Design and implementation of a RS-485 Repeater in an Industrial Environment

A Degree Thesis

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Abstract

The purpose of this project is to carry out all the process needed to design and check a RS-485 Repeater shield in an industrial environment.

First step to be done is to stablish all the product characteristics. Once it has been decided, design stage can be started. When all the objectives previously stablished are accomplished it is sent to an external enterprise so the shield can be built. During this time, a part list from all the components to be welded on it has to be written and also a list with the description of the functional tests to be performed.

When the shield is delivered, its components are welded and submitted to an exhaustive test (previously specified) to assure its correct performance in ordinary conditions.

Finally, since it shall be a product that has to be industrialized and commercialized, it has been submitted to some EMC tests to verify several quality and security requirements. Furthermore, a climatic test shall be done to guarantee its correct performance between its temperature working margins. This way, it is achieved a product that is CE compliant and competitive in the market.

Resum

El propòsit d'aquest projecte és la realització de tot el procés necessari per dur a terme el disseny i la validació d'un repetidor d'estats d'un panell de control en un entorn industrial.

El primer pas a realitzar és pactar amb el client totes les característiques del producte. Un cop s'han decidit, es comença la fase de disseny hardware del producte. Quan s'han complert tots els objectius preestablerts, s'envia a fabricar la PCB a una empresa externa. Durant aquest temps, s'ha de fer una llista del material necessari per muntar sobre ella i establir unes pautes per les proves que s'hauran de realitzar.

A l'arribar la placa, el següent pas és soldar els components i sotmetre-la a un assaig exhaustiu (prèviament especificat) per ratificar el seu correcte funcionament en condicions normals.

Finalment, donat que ha de ser un producte que es pugui industrialitzar i comercialitzar, es deuen realitzar una sèrie de proves d'EMC per verificar que compleixi amb uns certs requisits de qualitat i seguretat. A més, es durà a terme una prova climàtica per assegurar que treballa correctament dins dels marges de temperatura establerts. D'aquesta manera s'aconsegueix un producte CE i a la vegada competitiu al mercat.

Resumen

El propósito de este proyecto es la realización de todo el proceso necesario para llevar a cabo el diseño y la validación de un repetidor de estados de un panel de control en un entorno industrial.

El primer paso a realizar es pactar con el cliente todas las características del producto a diseñar. Una vez se han decidido estos requerimientos se empieza la fase de diseño hardware del producto. Cuando se han cumplido todos los objetivos preestablecidos, se manda fabricar la PCB a una empresa externa a ésta. Mientras se construye, se debe hacer una lista de material necesaria de los componentes a montar en ella y establecer unas pautas de las pruebas que se le deben realizar.

Al llegar la placa, el siguiente paso es soldar los componentes y someterla a un ensayo funcional exhaustivo (previamente especificado) para ratificar su correcto funcionamiento en condiciones normales.

Finalmente, dado que debe ser un producto que se pueda industrializar y comercializar, se deben realizar unas pruebas EMC para verificar que cumpla una serie de requisitos de calidad y seguridad. Además, se llevará a cabo una prueba climática para asegurar que trabaja correctamente dentro del margen de temperaturas establecido. De esta manera, se consigue un producto CE y a la vez competitivo en el mercado.

To my parents. I wouldn’t be here without their support during all these years.

Acknowledgements

This project wouldn't have been possible without the support received from UTC personnel, who taught me all I needed to carry out this project in a successful way and treated me as one member of the team. Thanks to Raul Perez for giving me the opportunity to develop this project and helping me during the whole process. Finally, thank you to Diego Mateo, who helped me with all I needed and guided me all this time.

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1. Introduction

The main goal of this project is to design a RS-485 Repeater PCB assembly that shall accomplish European Fire Detection normative. Design process used in I+D Department follows the V method.

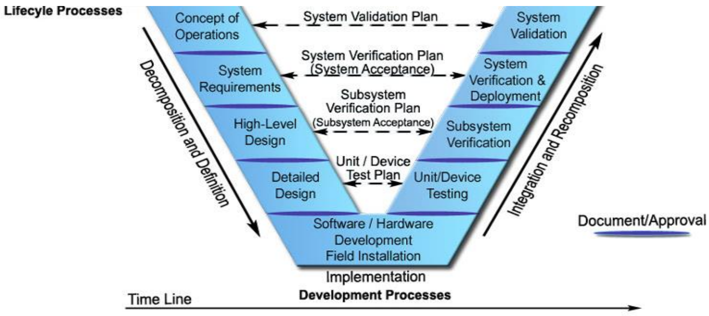

Figure 1. V method

It consists on several steps (from low–level to high-level of complexity) that shall be documented and approved by other staff members before moving forward to the next step. This procedure reduces the amount of mistakes during the whole project. First of all, the client proposed a customized product to be developed by the enterprise. When the proposal is approved, all the client needs shall be written in a Requirement's Document. Afterwards, design stage is worked out. Once the design has been validated, the shield construction starts in parallel with purchasing components and developing the validation test definition. As soon as PCB arrives, components are placed on it and it is submitted to an exhaustive validation using the equipment provided by the enterprise.

All projects developed in this company are done by, at least, a hardware engineer, a software engineer and a mechanical engineer. They shall work in parallel at the same time on all the requirements specified by the client. In this case, as communications protocol has not been specified yet, software engineer development is not necessary. Nevertheless, cooperative work with mechanical engineer shall be done to implement the housing.

1.1. Client's requirements

As already stated, requirements have to be set by the client before starting. It allows the engineers to develop the hardware according to application features.

a) Functional requirements
   - Serial Repeater shall be powered (by a wire less than 30m long):
     - From 1 to 4 repeaters: Powered by the powered by main panel (24 V_{DC}).
     - From 5 to 16 repeaters: Powered by an additional power supply of 24V_{DC}.
   - There shall be two manual configurations:
     - Address configuration: there can be as maximum 16 repeaters connected to the same Main Central and each one of them has to be distinguished from the others.
     - Shield configuration: there shall be the option of choosing the language (English-French) and if there is a display or not (there are two Repeater models, one which implements a LCD and the other which does not).
   - RS485 wire shall be the method used for communication and it shall be designed to allow a 9600 baud communication velocity (half duplex).

- Longest distance between first panel and last one shall be 1200m as maximum.
- Repeater and control panel shall be connected by 4 wires: 2 providing supply ($24V_{DC}$ and GND) and 2 allowing communication (A and B). In addition, there shall be the option to connect 4 shields as maximum to the same PCB, as it can be seen in next figure.

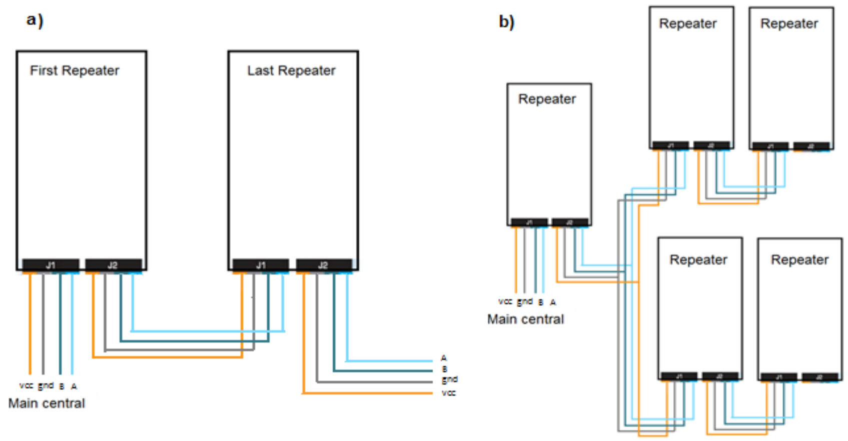

Figure 2. a) Serial repeater connection b) Allowable connection method

- Display shall be 4 lines x 20 characters.
- Buzzer beep shall be continuous in case of alert message and blink for all other events until the user stops it. Also, it shall be blinking during two hours after a lack of supply.
- SR shall have got the following LEDs:

Function	Color	Status
Power on	Green	ON: Serial Repeater is powered. OFF: Serial Repeater is off.
Out of service	Yellow	ON: Device out of service OFF: All devices working properly.
Disruption	Yellow	ON: Fault information is detected. OFF: Fault information is not detected.
Warning	Red	ON: Warning information is detected OFF: No alert information detected
General evacuation	Red	ON: Evacuation information is detected. OFF: Evacuation information not detected.
Alert	Red	ON: Alert is detected (at least one). OFF: No fire alarm information
Test	Yellow	ON: Test information is detected OFF: Test information is not detected
Line fault	Yellow	ON: Light on if there is a fault: o In communication with main station o On the line of evacuation sirens function. OFF: No failure detected in communication
Alarm	Yellow	ON: Standby state information restricts the alarm. OFF: Standby state information does not restrict the alarm.
Disruption	Yellow	ON: Line fault is detected (at least one) BLINK: Default position information is detected (at least one). OFF: Line fault/position fault not detected
Security	Red	ON: Realized information is detected

		BLINK: Anomaly is detected. OFF: Realized/ anomaly information not detected

Table 1 .LED definition

- SR shall have got the following buttons:

Name	Status
Scroll	Allow the access to any information except the ones related to alert messages and technical alarms.
Status	Allow the access to information related to alert messages and technical alarms.
Test	Allows visual and acoustic test signals from the concerned SR.
Mute	Allows the buzzer to stop the sound from SR.
Configuration	Allows the SR configuration.

Table 2. Button configuration

b) Mechanical requirements
  - Wire size range shall be between 12 and 30 AWG (RS485 normally is 24 AWG)
  - Box dimensions must be as maximum 250 mm x 150 mm x 50 mm.
  - IP shall be IP30.
  - Box material shall be V0.
  - Temperature working range shall be from -5ºC to 50ºC.
  - There shall be a key to enable the shield configuration.

c) Layout requirements
  - Serial Repeater shall have got ESD symbol in the silkscreen.
  - It shall have got the WEEE symbol in the silkscreen.
  - Layout shall allow an easy connection of wiring.
  - All connections shall be described in the silkscreen.
  - All switch options shall be described in the silkscreen.

d) Reliability requirements
  - Serial Repeater shall be compliant with the MTBF @ 25ºC with Ground, Fixed, Uncontrolled environment for Intelligent / CPU (>150 components) a value of 100.000 to 150.000 hours (TELCORDIA normative).

e) Approval requirements
  - Serial Repeater shall be CE compliant.

1.2. <u>Enterprise requirements</u>

In order to maintain the same criteria in all enterprise projects some requirements shall be followed when designing. These requirements are focused on the industrialization stage.

- All components assembled in Serial Repeater shall have if possible a second source identified to avoid the risk of getting obsolete and to let the product continue on the market without modifying the initial design.

- Use SMD components instead of TH if possible to allow an automatic assembly (reducing its fabrication cost).

