvl-en-gpios   = <&gpio0 11 GPIO_ACTIVE_HIGH>;
    batchrg-int-gpios = <&gpio0 10 GPIO_ACTIVE_LOW>;
   };
};
```

Listing 6.17 – *DT ADC* Proprieties Description

Kconfig :

On the *nRF9160 SiP ADC* requier to enable both *ADC* and *SAADC*, as shown in the listing 6.18 :

```
# ******************************************** #
# ADC                                          #
# ******************************************** #
CONFIG_ADC=y
CONFIG_ADC_NRFX_SAADC=y
```

Listing 6.18 – Application *ADC* Configuration

6.6.4 Debug and Logging - *UART* :

Devicetree :

The *UART* description in the application *DT* overlay is described in listing 6.19 :

```
&uart0 {
  status = "okay";
  current-speed = <115200>;
  pinctrl-0 = <&uart0_default>;
  pinctrl-1 = <&uart0_sleep>;
  pinctrl-names = "default", "sleep";
};
```

Listing 6.19 – *DT UART* Description

The *UART* description from the listing 6.19 shows new kind of propriety which is the pinctrl node. This node must be defined in a node external to the *UART* node as shown in the listing 6.20 :

```
&pinctrl {

  uart0_default: uart0_default {
    group1 {
      psels = <NRF_PSEL(UART_TX, 0, 6)>;
    };
    group2 {
```

```
      psels = <NRF_PSEL(UART_RX, 0, 7)>;
      bias-pull-up;
    };
  };

  uart0_sleep: uart0_sleep {
    group1 {
      psels = <NRF_PSEL(UART_TX, 0, 6)>,
        <NRF_PSEL(UART_RX, 0, 7)>;
      low-power-enable;
    };
  };
};
```

Listing 6.20 – *DT UART* Pinctrl Description

As shown in the listing 6.20, a peripheral can use two different *pinctrl* definitions at the same time. This is a very useful tool that allows you to define different definitions of a specific peripheral depending on the mode it is used in, for example, normal mode and low-power-mode.

Kconfig :

When using *UART*, it is possible to enable *UART* interrupt driven configuration using the command described in the listing 6.21 :

```
# ******************************************** #
# UART Interrupt support                       #
# ******************************************** #
CONFIG_UART_INTERRUPT_DRIVEN=y
```

Listing 6.21 – Application *UART* Configuration

Listings 6.22 and 6.23 illustrates the application configuration of *Logging* and *Debugging* options :

```
# ********************************************** #
# Zephyr/nrf log configuration                   #
# 0 -> off, 1 -> err, 2 ->wrn, 3 -> inf, 4 ->dbg #
# ********************************************** #
CONFIG_CONSOLE=y
CONFIG_LOG=y
CONFIG_LOG_MODE_IMMEDIATE=y
CONFIG_LOG_BACKEND_SHOW_COLOR=y
CONFIG_LOG_INFO_COLOR_GREEN=y
# ******************************************** #
# UART logging                                 #
# ******************************************** #
CONFIG_UART_CONSOLE=y
# ******************************************** #
# RTT logging                                  #
# ******************************************** #
#CONFIG_USE_SEGGER_RTT=y
#CONFIG_RTT_CONSOLE=y
#CONFIG_LOG_BACKEND_RTT=y
```

Listing 6.22 – Application *Logging* Configuration

```
# ****************************************** #
#  DEBUG settings                            #
# ****************************************** #
CONFIG_DEBUG=y
CONFIG_DEBUG_THREAD_INFO=y
CONFIG_DEBUG_OPTIMIZATIONS=y
CONFIG_DEBUG_INFO=y
CONFIG_DEBUG_COREDUMP=n
```

Listing 6.23 – Application *Debug* Configuration

6.6.5 Serial Bus - *I2C* :

Devicetree :

The definition and configuration of the *I2C* driver is very similar to that of *UART* and is shown in listings 6.24 and 6.25 :

```
&i2c1 {
    compatible = "nordic,nrf-twim";
  status = "okay";
    pinctrl-0 = <&i2c1_default>;
    /* sleep state (only applicable if CONFIG_PM_DEVICE=y) */
    pinctrl-1 = <&i2c1_sleep>;
    /* state assigned to each pinctrl-N property by index */
    pinctrl-names = "default", "sleep";
    clock-frequency = <I2C_BITRATE_STANDARD>;
};

&i2c2 {
    status = "disabled";
};
```

Listing 6.24 – *DT I2C* Description

```
&pinctrl {
    /* configuration for i2c1 device, default state */
  i2c1_default: i2c1_default {
    group1 {
      psels = <NRF_PSEL(TWIM_SDA, 0, 8)>,
        <NRF_PSEL(TWIM_SCL, 0, 9)>;
    };
  };

  i2c1_sleep: i2c1_sleep {
    group1 {
      psels = <NRF_PSEL(TWIM_SDA, 0, 8)>,
        <NRF_PSEL(TWIM_SCL, 0, 9)>;
      low-power-enable;
    };
  };
};
```

Listing 6.25 – *DT I2C* Pinctrl Description

Kconfig :

Similar to the *ADC* configuration, the *I2C* configuration on the *nRF9160* requires to enable both *I2C* and *I2C NRFX APIs*, as shown in the listing 6.26 :

```
# ******************************************** #
# I2C                                          #
# ******************************************** #
CONFIG_I2C=y
CONFIG_I2C_NRFX=y
```

Listing 6.26 – Application *I2C* Configuration

6.6.6 Serial Bus - *SPI* :

Nearly identical to the definition and configuration of the *I2C API*, the *SPI* definition and configuration is illustrated in listings 6.27 to 6.29 :

Devicetree :

The *DT* application overlay has a small difference from the *I2C* which is the additional *LS0XX* display driver definition as shown in the listing 6.27. The *LS0XX* display driver definition is used to configure the display specifications such as width, height and serial communication max frequency.

```
&spi3 {
    status = "disabled";
};

&spi2 {
  compatible = "nordic,nrf-spim";
  status = "okay";
    cs-gpios = <&gpio0 28 GPIO_ACTIVE_HIGH>,  //Display scs
        <&gpio0 20 GPIO_ACTIVE_LOW>;  //Accelerometer scs
  pinctrl-0 = <&spi2_default>;
  pinctrl-1 = <&spi2_sleep>;
  pinctrl-names = "default", "sleep";
  ls0xx: ls0xx@0 {
    compatible = "sharp,ls0xx";
    label = "DISPLAY";
    spi-max-frequency = <2000000>;
    width = <160>;
    height = <68>;
    reg = <0>;
  };
};
```

Listing 6.27 – *DT SPI* Description

```
&pinctrl {
  spi2_default: spi2_default {
    group1 {
      psels = <NRF_PSEL(SPIM_SCK, 0, 30)>,
          <NRF_PSEL(SPIM_MISO, 0, 29)>,
          <NRF_PSEL(SPIM_MOSI, 0, 31)>;
    };
  };

  spi2_sleep: spi2_sleep {
    group1 {
      psels = <NRF_PSEL(SPIM_SCK, 0, 30)>,
          <NRF_PSEL(SPIM_MISO, 0, 29)>,
          <NRF_PSEL(SPIM_MOSI, 0, 31)>;
      low-power-enable;
    };
  };
};
```

Listing 6.28 – *DT SPI* Pinctrl Description

Kconfig :

```
# SPI                                           #
# ********************************************* #
CONFIG_SPI=y
```

Listing 6.29 – Application *SPI* Configuration

6.6.7 Motor Driver :

The motor driving functionality of the *LTEWatch* application requires macros definitions to describe *GPIOs* pin used to drive motors and also uses *aliases* node to share *GPIOs* that are also defined as LEDs. The definition of the zephyr,user node and the aliases node is illustrated in the listing 6.30 :

Devicetree :

```
/ {
  zephyr,user {
    // Clock Motors
    motor-max-number   = <3>;
    motor-d1m1-gpios   = <&gpio0 0 GPIO_ACTIVE_HIGH>;
    motor-d1com-gpios  = <&gpio0 1 GPIO_ACTIVE_HIGH>;
    motor-d1m2-gpios   = <&gpio0 2 GPIO_ACTIVE_HIGH>;
    motor-d2m1-gpios   = <&gpio0 5 GPIO_ACTIVE_HIGH>;
    motor-d2com-gpios  = <&gpio0 4 GPIO_ACTIVE_HIGH>;
    motor-d2m2-gpios   = <&gpio0 3 GPIO_ACTIVE_HIGH>;
   };
   aliases {
    motord3m1   = &led0;
    motord3com  = &led1;
    motord3m2   = &led2;
  };
};
```

Listing 6.30 – *DT Motor* Proprieties and Aliases Description

Kconfig :

The stepper motors used to display the time are driven using time-critical control signals. To ensure the accuracy and consistency of the motor control signal, the signal timing uses the *RTC* as time reference. The *RTC* driver configuration for the *nRF9160* is shown in the 6.31 listing :

```
# ******************************************** #
# RTC Config                                   #
# ******************************************** #
CONFIG_NRFX_RTC0=y
# To run in non-secure mode, you need to add RTC0 to spm.c
CONFIG_COMPILER_OPT="-DNRFX_RTC_ENABLED=1 -DNRFX_RTC0_ENABLED=1"
```

Listing 6.31 – Application *RTC* Configuration

6.6.8 *Display* :

Devicetree :

```
/ {
  chosen {
    zephyr,display = &ls0xx;
  };

};
```

Listing 6.32 – *DT Display* Description

```
/ {
  zephyr,user {
    // Display
    disp-en-gpios = <&gpio0 27 GPIO_ACTIVE_HIGH>;
   };
};
```

Listing 6.33 – *DT Display* Proprieties Description

Kconfig :

```
# ******************************************** #
# Config Display                               #
# ******************************************** #
CONFIG_LV_Z_MEM_POOL_NUMBER_BLOCKS=16
CONFIG_DISPLAY=y
CONFIG_LVGL=y
CONFIG_LV_MEM_CUSTOM=y
CONFIG_LV_USE_LABEL=y
CONFIG_LV_USE_IMG=y
CONFIG_LV_FONT_DEFAULT_MONTSERRAT_16=y
CONFIG_LV_COLOR_DEPTH_1=y
CONFIG_LS0XX=y
CONFIG_LV_TXT_ENC_UTF8=y
```

Listing 6.34 – Application *Display* Configuration

6.6.9 *GNSS* Receiver :

Devicetree :

```
/ {
  zephyr,user {
    // GNSS Receiver
    gps-rst-gpios = <&gpio0 25 GPIO_ACTIVE_LOW>;
    gps-en-gpios  = <&gpio0 26 GPIO_ACTIVE_HIGH>;
   };
};
```

Listing 6.35 – *DT GNSS* Proprieties Description

Kconfig :

```
# ********************************************** #
# UBXLIX configuration (GNSS)                    #
# ********************************************** #
CONFIG_UBXLIB=y
CONFIG_UBXLIB_GNSS=y
CONFIG_UBXLIB_CELL=y
CONFIG_UBXLIB_TEST=n
```

Listing 6.36 – Application *GNSS* Configuration

6.6.10 *LTE* Modem & *MQTT* :

Kconfig :

```
# ********************************************** #
# Networking                                     #
# ********************************************** #
CONFIG_NETWORKING=y
CONFIG_NET_NATIVE=n
CONFIG_NET_SOCKETS_OFFLOAD=y
CONFIG_NET_SOCKETS=y
CONFIG_NET_SOCKETS_POSIX_NAMES=y

# ********************************************** #
# LTE configuration                              #
# ********************************************** #
CONFIG_LTE_LINK_CONTROL=y
CONFIG_LTE_AUTO_INIT_AND_CONNECT=n

# Modem library
CONFIG_NRF_MODEM_LIB=y

# Antenna
CONFIG_MODEM_ANTENNA=y
CONFIG_MODEM_ANTENNA_AT_MAGPIO="AT%XMAGPIO=1,0,0,1,1,1574,1577"
CONFIG_MODEM_ANTENNA_AT_COEX0="AT%XCOEX0=1,1,1565,1586"

# ********************************************** #
# MQTT configuration                             #
```

```
# ********************************************* #
# MQTT Zephyr configuration
CONFIG_MQTT_LIB=y
CONFIG_MQTT_CLEAN_SESSION=y
CONFIG_NRF_CLOUD_MQTT=n
# MQTT custom configuration
CONFIG_MQTT_KEEPALIVE=20
# MAX sockets simultaneously open
CONFIG_POSIX_MAX_FDS=9
```

Listing 6.37 – Application *LTE/MQTT* Configuration

6.7 Overview of *LTEWatch* Application Software

To provide a better idea of the developed small watch application, the project structure is illustrated in project trees 6.6 to 6.11.

In the next project trees, the flowing color-code is used :

1. **Blue** : Unmodified source files imported from other applications
2. **Orange** : Slightly modified source files imported from other applications, most current modification is adaptation to *Zephyr RTOS*
3. **Red** : New files created for the *LTEWatch* application

```
src/
└── app/
    ├── config/
    ├── appfactory.cpp
    ├── eventid.h
    ├── picowatch.h
    └── picowatch.cpp
├── board/
├── core/
    ├── factory.h
    ├── factory.cpp
    └── main.cpp
└── library/
    ├── mcu/
    ├── mdw/
    ├── project-config
        ├── debug-config.h
        └── platform-config.h
    └── xf/
```

TREE 6.6 – *LTEWatch* Application Project Structure

```
src/library/mcu/
├── hal/
│   ├── battery/
│   │   ├── bathal.h
│   │   └── bathal.cpp
│   ├── critical/
│   ├── gpio/
│   │   ├── gpiohal.h
│   │   ├── gpiohal.cpp
│   │   ├── ledhal.h
│   │   └── ledhal.cpp
│   └── motor/
│       ├── motordriverhal.h
│       └── motordriverhal.cpp
└── tools/
    ├── sdktool.h
    └── dktool.cpp
```

Tree 6.7 – *LTEWatch* Application Project Structure - *mcu*

```
src/library/mdw/
├── common/
└── partners/
    ├── battery/
    │   ├── config/
    │   │   └── batt-config.h
    │   ├── driver/
    │   │   └── drv_bq25180.h
    │   ├── batterymanager.h
    │   ├── batterymanager.cpp
    │   └── ibatteryobserver.h
    ├── calendar/
    │   ├── config/
    │   │   └── calendar-config.h
    │   ├── interface/
    │   │   └── calendarobserver.h
    │   ├── XF/
    │   │   └── calendarevent.h
    │   ├── calendar.h
    │   ├── calendar.cpp
    │   ├── datetime.h
    │   └── datetime.cpp
    └── motor/
```

Tree 6.8 – *LTEWatch* Application Project Structure - *mdw*

```
src/library/mdw/partners/motor/
├── config/
│   └── motor-config.h
├── interface/
│   ├── motorctrlobserver.h
│   └── motordriverobserver.h
├── XF/
│   ├── motorendevent.h
│   ├── motorevent.h
│   └── motorinitevent.h
├── motor.h
├── motor.cpp
├── motorcontroller.h
├── motorcontroller.cpp
├── motordriver.h
├── motordriver.cpp
└── motorid.h
```

Tree 6.9 – *LTEWatch* Application Project Structure - *mdw/partners/motor*

```
src/library/mdw/common/
├── button/
│   ├── config/
│   │   └── button-config.h
│   └── interface/
│       ├── buttonobserver.h
│       ├── button.h
│       ├── buttoncontroller.h
│       ├── buttoncontroller.cpp
│       └── buttonid.h
├── core/
├── critical/
├── display/
│   ├── config/
│   │   └── disp-config.h
│   ├── dispcontroller.h
│   └── dispcontroller.cpp
└── gnss/
    ├── config/
    │   └── gnss-config.h
    ├── gnsscontroller.h
    ├── gnsscontroller.cpp
    └── ignssobserver.h
```

Tree 6.10 – *LTEWatch* Application Project Structure - *mdw/common*