- Smaller size than 0603 for SMD components is not allowed.

- All Serial Repeater components must be ROHS compliant (mandatory for commercialize electronic products).

- All TP shall be placed in one side if possible for allowing an automatic test in the factory (ICT system).
- Microcontroller must be used in other enterprise design if it is chosen.
- Components shall be used in other designs if possible to reduce its cost.

2. State of the art of the technology applied in this thesis:

Considering the requirements, main product structure shall be:

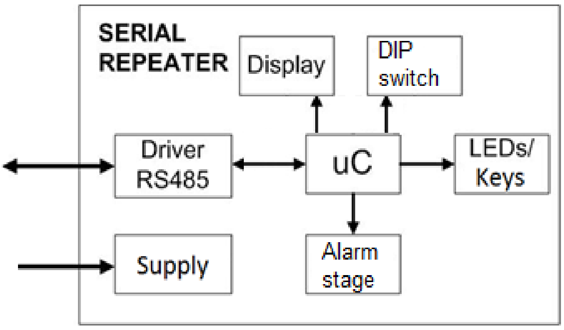

Figure 3. Main Serial Repeater structure

Before design stage some research shall be done to know, among the several possibilities, which technological options will be implemented in the shield:

- Main shield's control

Two options have been considered to control the shield: a microcontroller or a FPGA. Both are used in similar applications but there are many differences between them. FPGAs are slower and less powerful efficient than microcontrollers. In addition, they can't deal with systems as complex as uC do. However, FPGA are reprogrammable devices and that means more flexibility when designing in contrast with uC, which are limited by its structure. Thus, FPGA's development time is higher because it needs to be configured from the beginning matching all the modules needed. Knowing these differences, an uC is chosen because it fits better the shield necessities.

- Shield structure

The amount of layers is an important factor to take into account. Four or more layers provide some benefits than 2-layer shield does not. The main difference resides in that in 4-layer there are a GND and a VCC layer, which are between strip layers. Then, physical structure is top layer, GND, VCC and bottom layer. Thanks to these two internal layers there is no need of routing strips from input voltage to all the components in order to supply them but only using a via near the voltage pin of the component. It reduces the amount of strips, strip's longitude and it saves space in top and bottom layers for placing more components. Moreover, it protects the circuitry from external parasitic noise and prevents the shield from emitting electromagnetic radiation. Otherwise, using more than 4 layers is not necessary due to the shield complexity. According to this, 4-layer PCB is chosen.

- Buttons

There is different technology for buttons to carry out this stage. It has been considered using tactile buttons, mechanical push-buttons (SMD) and Lexan keypad. This product will be used by people from security personnel to operators. Tactile buttons are discarded because operators wear thick gloves in many cases and this technology can obstruct their job. SMD push-buttons are a good option but it means that the housing shall have got holes where buttons are placed. This option makes the shield weaker in front of ESD than using a Lexan keypad. In addition, mechanical button life expectancy is shorter than any other choice and it would reduce the product's life. Lexan keypad is made of thermoplastic material and contains buttons inside. These buttons are isolated from the outside and from the shield, avoiding ESD problems and protecting the shield from water and dust. Thus, Lexan keypad is the chosen option.

- **Supply**

Shield is powered by $24V_{DC}$. It has to be reduced to supply the shield components. For that purpose, a regulator or a DC/DC converter can be used. In order to decide which one is more suitable for each situation, these features shall be considered:

- **Area**. Area used for placing a DC/DC converter is higher than a regulator.
- **Electrical noise** of DC/DC is higher than regulator's caused by its commutation (called ripple voltage). It can be spread through the shield.
- **Cost:** DC/DC converters are more expensive but the difference is not very high.
- **Efficiency**: On one hand, regulator's efficiency is conditioned by its input/output voltage. It can be estimated by using next formula:

$$Po = Pi \cdot \rho$$
$$Vo \cdot Io = Vi \cdot Ii \cdot \rho$$

Assuming that Io is approximately the same value as Ii:

$$\rho = \frac{Vo}{Vi}$$

On the other hand, the DC/DC efficiency is approximately between 70% and 95%. Hence, regulator's efficiency is lower than DC/DC's. Having in mind these features, the best option for each case has been chosen in Power design stage (see 3.1.2).

- **Alert**

There are two possibilities to implement the sound: a piezo-electric sounder or a buzzer. Piezo electric sounder is the cheapest option and it can be set the oscillation frequency, but an external oscillator circuitry is needed to make it sound, increasing the price and the time spent in design. Otherwise, the buzzer is supplied by DC current and there is no need of more components. Despite the higher price, the buzzer is chosen due to its simplicity.

- **Alarm supply**

A battery or a super capacitor can be the devices used to supply a circuitry which makes sound the alarm. Batteries are heavier than capacitors. Battery charging and discharging time is higher than capacitor's but capacitor's life time is longer than battery's. In addition, capacitors can be charged more times than batteries without being damaged. Bearing in mind all these features, super capacitor is the device chosen for this purpose.

3. Methodology / project development:

3.1. Design

3.1.1. Microcontroller stage

First parameter to take into account for choosing the most suitable microcontroller for this purpose is the number of GPIO pins that shall have.

Pin usage	Number of pins
LCD (8 for data, R/W, Enable, Backlight, RS)	12
LEDs	11
Switches	5
Dip-switch	7
Buzzer	1
RS485 Communications (RX, TX, Enable)	3
Debug (RX, TX)	2
JTAG	5
V_{SENSE}	1
Boot mode	1
External oscillator	2
TOTAL	**50**

Table 3. GPIO uC pins

One request from Requirement's document is that the microcontroller should be used in other enterprise design. In accordance to that, there are four microcontrollers currently in use: STM32L052C6T6, STM32F101RCT6, STM32F103RCT6, and STM32F105RCT6.

FEATURES	STM32L052C6T6	STM32F101RCT6	STM32F103RCT6	STM32F105RCT6
Speed	32MHz	36MHz	72MHz	72MHz
I/O	37	51	51	51
Memory	32kx8	32kx8	48kx8	64kx8
Quantity purchased by enterprise	5000	4500	5000	7000
Price/uC	2.63€	4.11€	4.25€	3.25€

Table 4. Microcontroller features

From Table 4 it is seen that the first device does not have enough pins to this purpose, so it can be discarded. Speed and memory from the rest of the devices are good enough for this application (>36 MHz and 32kx8). As these features are suitable, the main difference consists on their cost. STM32F105RCT6 is the most used device by far so its price is the lowest one. Then, uC chosen is STM32F105RCT6. Moreover, choosing this one it is prevented a lack of memory or not working fast enough in future firmware updates.

Once uC is selected, its implementation can be done:

1) Pin assignment

Pins have been assigned having in mind the disposition of the components on the shield to avoid using long strips. Detailed pin assignment can be seen in ANNEX 1.

2) BOOT configuration

Boot mode is used to reprogram Flash memory by using USART peripherals, CAN2 or USB OTG FS. In this case, USART is the way used to perform this action. Pin BOOT0 and BOOT1 configure the boot mode according to the following table [1]:

BOOT1	BOOT0	Number of pins
X	0	User Flash memory
0	1	System memory
1	1	Embedded SRAM

Table 5. Boot loader configuration

Embedded SRAM is not used, so BOOT1 shall be set to 0 permanently. Using the proper hardware, BOOT0 can be set to 0 or 1. Default value boots CPU from internal Flash, but if BOOT0 is set to 1 it boots CPU from USART (Debug).

3) Reset

Microcontroller shall be protected against voltage supply drops. Two protection methods are designed. First one is done by software supervision. It consists on a voltage divider from PS ($24V_{DC}$) to an acceptable voltage for the uC ($3.3V_{DC}$). This voltage can be constantly checked via software and act before PS goes below the minimum voltage that the uC can allow.

The other method implemented is an external voltage supervisor. It provides a reset signal 140ms after 3.3V declines below a pre-set threshold (in this case 2.89V).

4) Debug and Jtag

Debug is used to upload the firmware to the microcontroller when BOOT0 to 1. In addition, it is used as a communication port by hardware engineers to check the correct shield performance. Jtag is placed in order to be used by software engineers and in the last steps of the industrialization process to check the correct performance of the shield by other enterprise.

5) Oscillator

High Speed External clock can be supplied using a 3 to 25 MHz crystal resonator oscillator. Looking at the enterprise component's list there are currently 4 crystal oscillators in use: 32.7 kHz, 16 MHz, 18 MHz and 25 MHz. This choice is commonly related with Firmware implementation. However, as firmware needs are not known yet, it can be supposed that a clock from 10MHz to 20 MHz would fit perfectly this application. First and last oscillators are discarded. Any of the other two crystals can be used. 16 MHz is a slower time domain clock and due to that fact power consumption is smaller. Device chosen is HOSONIC HC-495SMA (16MHz) and it has got the following characteristics:

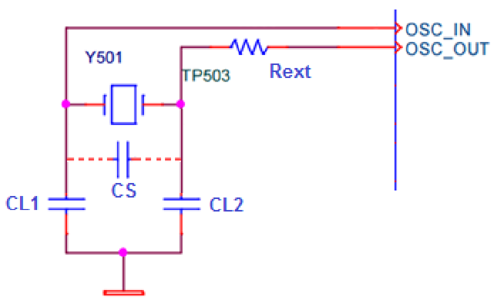

Figure 4. Oscillator Design

C_{LOAD}= 18pF ESR (max) =40 Ω
C_O= 7pF (shunt capacitance) F=16MHz

Solving formula (1) assuming the same value for C_{L1} and C_{L2}, their values can be found [2]:

$$C_{LOAD} = \frac{C_{L1} \cdot C_{L2}}{C_{L1}+C_{L2}} + C_{SHUNT} \quad (1)$$

$$\mathrm{C_{L1} = C_{L2} = 22pF}$$

To assure the oscillation will be started and maintained by the oscillator, its gain margin shall be higher than a factor of 5.

$$Gain_{margin} = \frac{gm}{gm_{crit}} \quad (2)$$

Where gm is the oscillator transconductance specified in the microcontroller datasheet (in this case gm=25mA/V) and gm_{crit} is the minimal oscillator transconductance required to maintain an astable oscillation. It can be calculated with the following formula:

$$gm_{crit} = 4 \cdot ESR \cdot (2\pi F)^2 \cdot (C_o + C_{LOAD})^2 \quad (3)$$

$$gm_{crit} = 1.01mA/V$$

Introducing this value into (2) is checked that the oscillation is guaranteed.

$$Gain_{margin} = 24.73 \gg 5$$

Last component to calculate is R_{ext}, which forms a low-pass filter that drive the oscillator to begin at the fundamental frequency and not at the overtones.

$$R_{ext} = \frac{1}{2\pi F C_{L1}} = 452.14\Omega \quad (4)$$

Once this resistance is calculated it is needed to check the $gain_{margin}$ again.

$$gm_{crit} = 4 \cdot (ESR + R_{ext}) \cdot (2\pi F)^2 \cdot (C_o + C_{LOAD})^2 = 12.43mA/V \quad (5)$$

Introducing this value into formula (2) becomes a $gain_{margin}$=2. It is lower than the minimum gain recommended to assure the oscillation, so this resistance value is not good for this design. Using again formula (2) can be calculated $gm_{crit\ max}$ and using formula (5) can be calculated $R_{ext\ min}$.

$$gm_{crit_{max}} = \frac{gm}{Gain_{margin\ min}} = \frac{25mA/V}{5} = 5mA/V$$

$$R_{ext\ max} = 157{,}89\Omega$$

Choosing a R_{ext} lower than the above value, oscillator performance is assured. Then:

$$R_{ext} = 100\Omega$$

That value makes a gain margin of 7.06. Thus, the oscillation is guaranteed for these capacitors and resistance values.