```
src/library/mdw/common/
├── gpio/
│   ├── config/
│   ├── interface/
│   ├── XF/
│   ├── basecontroller.h
│   ├── basecontroller.cpp
│   ├── gpio.h
│   ├── gpio.cpp
│   ├── gpiocontroller.h
│   ├── gpiocontroller.cpp
│   ├── gpioid.h
│   ├── ledcontroller.h
│   └── ledcontroller.cpp
├── lte/
├── mqtt/
├── picoxf/
│   ├── picoevent.h
│   ├── picoevent.cpp
│   ├── picoireactive.h
│   ├── picoxf.h
│   └── picoxf.cpp
└── pool/
```

Tree 6.11 – *LTEWatch* Application Project Structure - *mdw/common*

As shown in project trees 6.6 to 6.11 many files are unmodified or slightly modified. Those files were provide by Patrice Rudaz from the *HEVS* in order to make the software application development faster and easier. Those files come from two different projects from Patrice Rudaz :

— MoskitoWatch Application

— BikeBox Application

The unmodified files will not be presented in this chapter. The slightly modified files are most often just adapted for *Zephyr RTOS* by replacing any timers with the *Zephyr* kernel timer *API k_timer* or replacing old *GPIO API* used by the new *GPIO* and *GPIOTE APIs* from *Zephyr RTOS* and also the implementation of the *RTC API* of *MotorDriverHal* for *Zephyr RTOS*.

6.8 Battery Manager

The *Batter Manager* module implement features required to use the *BQ25180* battery charger. For this module a compatible driver for the *BQ25180 drv_bq25180.h* and two classes *BatHal* and *BatteyManager* were created.

6.8.1 BatteryManager Class Diagram :

Figure 6.12 illustrates the class diagram of *BatteryManager* :

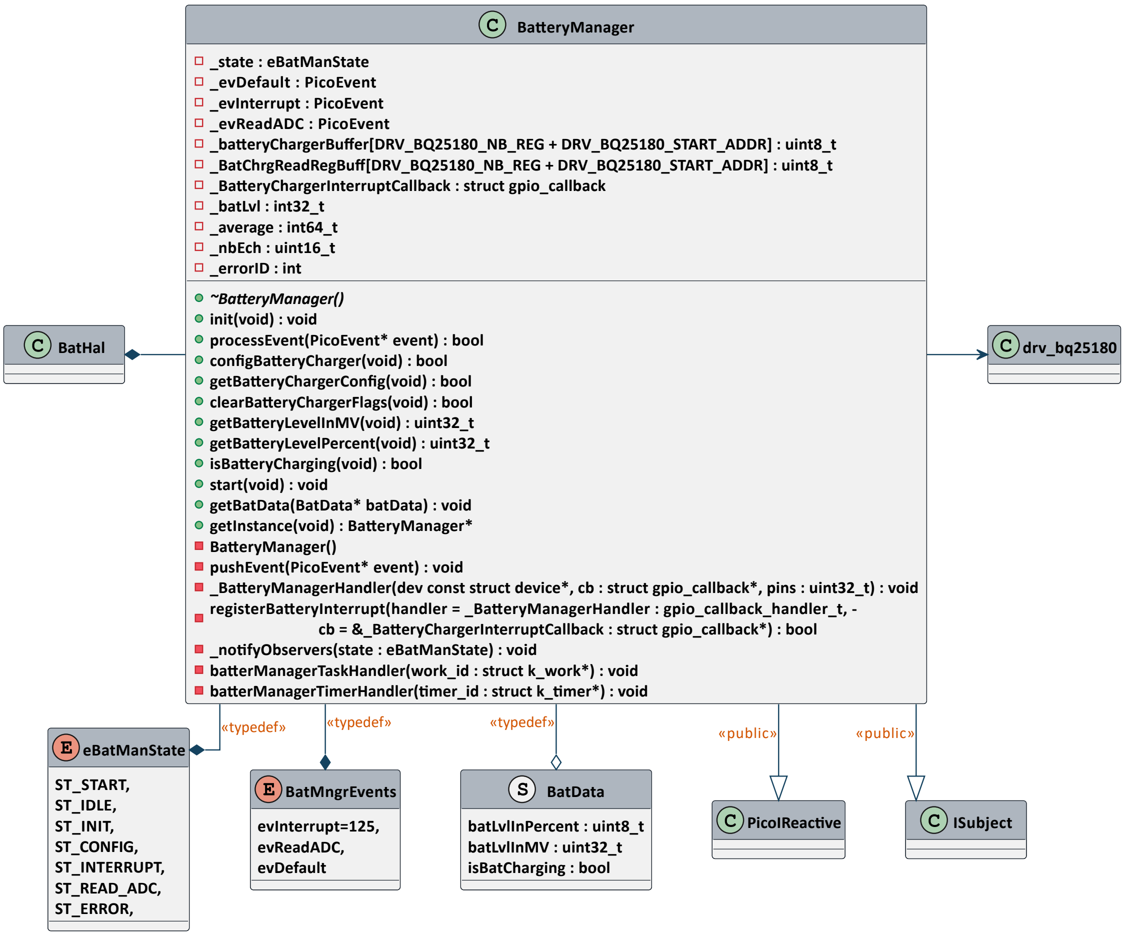


Figure 6.12 – *BatteryManager* Class Diagram

6.8.2 Battery Charger Driver - *drv_bq25180.h*

The *drv_bq25180.h* file is a driver for the *BQ25180*. This driver provides many useful elements to implement the *BQ25180* more easily.

6.8.3 Battery Hardware Abstraction Layer (BatHal)

Figure 6.13 illustrates the class diagram of *BatHal* :

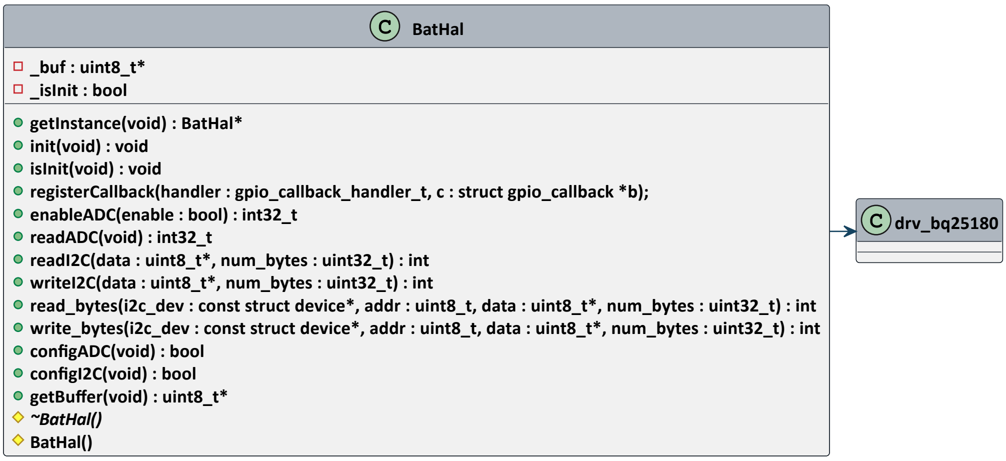


Figure 6.13 – *BatHal* Class Diagram

Functions described in figure 6.13 are required by the *BatteryManager* class to to interface with the *BQ25180* battery charger and the *ADC* input connected to the battery level monitoring circuit.

6.8.4 BatteryManager State Diagram :

Figure 6.14 illustrate the state diagram of *BtteryManger* class :

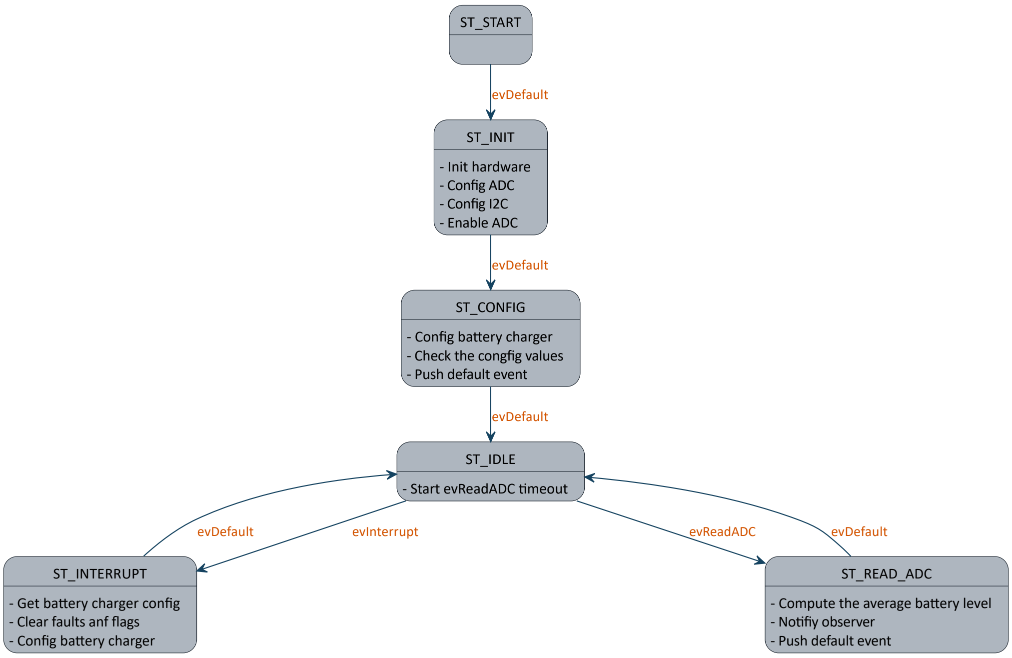


Figure 6.14 – *BatteryManager* State Diagram

6.9 Display

6.9.1 *DispController* Class Diagram

Figure 6.15 illustrates the class diagram of *DispController* :

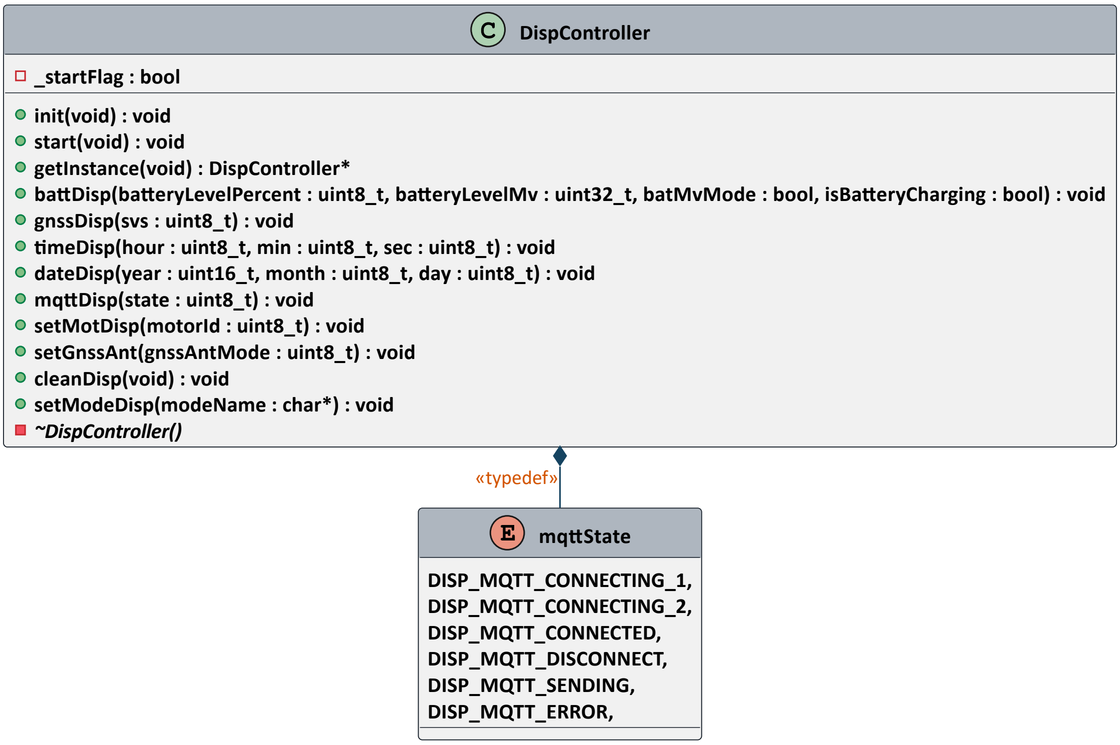


Figure 6.15 – *DispController* Class Diagram

6.10 *GNSS* Receiver

6.10.1 *GNSS* controller

GnssController application is based on the *msg_main.c* from the *ubxlib* repository : `https://github.com/u-blox/ubxlib/blob/master/example/gnss/msg_main.c`

GnssController Class Diagram

Figure 6.16 illustrates the class diagram of *GnssController* :

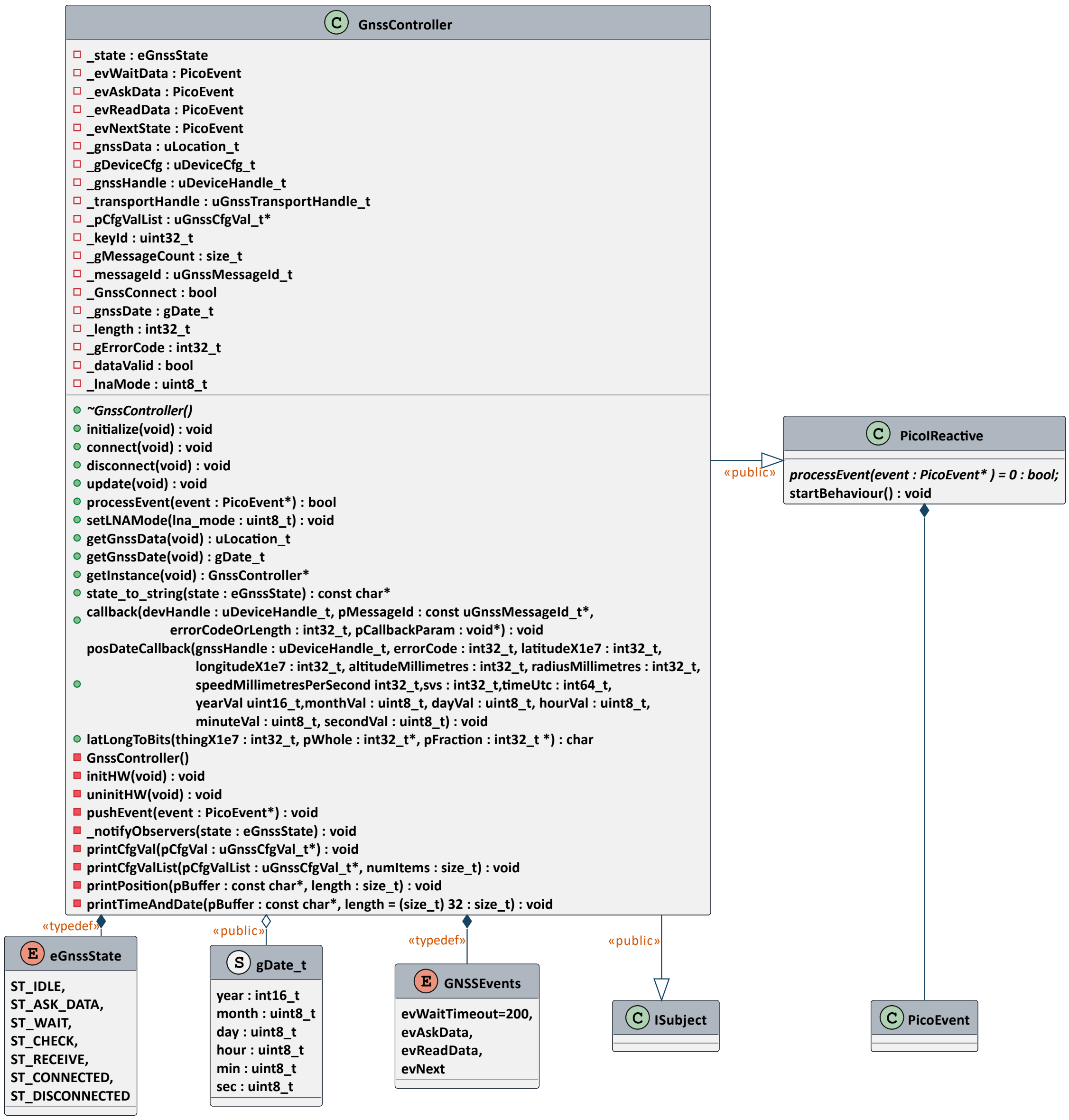


Figure 6.16 – *GnssController* Class Diagram

GnssController State Diagram

Figure 6.17 illustrates the state diagram of *GnssController* class :

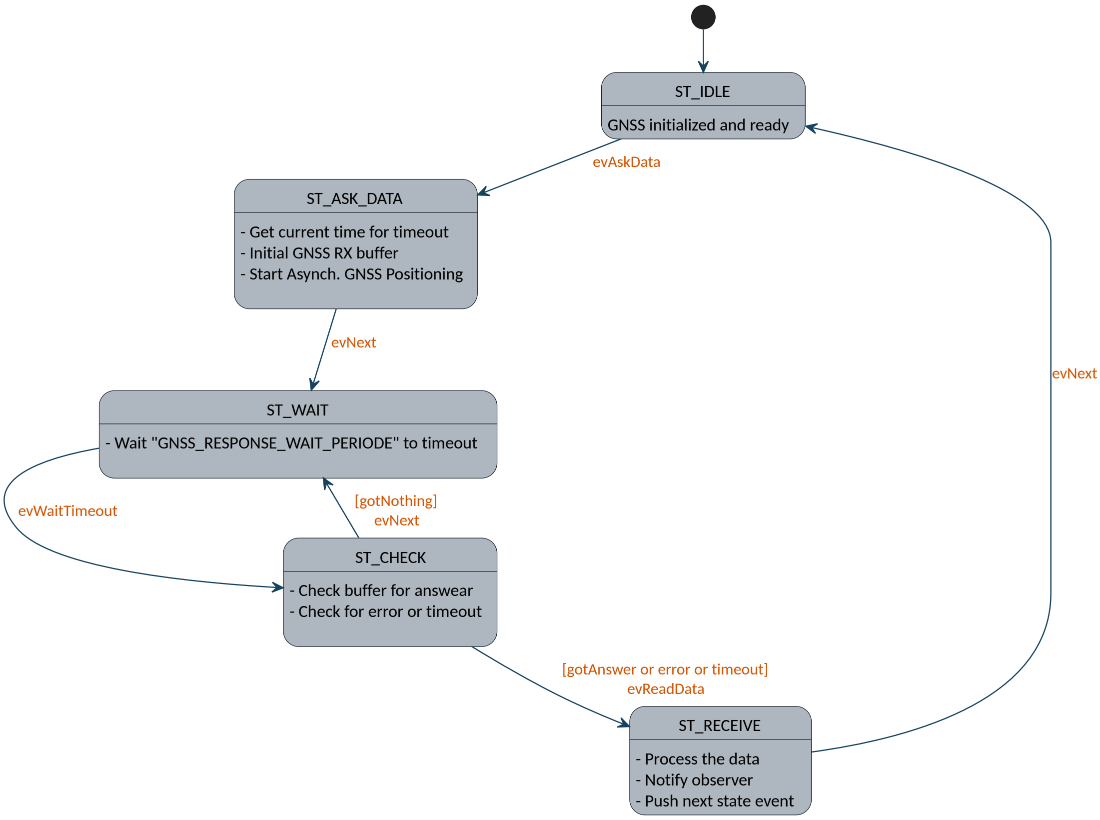


Figure 6.17 – *GnssController* State Diagram

6.11 *LTEWatch* Application

6.11.1 *Factory* Class Diagram

Figure 6.18 illustrates the class diagram of *Factory* :

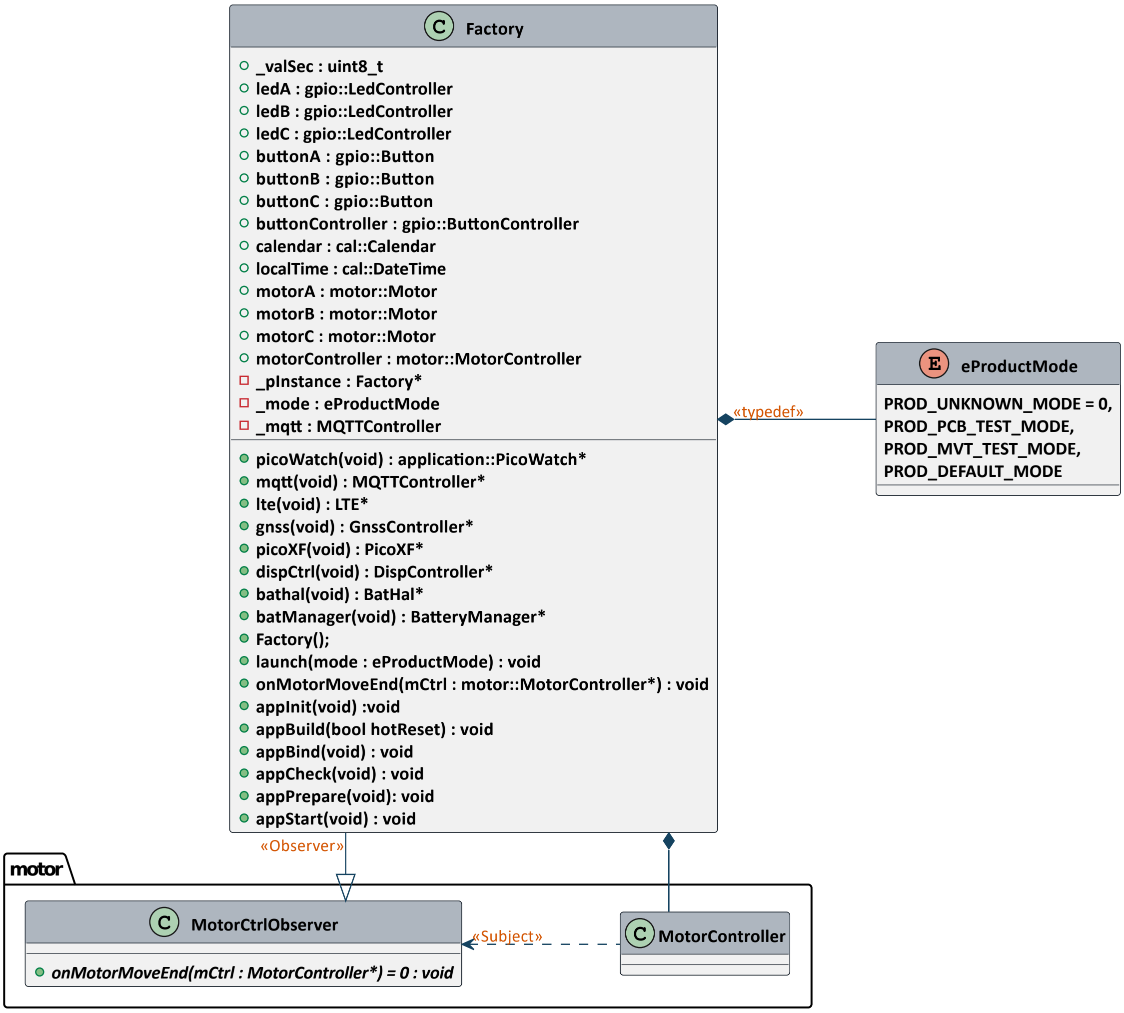


Figure 6.18 – *Factory* Class Diagram

6.11.2 *PicoWatch* Class Diagram

PicoWatch is the main class of the *LTEWatch* firmware. This class controls all modules of the application.

Figure 6.19 and figure 6.20 illustrate the class diagrams of *PicoWatch* :

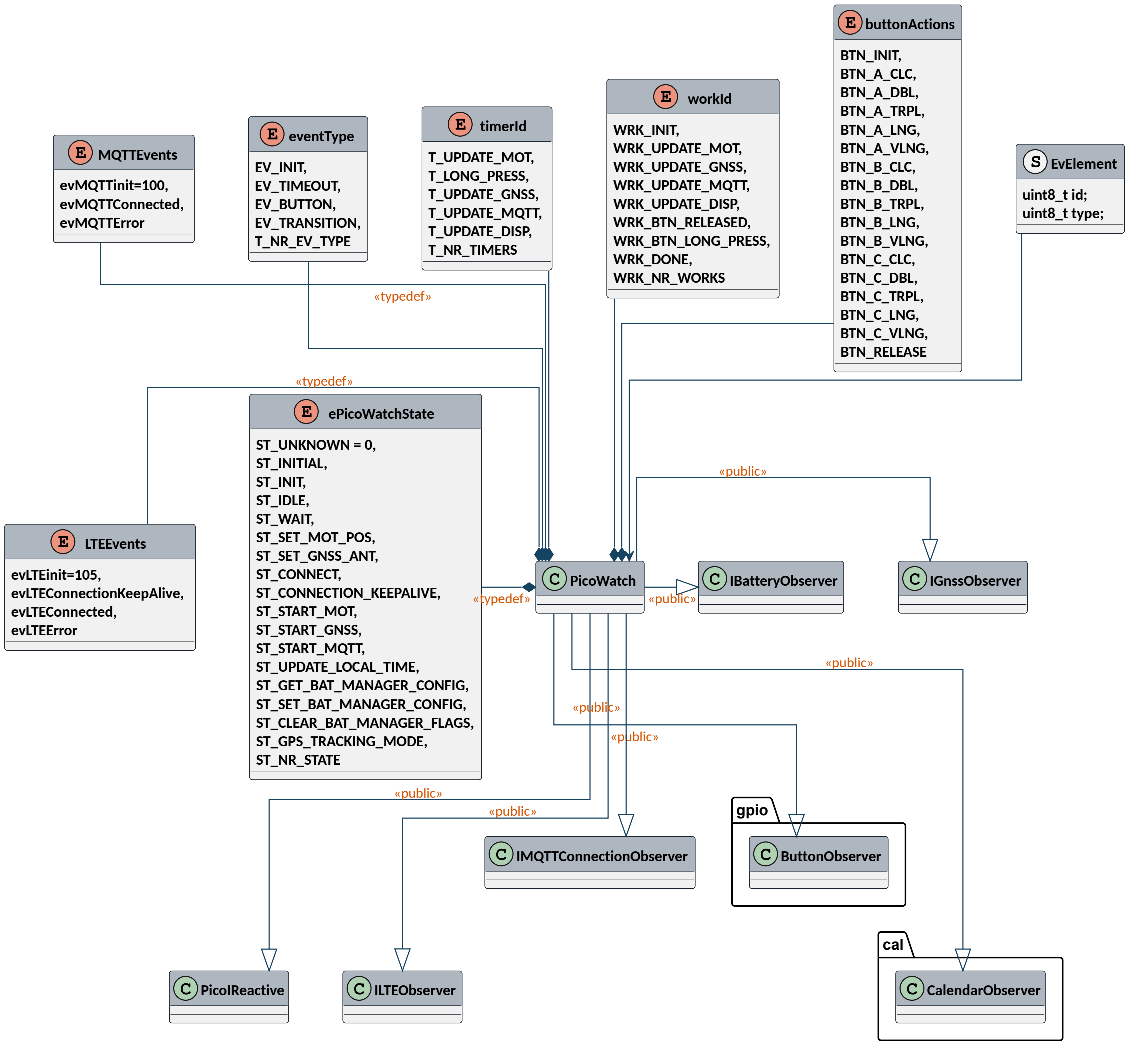


Figure 6.19 – *PicoWatch* Class Diagram - Part 1

Figure 6.20 – *PicoWatch* Class Diagram - Part 2

6.11.3 *PicoWatch* State Diagram

Figure 6.21 illustrates the state diagram of *PicoWatch* class :

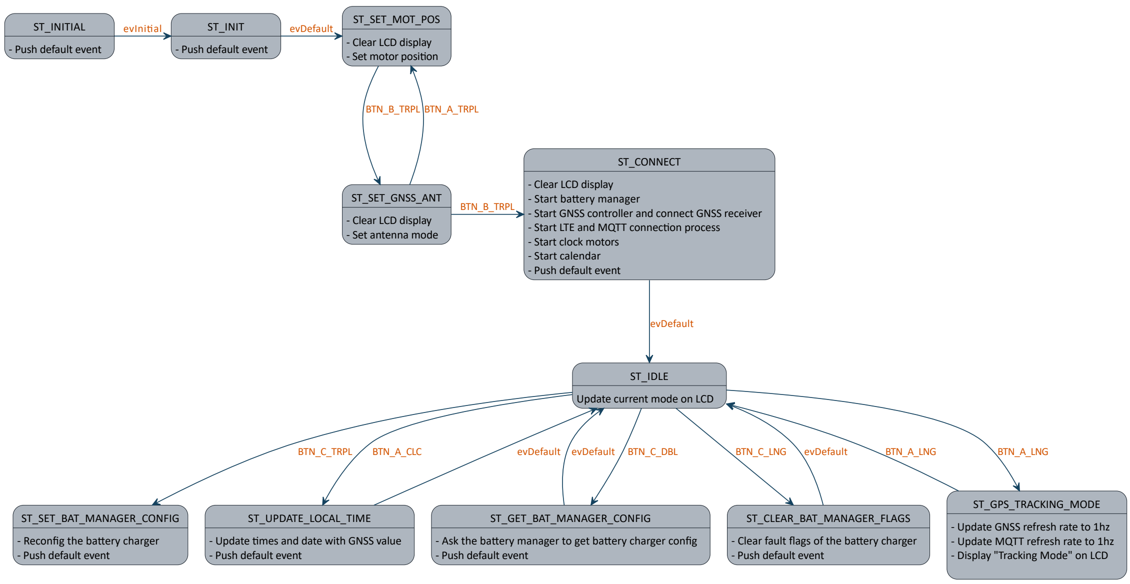


FIGURE 6.21 – *PicoWatch* State Diagram

6.11.4 *PicoWatch - MQTT* Internal State Diagram

Figure 6.22 illustrates *PicoWatch - MQTT* internal state diagram :

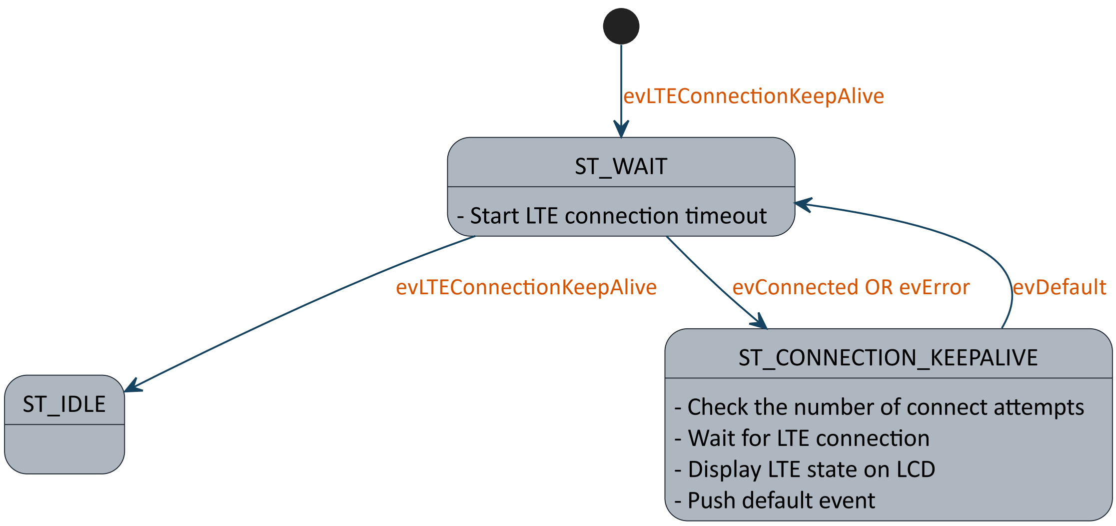


FIGURE 6.22 – *PicoWatch - MQTT* State Diagram

6.11.5 *PicoWatch* - Common Name-space - Class Diagram

Figure 6.23 illustrates the diagram of *PicoWatch common* classes from *LTEWatch* application :

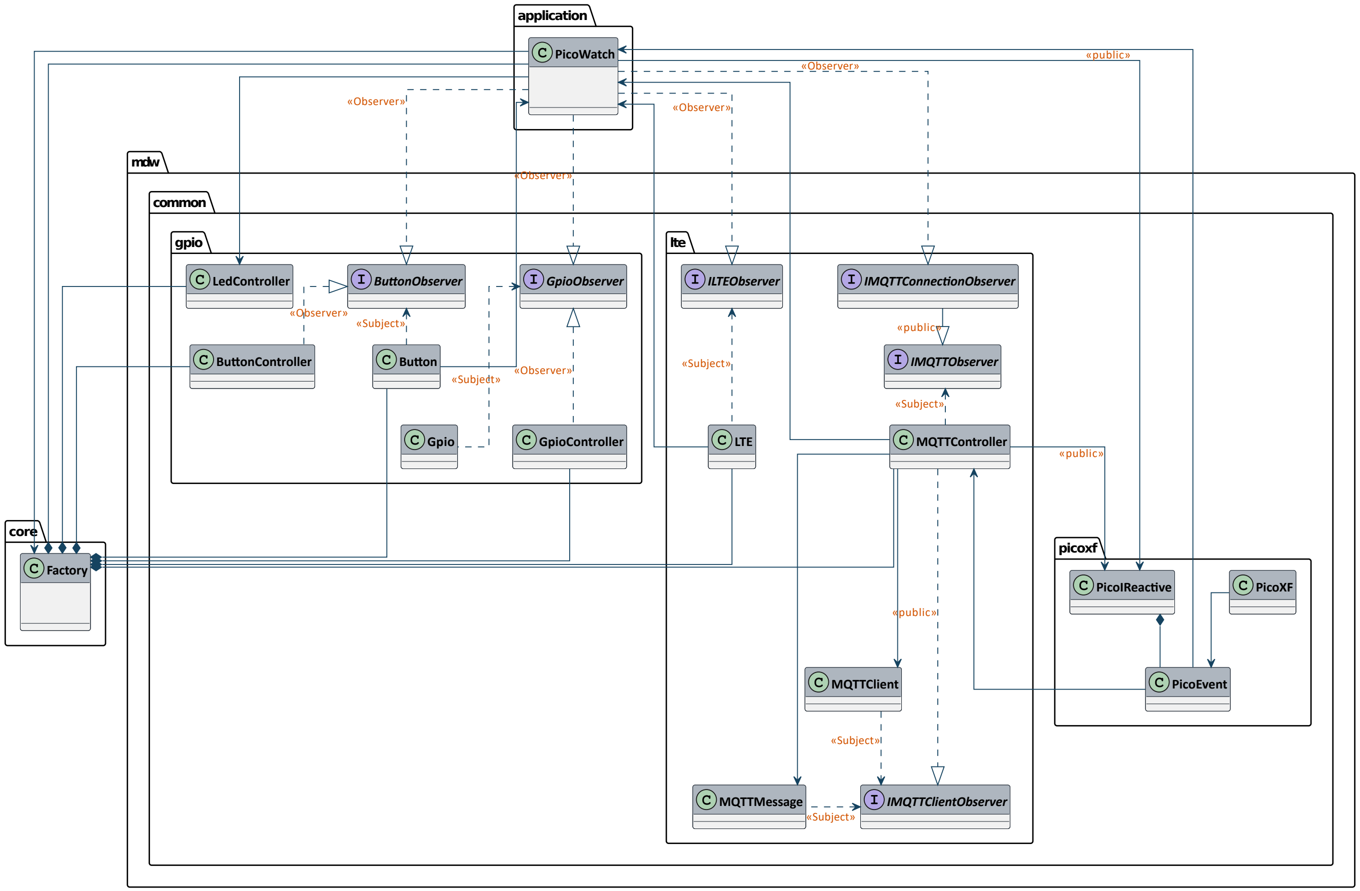


Figure 6.23 – Name-space : *common* from *PicoWatch* Application

6.11.6 *PicoWatch* - Partners Name-space - Class Diagram

Figure 6.24 illustrates the diagram of *PicoWatch partners* classes from *LTEWatch* application :

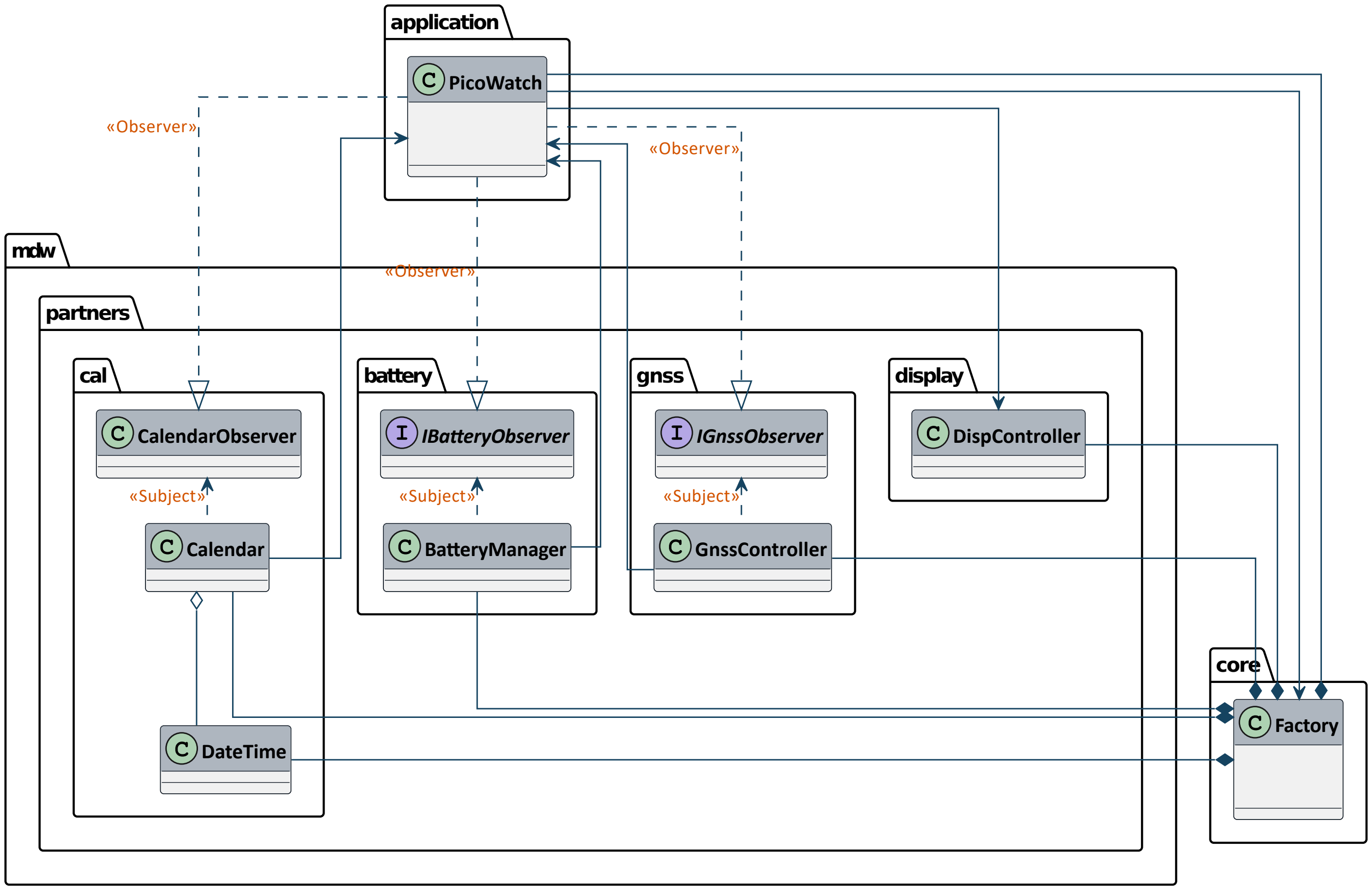


Figure 6.24 – Name-space : *partners* from *PicoWatch* Application

6.12 Motor Driver

6.12.1 Motor driver Classes Diagram

Figure 6.25 illustrates the architecture of classes in relation with motor driver :

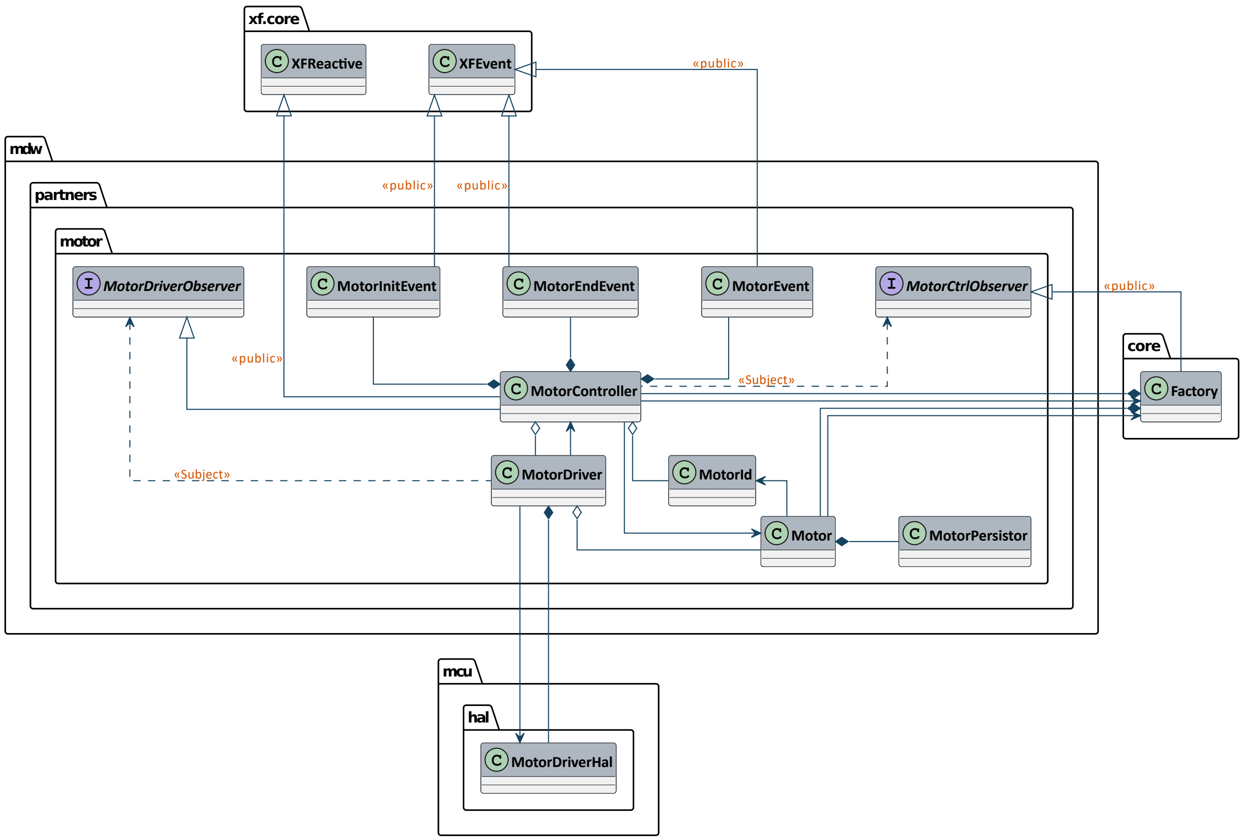


Figure 6.25 – Motor driver related classes Diagram

6.13 Pico XF

6.13.1 *PicoXF* Class Diagram

Figure 6.26 illustrates the class diagram of *PicoXF* :

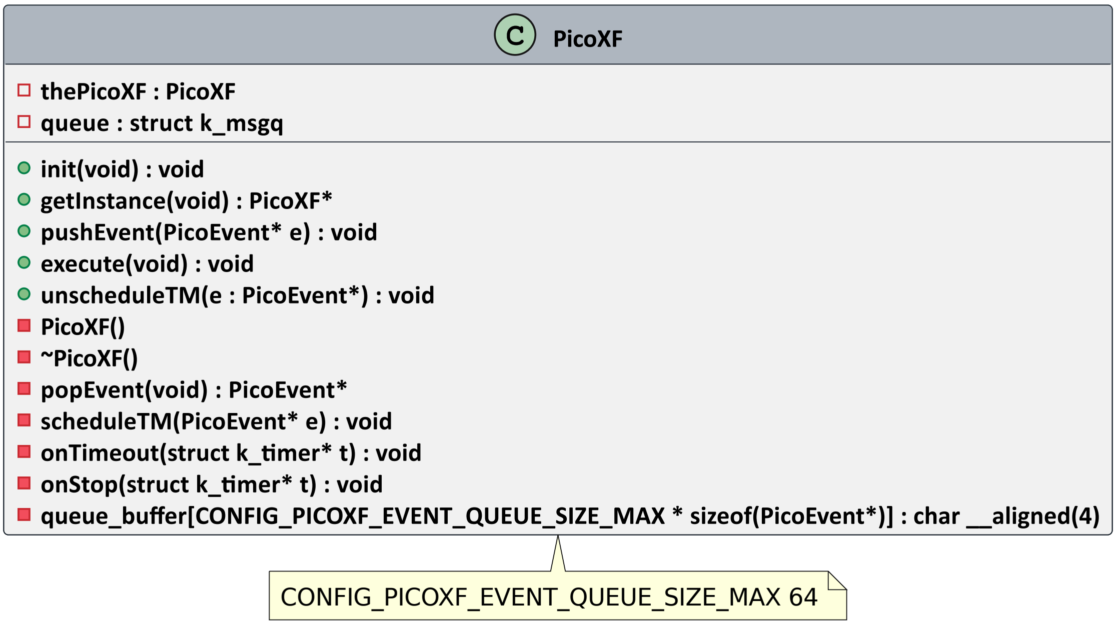


Figure 6.26 – *PicoXF* Class Diagram

6.13.2 *PicoIReactive* Class Diagram

Figure 6.27 illustrates the class diagram of *PicoIReactive* :

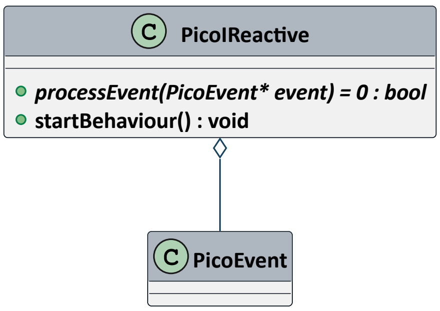


Figure 6.27 – *PicoIReactive* Class Diagram

6.13.3 *PicoEvent* Class Diagram

Figure 6.28 illustrates the diagram of *PicoEvent* class from *LTEWatch* application :

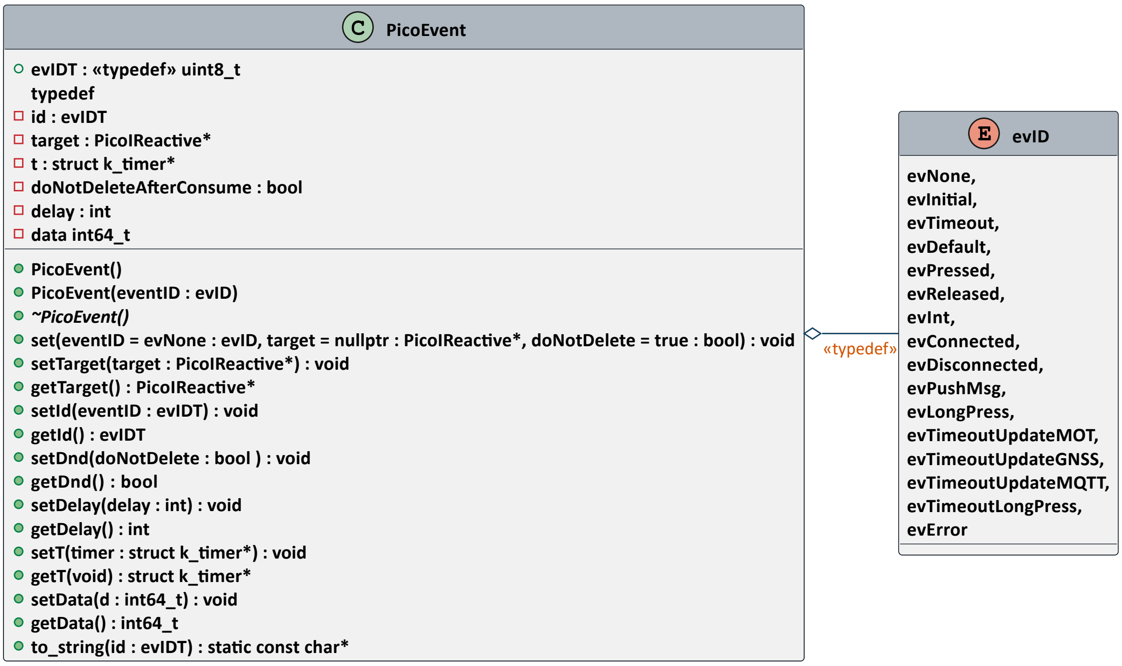


Figure 6.28 – *PicoEvent* Class Diagram

7 Test and Result

7.1 *LTEWatch* Prototype Board - Power-On

Before diving in the *LTEWatch* prototype board, modification, power-on and testing, It seems important to specify that the prototypes *PCB* were ordered from Euro Circuits fully assembled. As mentioned on page 75, many components of the *LTEWatch* prototype board were selected in *BGA* or similar tiny packages in order to design a hardware solution as compact as possible.

7.1.1 Prototype Board Objectives

An important aspect of the project is to assembly and validate a proof of concept prototype board. This prototype board has the following objectives :

1. **Concept Validation :**
   — Proof of concept to validate device hardware design
2. **Software Development :**
   — Functional development board for software experimentation and implementation
3. **Performance Testing :**
   — Experimental board for feature and performance testing
4. **RF Design Platform :**
   — Development board for designing and testing custom RF antennas

7.1.2 Prototype Board Modification

As expected, before powering-on the prototype board, it is necessary to make some corrections and modifications to the receive boards in order to make them fully operational.

BAT_LVL ADC Input Pin

Rooting of the *PCB* was done by Steve Gallay of *HEVS*. To simplify rooting he changed the pin assignment of the *nRF9160* and this change was a good idea. The only problem was that it switched the battery level voltage measurement pin which is an analog input to a digital input pin of the *MCU*. To make battery level monitoring available, it is necessary to modify this connection by connecting the *BAT_LVL* line to an available *AIN* pin of the *nRF9160*. Because there was not a single *AIN* pin available, I decided to sacrifice the *BTN3* button, which is connected to the *AIN3* pin of the MCU.

Schematic of the *BAT_LVL* signal modification is illustrated on figure 7.1 :

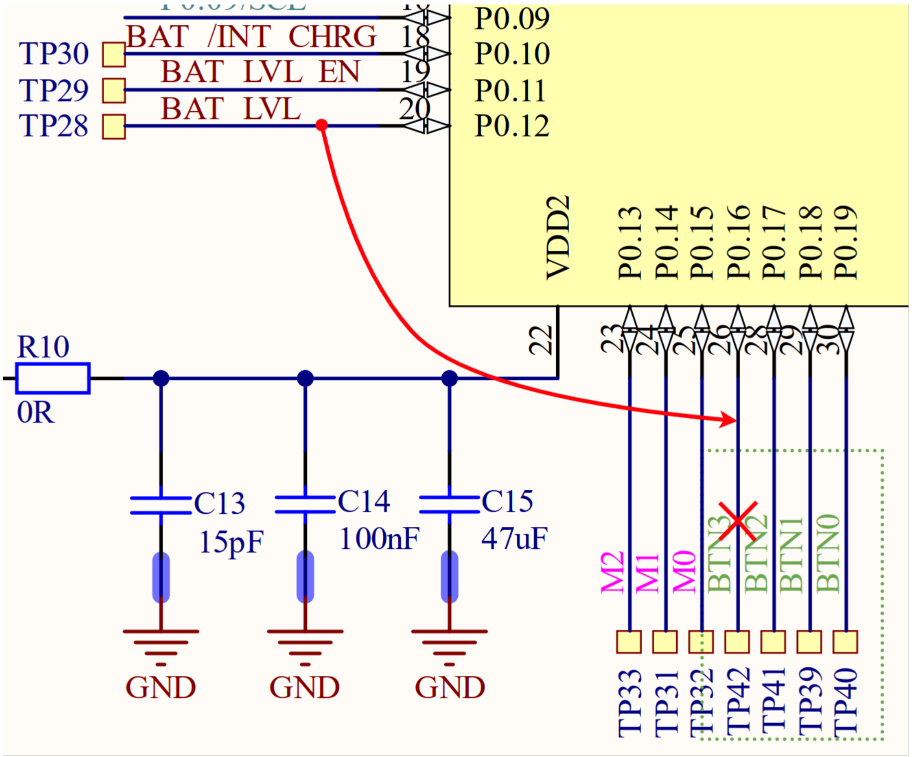


Figure 7.1 – *BAT_LVL* Signal Pin Modification Schematic

It is also necessary to unplug the power connection to *BTN3* or it will be impossible to measure the battery level. The button debounce capacitor must also be removed to preserve the dynamic characteristic of *BAT_LVL* signal.

The result of the modification (green wire) is illustrated on figure 7.2 :

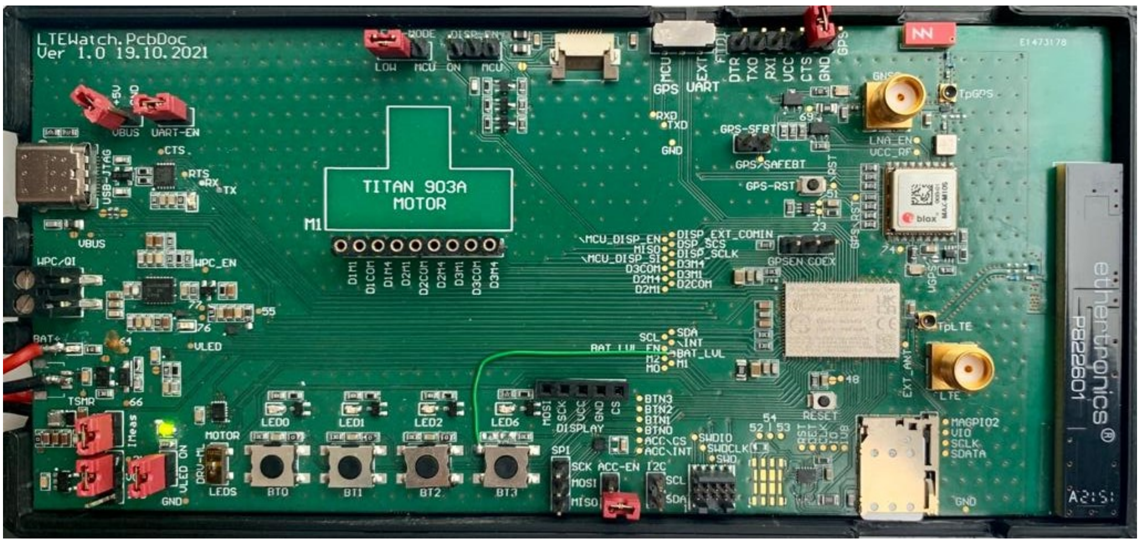


Figure 7.2 – Result of the *BAT_LVL* Signal Pin Modification (Green Wire)

Buttons Interface Modification

The *buttons* interface of the *user interface* block allows you to choose between several types of button connection with the *MCU*. The chosen configuration requires short-circuiting the series resistors added to the button lines.

Schematic of *buttons* interface modification is illustrated on figure 7.3 :

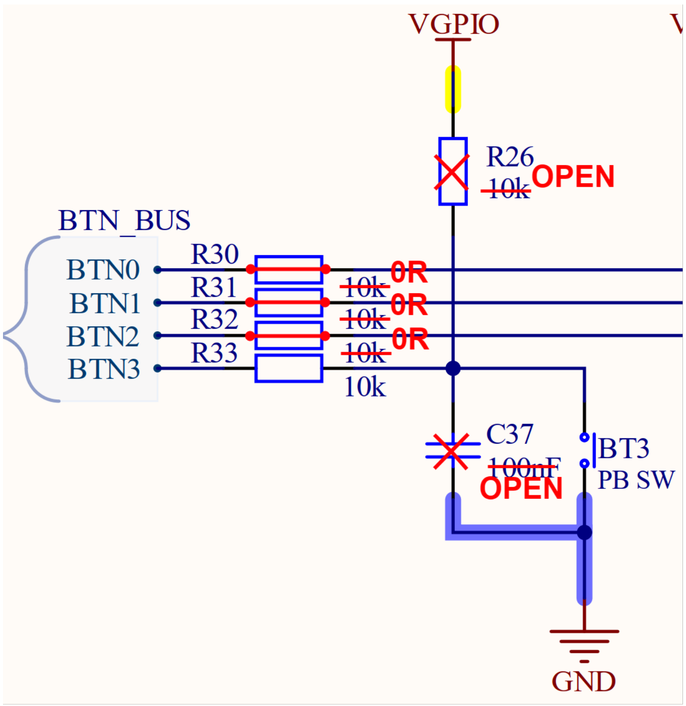


FIGURE 7.3 – Schematic of *Buttons* Interface Modification

Figure 7.3 also illustrates the modifications needed to be processed on *BTN3*.

7.1.3 Prototype Board Power-on

To validate the *LTEWatch* prototype, it is necessary to realize a power-on of the board. To avoid any damage on the board, the power-on process is the following :

1. **Battery Charger Unit :**
   - 1.1 **Conditions :**
     - 1.1.1 Jumper **P5** (*IMEAS*) is disconnected
     - 1.1.2 No battery is connected
     - 1.1.3 R_{65} and R_{73} are not mounted (open)
     - 1.1.4 Jumper **P7** (*VGPIO*) is disconnected
     - 1.1.5 Jumper **P6** (*VLED*) is disconnected
   - 1.2 **Power-on Process :**
     - 1.2.1 Connect a 5 V source with current limited to 100 mA to **P12** (*VBUS*)

1.2.2 Measure voltage on **TP55**

1.2.3 Voltage on **TP55** should be between 4.2 V and 5 V

2. **+3V3 Buck-Boost Converter :**
   2.1 **Conditions :**
      2.1.1 Jumper **P5** (*IMEAS*) is connected
      2.1.2 No battery is connected
      2.1.3 R_{65} is mounted
      2.1.4 R_{73} is mounted
      2.1.5 Jumper **P7** (*VGPIO*) is disconnected
      2.1.6 Jumper **P6** (*VLED*) is disconnected
   2.2 **Power-on Process :**
      2.2.1 Connect a 5 V source with current limited to 100 mA to **P12** (*VBUS*)
      2.2.2 Measure voltage on the **+3V3** pin of jumper **P7** (*VGPIO*)
      2.2.3 Voltage on **+3V3** pin should be 3.3 V
3. **+1V8 LDO Regulator :**
   3.1 **Conditions :**
      3.1.1 Same as for *+3V3 Buck-Boost Converter*
   3.2 **Power-on Process :**
      3.2.1 Connect a 5 V source with current limited to 100 mA to **P12** (*VBUS*)
      3.2.2 Measure voltage on the **+1V8** pin of jumper **P7** (*VGPIO*)
      3.2.3 Voltage on **+1V8** pin should be 1.8 V
4. **USB-C Connector :**
   4.1 **Conditions :**
      4.1.1 Same as for *+3V3 Buck-Boost Converter*
   4.2 **Power-on Process :**
      4.2.1 Connect a **USB-C cable** to connector **J1** (*USB-C*) of the board
      4.2.2 Measure voltage on the **+3V3** pin of jumper **P7** (*VGPIO*)
      4.2.3 Voltage on **+3V3** pin should be 3.3 V
      4.2.4 Measure voltage on the **+1V8** pin of jumper **P7** (*VGPIO*)
      4.2.5 Voltage on **+1V8** pin should be 1.8 V
5. **Supply the *nRF9160***
   5.1 Bridge **middle** pin and **+3V3** pin of jumper **P7**
   5.2 Bridge **P5** (*IMEAS*)
   5.3 Flash the *nRF9160* using connector **J2** (*Segger J-Link SWO JTAG*)

7.1.4 *LTEWatch* Board Power-On Result :

The result of *LTEWatch* board power-on process is described in table 7.2 :

BLOCK	TP	EXPECTED	MESURED	UNIT	OK/KO
Battery Charger Unit	TP55	4.20 . . . 5.00	4.36	V	OK
+3V3 Buck-Boost Converter	*+3V3* of P7	3.310	3.	V	OK
+1V8 LDO Regulator	*+1V8* of P7	1.8	1.810	V	OK
USB-C Connector	*+3V3* of P7	3.30	3.312	V	OK
USB-C Connector	*+1V8* of P7	1.8	1.807	V	OK

TABLE 7.1 – *LTEWatch* Board Power-On Process Result Table

As shown in table 7.2 the power-on of *LTEWatch* prototype board is a success. The next steps are validation of the specifications of the prototype board.

7.2 *LTEWatch* Prototype - Test & Validation

Once the *LTEWatch* prototype board has been successfully powered-on, it is possible to validate the prototype board features that were successfully implemented, based on the prototype specification described on page 3.1.

BLOCK	SPECIFICATION	OK/KO
Power supply	Powered by a battery	OK
	Rechargeable by USB-C and *WPC*	OK
	Battery life of at least one day	OK
Data Display	Time is displayed with 3 clock hands	OK
	LCD must be implemented	OK
User Interface	The user interface must be done with four push-buttons	OK
	Accelerometer can be added	OK
Computing Unit	Must use the **nRF9160**	OK
RF Communication	Must implement a GNSS receiver	OK
	Must implement an LTE-M / NB-IoT transceiver	OK
	Must have on-board antenna for both GNSS and LTE-M	OK
	Must have SMA connectors for GNSS and LTE-M	OK
Mechanical Specification	Build a prototype board	OK

TABLE 7.2 – *LTEWatch* Specifications Validation

As shown on table 7.2, most specifications are satisfied, the only two that are completely satisfied are :

1. **The user interface must be done with four push-buttons :**
   This specification is not entirely satisfied because one of the buttons have been sacrificed because of a rooting mistakes. The board still implements three fully programmable and functional buttons, *BT0, BT1* and *BT2*.
2. **Accelerometer can be added :** due to the limited time available, the accelerometer could not be implemented during the project. On the other hand, the accelerometer is integrated on the board and the *SPI* communication is already implemented for the display. The only remaining tasks are only software development tasks, which are importing a suitable driver for the accelerometer and to add it to the small watch application.

7.2.1 Validation of the Display

The display is fully implemented and functional. To validate its implementation, *LTEWatch* application start-up process is demonstrated bellow :

1. **Connect the battery to the board**
2. ***LTEWatch* is in *Set Motor Position* mode :**

(a) Set Second (b) Set Minute (c) Set Hour

Figure 7.4 – Display Test - Set Motor Position

— Click *BT1* : Move selected clock hands 1 step clockwise
— Click *BT0* : Move selected clock hands 1 step counterclockwise
— Long Press *BT1* : Continuously move selected clock hands clockwise
— Long Press *BT0* : Continuously move selected clock hands counterclockwise
— Double Click *BT1* : Change selected clock hand forward
— Double Click *BT0* : Change selected clock hand backward
— Triple Click *BT1* : Save and exit to next mode
— Triple Click *BT0* : Save and exit to previous mode

3. ***LTEWatch* is in *Set GNSS Antenna* mode :**

(a) On-board Antenna (b) External Antenna

Figure 7.5 – Display Test - Set *GNSS* Antenna Mode

— Click *BT1* : Select next antenna option
— Click *BT0* : Select previous antenna option
— Triple Click *BT1* : Save and exit to next mode
— Triple Click *BT0* : Save and exit to previous mode

4. ***LTEWatch* Application is starting up :**

(a) App. Start (b) *MQTT* Connecting (c) *MQTT* Connected

Figure 7.6 – Display Test - *LTEWatch* Application Start-Up

5. ***LTEWatch* is in *Normal* mode :**
During this mode, the *GNSS* position update and the refresh rate of sending *MQTT* data is determined by the current speed of the device. If the movement speed of the device increases, the refresh rate also increases and if the movement speed of the device decreases, the refresh rate also decreases.

(a) *GNSS* Connected (b) Bat Level In mV

Figure 7.7 – Display Test - Normal Mode

- Click *BT0* : Update time and date value with *GNSS* receiver's data
- Double Click *BT2* : Change battery level unit (mV/%)
- Triple Click *BT2* : Reset battery charger configuration
- Long Press *BT0* : Change active mode (*Normal/Tracking*)

6. ***LTEWatch* is in *Tracking* mode :**

Figure 7.8 – Display Test - Tracking Mode

During this mode, the *GNSS* position is updated every second. The *MQTT* data are sent every second as well.

7.2.2 Validation of *GNSS* and *LTE-M/NB-IoT*

In order to validate the *GNSS* position, *LTE-M/NB-IoT* and *MQTT* communication, a *Thingsboard* dashboard was created. To do so, Patrice Rudaz help me to log my device on one of *HEVS* servers : `https://tb.ecs.hevs.ch/`. Once done, a graphical user interface was created. This dashboard is public and is accessible with this link : `https://tb.ecs.hevs.ch/dashboard/4d6aa6b0-9701-11ed-8466-731d9ee1dd28?publicId=4bb1eaf0-ab74-11ec-aeec-99b485820668`.

The dashboard display the following information :

— *GNSS* position tracking on *OpenStreetMap*

— Number of satellites connected to the *GNSS* receiver of the device (*SVS*)

— Speed of the device

— Battery level in %

— Last published altitude of the device

— *GNSS* Altitude Tracking

— Battery level in mV

— Graph of published altitude values

— Graph of published speed values

— Graph of published *SVS* values

— Graph of published battery level values

The created *Thingsboard* dashboard is illustrated in figure 7.9 :

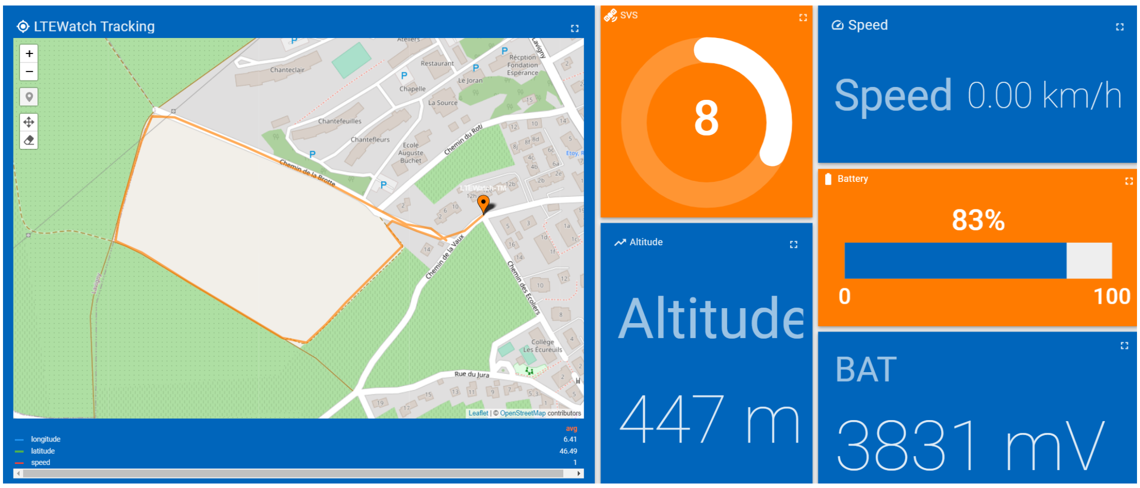


Figure 7.9 – *LTEWatch* - Dashboard (Thingsboard)

With the created dashboard illustrated in figure 7.9, it is possible to validate the *GNSS* receiver and the *LTE-M/NB-IoT* modem implementation by testing multiple tracking scenarios.