3.1.2. Power stage

Power stage shall supply all the other stages, providing them the necessary voltage and current to assure their correct performance. Before starting, it has to be chosen which voltage will supply each component from the shield. Microcontroller shall be powered with 3,3 V. Same happen with switches and DIP-Switches because they are connected to the microcontroller as inputs. LCD, LEDs and buzzer shall be powered with 5 V. Furthermore, communication stage shall be isolated from the rest of the circuitry. This is due to communication wire can be as far as 1200m long. Along this distance it is exposed to different elements (as for example lightning) that could damage the shield. Thence, there are 3 different voltages on the shield: 5 V, 5 V isolated and 3,3 V.

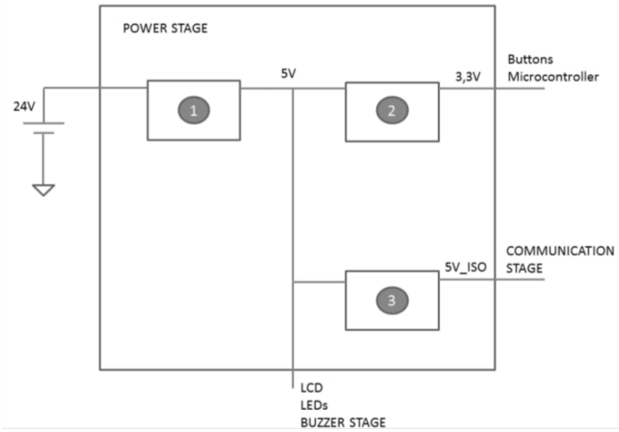

Figure 5. Shield main voltages

1) 24V to 5V

Voltage supply shall be reduced from 24 V to 5 V. In this case regulator's efficiency would be:

$$\rho = \frac{Vo}{Vi} = \frac{5}{24} = 0.208 \; = 20.8\%$$

In comparison to a DC/DC converter (70%-95%), regulator's efficiency is too low. Despite DC/DC higher size and cost, its efficiency is also higher and this is the most important factor to take into account for this stage. For that reason, choosing the converter is the best option. In order to obtain 5 V from 24 V a Step-Down converter is needed. Analyzing it, two states are distinguished (continuous mode):

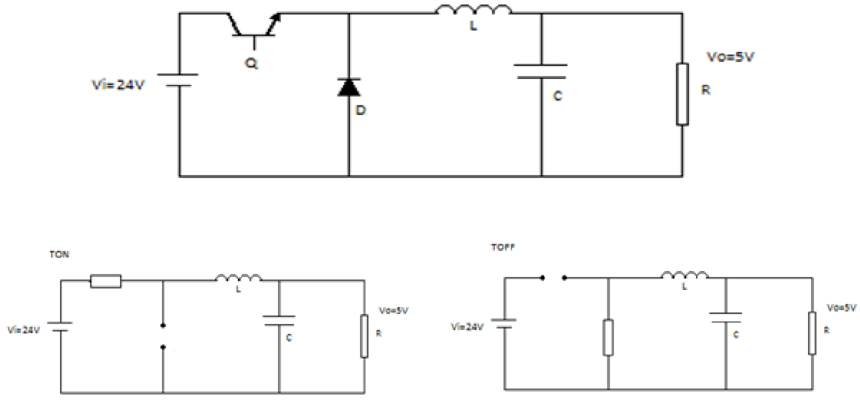

Figure 6. Step-down converter

In general terms inductor voltage shall be:

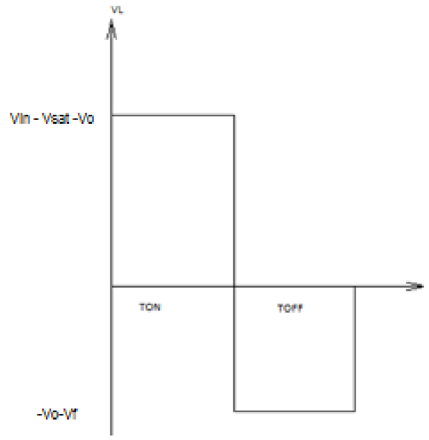

Figure 7. Inductor voltage

During t_{on}, inductor current (I_L) is the same as the current which goes through the transistor, and during t_{off} , I_L is the same as the current that goes through the diode:

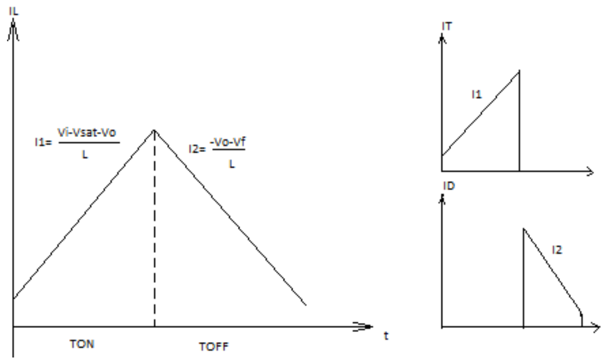

Figure 8. Inductor current, diode current and TRT current

$$I_{L_{on}} = I_{Trt} = \frac{(V_i - V_{sat} - V_o)t_{on}}{L} \quad (1)$$

$$I_{L_{off}} = I_{diode} = \frac{(-V_f - V_o)t_{off}}{L}$$

Ratio between ton and t_{off} is determined assuming that the output voltage is continuous and inductor current reaches to 0 mA. In this case:

$$I_{L_{on}} \cdot t_{on} = I_{L_{off}} \cdot t_{off}$$

$$\frac{V_i - V_{sat} - V_o}{L} t_{on} = \frac{-V_o - V_f}{L} t_{off}$$

$$\frac{t_{on}}{t_{off}} = \frac{V_o + V_f}{V_i - V_{sat} - V_o} \quad (2)$$

If output voltage remains constant, output current should be equal to the average current into the inductor:

$$I_{L_{average}} = I_o$$

$$\frac{I_{Lmax}\, t_{on}}{2} + \frac{I_{Lmax} t_{off}}{2} = I_o T$$

$$I_{Lmax} = I_o \cdot 2 \quad (3)$$

Using I_C current (I_L current without offset) it is possible to work out the ripple voltage:

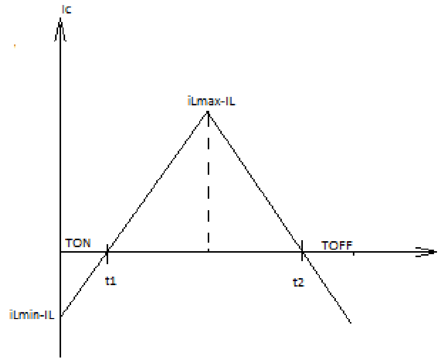

Figure 9. Output capacitor current

$$\Delta ilpp = ilmax - IL - (ilmin - IL) = ilmax - \left(ilmax - \frac{V_i - V_{sat} - V_o}{L} t_{on}\right) = \frac{V_i - V_{sat} - V_o}{L} t_{on}$$
$$= I_{peak}$$

$$(t2 - t1) = t_{on} + \frac{t_{off}}{2} - (t_{on} - \frac{t_{on}}{2}) = \frac{(t_{off} + t_{on})}{2}$$

$$\Delta V_{opp} = \frac{1}{C_o} \int_{t_1}^{t_2} I_c \, dt = \frac{1}{2C_o} (t_2 - t_1) \cdot (ilmax - I_L) = \frac{1}{2C_o} \cdot \frac{(t_{off} + t_{on})}{2} \cdot \left(\frac{\Delta ilpp}{2}\right)$$
$$= \frac{1}{2C_o} \cdot \frac{(t_{off} + t_{on})}{2} \cdot \left(\frac{I_{peak}}{2}\right)$$

$$\Delta V_{opp} = \frac{T \cdot I_{pic}}{8C_o} \quad (4)$$

Once main formulas are obtained from general step-down converter analysis, MC34063 oscillator is chosen to be used as a commuting transistor. Next figure shows one possible connection for a buck converter operation [3]:

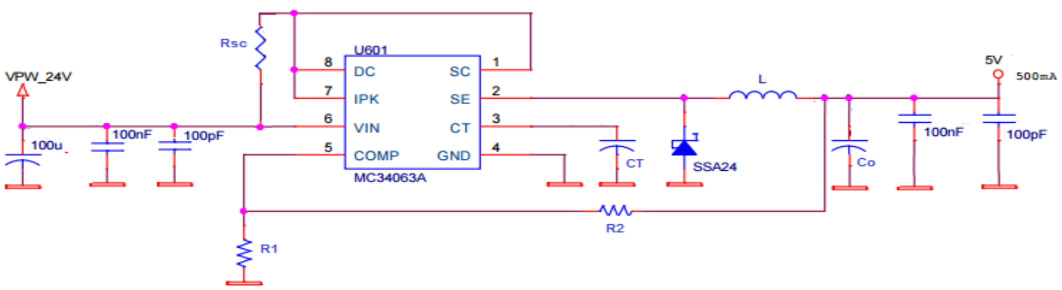

Figure 10. DC/DC converter design

Thanks to this connection and next data, converter is designed.

$f_{min}=T_{max}^{-1}$= 50 kHz	V_O = 5 V
V_O=5 V	$\Delta V_{opp}=V_O \cdot 5\%$= 25 mV
I_o=500 mA	V_F= 0.8 V
V_{IN}= 24 V (±10%= 21.6 V to 26.4 V)	V_{sat}= 0.8 V

MC34063 monitors its operation frequency by charging and discharging C_T capacitor between its upper and lower preset threshold. Ramp-up is at the most 6 times longer than ramp-down, obtaining a maximum ratio of 0.875. Using formula (2) maximum buck converter ratio is worked out:

$$\frac{t_{on}}{t_{off}} = \frac{V_o + V_f}{V_{i\,min} - V_{sat} - V_o} = \frac{5V + 0.8V}{21.6V - 0.8V - 5V} = 0.36$$

It doesn't exceed the maximum oscillator ratio. Using data from above, maximum period is:

$$T_{max} = t_{on} + t_{off} = \frac{1}{f_{min}} = 20\ us \qquad (5)$$

Introducing (2) in the above formula it is found t_{onmax} and t_{off}:

$$t_{on} + t_{off} = t_{on} + \frac{t_{on}}{0.36} = ton(3.8) = 20\ us$$

$$t_{on\,max} = 5.3\ us \qquad (6)$$

$$t_{off} = 14.7\ us$$

From formula (1) it is known the minimum value that can take the inductance using I_{Lmax} (which is the current that goes through the inductance during ton) and formula (3):

$$I_{Lon} = I_{Lmax} = I_{peak} = I_{Trt} = I_o \cdot 2 = 500\ mA \cdot 2 = 1\ A$$

$$Lmin \geq \frac{(V_i - V_{sat} - V_o)t_{on}}{I_{Lmax}} = \frac{21.6\ V - 0.8\ V - 5\ V}{1\ A} 5.3\ us = 83.74\ uH$$

L chosen is 220 uH.

Pin number 5 is the input of a comparator between 1.25 V and the voltage that goes in by this pin. For that reason:

$$V_{R1} = V_o\left(\frac{R_1}{R_1 + R_2}\right) = 1.25\ V$$

Choosing R1=3.6 kΩ, R2 gets a value of 1.2 kΩ. Furthermore, longest switch conduction time is the same as $t_{on\,max}$, which is controlled by the charge of C_T. Thus, capacitor minimum value can be calculated by using the minimum oscillator charging current and the difference of voltage between upper threshold and lower threshold level (1.25 V - 0.75 V = 0.5 V) during $t_{on\,max}$:

$$C_{T\,min} = I_{chg\,min}\frac{\Delta t}{\Delta V} = 24\ us\frac{t_{onmax}}{0.5\ V} = 316.8\ pF \cong 470\ pF$$

Applying formula (5) the lowest value that C_O can take is:

$$C_{o\,min} = \frac{I_{peak}T}{8\Delta V_{oppmax}} = 100\ uF \cong 220\ uF$$

Current limit is set by R_{SC} resistor, which is located between supply voltage and the output switch. Voltage of this resistor is monitored by pin 7 and when it is higher than a preset value (330 mV) the current limit circuitry provides an extra of current to charge C_T as fast as possible for limiting the amount of energy stored in the inductor. Current limit resistor can be set by using the current level of I_{peak} when V_{IN} is its maximum, and from this current, R_{SC} value can be found.

$$I'_{Trt} = \frac{(V_i - V_{sat} - V_o)t_{on}}{Lmin} = \frac{24\,V - 0.8\,V - 5\,V}{83.74\,uH} 5.3\,us = 1.15\,A$$

$$R_{sc} = \frac{0.33}{I'_{peak}} = 0.3\,\Omega$$

DC/DC converter is simulated in ANNEX 3.

2) 5V to 3.3V

A circuitry that turns 5 V into 3.3 V is needed to supply buttons and microcontroller. In this case, efficiency would be:

$$\rho = \frac{Vo}{Vi} = \frac{3.3\,V}{5\,V} = 0.66 = 66\%$$

This efficiency value is near to DC/DC efficiency. Also its cost, area and noise are lower than using a DC/DC converter. This regulator shall provide current to switches and DIP-switches ($I_{Buttons} \backsimeq 0$) and to microcontroller ($I_{uC} \backsimeq 20$ mA). Adding some margin (20mA), current supplied by the regulator is $I_{REG\ max}$=40 mA. Then, power that the regulator shall dissipate is:

$$P_{Dmax} = (Vi - Vo) \cdot I_{REG_{max}} = (5\,V - 3.3\,V) \cdot 40\,mA = 68\,mW$$

Bearing in mind the current which goes through the regulator shall be higher than 40mA, regulator chosen is LD1117A (SOT-223) because it can supply an I_{max} up to 200mA. Package suitability shall be tested (if it is able to dissipate the maximum power).

$$R_{thJA} = \frac{\Delta T}{P_D}$$

Where:

R_{thJA} = 110ºC/W

T_{MAX}=125ºC (maximum regulator's temperature).

T_{AMB}=50ºC (maximum temperature that the shield can reach).

ΔT= T_{MAX}-T_{AMB}=125ºC-50ºC=75ºC

$$P_{D_{reg}} = \frac{\Delta T}{R_{thJA}} = \frac{75}{110} = 681.8\,mW$$

As P_{Dreg}>>P_{Dmax}, it can be concluded that this package fits perfectly with this purpose.

3) 5v to 5v isolated

Communications shall be supplied by 5 V isolated in order to divide the communication's stage from the rest of the circuit. This device shall supply the RS485 driver and an isolator for communication wires which arrive to the uC. Both are supplied by 5 V and consume approximately (adding some margin) 150 mA in its highest performance. For this purpose is used F0505M, a DC/DC converter that can provide up to 200mA and is able to dissipate 1 W.

3.1.3. Communications stage

In this stage communications between microcontroller and main panel shall be guaranteed. RS-485 is the wire used to carry out this performance, which allows driving data to 1.2 km (if the cable length were larger it would be “refreshed”). Communication cable is a twisted pair of 24 AWG (0.5461 mm of diameter) as requirements demands. These wires are balanced line wires, which are a pair of lines transmitting differential signal with a voltage that varies from 2 V to 6 V across them. Besides, these cables are controlled by a driver that allows master-slave communication. In this design is used DS36276M.

There is the possibility that the transmitted signal is not absorbed at all by the Repeater’s load and a portion of it can go back into the line [4] [5]. This is due to the line impedance doesn’t match with the end of the line load. To avoid it, a load at the end of the line is needed. It is not mandatory if propagation delay of the data line is much less than one width bit. At 9600 bauds a width bit is:

$$9600\ bauds = \frac{1bit}{T_{bit}}$$

$$T_{bit} = 104.66\ us$$

Using a propagation velocity of 0.66c, being c light velocity, 1.2km of cable and assuming that reflections will damp out in three “trips” up and down the cable, signal will stabilize at:

$$T_{data} = \frac{0.66 \cdot c}{1.2\ km \cdot 3\ trips} = \ 18.5\ us$$

As we can see propagation delays are lower than one bit width. It can be concluded that an end load is not mandatory. However, to assure its correct performance is used anyway in the first and in the last Serial Repeater of the line. The most common value used for this terminal resistor is 120 Ω because it matches with the line impedance. Receiver output state from RS-485 is logic high whether V_{AB}>200 mV and logic low whether V_{AB}< -200 mV. If input voltage is between these limits the output state is not defined. This happen when it is in idle state (drivers are not active). V_{AB} is near to 0 and receivers detect random states. To maintain this minimum voltage difference, bias resistors are needed. They can be placed near to any driver of the line and are composed by a pull up in data line A and a pull down on data line B.

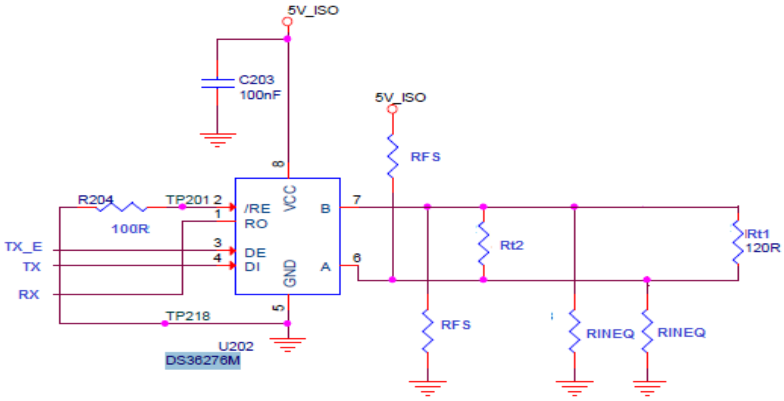

Figure 11.DS36276M bias resistors

As said before, line impedance is Zo=120 Ω and R_{t1} takes the same value to avoid the reflectivity of the signal:

$$\rho = \frac{Zo - R_{t1}}{Zo + R_{t1}} = 0$$

In Requirement's stage, it is asked to be able to connect 16 devices in the RS-4835 network. Each Receiver connected has an input impedance of 12 kΩ. Then, 16 devices connected in parallel give an equivalent resistance of 750 Ω. Assuming that R_{t1} is the same value as R_{t2} (because both are termination resistances) it results another 60Ω. Total load is:

$$R_{EQ} = \frac{1}{\frac{1}{60\Omega} + \frac{1}{750\Omega}} \cong 55.55\ \Omega$$

Worst case for V_{AB} is when it is added noise to the signal. It is supposed 20mV of noise. Applying these values I_{bias} can be worked out:

$$I_{bias} == \frac{V_{bias}}{R_{EQ}} = \frac{220\ mV}{55.55\ \Omega} = 3.96\ mA$$

Knowing bias current value it can be created from voltage supply:

$$R = \frac{V_{supply}}{I_{bias}} = \frac{5\ V}{3.96\ mA} = 1262.61\ \Omega$$

Using half of this value as a pull up resistor and the other half as a pull down resistor:

$$R_{FS} = 631.3\ \Omega \cong 620\ \Omega$$

As said before, communication wire can be 1200 m long. This wire is exposed to different elements that can damage the shield. For that reason, isolation is needed. Furthermore, the same device allows a decrease in the voltage because communications are supplied with 5 V and microcontroller with 3.3 V. ADUM1402 is the device used for this purpose.

3.1.4. Interface stage

- **LEDs**

Eleven LEDs shall be implemented to show the alert information in a visual way. As it is wanted to build housing as closer as possible from the shield, gull wing LED's are used. The ones used in this design are: LT0223-A7-TZC1 (green), LT0243-A7-TZC1 (red), LT0233-A7-TZC1 (yellow). Each led is controlled by one microcontroller I/O pin. Microcontroller can provide enough current to switch on a LED because it can supply up to 25 mA per pin. Nevertheless, the total current that the uC can provide is 150 mA as maximum and in some cases this maximum current could not be enough, i.e. in worst case, if all LEDs were on, total current supplied would be 220 mA as maximum (supplying every LED with 20 mA approximately). To solve that problem NPN transistors are used. Thanks to that device, applying fewer current on the gate it is possible to switch on the LED. Transistor used is DTC124EE, which includes 2 resistances inside of 22 kΩ. These resistances reduce the used area and the device's prize. Also, as these resistors are isolated, parasitic effects are completely eliminated.