Figures 7.10 to 7.11 illustrates the test of the *LTEWatch* prototype board *GNSS* accuracy. This test uses the *LTEWatch* in tracking mode and the on-board *GNSS* antenna and on-board *LTE-M/NB-IoT* antenna :

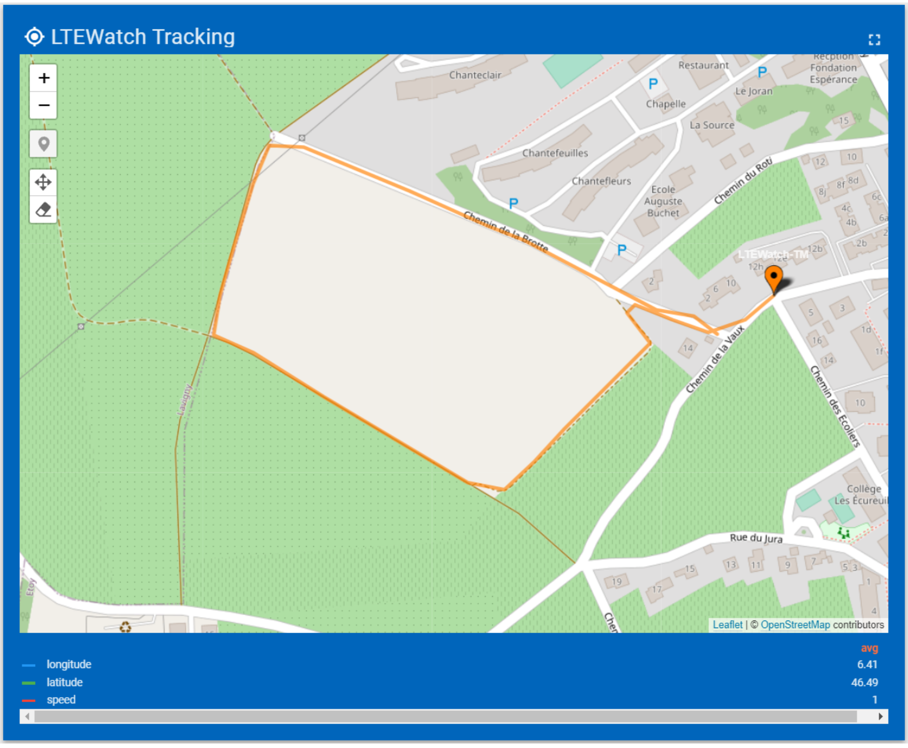


Figure 7.10 – *LTEWatch* - GNSS Tracking Accuracy

As figure 7.10 shows, the *GNSS* tracking accuracy is very good, even with the tiny *GNSS* on-board antenna. The tracking line (in orange) follows roads and paths very well. This result is very satisfying and validates the tracking mode of the *LTEWatch* prototype board. The following figure 7.11 illustrates the altitude tracking that was published during the previous route.

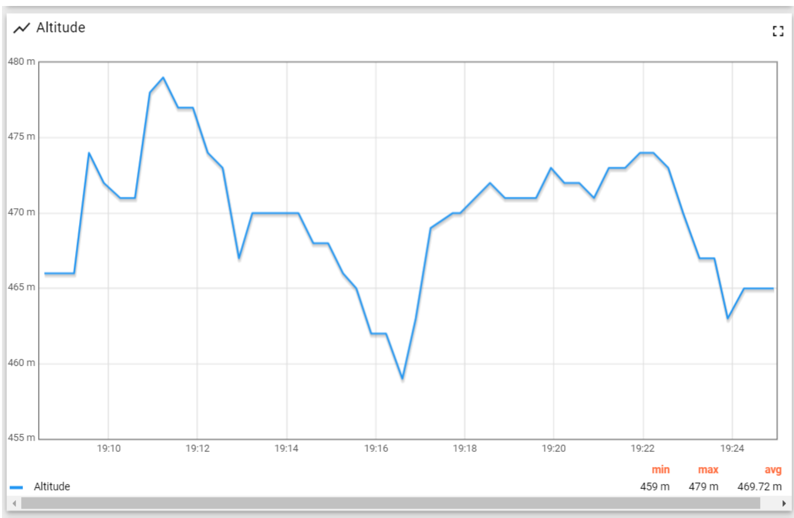
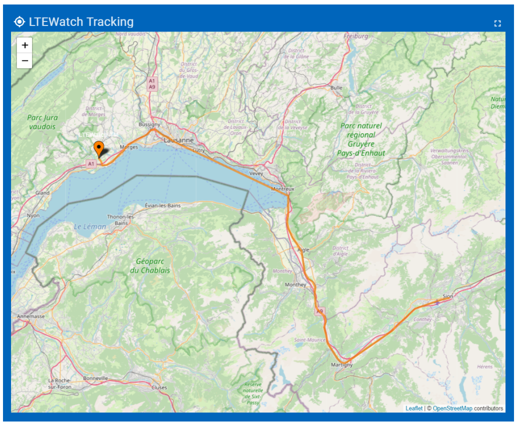
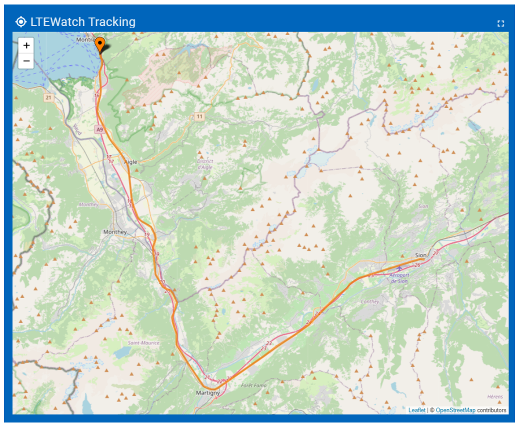


Figure 7.11 – *LTEWatch* Tracking Test - Altitude Accuracy

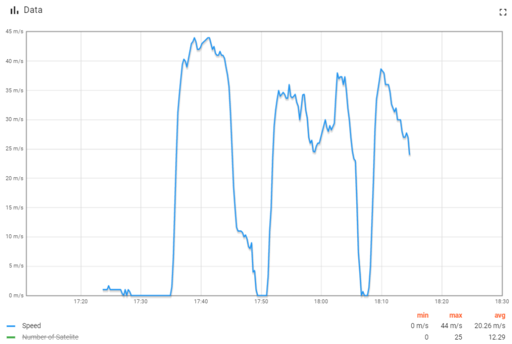
Once the tracking mode of the *LTEWatch* prototype board has been validated, it is interesting to try a much more complicated scenario by testing *GNSS* tracking over a long distance journey. The figure 7.12 illustrates the tracking *GNSS* of the trajectory in train from my home to the *HEVS*.



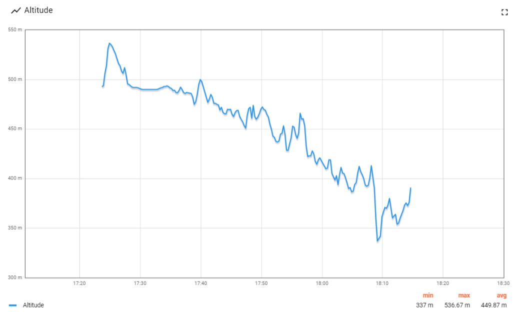
(a) *GNSS* Position Tracking



(b) *GNSS* Position Tracking



(c) *GNSS* Speed Tracking



(d) *GNSS* Altitude Tracking

Figure 7.12 – *GNSS* & *LTE-M/NB-IoT* Validation - Long Distance Tracking

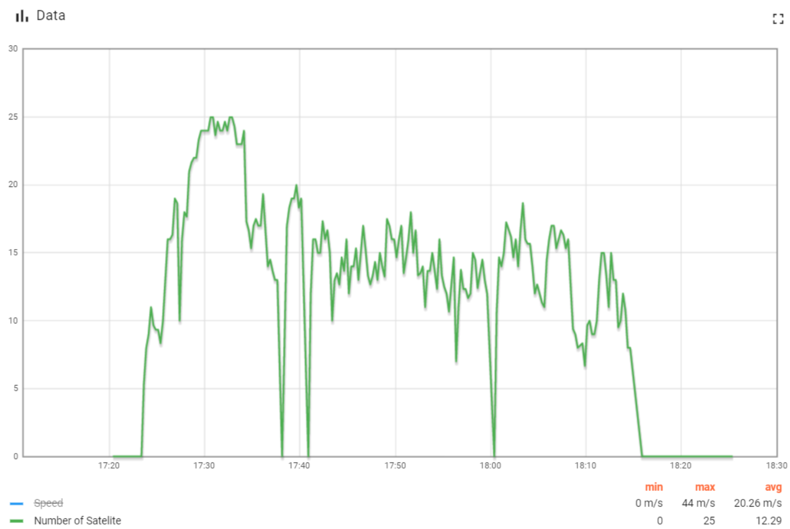


Figure 7.13 – *GNSS* & *LTE-M/NB-IoT* Validation - Number of Satellite (*SVS*)

8 Discussion

8.1 Result of the *LTEWatch* Project

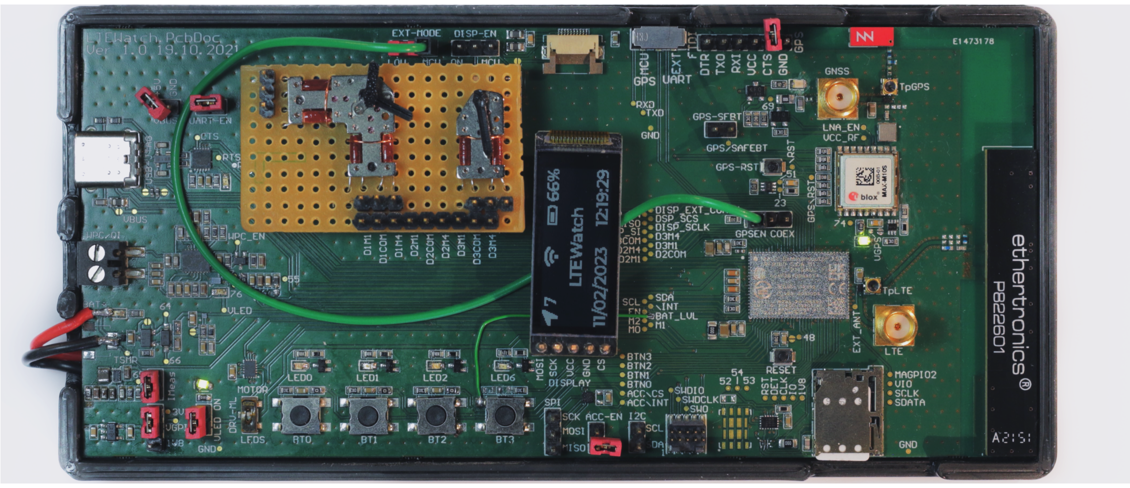


FIGURE 8.1 – *LTEWatch* Prototype Device

It is now time to make the point on the project that has been carried out. Firstly, this work was a very complex and complete project which required a very varied panoply of skills by covering all steps of a device prototype design and realization. At the end of the project, a functional prototype board «LTEWatch» have been designed, built and validated.

Figure 8.2 illustrates the *LTEWatch* prototype device that was made for this Master Thesis Project :

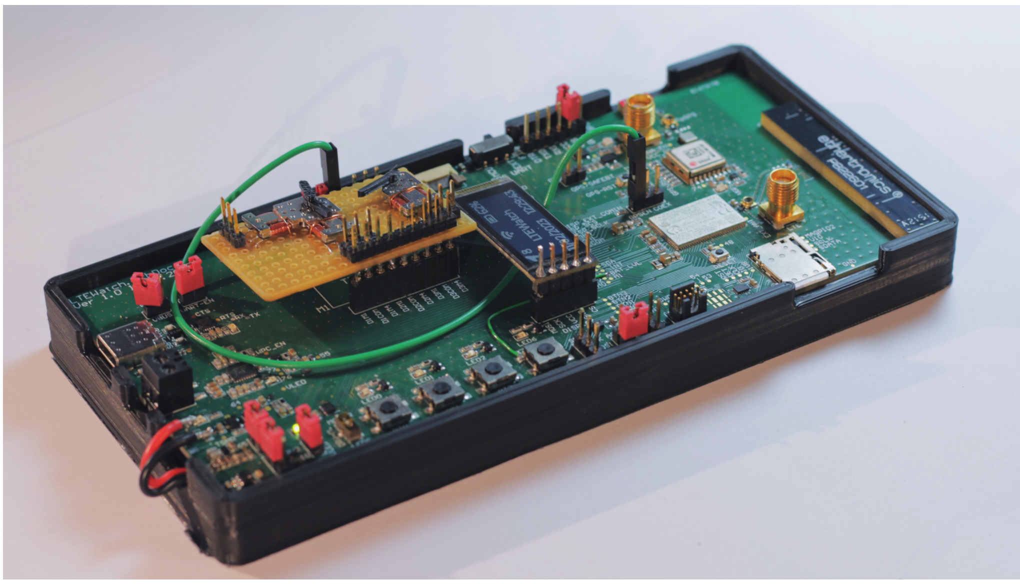


FIGURE 8.2 – *LTEWatch* Prototype Device

The finished *LTEWatch* prototype device validates the following features :

1. **Power Supply :**
   — Recharge by *USB-C*
   — Suitable for *Li-Ion* and *LiPo* single cell batteries with programmable battery manager
   — Battery level monitoring and displaying
   — *WPC/QI* wireless battery charging capability
2. **User Interface :**
   — Display hour, minute and second using tiny stepper motors
   — Four fully programmable push button to operate the device
   — Graphical interface using an ultra-low-power SHARP *Memory-In-Pixel (MIP) LCD*
   — 3-axis ultra-low-power *MC3635* accelerometer from mCube
3. ***GNSS* :**
   — *GNSS* tracking using *MAX-M10S* ultra-low-power *GNSS* receiver from u-blox
   — Selectable external antenna via SMA or on-board *DUO mXTEND (NN03-320)* from igion
4. ***LTE-M/NB-IoT* :**
   — Selectable external antenna via *SMA* or on-board *P822601* antenna from Kyocera
   — Data publishing on a *ThingsBoard* server by *LTE-M/NB-IoT* using *MQTT* protocol
   — Connector for *SIM* and *eSIM* card

8.2 Remaining Work and Further Improvement

Due to the relatively limited time available for this project, it was only possible to dedign a prototype board of *LTEWatch* and even if most of the specifications were implemented it still remains some tasks that should be finished :

1. **Accelerometer :**
   — Find a *Zephyr* compatible driver for the *MC3635* accelerometer
   — Implement accelerometer functionality in *LTEWatch* firmware
   — Implement accelerometer wake-up function and activity tracking features
2. ***LTE-M/NB-IoT* Custom Antenna :**
   — Look for an antenna design solution such as an antenna integrated in the watch strap or in the case
   — Design and simulate a custom antenna solution
   — Test custom solution performance
3. **Power Management and Consumption :**
   — Implement low power and power management features from *Zephyr* and *nRF Connect SDK*
4. **Bluetooth & Wifi :**
   — Integrate the *nRF52840* in the hardware design to add *bluetooth* and *Wifi* features for improved connectivity
5. **Round PCB :**
   — Clean *LTEWatch* hardware design by removing all unnecessary modules and components
   — Root a compact round PCB for a smart-watch design
6. **Mechanical :**
   — Design a *3D* printed case for the round PCB
   — Design a watch strap solution that can integrate a custom antenna

9 Conclusion

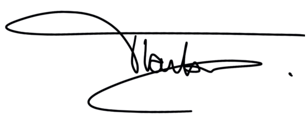
Now that the time has come to complete this project, it is finally time to draw conclusions. First, the least that can be said is that this work was an ambitious project that required many varied and complex tasks to be carried out. Producing a complete prototype from almost scratch is a colossal task that requires many decisions to be made in order to give shape to the project. Many different tasks firstly means a wide variety of skills, which makes this project very interesting, but also requires being efficient at each stage of the project to allow everything to be done on time. This project covered both hardware design and software design, but it also required some creativity to find quick and accessible solutions for each question or problem, which made this work fascinating.

This project was my first practical implementation of cellular and *GNSS* application. Not being particularly comfortable with the development of this kind of device, I wanted to ensure things as much as possible by adding a lot of back-up plans and alternative solutions to the design of my prototype. This made the hardware design quite complex, which in part delayed the order of the *PCBs* and their late arrival during the project. Because of this, most of the software was developed on the *nRF9160DK* board with evaluation modules. This way of working forced me to design the software in such a way as to make it as easy as possible to export it to the prototype board. This approach worked well, because the software was ported to the prototype board in less than a week. I then had a second week to sort out all design issues, but as I had been extremely foresighted when designing the hardware, there were only few small changes to be made and the prototype board was validated in one week, leaving me only one weak to finish my report before the project submission date.

I am finally very satisfied with the result obtained, because I managed to make a functional prototype which allowed to validate nearly all specifications decided at the beginning of the project. The prototype board is therefore a success. However, I am still a little frustrated that the project stops right after the validation of the prototype. This step still only corresponds to the beginning of the realization of the smart-watch, and I would have really appreciated being able to continue the project to create a functional and finished smart-watch.

Signatures

Lausanne, 17 février 2023
Tristan Traiber



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List of Figures

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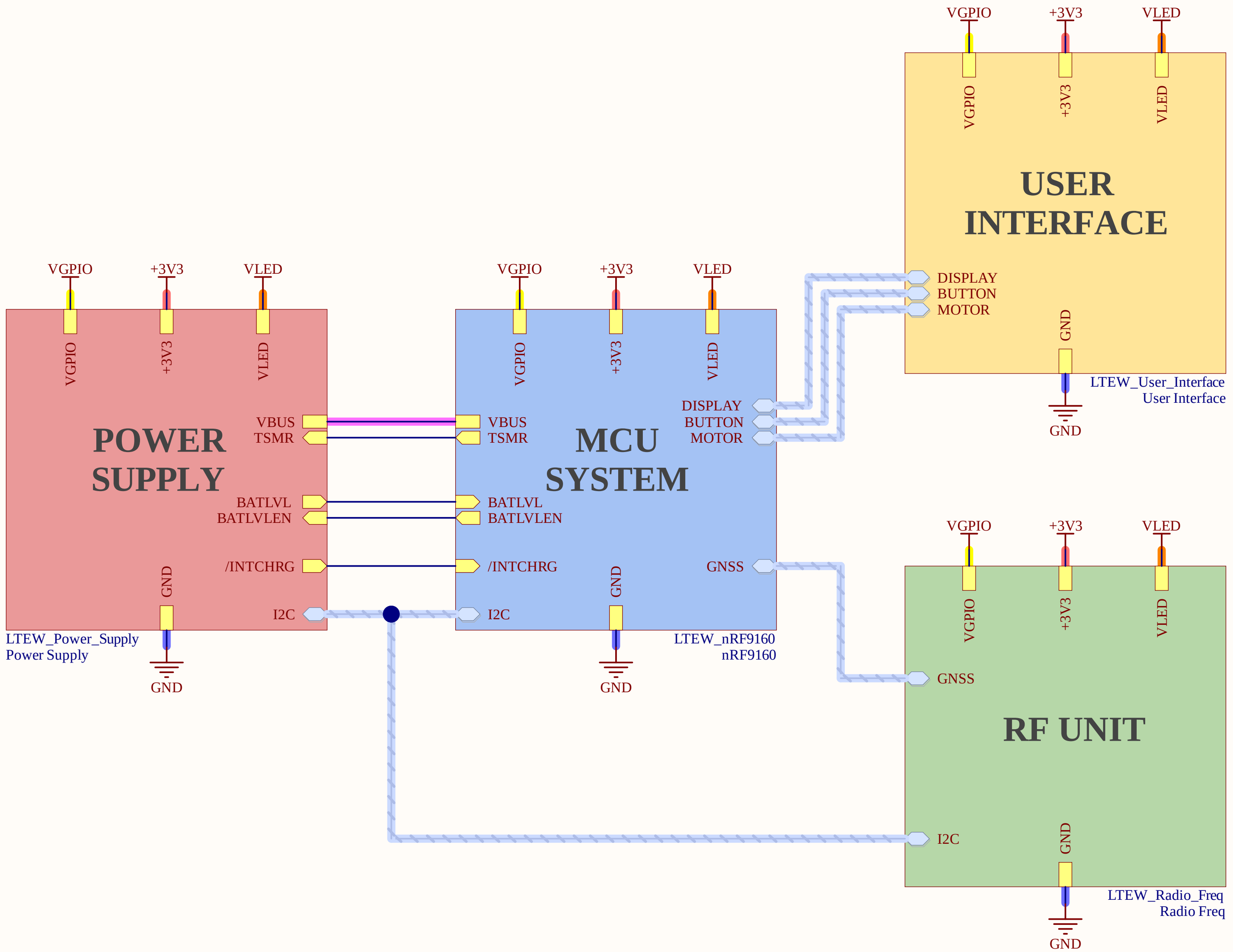
10 Appendix

10.1 *LTEWatch* Electrical Schematic



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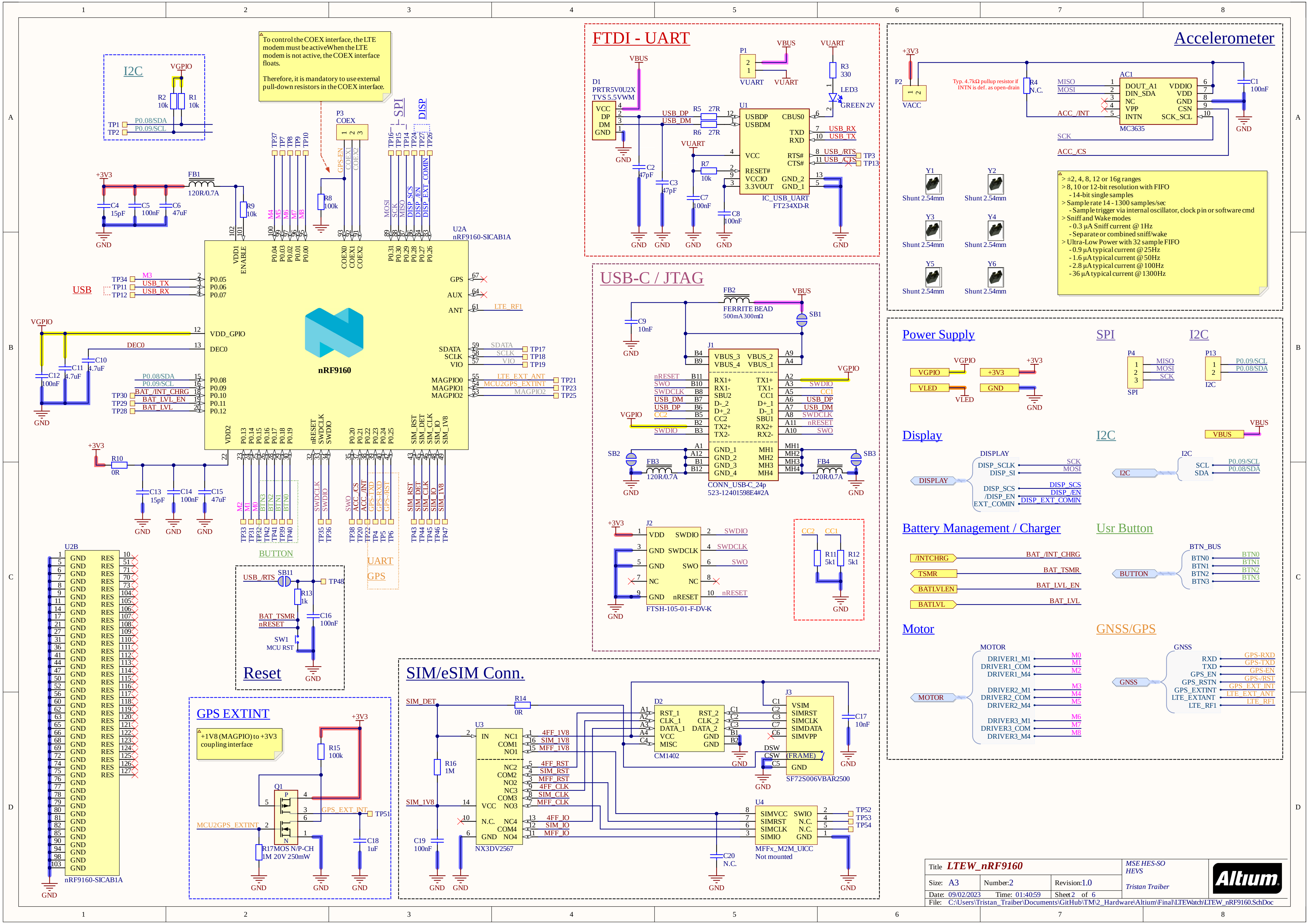
I2C
FTDI - UART
Accelerometer
USB-C / JTAG
Power Supply
SPI
I2C
Display
I2C
Battery Management / Charger
Usr Button
Motor
GNSS/GPS
Reset
GPS EXTINT
SIM/eSIM Conn.
USB
BUTTON
UART
GPS
nRF9160
U2A nRF9160-SICABIA
U2B nRF9160-SICABIA
To control the COEX interface, the LTE modem must be active When the LTE modem is not active, the COEX interface floats.
Therefore, it is mandatory to use external pull-down resistors in the COEX interface.
+1V8 (MAGPIO) to +3V3 coupling interface
Typ. 4.7kΩ pullup resistor if INTN is def. as open-drain
> ±2, 4, 8, 12 or 16g ranges
> 8, 10 or 12-bit resolution with FIFO
- 14-bit single samples
> Sample rate 14 - 1300 samples/sec
- Sample trigger via internal oscillator, clock pin or software cmd
> Sniff and Wake modes
- 0.3 µA Sniff current @ 1Hz
- Separate or combined sniff/wake
> Ultra-Low Power with 32 sample FIFO
- 0.9 µA typical current @ 25Hz