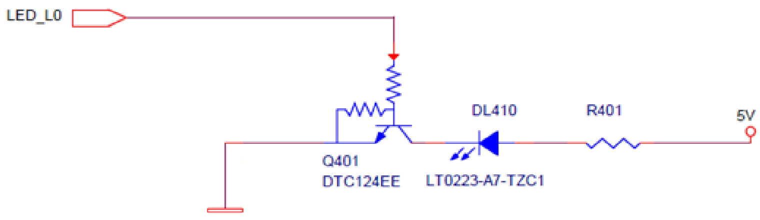

Figure 12. LED design

On first instance, current going through the LED (green) is set to Ic_{MAX}=15 mA. If I_C takes this value V_{CESAT}≅0.1V, h_{FE}=250 and luminous intensity is the 80% that the LED is able to give. Knowing that, its forward voltage is V_{LED}=2 V, then:

$$V_{5V} - V_{RES} - V_{LED} - V_{CEsat} = 0$$

$$R_{RES} = \frac{5v - 2v - 0.1v}{15mA} = 193.4 \cong 200\ \Omega$$

Looking at I_B:

$$I_B = \frac{I_C}{\beta} = \frac{15mA}{250} = 60\ uA$$

The minimum I_B current needed to saturate the transistor is 60 uA. Now if we look at I_B current given by the microcontroller:

$$I_B = I_R = \frac{VuC}{R_{in}} = \frac{3.3\ V}{22\ k\Omega} = 150\ uA$$

It can be concluded that I_B is much higher than Ic/h_{FE} (150 uA >> 60 uA) and Trt would be always saturated when the pin is on. Final resistance chosen is 220 Ω. Then, I_C=13.2 mA and I_B=52.72 uA. LEDs have been simulated in ANNEX 4.

- **Buttons and DIP switches**

Pull-up buttons are designed following the design in Figure 13.a. It means that microcontroller is always reading a logic ‘1’ until the button is pressed. Then it detects logic ‘0’. Microcontroller reads ‘0’ or ‘1’ depending on V_{IH} and V_{IL} values. V_{IH} is the lowest value that the microcontroller takes as a logic ‘1’ and V_{IL} is the highest value that the microcontroller takes as a logic ‘0’. For STM32F105 these values are V_{IH} =1.83 V and V_{IL}=1.16 V. In addition, values for pull-up resistors need to be chosen to satisfy two conditions:

1) When button is not pressed, R1 controls the amount of voltage on the uC input pin.
2) When button is pressed, R1 controls the amount of current that flows into the uC.

To satisfy 1st condition and be over V_{IH}, R1 shall be at least an order of magnitude less than the input impedance of the uC input pin. This resistance can vary from 100 kΩ to 1MΩ. Then:

$$V_{uC} > V_{IH}$$

$$V_{uC} = \frac{R_{100k}}{R_{100k} + R1} \cdot 3.3\ V > 1.83\ V$$

$$R1_{max} < 80.3\ k\Omega$$

To satisfy 2nd condition, injected current into the uC shall be lower than the maximum allowed (25 mA injected by all its I/O pins). Input pins are 15 (1 from BOOT mode, 7 DIP switches, 5 buttons, V_{SENSE} and 1 input from RS485 wire). Each pin shall allow 1.66 mA. Thus, minimum resistance to reach this condition is:

$$V = Imax \cdot R1$$

$$R1_{min} > \frac{3.3V}{1.66\,mA} = 1980\ \Omega$$

The resistance value shall be 1980 Ω<R1<80.3 kΩ. Selected value is 10 kΩ. Pull-up resistor values for DIP switches can be designed by this way, obtaining the same result.

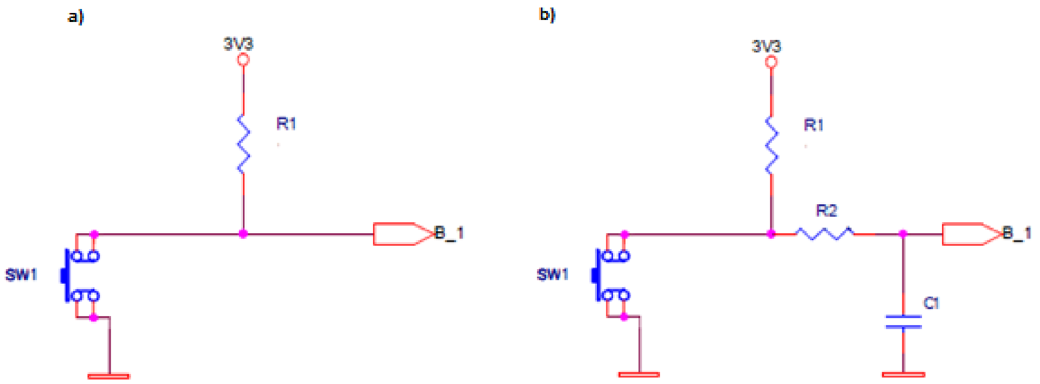

Figure 13. a) Pull-up button design, b) RC filter for button design

Furthermore, bounces can appear in buttons when voltage goes from 3.3 V to 0 V and backwards. To arrange it a RC filter is used. Figure 13.b shows the disposition of the components. An ordinary value for a τ of a debouncing circuitry is on the order of milliseconds. Value chosen in first instance is 10ms. If R2=10 kΩ, capacitor value is:

$$\tau = R2 \cdot C1 = 10\ ms$$

$$C1 = \frac{10ms}{10k\Omega} = 1\ uF$$

Adding this filter, circuit changes to:

$$V_{uC} = \frac{R_{100k}}{R_{100k} + (R1 + R3)} \cdot 3.3\ V = 2.75\ V > 1.83\ V$$

Worst voltage V_{uC} case is not a problem because it accomplishes the condition to be detected as a logic'1'. τ can be a problem because whether it is so large two consecutive button presses can be overlaid and took as a single one. As every kind of switch has got a different bounce response, capacitor value will be modified when testing if it is needed.

- **Alert Stage**

In this stage two needs shall be solved:

1) Buzzer shall sound to announce a warning. It can be an intermittent or a continuous sound depending on the kind of warning it is announcing.
2) When voltage supply is disconnected the shield shall detect it and alert the user by an intermittent alarm sound that shall remain enabled at least during two hours.

First necessity is solved by connecting the alarm device to the uC and putting the I/O pin in high or low. Second necessity needs a group of components to allow the alarm sound in case of supply failure. Two possibilities are considered for this purpose: doing it by firmware or by hardware. On one hand, a circuitry that allows an intermittent sound can be powered when supply fails using hardware while the rest of the shield is disconnected. On the other hand, firmware way is done by only supplying the uC and the buzzer. Firmware allows the uC to be in sleep mode until a certain time that wakes up to put in high the I/O buzzer pin. Considering them, hardware option is the chosen one.

This design is divided in three parts:

a) Train of pulses to obtain the intermittent sound.

A train of pulses in order to switch on and off the buzzer is designed. For this purpose it is used a 7555 (low consumption 555). Duty cycle shall be as low as possible to reduce current consumption and prolong as long as possible the warning time. A DC of 2% and 6 seconds between beeps are chosen.

$$DC = 0.02 = \frac{T_H}{T_H + T_L}$$

$$T_L = 0.125\ s; \quad T_H = 6\ s$$

To obtain a train of pulses with these features is needed an astable configuration but with the addition of a diode in parallel with R_B (see Figure 14) [6]. This diode allows the DC decrease more than the 50% and makes the capacitor charges only by R_A and discharges only by R_B:

$$T_H = 0.7 \cdot R_A C_1$$

$$T_L = 0.7 \cdot R_B C_1$$

If the value of the capacitor is set to 10uF R_A and R_B are:

$$R_A \cong 18\ k\Omega$$

$$R_B \cong 860\ k\Omega$$

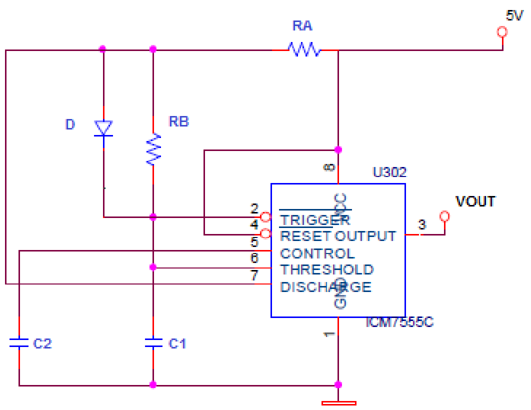

Figure 14. 7555 Timer design

b) Super-capacitor as a supply for more than two hours the alert stage.

- **Charging stage**

The amount of current that charges the capacitor shall be set to let the rest of the shield works properly. Supposing the rest of the shield can carry on its normal performance with less than 300 mA, it leaves 200 mA to charge the capacitor. In order to avoid making the converter supply its maximum current allowed, 110 mA are chosen to charge the capacitor.

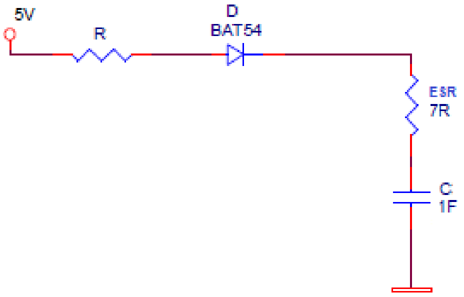

Figure 15. Charging stage design

In a first instance, V_C=0 (because capacitor is fully discharged), I_R= 110 mA and ESR=7 Ω. Diode's behavior changes during its operation. Depending on the amount of current that goes through it, more or less voltage is dissipated. When current is 110 mA, V_D=0.8 V and when $I_{charging} \cong$ 0 A $V_D \cong$ 0.2 V. So, to simplify the calculus it is supposed a constant voltage of V_D=0.5 V (average case).

$$Vin - V_R - V_D = V_C$$

$$Rc = \frac{5\,V - 0.5\,V}{110\,mA} = 40.9\ \Omega$$

$$R_c = R_{Ext} + ESR$$

$$R_{Ext} \cong 34\ \Omega$$

Now, with this value it is possible to calculate the charging time:

$$i_c(t) = Ie^{\frac{-t}{R_c C_1}}$$

When ic(t) = I/e time is equal to 1ꞇ. Knowing the value of ꞇ it is possible to calculate the charging time (T_{Charge}= 5ꞇ).

$$\mathrm{t} = ꞇ = R_c C_1 = 40.9\ s$$

$$T_{charge} = 5ꞇ \cong 205\ s$$

As a first approximation, it can be said that charging time is 205 s long. For being more accurate, this stage has been simulated giving a charging value of T_{charge}= 229 s. The difference between simulation and theoretical calculus is due to the approximation of the diode's behaviour and non-ideal components.

- **Discharging Stage**

In this stage there are two different current consumptions. During 6 seconds charging current is the one needed to supply 7555 timer and the oscillator circuit. During 125 ms, current consumed is the one needed to supply 7555 timer, the oscillator circuit and the buzzer. Thus, average current is:

	$I_{BUZZER\ (max)}$	$I_{7555\ (max)}$	$I_{OSCILLATOR}$	I_{TOTAL}
T_{6s} (98%)	0A	200 uA	2.19 uA	202.190 uA
T_{125ms} (2%)	3mA	200 uA	140 uA	3.314 mA
$I_{AVERAGE}$				264.346 uA

Table 6. Average Backup Current

Introducing this data into the next formula, discharge time is [7]:

$$T_{disch} = 0.8 \cdot \frac{C \cdot (V_o - IR_c - V_1)}{I + I_{Leakage}} = \frac{0.8 \cdot (4.8\,V - 264.346\,uA \cdot 7\Omega - 2\,V)}{264.346\,uA + 2\,uA} = 8404.55\,s$$

Discharge time is 2 h 20 min. This is a pessimistic value because it has been considered the 7555 worst current case and worst capacitance value (factor 0.8).

c) Detection of a supply disconnection.

It is needed a circuitry that allows charging the super-capacitor when voltage supply is connected. Also, when that happen the entire shield stops working except the buzzer and the 7555 to warn the user. These components shall be supplied by the super-cap. This performance is shown in final schematic in ANNEX 10. While voltage supply is powering the system, super capacitor is constantly charging and the PMOS avoids the current goes through the other components. When that voltage supply is disconnected, PMOS gate voltage is referred to ground and allows current going through it. Super capacitor starts discharging its voltage to power the 7555 oscillator and the buzzer. Simulation from alert stage can be seen in ANNEX 5.

- LCD

Backlight from LCD has to be designed considering that its current consumption is 260mA and its dissipated voltage is 4.2 V.

$$Vin - V_{BL} - V_R - V_{CEsat} = 0$$

$$R = \frac{5\,V - 4.2\,V - 0.1\,V}{260\,mA} = 3\,\Omega$$

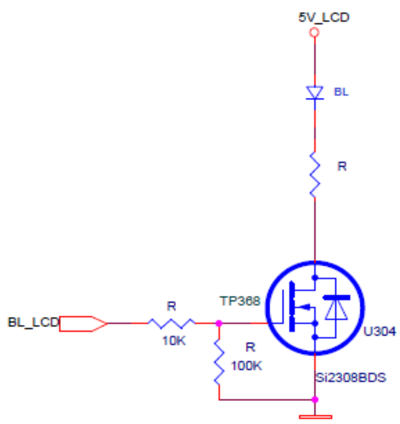

Figure 16.LCD backlight

When uC pin is giving logic '1' ON state and Ohmical region shall be assured:

$$V_{GS} > V_T$$

$$V_{uC} \cdot \frac{R_{100k}}{R_{100k} + R_{10k}} = 3\,V > 2.5\,V$$

It is working in ON state.

$$V_{DS} < V_{GS} - V_T$$

$$V_{5V} - I_{BL} \cdot R - V_{BL} - V_{CEsat} < 3\,V - 2.5\,V$$

$$0.02\,V < 0.5\,V$$

It is working in Ohmical region.

3.2. MTBF

Mean time between failures (MTBF) is used to measure the reliability of a repairable product [7][9]. It allows the engineer knowing the life time of the product designed. It is measured in hours and according with TELCORDIA's normative, Serial Repeater shall be at least 100.000 life hours.

Once applied this test, this product will be operative an average of 959.431 h. It is higher than the requirements, so this test is passed. Furthermore, its reliability during the first three years is 97%, is to say 3 of every 100 products will be repaired during these three years of performance (assuming three years of guarantee).

Brief explanation about the procedure followed to reach this value can be seen in ANNEX 2.

4. Results

The scope of this point is to describe and carry out all the necessary tests to evaluate the correct hardware design and performance of Serial Repeater. These tests shall be written in a document describing the steps followed to develop them. The aim of this document is to carry out the tests always in the same way and repeating the same steps (in case they have to be done twice or by another person).

4.1. Functional tests

4.1.1. Power stage

1) 24V to 5V

To check the correct DC/DC conversion some tests shall be done:

- **DC/DC converter frequency:** Minimum frequency value of the DC/DC converter stablished by C_T can be seen in Figure 17. It is the same value as the calculated in its design (headland 3.1.2).

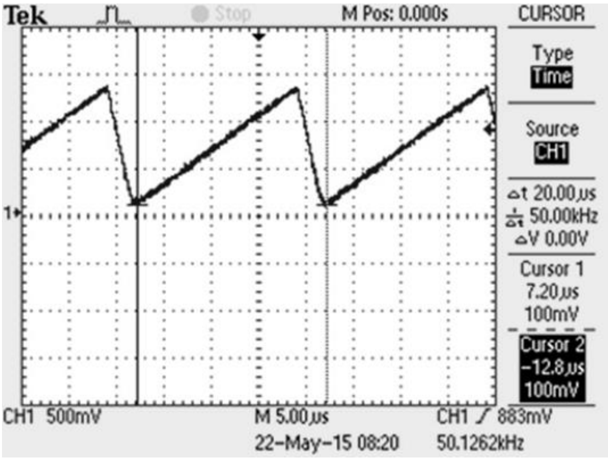

Figure 17. CT capacitor period

- **Line regulation:** This test analyses the ability to maintain the specified output voltage in case that input voltage varies. It is done by measuring converter V_{IN} and V_{OUT}.

	PROCEDURE	EXPECTED BEHAVIOUR	RESULTS
1	Adjust PS to 10V Measure 5V	24VIN = 10 V 5V = (4.95 - 5.05) [V]	24VIN = 10 V 5V=4.98 V
2	Adjust PS to 21.6V Measure 5V	24VIN = 21.6 V 5V = (4.95 - 5.05) [V]	24VIN = 21.6 V 5V=5.02 V
3	Adjust PS to 24V Measure 5V	24VIN = 24 V 5V = (4.95 - 5.05) [V]	24VIN = 24 V 5V=5.04 V
4	Adjust PS to 26.4V Measure 5V	24VIN = 26.4 V 5V = (4.95 - 5.05) [V]	24VIN = 26.4 V 5V=5.04 V
5	Adjust PS to 30V Measure 5V	24VIN = 30 V 5V = (4.95 - 5.05) [V]	24VIN = 30 V 5V=5.04 V

Table 7. Line Regulation test

Based on these results it can be said that this converter maintains the output voltage stable with an error of 60 mV.

- **Load regulation:** This test analyses the ability of the circuit to maintain the specified output voltage when demanded current (Io) changes. Steps to carry out this test are explained in ANNEX 6.

	PROCEDURE	RESULTS
1	Adjust PS to 24 V Adjust Io to 0.1 mA Measure 5 V Measure Iin	24VIN = 24 V Io=0.1 mA 5V=4.999 V Iin= 0.030 A
2	Adjust Io to 0.2 mA Measure 5 V Measure Iin	Io =0.2 mA 5V=4.995 V Iin=0.056 A
3	Adjust Io to 0.3 mA Measure 5 V Measure Iin	Io =0.3 mA 5V=4.994 V Iin=0.083 A

4	Adjust Io to 0.4 mA Measure 5 V Measure Iin	Io=0.4 mA 5V=4.990 V Iin=0.109 A
5	Adjust Io to 0.5 mA Measure 5 V Measure Iin	Io =0.5 mA 5V=4.978 V Iin=0.134 A

Table 8. Load Regulation test

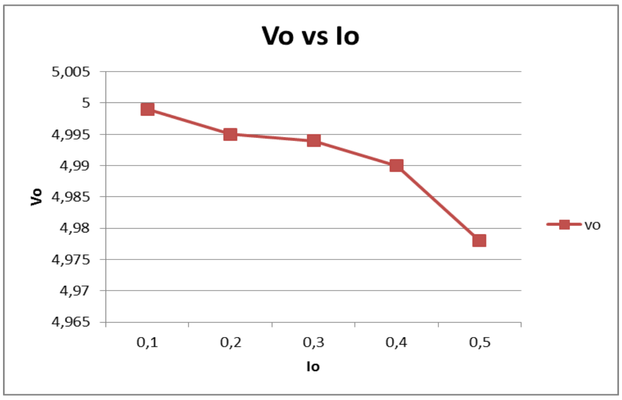

Figure 18. DC/DC converter Output voltage VS Output current

Figure 18 shows the accuracy of the circuitry to maintain a constant output voltage. This circuitry is able to maintain its output voltage with a maximum error of 21 mV. If output current increases, difference between desired output voltage value and the real one increases too.

- **Efficiency**: From Table 8 it is possible to calculate the converter's performance depending on the required output current. Efficiency goes from 69% to 77%.

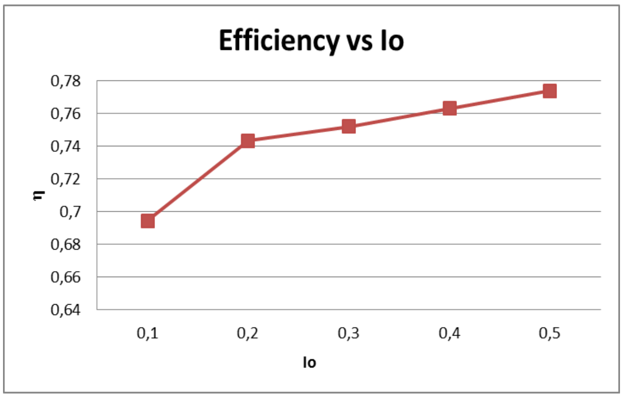

Figure 19. DC/DC efficiency VS Output current

- **Ripple voltage:** Output voltage contains a ripple overlaid to the constant 5 V. It was designed to be 25 mVpp but as it is a converter controlled by varying its duty cycle and its frequency at the same time, ripple voltage varies in each period. However, manufacturer from this device warns about that this result can happen, so it is a normal feature.

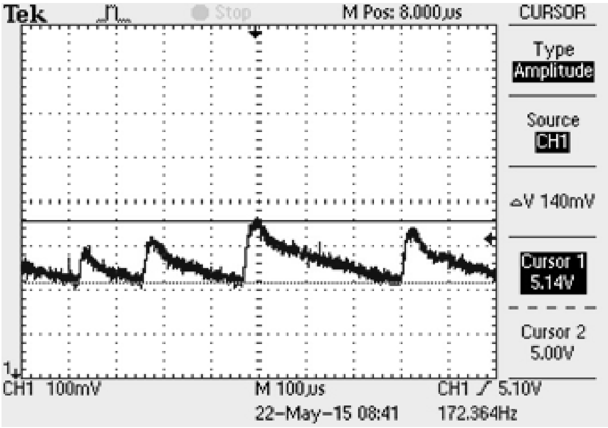

Figure 20. Output Ripple voltage

	PROCEDURE	EXPECTED BEHAVIOUR	RESULTS
1	Adjust PS to 24 V Measure Vripple 5 V	24VIN = 24 V Vripple(5 V) = 25 mVpp	24VIN = 24 V Vripple=140 mVpp

Table 9. Vripple test

- **Inductor output voltage:** Looking at Figure 21, voltage before going through the output inductor acts as it has been supposed in the previous design. This figure shows its discontinuous performance and matches with designed V_L, having as a maximum voltage 19 V in t_{on} and a minimum voltage of -5 V in t_{off}.