- 1.6 µA typical current @ 50Hz
- 2.8 µA typical current @ 100Hz
- 36 µA typical current @ 1300Hz
MC3635
FT234XD-R
CONN_USB-C_24p 523-12401598E4#2A
FTSH-105-01-F-DV-K
NX3DV2567
CM1402
SF72S006VBAR2500
MFFx_M2M_UICC Not mounted
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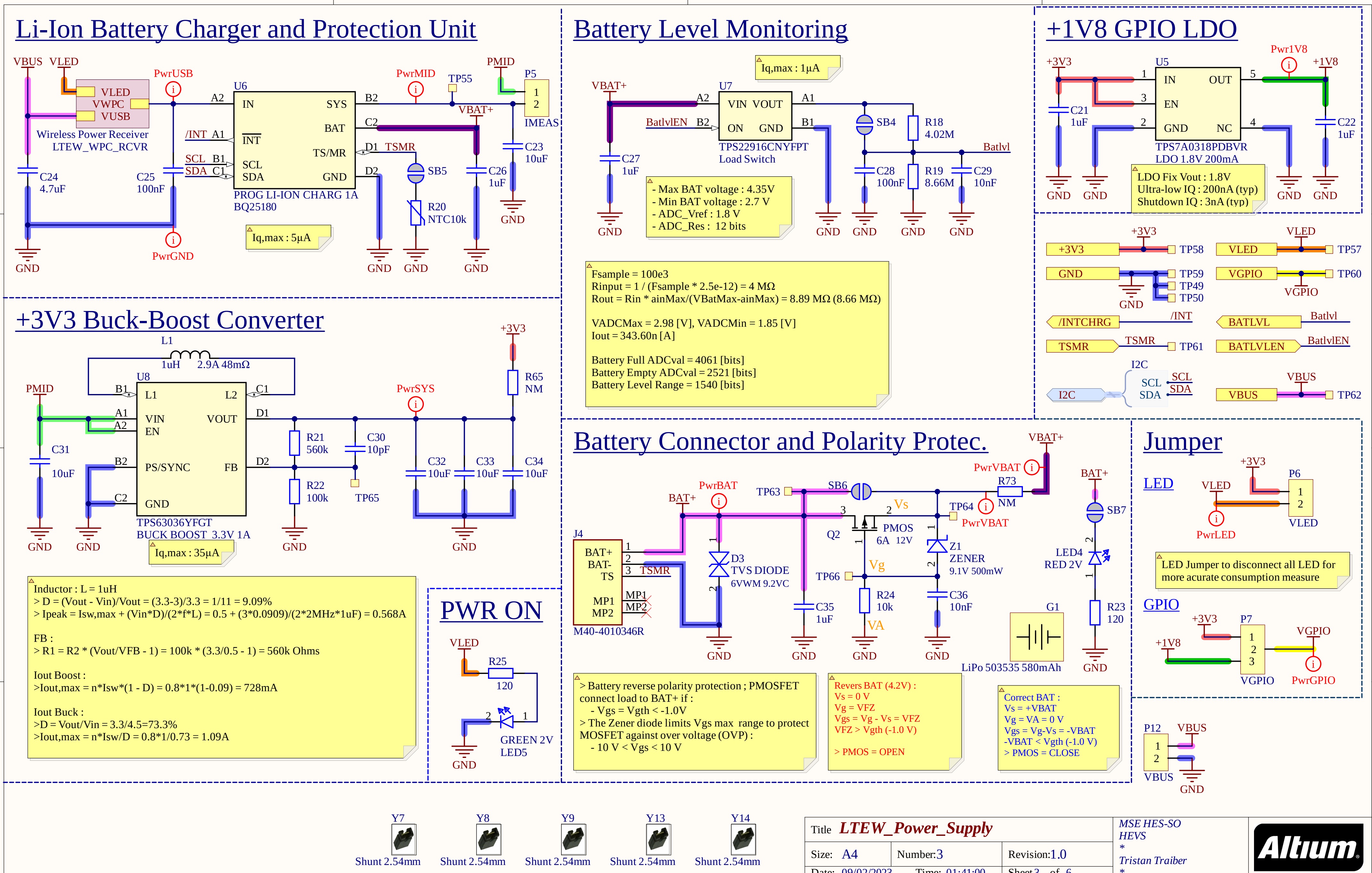
MSE HES-SO HEVS
Tristan Traiber
Altium



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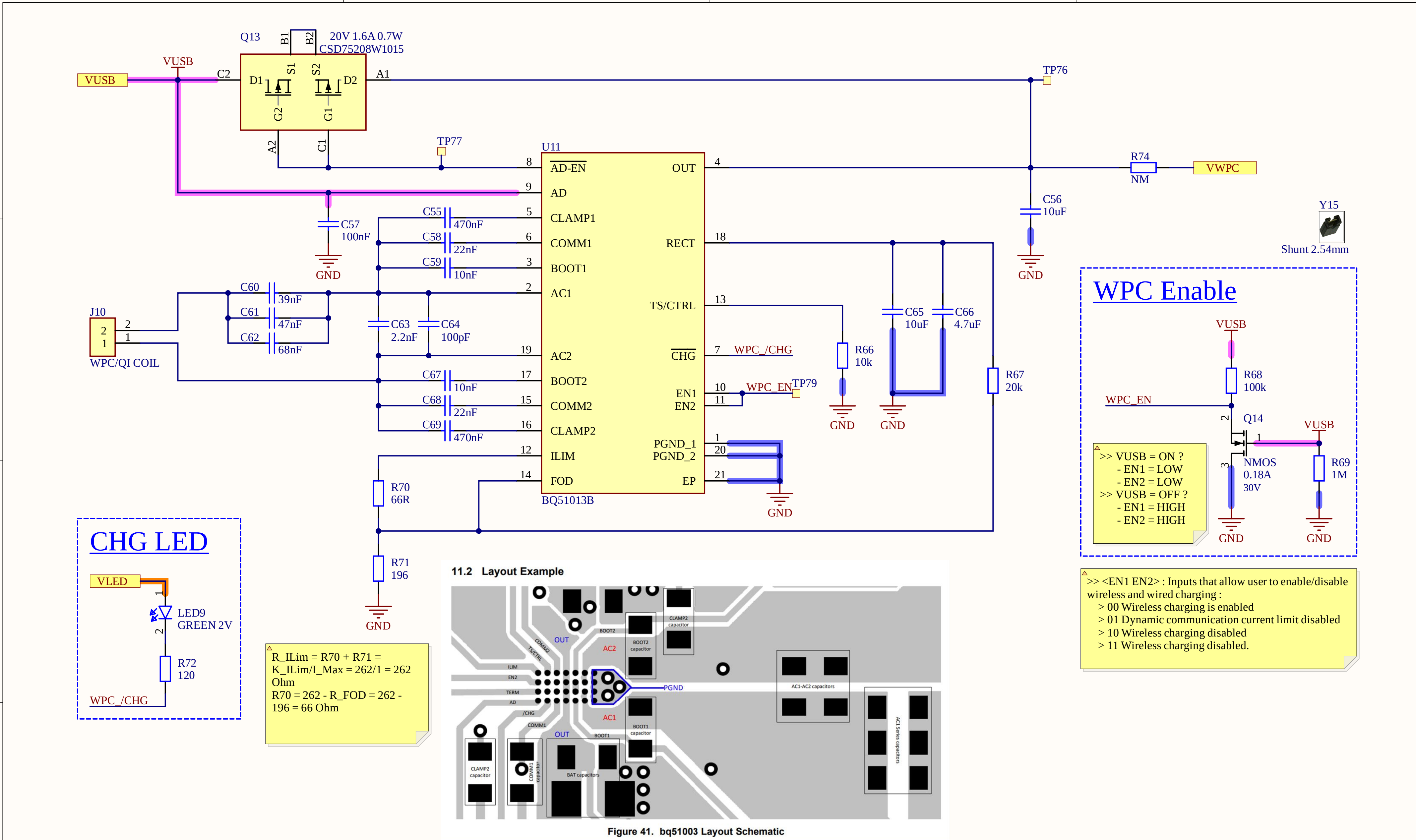
MSE HES-SO
HEVS
*
Tristan Traiber
*



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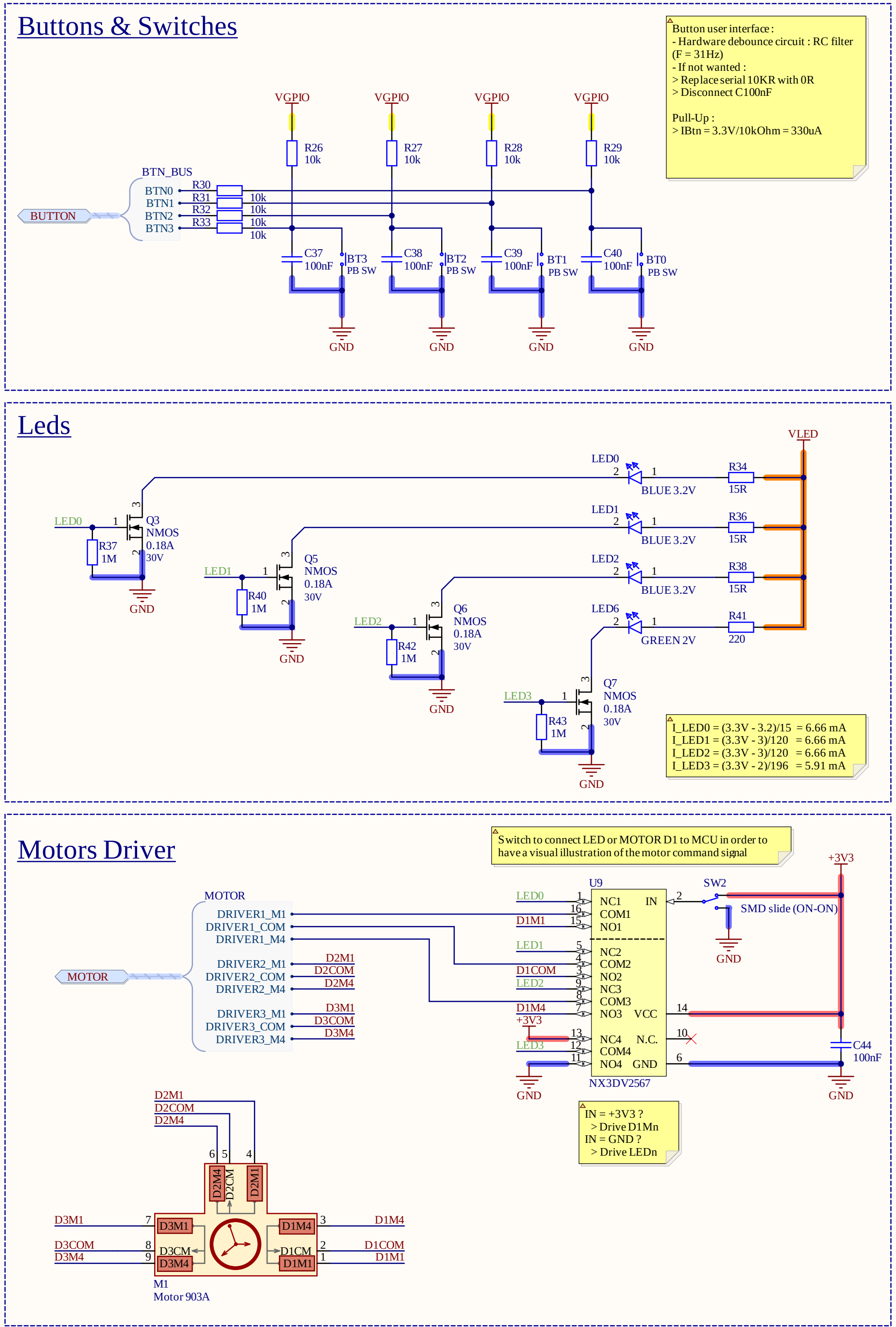
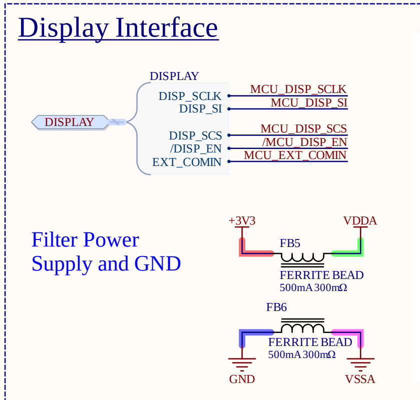




4. Input Terminal names and function

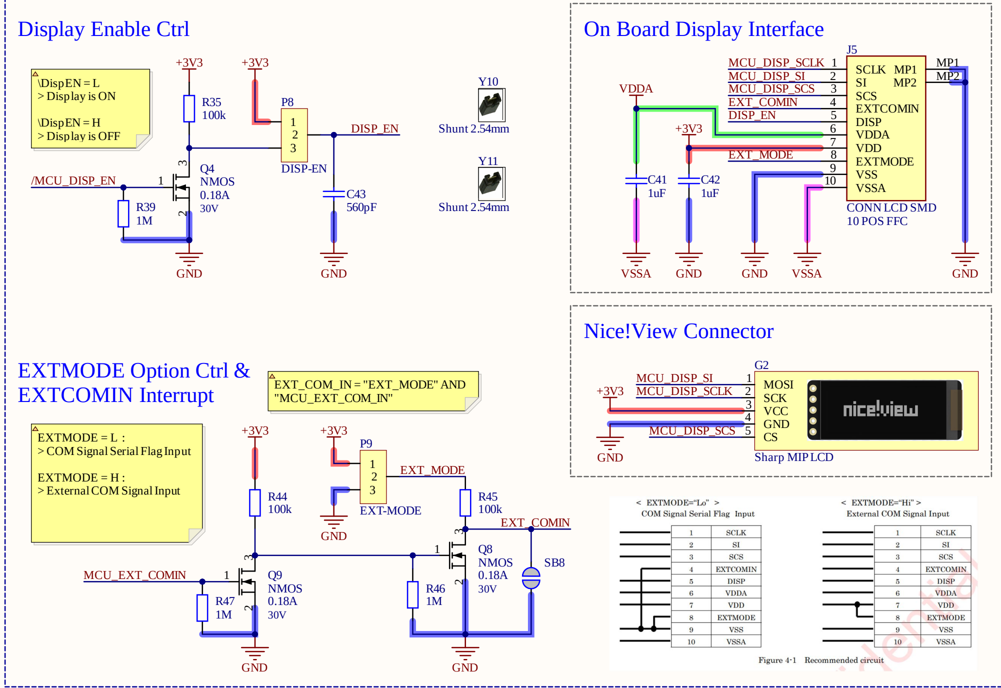
4-1) Input Terminal

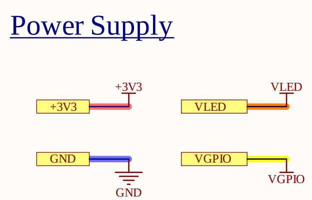
Table 4

No.	Code	I/O	Voltage	Signal name	Remark
1	SCLK	I	0/3.0 (V)	Serial clock signal	
2	SI	I	0/3.0 (V)	Serial input signal	
3	SCS	I	0/3.0 (V)	Chip select signal	
4	EXTCOMIN	I	0/3.0 (V)	COM inversion polarity input pin	
5	DISP	I	0/3.0 (V)	Display ON/OFF switching signal	4-2
6	VDDA	I	3.0(V)	Power source for Analog	
7	VDD	I	3.0(V)	Power source for Logic	
8	EXTMODE	I	0/3.0 (V)	COM inversion mode switch terminal	4-1
9	VSS	I	0(V)	Logic ground	
10	VSSA	I	0(V)	Analogue ground	

【Remark 4-1】"H"=EXTCOMIN singal enabled, "L"=Serial input flag enabled.
When "H", connect EXTMODE to VDD and when "L" to VSS.

【Remark 4-2】ON/OFF for LCD display only. Memory data is maintained.
When "H", displays with memory data, and when "L", displays all white with memory data maintained.





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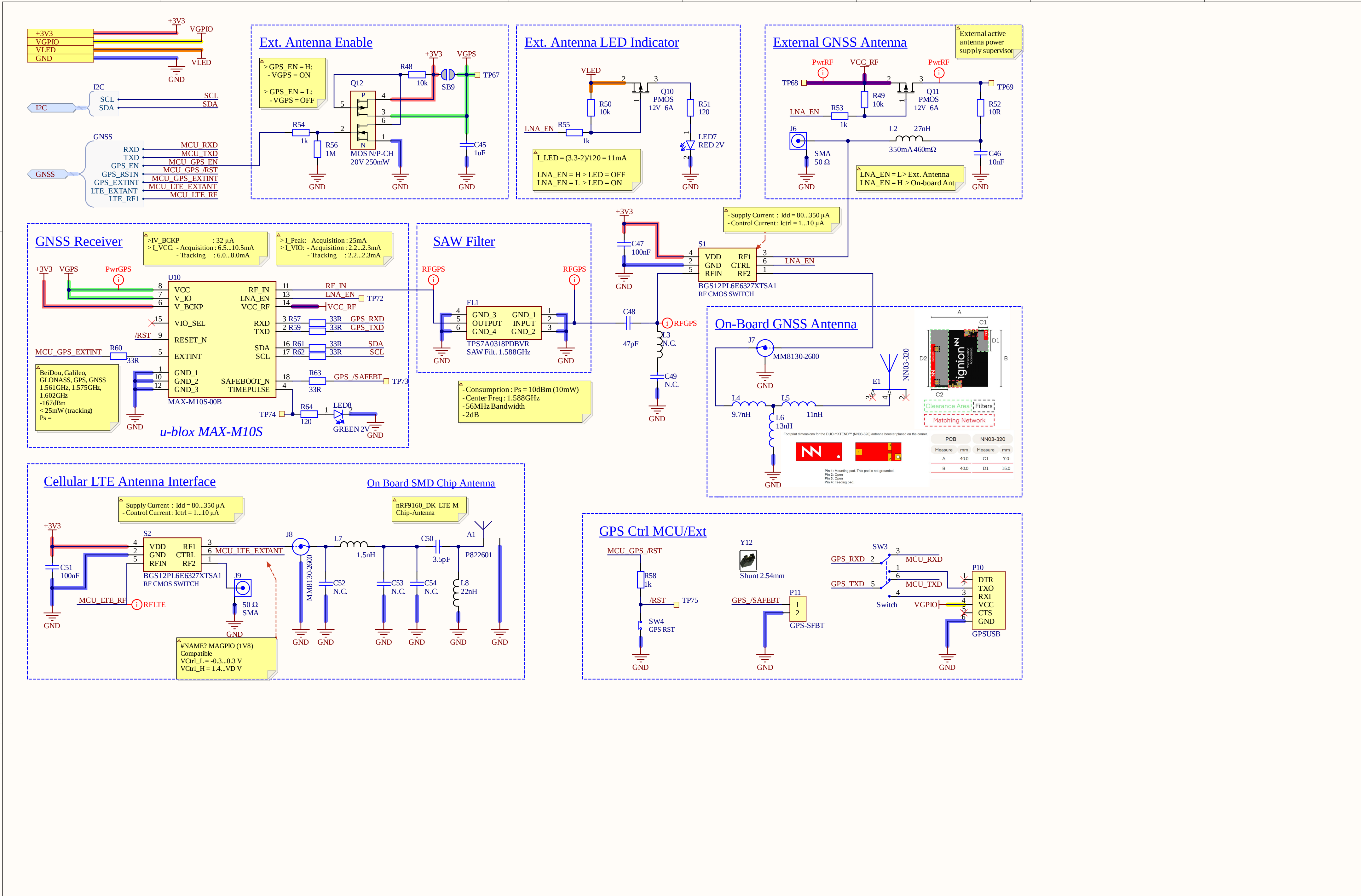
MSE HES-SO
HEVS
*
Tristan Traiber
*



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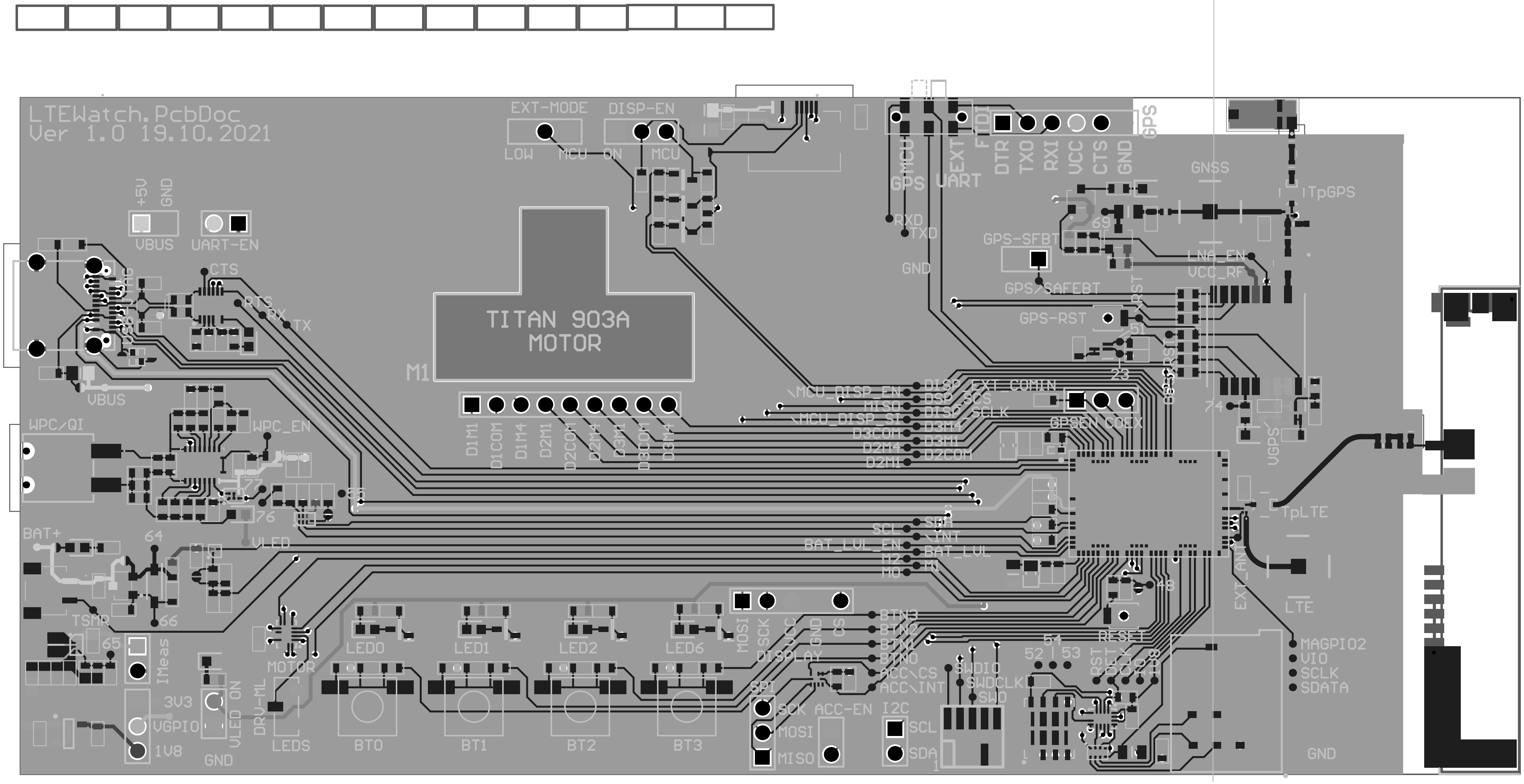


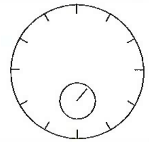
LTEWatch.PcbDoc
Ver 1.0 19.10.2021
EXT-MODE
DISP-EN
LOW
MCU
ON
MCU
TITAN 903A
MOTOR
M1
GPS
UART
FTDI
DTR
TXO
RXI
VCC
CTS
GND
GNSS
GPS-SFBT
GPS-SAFEBT
GPS-RST
LNA_EN
VCC_RF
VBUS
UART-EN
WPC/QI
WPC_EN
BAT+
TSMP
IMeas
3V3
VGPIO
1V8
GND
VLED ON
DRV-ML
LEDS
MOTOR
LED0
LED1
LED2
LED6
BT0
BT1
BT2
BT3
MOSI
SCK
VCC
GND
CS
DISPLAY
SPI
SCK
MOSI
MISO
ACC-EN
I2C
SCL
SDA
SWDIO
SWDCLK
SWO
RESET
MAGPIO2
VIO
SCLK
SDATA
TpGPS
TpLTE
LTE
EXT_ANT
VGPS
GPSEN
COEX
D1M1
D1COM
D1M4
D2M1
D2COM
D2M4
D3M1
D3COM
D3M4
BAT_LVL_EN
BAT_LVL

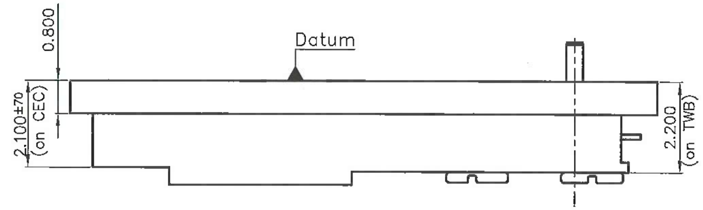
Line #	ID/assembly	Name	Tolerance	Voltage	TempCoef	Description	Designator	Footprint	Quantity	Manufacturer 1	Manufacturer Part Number 1	Manufacturer Lifecycle 1	Supplier 1	Supplier Part Number 1	Supplier Unit Price 1	Supplier Subtotal 1
		PBC001				ANTENNA PRESTTA OCTABAND LTE	A1	PBC001	1				Digi-Key	889-1057-1-ND		
		MC3635				Accelerometers X, Y, Z Axis ±2g, 4g, 8g, 12g, 16g 10-LGA (1.6x1.6)	AC1	MC3635	1				Mouser	498-MC3635		
		SKHUALE010				Tactile Switch, SPNO, SMD, 160gf, 6.2x6.3x2.5mm	BT0, BT1, BT2, BT3	Switch-PB-SMD-BT0, Switch-PB-SMD-BT1, Switch-PB-SMD-BT2, Switch-PB-SMD-BT3	4				Mouser	688-SKHUALE010		
		100nF				0.1 µF ±10% 25V Condensateurs céramique X7R 0603 (1608 métrique)	C1, C5, C7, C8, C12, C14, C16, C19, C25, C26, C27, C36, C39, C42, C44, C51, C57	C0603	17				Digi-Key	1276-1006-1-ND		
		47pF				47 pF ±5% 25V Ceramic Capacitor C0G, NP0 0603 (1608 Metric)	C2, C3	C0603	2				Digi-Key	399-C0603C470J3GACTRCT-ND		
		18pF				18 pF ±5% 25V Ceramic Capacitor C0G, NP0 0603 (1608 Metric)	C4, C13	C0603	2				Digi-Key	478-10804-1-ND		
		10uF				10 µF ±10% 10V Ceramic Capacitor X5R 0805 (2012 Metric)	C6, C15	CAPC2012X11L	2				Digi-Key	490-9961-1-ND		
		10nF				10000 pF ±5% 25V Condensateurs céramique C0G, NP0 0603 (1608 métrique)	C9, C17, C29, C38, C46, C55, C67	C0603	7				Digi-Key	445-2664-1-ND		
		4.7uF				4.7 µF ±10% 25V Condensateurs céramique X5R 0603 (1608 métrique)	C10, C11, C24, C60	C0603	4				Digi-Key	490-7199-1-ND		
		1uF				1 µF ±10% 25V Ceramic Capacitor X7R 0603 (1608 Metric)	C18, C21, C22, C28, C37, C35, C41, C42, C45	C0603	9				Mouser	187-CL10B105KA8NNNC		
		N.C.				N.C.	C20	C0603	1							
		10uF				10 µF ±10% 25V Ceramic Capacitor X5R 0805 (2012 Metric)	C23, C31, C32, C33, C34, C56, C59	C0603	7				Mouser	81-GRM188R61E106KA3J		
		10pF				10 pF ±5% 50V Ceramic Capacitor C0G, NP0 0603 (1608 Metric)	C30	C0603	1				Digi-Key	478-1163-1-ND		
		560pF				560 pF ±5% 25V Ceramic Capacitor C0G, NP0 0603 (1608 Metric)	C43	C0603	1				Digi-Key	311-3957-1-ND		
		100nF				0.1 µF ±10% 25V Ceramic Capacitor X7R 0402 (1005 Metric)	C47	C0603	1				Digi-Key	1276-6720-1-ND		
		47pF				47 pF ±5% 25V Ceramic Capacitor C0G, NP0 0402 (1005 Metric)	C48	CAPC1005X55N	1				Digi-Key	1292-1324-1-ND		
		N.C.				N.C.	C49, C52, C53, C54	CAPC1005X55N	4							
		3.5pF				3.5 pF ±0.1pF 50V Condensateurs céramique C0G, NP0 0402 (1005 métrique)	C50	CAPC1005X55N	1				Mouser	81-GJM1555C1H3R5BB1D		
		470nF				0.47 µF ±10% 25V Ceramic Capacitor X7R 0603 (1608 Metric)	C55, C69	C0603	2				Digi-Key	490-3291-1-ND		
		22nF				0.022 µF ±10% 25V Ceramic Capacitor X7R 0603 (1608 Metric)	C58, C68	C0603	2				Digi-Key	399-C0603C223K3RACTRCT-ND		
		39nF				0.039 µF ±10% 50V Ceramic Capacitor X7R 0603 (1608 Metric)	C60	C0603	1				Digi-Key	1292-1436-1-ND		
		47nF				0.047 µF ±10% 25V Ceramic Capacitor X7R 0603 (1608 Metric)	C61	C0603	1				Digi-Key	478-1235-6-ND		
		68nF				0.068 µF ±10% 25V Ceramic Capacitor X7R 0603 (1608 Metric)	C62	C0603	1				Digi-Key	1292-1462-1-ND		
		2.2nF				2200 pF ±5% 25V Ceramic Capacitor X7R 0603 (1608 Metric)	C63	C0603	1				Digi-Key	478-10683-1-ND		
		100pF				100 pF ±5% 25V Ceramic Capacitor C0G, NP0 0603 (1608 Metric)	C64	C0603	1				Digi-Key	478-06030A101JAT2ACT-ND		
		TVS 5.5V/WM				Clamp Ipp Tvs Diode Surface Mount SOT-143B	D1	PRTR5V0U2X	1				Digi-Key	1727-3884-1-ND		
		DM1402				EMI Network Filter Arrays SIM CARD EMI FILTER WITH ESD PROTECTION	D2	DM1402	1				Digi-Key	DM1402-DECP/DSTR-ND		
		TVS DIODE				9.2V Clamp 5A (8/20µs) Ipp Tvs Diode Surface Mount SOD-882	D3	SP1007010TG	1				Digi-Key	F6187CT-ND		
		NN03-320				Dual port antenna booster for GNSS, Bluetooth, 5G and UWB (1561 - 1606MHz, 2400 - 2500MHz, 3400 - 3800MHz, 3100 - 4800MHz and 6000 - 10600 MHz)	E1	ICVR_NN03-320	1				Digi-Key	2119-NN03-320CT-ND		
		120R/0.7A				Ferrite Bead, 120 Ohm @ 100MHz, 700mA, 130 mOhm Max	FB1, FB3, FB4	INDC1005X50L	3				Digi-Key	490-5439-1-ND		
		FERRITE BEAD				600 Ohms @ 100 MHz 1 Power, Signal Line Ferrite Bead 0805 (2012 Metric) 500mA 300mOhm	FB2, FB5, FB6	BEADC2012X110N	3				Digi-Key	240-2399-1-ND		
		TPS7A0318PDBVR				1.588GHz Frequency GPS RF SAW Filter (Surface Acoustic Wave) 2dB 56MHz Bandwidth 6-SMD, No Lead	FL1	B39162B3913U410	1				Digi-Key	B39162B3913U410CT-ND		
		LiPo 503535 580mAh				503535 3.8v 580mAh round lipo battery cells (Order : shorturl.at/tEFMZ)	G1	Battery_Lipo_503535	1					https://batteryzone.de/products/503535-580mah-hochspannung-3-8v-runde-polymer-smart-watch-moxibustion-instrument-auto-smart-box-batterie?_pos=1&_sid=59cfd2d74&_ss=r		
		Sharp MIP LCD				503535 3.8v 580mAh round lipo battery cells (Order : shorturl.at/tEFMZ)	G2	SHARP_MIP_LCD	1					https://keycapsss.com/keyboard-parts/parts/219/nice-view-1.08-e-paper-display		
		CONN_USB-C_24p				USB-C (USB TYPE-C) USB 3.2 Gen 2 (USB 3.1 Gen 2, Superspeed + (USB 3.1)) Receptacle Connector 24 Position Surface Mount, Right Angle; Through Hole	J1	12401598E42A - JTAG	1				Mouser	523-12401598E4#2A		
		FTSH-105-01-F-DV-K				Connector Header Surface Mount 10 position 0.050" (1.27mm)	J2	HDR_2x5-SMD-1.27mm-K	1				Digi-Key	SAM8796-ND		
		SF72S006VBAR2500				n 8 (6 + 2) Position Card Connector NANO SIM Surface Mount, Right Angle Gold	J3	SF72S006VBAR2500	1				Digi-Key	670-2967-6-ND		
		M40-4010346R				Connector Header Surface Mount, Right Angle 3 position 0.039" (1.00mm)	J4	M404010346R	1				Digi-Key	M40-4010346R-ND		
		CONN LCD SMD				10 Position FFC, FPC Connector Contacts, Top 0.020" (0.50mm) Surface Mount, Right Angle	J5	FH12A10S05SH55	1				Digi-Key	HFK110CT-ND		
		SMA				SMA Connector Jack, Female Socket 50Ohm Surface Mount Solder	J6, J9	73251-1350 - GNSS, 73251-1350 - LTE	2				Digi-Key	WM9357-ND		
		MM8130-2600				Coaxial Connector with Switch	J7, J8	COAXIAL-SWF - GNSS, COAXIAL-SWF - LTE	2				Digi-Key	490-4981-1-ND		
		WPC/QI COIL				2 Position Wire to Board Terminal Block Horizontal with Board 0.138" (3.50mm) Surface Mount	J10	23839422	1				Digi-Key	17-2383942-2CT-ND		