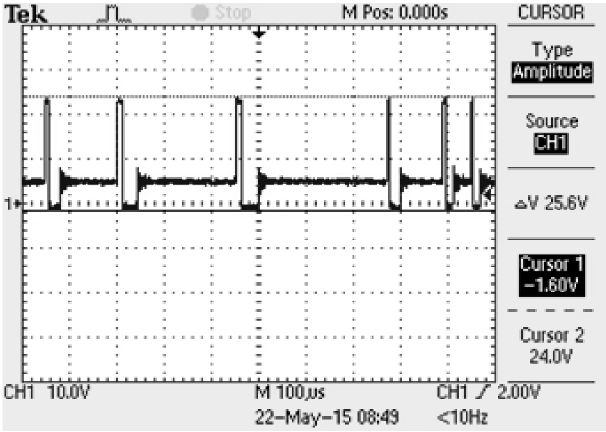

Figure 21. Output inductor voltage

1) 5V to 3.3V

For checking the correct regulator performance, output voltage is measured when input voltage changes. Output voltage variation doesn't affect other devices supplied to 3.3 V because its input voltage margin allows the maximum variation detected (ΔV=30 mV).

	PROCEDURE	EXPECTED BEHAVIOUR	RESULTS
1	Adjust PS to 10V Measure 3V3	24VIN = 10 V 3V3 = (3.267 – 3.333)[V]	24VIN = 10 V 3V3 = 3.30 V
2	Adjust PS to 21.6 V Measure 3V3	24VIN = 21.6 V 3V3 = (3.267 – 3.333)[V]	24VIN = 21.6 V 3V3 = 3.32 V
3	Adjust PS to 24 V Measure 3V3	24VIN = 24 V 3V3 = (3.267 – 3.333)[V]	24VIN = 24 V 3V3 = 3.32 V
4	Adjust PS to 26.4 V Measure 3V3	24VIN = 26.4 V 3V3 = (3.267 – 3.333)[V]	24VIN = 26.4 V 3V3 = 3.33 V

5	Adjust PS to 30 V Measure 3V3	24VIN = 30 V 3V3 = (3.267 – 3.333)[V]	24VIN = 30 V 3V3 = 3.33 V

Table 10. LD1117A test

2) 5V to 5V isolated

As in above regulator test, output voltage from the 5-to-5 V isolator is measured for different input values.

PROCEDURE		EXPECTED BEHAVIOUR	RESULTS
1	Adjust PS to 10 V Measure 5V_ISO	24VIN = 10 V 5V_ISO= (4.25-5.75) [V]	24VIN = 10 V 5V_ISO=5.44 V
2	Adjust PS to 21.6 V Measure 5V_ISO	24VIN = 21.6 V 5V_ISO= (4.25-5.75) [V]	24VIN = 21.6 V 5V_ISO=5.47 V
3	Adjust PS to 24 V Measure 5V_ISO	24VIN = 24 V 5V_ISO= (4.25-5.75) [V]	24VIN = 24 V 5V_ISO= 5.50 V
4	Adjust PS to 26.4 V Measure 5V_ISO	24VIN = 26.4 V 5V_ISO= (4.25-5.75) [V]	24VIN = 26.4 V 5V_ISO=5.63 V
5	Adjust PS to 30 V Measure 5V_ISO	24VIN = 30 V 5V_ISO= (4.25-5.75) [V]	24VIN = 30 V 5V_ISO=5.70 V

Table 11. FS0505M test

This device is not very accurate due to this variation of ΔV=0.26 V between the input and the output. Other better isolators could be chosen but considering that components supplied by it can work properly and its lower price against other converters this one is chosen for this purpose.

4.1.2. Microcontroller stage

1) Oscillator frequency

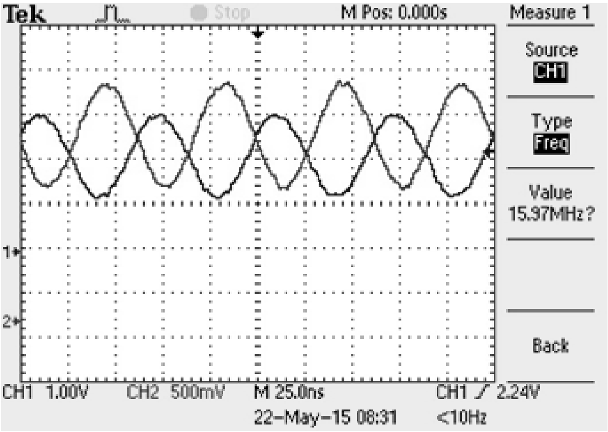

Figure 22. Oscillator voltage and its negative feedback

Oscillator frequency shall be checked to see if starting condition has been accomplished. As it can be seen in Figure 22, oscillator frequency is nearly 16 MHz (as designed in point 3.1.1.). Besides, V_{OUT} is the same as V_{IN} but amplified and moved 180º because it works in linear region and has got negative feedback.

2) Digital input pins

Docklight has been chosen to check the shield design. Docklight is a simulation tool for testing serial communications protocols (as RS485). Thanks to introducing a “hardware test” into the uC it is possible to send commands (previously defined in HW test) to the shield and be processed by the microcontroller to active or inactive GPIO pins and check PCB stages.

- **Buttons**

Figure 23 shows microcontroller input voltage coming from buttons. Without RC filter (left figure) few presses could be detected due to debouncing effect, but thanks to the filter (right figure) this problem is fixed. Design from headland 3.1.4 was oversized for this kind of buttons. With these values two consecutive presses could be overlaid and one of them loses its information. To avoid it C=100nF is used, reducing τ to 1ms (t_{disch}≈5 ms).

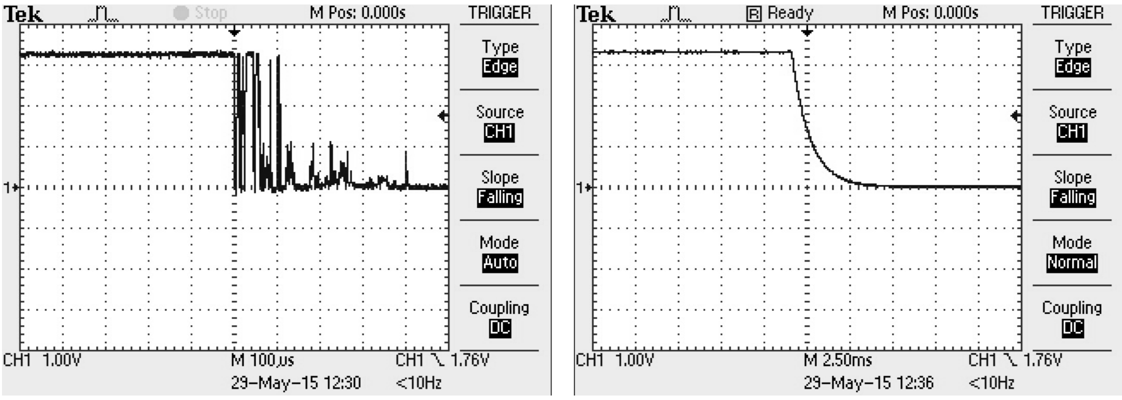

Figure 23. Button presses without and with RC filter

Besides, buttons are tested to know if analogic-digital conversion is done correctly.

	PROCEDURE	EXPECTED BEHAVIOUR	RESULTS
1	B_0 pushed	B_0<=1.16 V	B_0 = 0.601 V
	B_0 not pushed	B_0>=1.83 V	B_0 = 3.294 V
2	B_1 pushed	B_1<=1.16 V	B_1 = 0.606 V
	B_1 not pushed	B_1>=1.83 V	B_1 = 3.291 V
3	B_2 pushed	B_2<=1.16 V	B_2 = 0.608 V
	B_2 not pushed	B_2>=1.83 V	B_2 =3.291 V
4	B_3 pushed	B_3<=1.16 V	B_3 = 0.610 V
	B_3 not pushed	B_3>=1.83 V	B_3 = 3.280 V
5	B_4 pushed	B_4<=1.16 V	B_4 = 0.606 V
	B_4 not pushed	B_4>=1.83 V	B_4 = 3.290 V

Table 12. Buttons test

- **Dip-switch**

Same procedure as in previous section is done to test DIP-switches correct voltage detection.

	PROCEDURE	EXPECTED BEHAVIOUR	RESULTS
1	SW1_0 ‘ON’	SW1_0>=1.83 V	SW1_0=3.291 V
	SW1_0 ‘OFF’	SW1_0<=1.16 V	SW1_0=0.001 V
2	SW1_1 ‘ON’	SW1_1>=1.83 V	SW1_1=3.293 V
	SW1_1 ‘OFF’	SW1_1<=1.16 V	SW1_1=0.000 V

3	SW1_2 'ON' SW1_2 'OFF'	SW1_2>=1.83 V SW1_2<=1.16 V	SW1_2=3.290 V SW1_2=0.001 V
4	SW2_0 'ON' SW2_0 'OFF'	SW2_0>=1.83 V SW2_0<=1.16 V	SW2_0=3.294 V SW2_0=0.001 V
5	SW2_1 'ON' SW2_1 'OFF'	SW2_1>=1.83 V SW2_1<=1.16 V	SW2_1=3.290 V SW2_1=0.000 V
6	SW2_2 'ON' SW2_2 'OFF'	SW2_2>=1.83 V SW2_2<=1.16 V	SW2_2=3.291 V SW2_2=0.000 V
7	SW2_3 'ON' SW2_3 'OFF'	SW2_3>=1.83 V SW2_3<=1.16 V	SW2_3>=3.291 V SW2_3<=0.001 V

Table 13. DIP-Switch test

3) Digital Output pins

- **LEDs**

LEDs are checked by measuring its led voltage and current. Led voltage is measured with a tester. Led current is checked by measuring the voltage that drops in the resistance and applying Ohm's law.