		2.9A 48mΩ				1 µH Shielded Drum Core, Wirewound Inductor 2.9 A 48mOhm Max 0806 (2016 Metric)	L1	1286ASH1R0MP2	1				Digi-Key	490-16593-1-ND		
		350mA 460mΩ				27 nH Unshielded Multilayer Inductor 350 mA 460mOhm Max 0402 (1005 Metric)	L2	LQG15WH0N7B02D	1				Digi-Key	490-2628-1-ND		
		N.C.				N.C.	L3	INDC1005X37N	1							
		9.7nH				9.7 nH Non blindé Bobiné Inducteur 1.4 A 81mOhms maxi 0402 (1005 métrique)	L4	LQW15AN10NG80D	1				Mouser	81-LQW15AN9N7G80D		
		11nH				11 nH Unshielded Drum Core, Wirewound Inductor 1.4 A 65mOhm 0402 (1005 Metric)	L5	LQW15AN10NG80D	1				Digi-Key	2035-1078-1-ND		
		13nH				13 nH Unshielded Drum Core, Wirewound Inductor 870 mA 140mOhm 0402 (1005 Metric)	L6	LQW15AN10NG80D	1				Digi-Key	2035-1525-1-ND		
		1.5nH				1.5 nH Non blindé Couche mince Inducteur 700 mA 250mOhms maxi 0402 (1005 métrique)	L7	INDC1005X37N	1				Digi-Key	535-10356-1-ND		
		22nH				22 nH Non blindé Bobiné Inducteur 780 mA 202mOhms maxi 0402 (1005 métrique)	L8	LQW15AN10NG80D	1				Digi-Key	490-7628-1-ND		
		BLUE 3.2V				Blue 470nm LED Indication - Discrete 3.2V 0603 (1608 Metric)	LED0, LED1, LED2	LEDC1608X80N	3				Digi-Key	732-4966-1-ND		
		GREEN 2V				Green 570nm LED Indication - Discrete 2V 0603 (1608 Metric)	LED3, LED5, LED6, LED8, LED9	LEDC1608X80N	5				Digi-Key	732-4980-1-ND		
		RED 2V				Red 625nm LED Indication - Discrete 2V 0603 (1608 Metric)	LED4, LED7	LEDC1608X80N	2				Digi-Key	732-4978-1-ND		
		Motor 903A				Titan 903A : 3 Hands Bidirectional, independent motor	M1	MOTOR	1							
		VUART				Header, 2-Pin	P1	HDR1X2 - UART	1				Mouser	649-1012937890201BLF		
		VACC				Header, 2-Pin	P2	HDR1X2 - ACCEL	1				Mouser	649-1012937890201BLF		
		COEX				Header, 3-Pin	P3	HDR1X3 - COEX	1				Digi-key	952-2263-ND		
		SPI				Header, 3-Pin	P4	HDR1X3 - SPI	1				Digi-key	952-2263-ND		
		IMEAS				Header, 2-Pin	P5	HDR1X2 - IMEAS	1				Mouser	649-1012937890201BLF		
		VLED				Header, 2-Pin	P6	HDR1X2 - VLED	1				Mouser	649-1012937890201BLF		
		VGPIO				Header, 3-Pin	P7	HDR1X3 - VGPIO	1				Digi-key	952-2263-ND		
		DISP-EN				Header, 3-Pin	P8	HDR1X3 - DISP_EN	1				Digi-key	952-2263-ND		
		EXT-MODE				Header, 3-Pin	P9	HDR1X3 - EXT_MODE	1				Digi-key	952-2263-ND		
		GPSUSB				Header, 6-Pin	P10	HDR1X6 - GPS	1				Digi-Key	732-5319-ND		
		GPS-SFBT				Header, 2-Pin	P11	HDR1X2 - GPSSAFEBOOT	1				Mouser	649-1012937890201BLF		
		VBUS				Header, 2-Pin	P12	HDR1X2 - VIN	1				Mouser	649-1012937890201BLF		
		I2C				Header, 2-Pin	P13	HDR1X2 - I2C	1				Mouser	649-1012937890201BLF		
		MOS N/P-CH				Mosfet Array N and P-Channel 20V 485mA, 370mA 250mW Surface Mount SC-89 (SOT-563F)	Q1, Q12	SOT50P160X60-6N	2				Digi-Key	SI1016X-T1-GE3CT-ND		
		PMOS				P-Channel 12 V 6A (Ta) 1W (Ta) Surface Mount SOT-23F	Q2, Q10, Q11	SSM3J332RLFT	3				Digi-Key	SSM3J338RLFCT-ND		
		NMOS				N-Channel 30 V 180mA (Ta) 260mW (Ta), 1.1W (Tc) Surface Mount SOT-323	Q3, Q4, Q5, Q6, Q7, Q8, Q9, Q14	SOT65P210X110-3N	8				Digi-Key	1727-1288-1-ND		
		20V 1.6A 0.7W				Mosfet Array 2 P-Channel (Dual) Common Source 20V 1.6A 750mW Surface Mount 6-DSBGA (1x1.5)	Q13	BGA6C50P2X3_95X145X62	1				Digi-Key	296-38339-1-ND		
		10k				10 kOhms ±1% 0.1W, 1/10W Chip Resistor 0603 (1608 Metric) Moisture Resistant Thick Film	R1, R2, R7, R9, R24, R26, R27, R28, R29, R30, R31, R32, R33, R48, R49, R50, R66	RES0603	17				Digi-Key	311-10.0KHRCT-ND		
		330				330 Ohms ±1% 0.1W, 1/10W Chip Resistor 0603 (1608 Metric) Automotive AEC-Q200 Thick Film	R3	RES0603	1				Digi-Key	CR0603-FX-3300ELFCT-ND		
		N.C.				N.C.	R4	RES0603	1							
		27R				27 Ohms ±1% 0.1W, 1/10W Chip Resistor 0603 (1608 Metric) Automotive AEC-Q200 Thick Film	R5, R6	RES0603	2				Digi-Key	P27.0HCT-ND		
		100k				RES SMD 100K OHM 1% 1/8W 0603	R8, R15, R22, R35, R44, R45, R68	RES0603	7				Digi-Key	311-100KCRCT-ND		
		0R				0 Ohms Jumper 0.1W, 1/10W Chip Resistor 0603 (1608 Metric) Moisture Resistant Thick Film	R10, R14	RESC2012X60N	2				Digi-Key	311-0.0GRCT-ND		
		5k1				5.1 kOhms ±1% 0.1W, 1/10W Chip Resistor 0603 (1608 Metric) Moisture Resistant Thick Film	R11, R12	RES0603	2				Digi-Key	311-5.10KHRDKR-ND		
		1k				1 kOhms ±1% 0.1W, 1/10W Chip Resistor 0603 (1608 Metric) Moisture Resistant Thick Film	R13, R53, R54, R55, R58	RES0603	5				Digi-Key	311-1.00KHRCT-ND		
		1M				1 MOhms ±1% 0.1W, 1/10W Chip Resistor 0603 (1608 Metric) Automotive AEC-Q200 Thick Film	R16, R17, R37, R39, R40, R42, R43, R46, R47, R56, R69	RES0603	11				Digi-Key	P1.00MHCT-ND		
		4.02M				4.02 MOhms ±1% 0,1W, 1/10W Pavé résistif 0603 (1608 métrique) Résistant à l'humidité Couche épaisse	R18	RES0603	1				Digi-Key	YAG5698CT-ND		
		8.66M				8.66 MOhms ±1% 0,1W, 1/10W Pavé résistif 0603 (1608 métrique) AutomobileAEC-Q200 Couche épaisse	R19	RES0603	1				Digi-Key	541-8.66MHCT-ND		
		NTC10k				NTC Thermistor 10k 0603 (1608 Metric)	R20	C0603	1				Digi-Key	P10547CT-ND		
		560k				560 kOhms ±1% 0.1W, 1/10W Chip Resistor 0603 (1608 Metric) Automotive AEC-Q200, Moisture Resistant Thick Film	R21	RES0603	1				Digi-Key	311-560KLDCT-ND		
		120				1 MOhms ±1% 0.1W, 1/10W Chip Resistor 0603 (1608 Metric) Automotive AEC-Q200 Thick Film	R23, R25, R51, R64, R72	RES0603	5				Digi-Key	A129677CT-ND		
		15R				15 Ohms ±1% 0.1W, 1/10W Chip Resistor 0603 (1608 Metric) Moisture Resistant Thick Film	R34, R36, R38	RES0603	3				Digi-Key	311-15.0HRTR-ND		
		220				220 Ohms ±1% 0.1W, 1/10W Chip Resistor 0603 (1608 Metric) Moisture Resistant Thick Film	R41	RES0603	1				Digi-Key	311-220HRTR-ND		
		10R				10 Ohms ±5% 0.25W, 1/4W Chip Resistor 0805 (2012 Metric) Automotive AEC-Q200 Thick Film	R52	RESC2012X60N	1				Digi-Key	2019-RK73B2ATTD100JCT-ND		
		33R				33 Ohms ±1% 0.1W, 1/10W Chip Resistor 0603 (1608 Metric) Thin Film	R57, R59, R60, R61, R62, R63	RES0603	6				Digi-Key	13-RT0603FRE0733RLCT-ND		
		NM				8.66 MOhms ±1% 0,1W, 1/10W Pavé résistif 0603 (1608 métrique) AutomobileAEC-Q200 Couche épaisse	R65, R73, R74	RES0603	3				Digi-Key	541-8.66MHCT-ND		
		20k				20 kOhms ±1% 0.1W, 1/10W Chip Resistor 0603 (1608 Metric) Moisture Resistant Thick Film	R67	RES0603	1				Digi-Key	311-20.0KHRCT-ND		
		66R				66.5 Ohms ±1% 0.1W, 1/10W Chip Resistor 0603 (1608 Metric) Moisture Resistant Thick Film	R70	RES0603	1				Digi-Key	311-66.5HRCT-ND		
		196				196 Ohms ±1% 0.1W, 1/10W Chip Resistor 0603 (1608 Metric) Moisture Resistant Thick Film	R71	RES0603	1				Digi-Key	311-196HRDKR-ND		
		BGS12PL6E6327XTSA1				RF Switch IC WLAN SPDT 50Ohm PG-TSNP-6-10	S1, S2	BGS12WN6E6327XTSA1	2				Digi-Key	BGS12PL6E6327XTSA1CT-ND		
		SKHUALE010				Tactile Switch, SPNO, SMD, 160gf, 6.2x6.3x2.5mm	SW1	Push Button C2.5X3.0 OMRON B3U-1000P(M)-B - MCU RST	1				Mouser	688-SKHUALE010		
		SMD slide (ON-ON)				SMD slide Switch (ON-ON)	SW2	CJS-120xA - M/L	1				Mouser	229-CJS-1200TA		
		Switch				SMD slide Switch (ON-ON)	SW3	JS102011JAQN - GPS	1				Digi-Key	CKN10722CT-ND		
		SKHUALE010				Tactile Switch, SPNO, SMD, 160gf, 6.2x6.3x2.5mm	SW4	Push Button C2.5X3.0 OMRON B3U-1000P(M)-B - GPS RST	1				Mouser	688-SKHUALE010		
		IC_USB_UART				USB Bridge, USB to UART USB 2.0 UART Interface 12-DFN (3x3)	U1	SON45P300X300X75-13N-D	1				Digi-Key	768-1178-1-ND		
		nRF9160-SICAB1A				Low power System-in-Package with integrated LTE-M/NB-IoT modem and GPS	U2	LGA50P1600X1050X104-161N	1				Digi-Key	1490-NRF9160-SICA-B1A-R7CT-ND		
		NX3DV2567				Low-ohmic four-pole double-throw analog switch	U3, U9	XQFN40P180X260X50-16N	2				Mouser	771-NX3DV2567GU115		
		MFFx_M2M_UICC				M2M UICC SIM Card	U4	SON127P600X90_HS-8N	1				N.A.	N.A.		
		TPS7A0318PDBVR				Linear Voltage Regulator IC Positive Fixed 1 Output 200mA SOT-23-5	U5	SOT95P280X145-5N	1				Digi-Key	296-TPS7A0318PDBVRCT-ND		
		BQ25180				Charger IC Lithium Ion/Polymer, Lithium Iron Phosphate 8-DSBGA	U6	BGA8C40P2X4_100X155X50	1				Mouser	595-BQ25180YBGR		
		TPS22916CNYFPT				Power Switch/Driver 1:1 P-Channel 2A 4-DSBGA	U7	BGA4C40P2X2_78X78X50	1				Mouser	595-TPS22916CNYFPT		
		TPS63036YFGT				Buck-Boost Switching Regulator IC Positive Adjustable 1.2V 1 Output 1A (Switch) 8-UFBGA, DSBGA	U8	BGA8C40P2X4_108X181X62	1				Mouser	595-TPS63036YFGT		
		MAX-M10S-00B				MAX-M10 RF Receiver BeiDou, Galileo, GLONASS, GPS, GNSS 1.561GHz, 1.575GHz, 1.602GHz -167dBm 921.6kbps	U10	MAXM10S00B	1				Mouser	377-MAX-M10S-00B		
		BQ51013B				Wireless Power Receiver PMIC 20-VQFN (3.5x4.5)	U11	BQ51050BRHLR	1				Mouser	595-BQ51013BRHLR		
		Shunt 2.54mm				Shunt Jumper 2.54mm Black	Y1, Y2, Y3, Y4, Y5, Y6, Y7, Y8, Y9, Y10, Y11, Y12, Y13, Y14, Y15	Shunt_2.54mm_Horizontal	15				Digi-Key	S9001-ND		
		ZENER				Zener Diode 9.1 V 500 mW ±6% Surface Mount SOD-123	Z1	SOD3716X145N	1				Digi-Key	BZT52C9V1-FDICT-ND		

10.2 Clock Single Hand Motor - T901

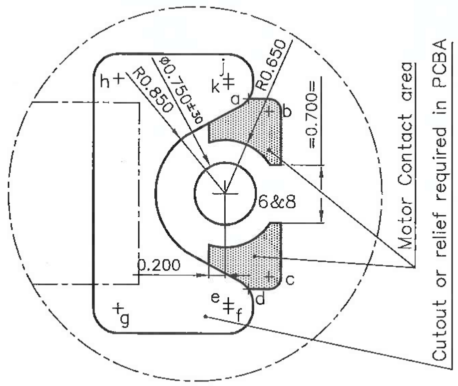
WATCH DIVISION

TECHNICAL DATA FOR TITAN (Bi-Directional) – T901A



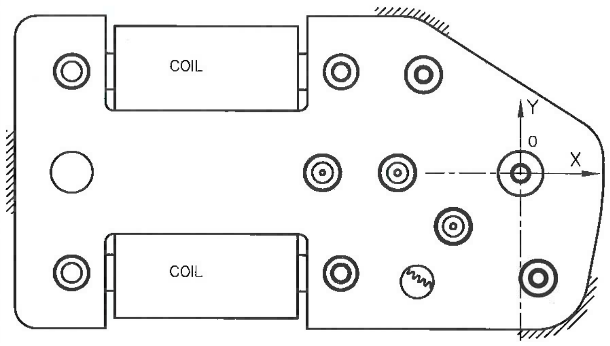


Detail at "G" (Scale 16:1)

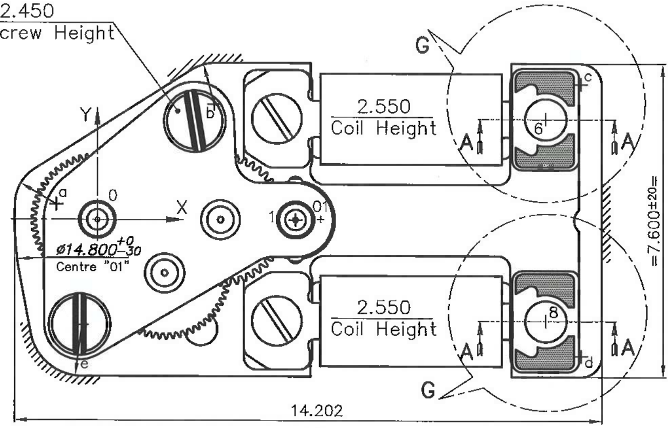


POS	X-AXIS	Y-AXIS	RADIUS
8	0.000	0.000	
a	0.285	1.150	
b	0.530	1.000	R0.150
c	0.530	-1.000	R0.150
d	0.285	-1.150	
e	0.040	-1.323	R0.300
f	0.040	-1.390	R0.300
g	-1.300	-1.390	R0.300
h	-1.300	1.390	R0.300
j	0.040	1.390	R0.300
k	0.040	1.323	R0.300

Functions	1 Hand
Angular rotation per pulse	2°
No of steps for 360° rotation	180
Direction	BI-DIRECTIONAL
Movement size	14.202 x 7.600 mm
Movt Thickness	2.550 (on COIL)
No. of jewels	06
Coil resistance	1.350 K ohms
Effective temperature range	0 to +55°C
Shock resistance	As per NIHS 91/10
Resistance to magnetic field	18.8 Oe



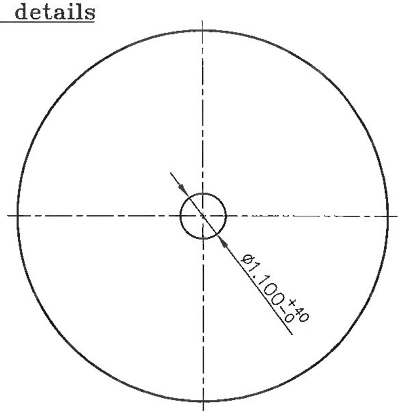
DIAL SIDE



BIRDGE SIDE

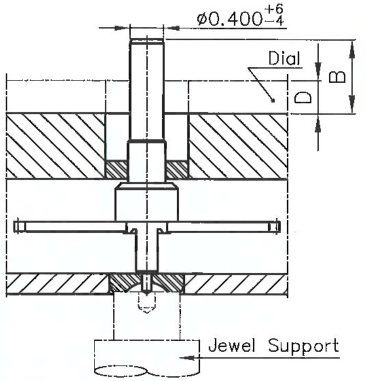
POS	X-AXIS	Y-AXIS	RADIUS
0	0.000	0.000	
01	5.395	0.014	
a	-0.995	0.374	R1.000
b	2.819	2.800	R1.000
c	11.697	3.300	R0.500
d	11.697	-3.300	R0.500
e	-0.377	-2.550	R1.250
6	10.847	2.450	
8	10.847	-2.450	

Dial details



Note: Hands shape to be followed according to the dial holes.

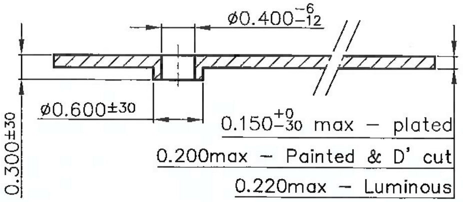
Hand fitting dimensions



Calibre	B	D max
LOW	0.760	0.300
STD	0.900	0.400
HIGH-1	1.320	0.800
HIGH-2	1.830	1.200
HIGH-3	2.330	1.600

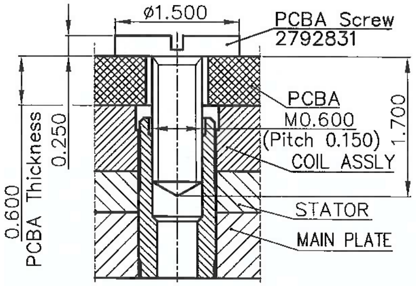
(Scale 16:1)

Hand Details



(Scale 16:1)

Section "A-A"



Note: PCBA Screw is not a part of Motor BOM

(Scale 16:1)

HAND	DESCRIPTION		HAND
	Imbalance mg.mm		60
	Inertia mg.mm²		–
	Weight mg (max).		350
	Length mm(max)	Brass	15

Notes :
1) All dimensions are in mm.
2) Tolerances in um.

Index	Alteration	Date	Sign
a	Electrical Parameters updated for 0.140mm Pivot modification	21.8.19	AF

	Prepared	Checked	Approved
Name			
Date	21/8/19	21/8/19	21/8/19

TITAN COMPANY LIMITED HOSUR 635 126

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Scale 10:1

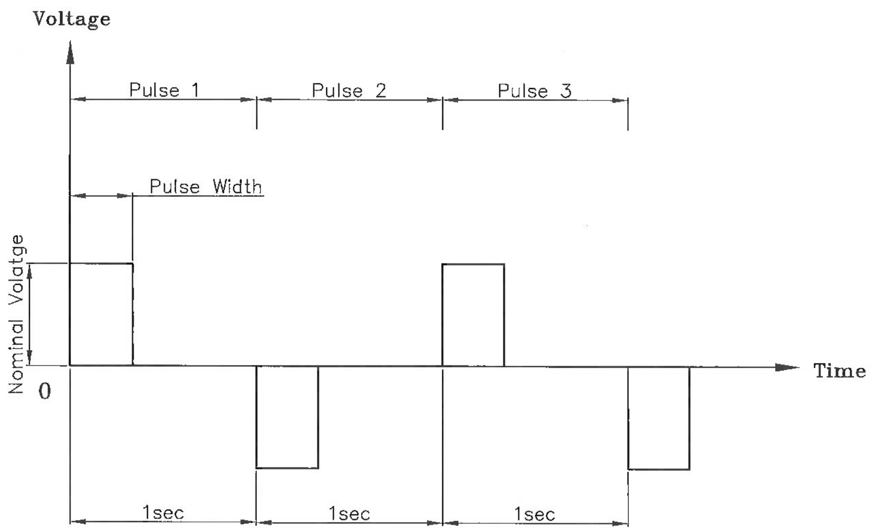
Sheet 1 of 2

K:\Drawings\INHOUSE GEAR BOX\Twin Coil\2D\General\T90X_Technical Data latest.dwg

WATCH DIVISION

TECHNICAL DATA FOR TITAN (Bi-Directional) – T901A

Wave forms

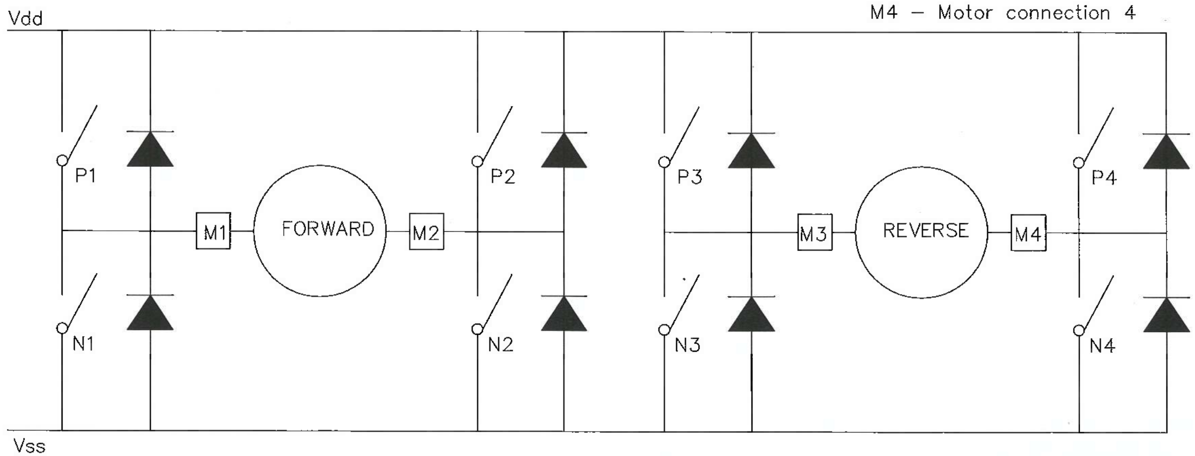


Motor driving parameters

SL	Description	Unit	Nominal Voltage (V) 2.10	Nominal Voltage (V) 3.00
01	Pulse Width	ms	4.5	3.0
02	Duty Cycle	%	100%	100%
03	Current consumption @ 64Hz	μA	335(Typ)~385(Max)	335(Typ)~385(Max)
04	Current Consumption @ 1Hz	μA	5.1(Typ)~5.3(Max)	4.9(Typ)~5.4(Max)
05	Driving torque (typ)	μNm	36 (Min)	36 (Min)
06	Voltage Range	V	1.6 ~ 2.5	1.8 ~ 4.0

M1 – Motor connection 1
M2 – Motor connection 2
M3 – Motor connection 3
M4 – Motor connection 4

Motor Driving Circuit



Notes :
1) All dimensions are in mm.
2) Tolerances in um.
3) Jewel support to be provided while hand fixing
4) Motor consumption is measured in WITSCHI AQ2

Index	Alteration	Date	Sign

	Prepared	Checked	Approved
Name			
Date	21/8/19	21/8/19	21/8/19

a

T-2946

Scale 10:1

Sheet 2 of 2

TITAN COMPANY LIMITED HOSUR 635 126

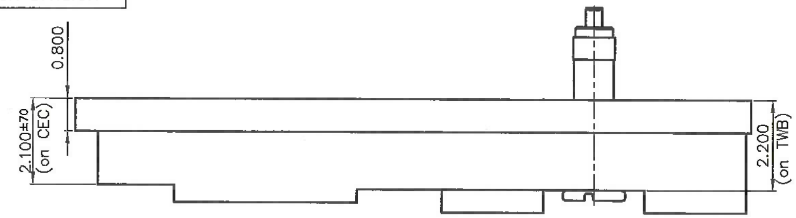
K:\Drawings\INHOUSE GEAR BOX\Twin Coil\2D\General\T90X_Technical Data latest.dwg

10.3 Clock Double Hands Motor - T902

TECHNICAL DATA FOR TITAN (Bi-Directional) – T902A

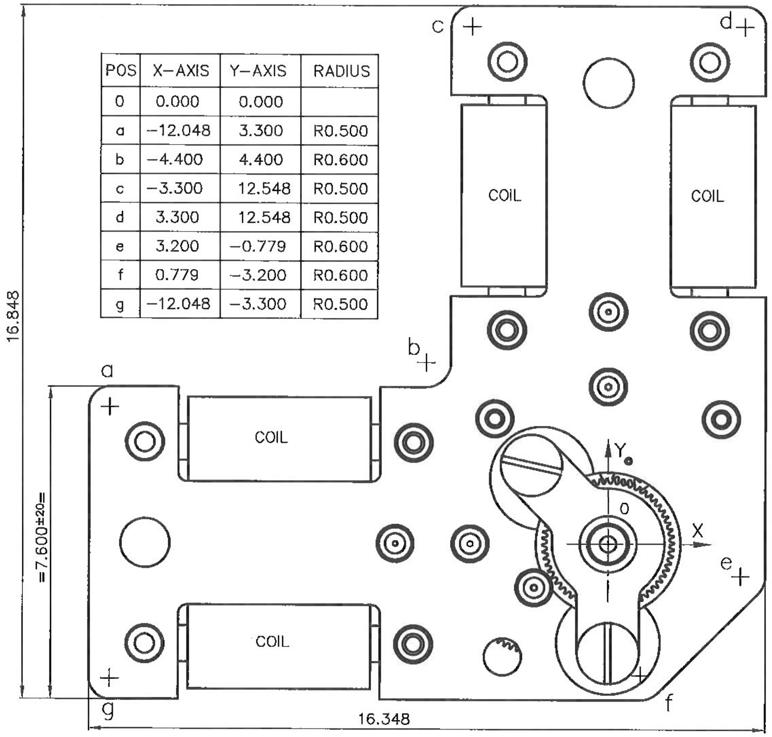
WATCH DIVISION

K:\Drawings\Motors\Twin Coil Motor\Twin Coil\2D\General\T90X_Technical Data latest.dwg

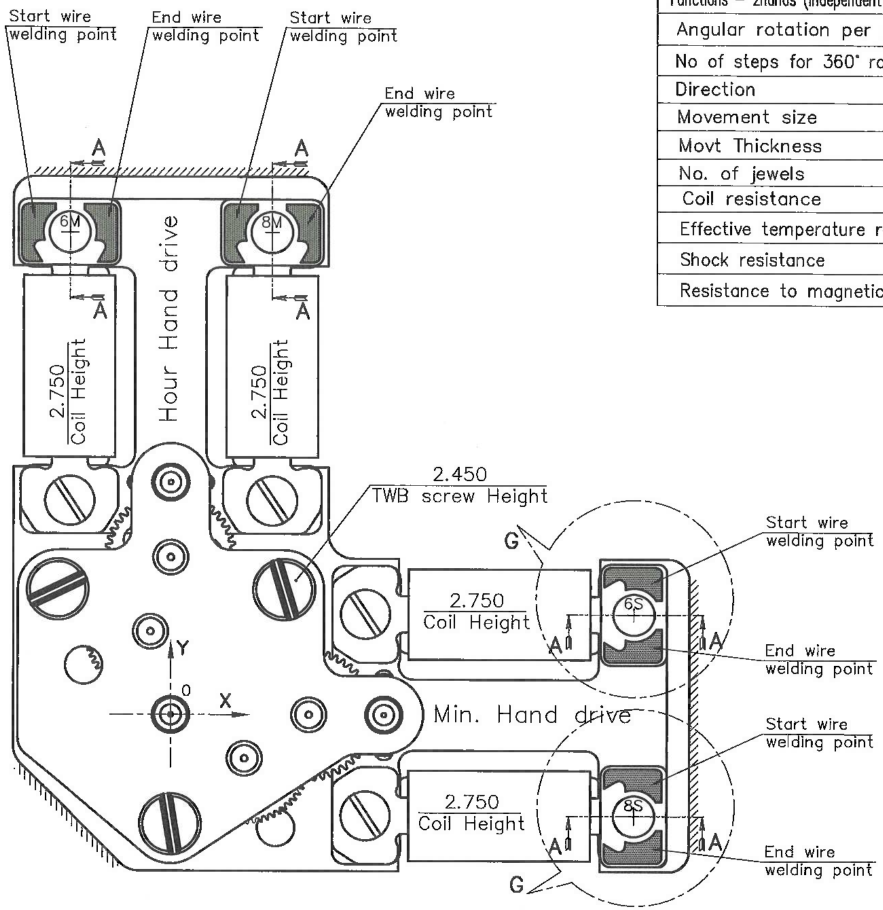


Functions – 2hands (Independent Control)	Hour Hand	Minute Hand
Angular rotation per pulse	2°	2°
No of steps for 360° rotation	180	180
Direction	BI–DIRECTIONAL	
Movement size	16.348 x 16.848 mm	
Movt Thickness	2.550 (on COIL)	
No. of jewels	08	
Coil resistance	1.350 K ohms	
Effective temperature range	–10 to +55°C	
Shock resistance	As per NIHS 91/10	
Resistance to magnetic field	18.8 Oe	

POS	X–AXIS	Y–AXIS	RADIUS
0	0.000	0.000	
a	–12.048	3.300	R0.500
b	–4.400	4.400	R0.600
c	–3.300	12.548	R0.500
d	3.300	12.548	R0.500
e	3.200	–0.779	R0.600
f	0.779	–3.200	R0.600
g	–12.048	–3.300	R0.500

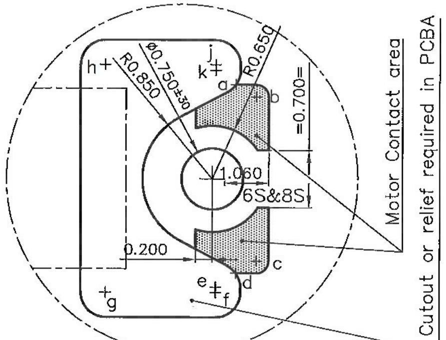


DIAL SIDE



POS	X–AXIS	Y–AXIS
0	0.000	0.000
6M	–2.450	11.698
8M	2.450	11.698
6S	11.198	2.450
8S	11.198	–2.450

BIRDGE SIDE



Detail at "G" (Scale 16:1)

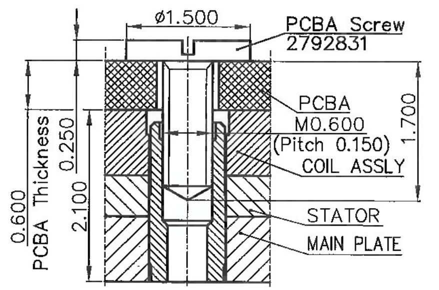
Pos. 6S, 8S

POS	X–AXIS	Y–AXIS	RADIUS
8S	0.000	0.000	
a	0.285	1.150	
b	0.530	1.000	R0.150
c	0.530	–1.000	R0.150
d	0.285	–1.150	
e	0.040	–1.323	R0.300

POS	X–AXIS	Y–AXIS	RADIUS
f	0.040	–1.390	R0.300
g	–1.300	–1.390	R0.300
h	–1.300	1.390	R0.300
j	0.040	1.390	R0.300
k	0.040	1.323	R0.300

Note: For Pos.6M, 8M – Rotate 90° anticlockwise direction

Section "A–A" (Scale 16:1)



Note: PCBA Screw is not a part of Motor BOM

Index	Alteration	Date	Sign
b	Coil height 2.750 was 2.550mm Hand fitting dimensions updated	28.10.21	RTMK
a	Electrical Parameters updated for 0.140mm Pivot modification	21.8.19	AF

	Prepared	Checked	Approved
Name			
Date	28/10/21		28/10/21

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Scale 10:1

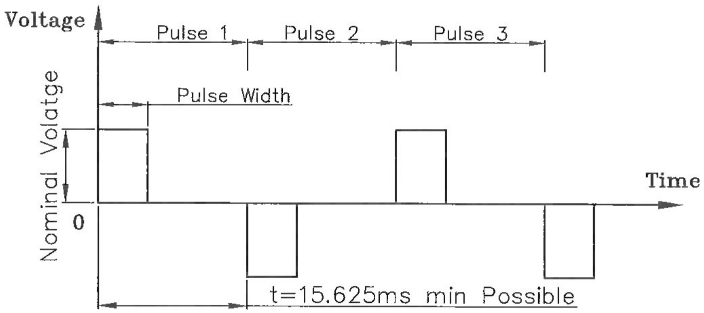
Sheet 1 of 2

TITAN COMPANY LIMITED HOSUR 635 126

WATCH DIVISION

TECHNICAL DATA FOR TITAN (Bi-Directional) – T902A

Wave forms

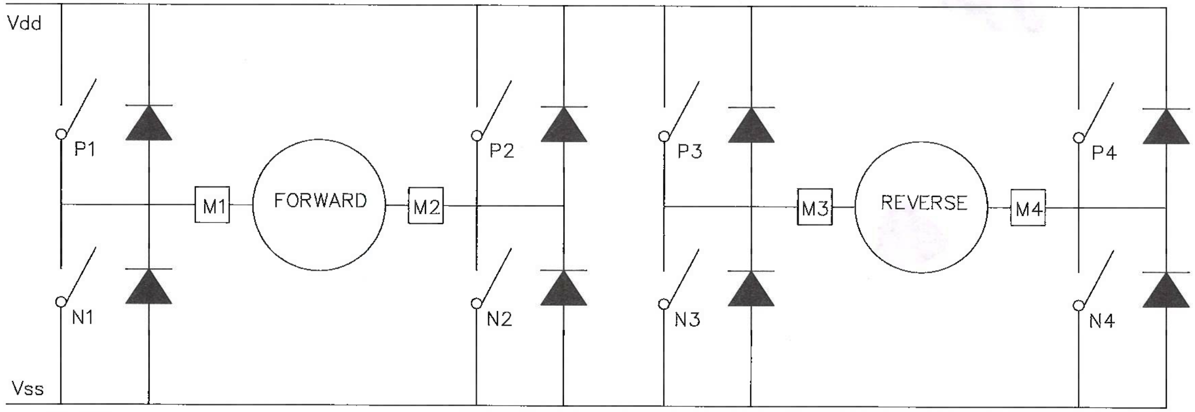


Note: *– Refer motor driving parameters table for the selections
– 't' parameter is defined based on the applications

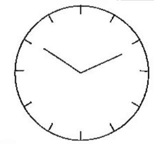
Motor driving parameters – Hour & Minute Hand

SL	Description	Unit	Nominal Voltage (V) 2.10	3.00
01	Pulse Width	ms	4.5	3.0
02	Duty Cycle	%	100%	100%
03	Current consumption @ 64Hz	μA	335(Typ)~385(Max)	335(Typ)~385(Max)
04	Current Consumption @ 1Hz	μA	5.1(Typ)~5.3(Max)	4.9(Typ)~5.4(Max)
05	Driving torque (typ)	μNm	36 (Min)	36 (Min)
06	Voltage Range	V	1.6 ~ 2.5	1.8 ~ 4.0

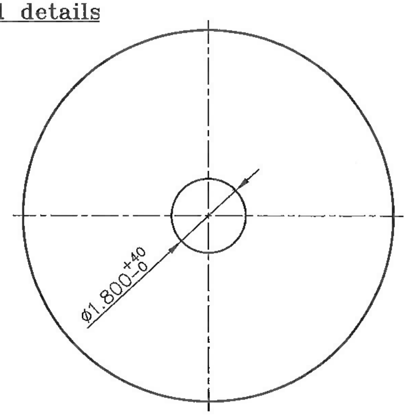
Motors Driving Circuit (For Hour & Minute motor)



M1 – Motor connection 1
M2 – Motor connection 2
M3 – Motor connection 3
M4 – Motor connection 4



Dial details



Note: Hands shape to be followed according to the dial holes.

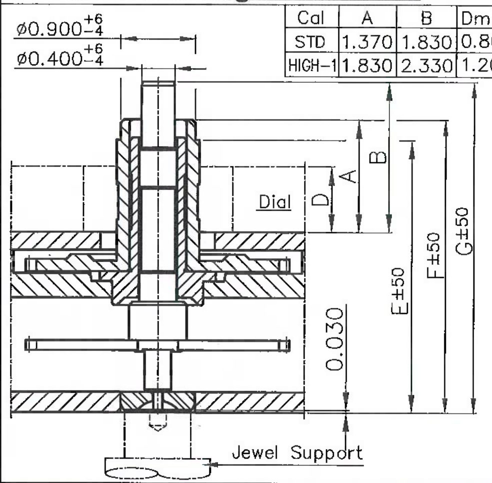
HAND	DESCRIPTION		HANDS
	Imbalance mg.mm		60
	Inertia mg.mm²		–
	Weight mg (max).		350
	Length mm(max)	Brass	15

Notes :

1) All dimensions are in mm.
2) Tolerances in um.
3) Jewel support to be provided while hand fixing
4) Motor consumption is measured in WITSCHI AQ2
5) Protective coating provided on both side of the coils

Hand fitting dimensions

Cal	A	B	Dmax	E	F	G
STD	1.370	1.830	0.800	3.270	3.570	4.030
HIGH-1	1.830	2.330	1.200	3.730	4.030	4.530

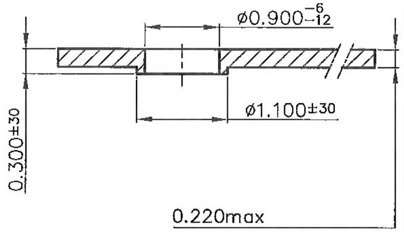


(Scale 16:1)

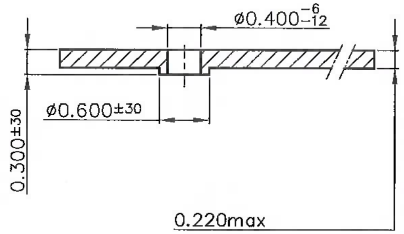
Hand Details

(Scale 16:1)

Hour hand



Minute Hand



Index	Alteration	Date	Sign

	Prepared	Checked	Approved
Name			
Date		20/10/21	23/10/21

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Sheet 2 of 2 Scale 10:1

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10.4 Ignion - NN03-320 Chip GNSS Antenna Simulation

ignion

Antenna Intelligence

YOUR ANTENNA DIGITAL TWIN

Antenna Intelligence Cloud™ report

COMPANY NAME	DATE	SERVICE REPORT NUMBER	IGNION SUPPORT
HEVS Sion	24/10/2022	1666600867927	marc.munoz@ignion.io

Congratulations on making a step forward in your design

Most of the engineers like you, that design with a Virtual Antenna® component, made their decision based on this trifecta:

1. Choosing an antenna versatile enough to cover any protocol or band.
2. Straightforward antenna design guidance and accessible support.
3. Predictable performance from initial concept all the way to your end-product.

Your requirements

APPLICATION
Wearables & Smartwatches

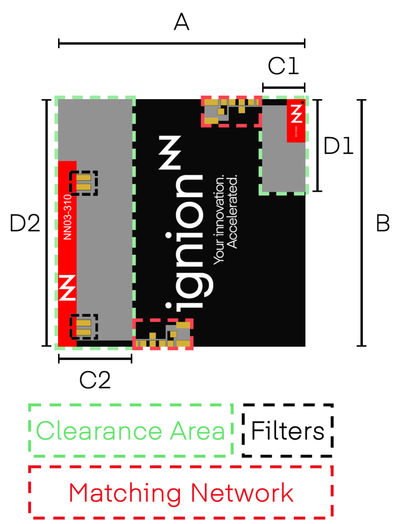
PCB DIMENSIONS
40.0 x 40.0 mm

SELECTED ANTENNA
NN03-320
NN03-310

COMMUNICATION STANDARDS & FREQUENCY RANGES
GNSS: 1559.0-1610.0 MHz
LTE-M: 791.0-960.0 MHz

Best antenna placement on your PCB

Sketch of the proposed antenna placement and the recommended clearance area for the Virtual Antenna® component.



PCB		NN03-320		NN03-310	
Measure	mm	Measure	mm	Measure	mm
A	40.0	C1	7.0	C2	12.0
B	40.0	D1	15.0	D2	40.0

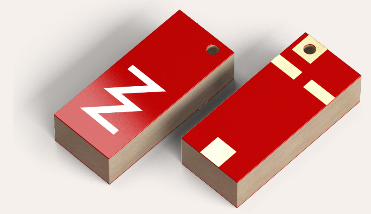
The sketch above is an approximate representation of the PCB design. The accurate model can be found in the Desing_Files_NNS1.0.zip attached in the same email where the report was received.

Your antenna design ready to use

ANTENNA 1

DUO mXTEND™ (NN03-320):

- **Application:** Wearables & Smartwatches.
- **Frequency Range(s):** 1559.0-1610.0 MHz for GNSS.
- **Tuning your antenna:** the optimized matching network is shown below.
- **Antenna footprint:** please refer to the datasheet link.



DUO mXTEND™

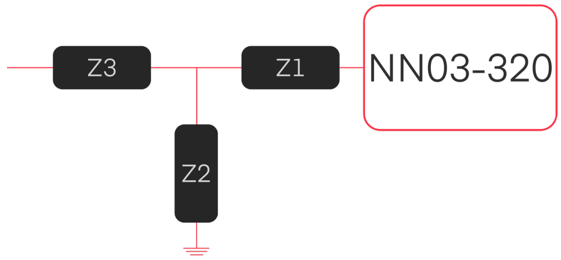
Dimensions 7.0 x 3.0 x 2.0 mm

Datasheet https://ignion.io/files/DS_NN03-320.pdf

Antenna Product Page

Matching Network Antenna 1

GNSS Matching Network topology



Comm. Standard	Component	Value	Part Number	Manufacturer
GNSS	Z1	11nH	LQW18AN11NG80	Murata
	Z2	13nH	LQW18AN13NG80	Murata
	Z3	9.7nH	LQW15AN9N7G80	Murata

The electronic component values correspond with the Matching Network when implemented on a bare PCB. These values may need further tuning and optimization when additional elements such as batteries, plastic covers, connectors, displays, etc. are added to your final device.

If you need further assistance, please contact our antenna specialists.

GET HELP

Your antenna design
ready to use

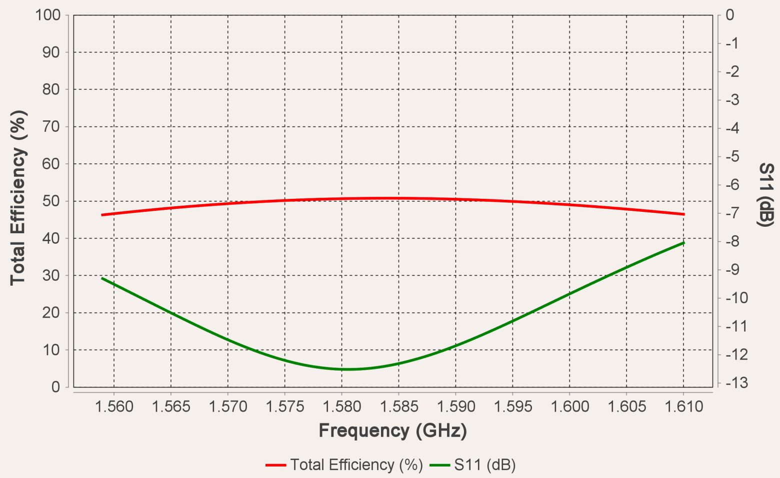
ANTENNA 1

Your Design overall Performance

Expected device performance with antenna 1

Your prototype using the NN03-320 antenna is expected to achieve the reflection coefficient (in dB) and total efficiency (in %) as shown in this graph.

Rule of thumb: it is desirable to have a reflection coefficient below -6 dB, ensuring proper impedance matching of the antenna component and optimized total efficiency.



INCREASE YOUR PERFORMANCE: to increase the performance we recommend evaluating your PCB again with increased dimensions (increasing length by 10 mm typically results in a total efficiency improvement of 0.5 dB).

	DUO mXTEND™ (NN03-320) for GNSS		
Frequency (MHz)	1559	1610	Avg 1559 - 1610
Total efficiency (%)	46.3	46.5	49.2

If you need further assistance, please contact our antenna specialists.

GET HELP

Your antenna design ready to use

ANTENNA 2

TRIO mXTEND™ (NN03-310):

- **Application:** Wearables & Smartwatches.
- **Frequency Range(s):** 791.0-960.0 MHz for LTE-M.
- **Tuning your antenna:** the optimized matching network is shown below.
- **Antenna footprint:** please refer to the datasheet link.

TRIO mXTEND™

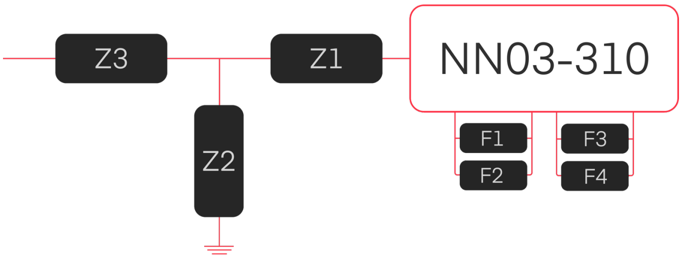
Dimensions 30.0 x 3.0 x 1.0 mm

Datasheet https://ignion.io/files/DS_NN03-310.pdf

Antenna Product Page

Matching Network Antenna 2

LTE-M Matching Network topology



Comm. Standard	Component	Value	Part Number	Manufacturer
LTE-M	F1	0 Ohm		
	F2	0 Ohm		
	F3	0 Ohm		
	F4	0 Ohm		
	Z1	19nH	LQW18AN19NG80	Murata
	Z2	8.6nH	LQW15AN8N6G80	Murata
	Z3	3.7pF	GJM1555C1H3R7WB01	Murata

The electronic component values correspond with the Matching Network when implemented on a bare PCB. These values may need further tuning and optimization when additional elements such as batteries, plastic covers, connectors, displays, etc. are added to your final device.

If you need further assistance, please contact our antenna specialists.

GET HELP

Your antenna design
ready to use

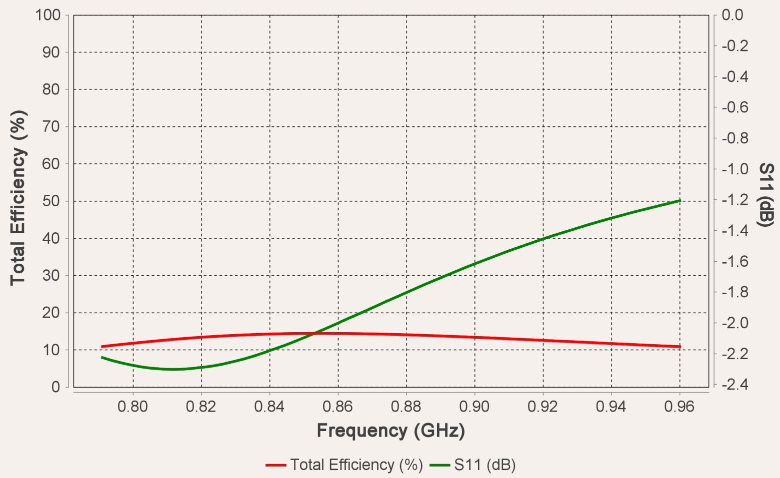
ANTENNA 2

Your Design overall Performance

Expected device performance with antenna 2

Your prototype using the NN03-310 antenna is expected to achieve the reflection coefficient (in dB) and total efficiency (in %) as shown in this graph.

Rule of thumb: it is desirable to have a reflection coefficient below -6 dB, ensuring proper impedance matching of the antenna component and optimized total efficiency.



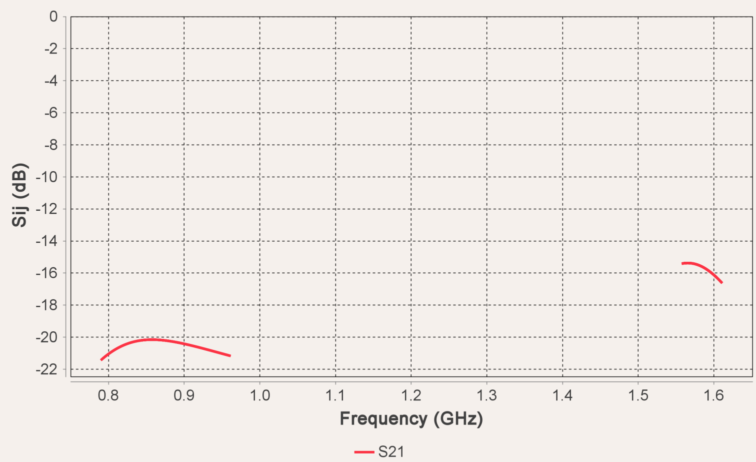
INCREASE YOUR PERFORMANCE: to increase the performance we recommend evaluating your PCB again with increased dimensions (increasing length by 10 mm typically results in a total efficiency improvement of 0.5 dB).

	TRIO mXTEND™ (NN03-310) for LTE-M		
Frequency (MHz)	791	960	Avg 791 - 960
Total efficiency (%)	10.9	10.9	13.1

Antenna Coupling

In multiantenna devices coupling coefficients indicate whether the antennas are electromagnetically isolated or not. For each antenna "i" to antenna "j", there is a Sij coupling trace that indicates the isolation levels between the antennas in the studied frequencies.

Rule of thumb: it is desirable to have antenna couplings below -10 dB, ensuring proper isolation between antenna components and optimized total efficiency.



TECHNICAL INFORMATION: coupling between two antennas can be significantly improved by increasing the distance between them.

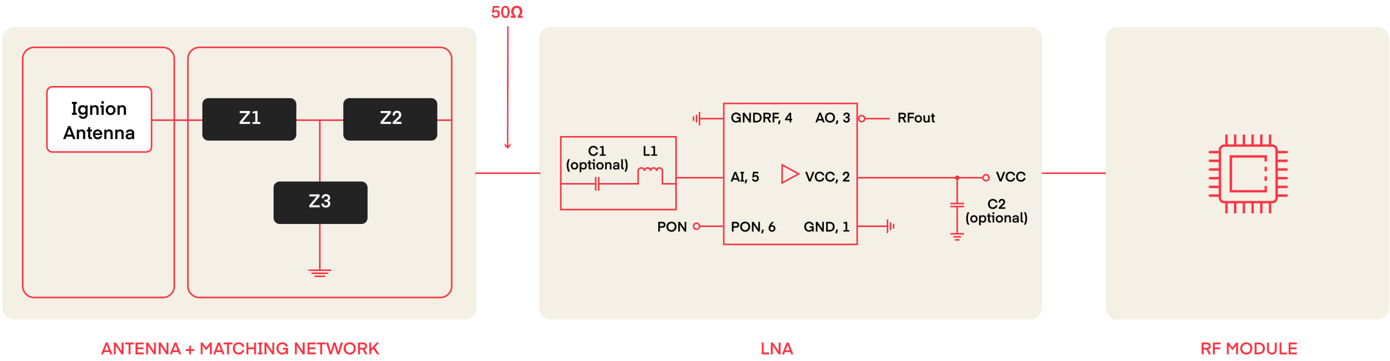
If you need further assistance, please contact our antenna specialists.

GET HELP

GNSS design recommendations

For GNSS applications it is recommended to include a Low Noise Amplifier (LNA) component unless the RF module already has it integrated.

The LNA should be included between the Matching Network of the antenna and the in/out port of the RF module.



It is important to follow the guidance included in the datasheet of the LNA supplier to achieve 50 ohms at the input of the antenna matching network.

If you need further assistance, please contact our antenna specialists.

GET HELP

Certification targets for LTE bands

To ensure your cellular IoT project success, it is important to ensure proper antenna performance in the context of the cellular certification targets early in the design phase. Verify the operator Total Radiated Power (TRP) requirements as these will set the main boundaries for your antenna requirements.

TRP Calculation:

TRP (dBm) = *ηa(dB) + P in RF module*

For example, in the US market AT&T has a set of requirements for IoT devices. A product with LTE CAT 1 is required to deliver a minimum of 30% of total efficiency in the LFR and a minimum of 50% in the HFR to meet the TRP (Total Raidated Power) requirements. Contact Ignion support to get help identifying the minimum antenna performance needed and the resulting minimum PCB size needed.

Band	Minimum TRP Requirement	Minimum TIS Requirement (Primary Antenna)	Minimum TIS Requirement (Secondary Antenna)
2	+20.0 dBm	-91 dBm/10MHz	-87 dBm/10MHz
4	+20.0 dBm	-93 dBm/10MHz	-89 dBm/10MHz
5	+18.0 dBm	-89 dBm/10MHz	-85 dBm/10MHz
12	+18.0 dBm	-91 dBm/10MHz	-87 dBm/10MHz
14	+17.0 dBm	-87 dBm/10MHz	-83 dBm/10MHz
17	+18.0 dBm	-88 dBm/10MHz	-84 dBm/10MHz
29	-	-88 dBm/10MHz	-84 dBm/10MHz
30	+19.0 dBm	-91 dBm/10MHz	-87 dBm/10MHz
66	+20.0 dBm	-93 dBm/10MHz	-89 dBm/10MHz

If you need further assistance, please contact our antenna specialists.

GET HELP

General design recommendations

for performance optimization
with Virtual Antenna® technology

1 CLEARANCE AREA

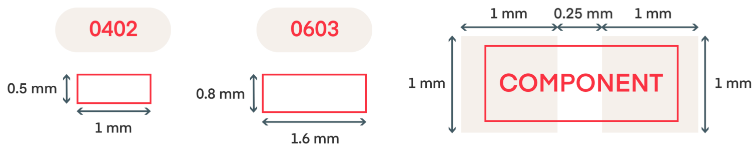
Consider the recommended clearance area in all directions around the antenna component. It must be free from electronic components, traces and ground plane in all PCB layers including the area underneath the antenna.

2 ANTENNA LOCATION

Keep the antenna in a corner of the PCB, as far as possible from other metalic components.

3 MATCHING NETWORK

Arrange pads for the Matching Network to host the 0402/0603 SMD components. Place pads as close as possible to the antenna feeding point and within the ground plane area. The Matching Network might need returning as other elements of your design are placed around the antenna. Use preferably high Q and tight tolerance components.



4 MATERIALS

Use low loss materials (i.e. PET plastic, Polyethylene Terephthalate) for the housings and enclosures.

5 MULTI-LAYER PCBs

Ensure that all the grounding sections in every PCB layer are properly connected through vias.

6 TRANSMISSION LINE AND RF CHIP

Design your transmission line connecting the Matching Network to your RF chip so that its characteristic impedance is 50 Ohms. Locate your RF chip as close as possible to the Matching Network to reduce losses.

7 GROUND PLANE LAYER

Ensure a continuous conducting ground plane in at least one layer of your PCB. Always maximize the surface of your ground area on the PCB of your device to maximize its radiation performance.

NEED MORE HELP COMPLETING YOUR DESIGN?

You are now ready to start designing your full device and building your prototype following the recommendations. Once you have designed your PCB layout you can submit the design file to Ignion for a sanity check.

SUBMIT YOUR DESIGN FILES

Ignion offers complete end-to-end design services.