PROCEDURE		EXPECTED BEHAVIOUR	RESULTS
1	Measure V_LED_L0 Measure I_LED_L0	V_LED_L0 =2.00 V I_LED_L0<=13.2 mA	V_LED_L0 =2.08 V I_LED_L0<=12.54 mA
2	Measure V_LED_L1 Measure I_LED_L1	V_LED_L1 =1.90 V I_LED_L1<=13.2 mA	V_LED_L1 =1.98 V I_LED_L1<=12.90 mA
3	Measure V_LED_L2 Measure I_LED_L2	V_LED_L2 =1.90 V I_LED_L2<=13.2 mA	V_LED_L2 =1.98 V I_LED_L2<=12.96 mA
4	Measure V_LED_L3 Measure I_LED_L3	V_LED_L3 =1.90 V I_LED_L3<=13.2 mA	V_LED_L3 =1.99 V I_LED_L3<=12.97 mA
5	Measure V_LED_L4 Measure I_LED_L4	V_LED_L4=1.90 V I_LED_L4<=13.2 mA	V_LED_L4=1.95 V I_LED_L4<=13.10 mA
6	Measure V_LED_L5 Measure I_LED_L5	V_LED_L5=1.90 V I_LED_L5<=13.2 mA	V_LED_L5=1.98 V I_LED_L5<=13.00 mA
7	Measure V_LED_L6 Measure I_LED_L6	V_LED_L6 =1.90 V I_LED_L6<=13.2 mA	V_LED_L6 =1.98 V I_LED_L6<=13.00 mA
8	Measure V_LED_L7 Measure I_LED_L7	V_LED_L7=1.90 V I_LED_L7<=13.2 mA	V_LED_L7=1.98 V I_LED_L7<=12.9 mA
9	Measure V_LED_L8 Measure I_LED_L8	V_LED_L8=1.90 V I_LED_L8<=13.2 mA	V_LED_L8=1.95 V I_LED_L8<=13.13 mA
10	Measure V_LED_L9 Measure I_LED_L9	V_LED_L9 =1.90 V I_LED_L9<=13.2 mA	V_LED_L9 =1.94 V I_LED_L9<=13.13 mA
11	Measure V_LED_L10 Measure I_LED_L10	V_LED_L10 =1.90 V I_LED_L10<=13.2 mA	V_LED_L10 =1.93 V I_LED_L10<=13.22 mA

Table 14. LEDs test

Values obtained are similar to the values expected with little variation that does not affect the correct performance of the LEDs.

- **Buzzer**

In alert stage shall be verified that buzzer sounds when microcontroller asks for it.

PROCEDURE		EXPECTED BEHAVIOUR	RESULTS
1	BUZZ_1 'ON'	Buzzer sounding	OK

Table 15. Buzzer test

4) Analog input pins

To check the correct performance of the analogic read from V_{SENSE} these input values have been measured for different V_{IN} and calculate the error rate between the expected value and the obtained one. Difference between them is as maximum a 2%. It can be caused by the resistor tolerances (1% each one). Thus, it can be concluded that V_{SENSE} takes values accurately.

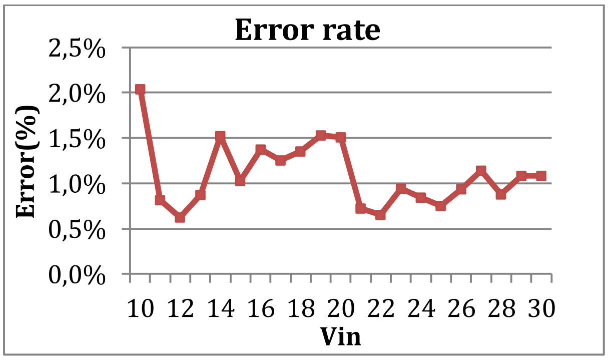

Figure 24. Error rate in VSENSE acquisition

5) Alert stage

When power supply is disconnected buzzer shall sound intermittently. To check it, some steps have to be followed:

PROCEDURE		EXPECTED BEHAVIOUR	RESULTS
1	Capacitor totally discharged Connect PS Measure charging time	V_{Cap}=0.00 V T≈229 s	V_{Cap}=0.00 V T=238 s
2	Capacitor fully charged Disconnect PS Measure discharging time	V_{Cap}=4.80 V Must be: T>=1 h Expectation: T= 8.77 ks ≈ 2 h 28 min	V_{Cap}=4.82 V T=9923s ≈ 2 h 45 min
3	Disconnect PS Measure T_{ON} from 7555 output Measure T_{OFF} from 7555 output	T_{ON}= 125 ms T_{OFF}=6 s	TON= 120 ms TOFF=6 s

Table 16. Alert stage test

Figure 25 shows the capacitor's charging stage. Capacitor is totally full when it gets 4.8 V. After charging 238 s it reaches 4.75 V (at 99% it is considered full).

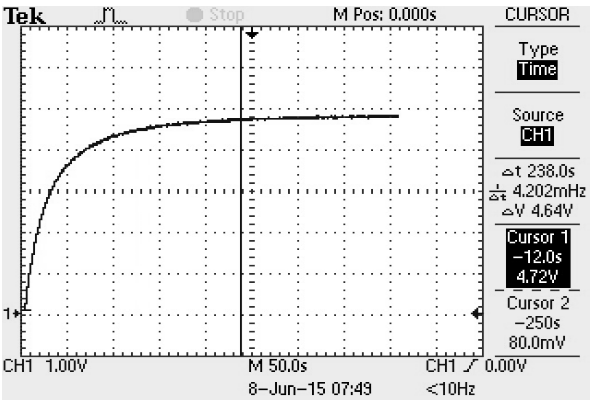

Figure 25. Capacitor's charging time

Discharging time has been measured every 15 minutes in order to check if it reaches the minimum conditions stablished in product specifications. Figure 26 shows capacitor's voltage discharge graphic. Red line is voltage from the capacitor and green line is the alert stage performance limit. It is conditioned by the minimum voltage supply that 7555 timer needs to work (2 V).

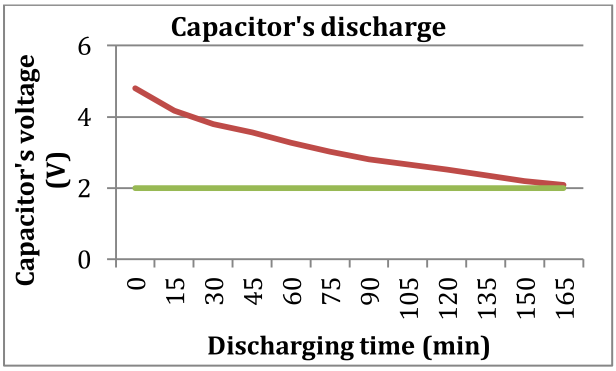

Figure 26. Capacitor's discharging time

T_{ON} (125 ms) and T_{OFF} (6 s) from timer 7555 are checked. Values match with theoretical estimation.

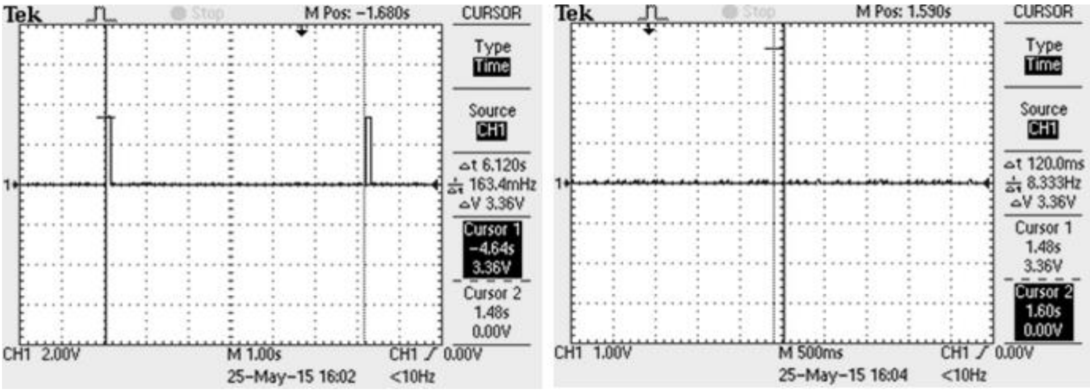

Figure 27. 7555 timings

4.2. Environmental test

In this stage thermal scanner test is done. It allows knowing the maximum shield temperature in operating condition and if it would be able to work in all its temperature range. This test is not normative but increases PCB reliability and quality.

At 27ºC, maximum temperature that the shield reaches is 39.4ºC. Then, ΔT=12.4ºC. As temperature acts like an offset, at maximum temperature that the Repeater shall work (50ºC) it would be at 62.4ºC. This maximum peak is obtained in both DC/DC converters (24V to 5 V and 5 V to 5 V isolated). All the components are able work at this temperature, so it can be said that the PCB works properly in all its temperature range.

Report from this test can be seen in ANNEX 7.

4.3. EMC tests

EMC tests shall apply to components that are going to be used in and around buildings in commercial, residential or industrial environments to assure its satisfactory operation in these places. In order to be a CE commercial product, Serial Repeater shall pass EMC tests shown in next table.

Test			Normative applied	Characteristics	Result
1	Conducted emissions Telecoms networks		EN61000-6-3: 2011	-	N.A.
2	Electrical safety		EN60950-1: 2011	-	N.A.
3	Surge	Over PS	EN 61000-4-5: 2006	I/O lines, common mode, 1 kV	N.A.
		Over RS485			PASSED
4	Fast transient / Burst	Over PS	EN61000-4-4: 2010	I/O lines, 1 kV	PASSED
		Over RS485			PASSED
5	ESD	Direct	EN61000-4-2: 2009	±2 kV, ±4 kV, ±6 kV, 10 discharges per voltage/polarity	STBY
		Indirect			PASSED
6	Conducted RFI	Over PS	EN 61000-4-6: 2009	All lines, 0.15–100 MHz, 10 V, AM 1 kHz/80%	STBY
		Over RS485			
7	Radiated Emissions test		EN61000-6-3: 2011	Enclosure, 30 MHz-1 GHz	STBY
8	Radiated Immunity Test		EN 61000-4-3: 2010	Enclosure, 80-2700 MHz, 10 V/m,/ AM 1 kHz/80%, 4 orientations, 2 polarizations	PASSED

Table 17. EMC tests

All setups, procedure and results of these tests are available in ANNEX 8.

5. Budget

In this section price of the project is analyzed. In an industrial environment, when prototyping, more than one product is made in order to work in parallel in hardware, mechanical and software development. In this case, 6 prototypes have been made.

- **Software Licenses**
  Licenses for software required to develop this project (ORCAD, Detectus AB, FreeCad, Visual Studio 2010, Docklight, Solid Edge, etc.) are provided by the enterprise for free, so it cannot be considered as a cost for this project. For this reason, software price is 0,00€.

- **Shield fabrication**
  Shield fabrication has been made in CIDEIN S.L. Diseño Circuitos Impresos. Total price for 6 shields is 356.28€.

- **Components**
  All components weld on one single shield cost 70.69€. Key used to enable or disable one of the buttons is 16.43€. Adding this prices, total component amount will be 87.12€ per shield, making a total of 522.72€ for 6 shields.

- **Housing**
  Housing is composed by three pieces. A silicon mold is needed for each piece in order to make the plastic pieces of the housing. Two of the molds (covers) cost 1000€ each one. Each single piece made in these molds costs 50€. The other mold (hold for LCD) costs 500€. Each piece made in this mold costs 30€.
  Thus, molds cost 2500€ and pieces for 6 prototypes cost 780€.

- **Hours spent**
  This project has been developed in 5 months, working 35hours/week. It is considered an average of 4 weeks worked per month. Bearing in mind that a junior engineer salary is 8€/hour, the total salary paid is 5600€.
  Housing has been done by a mechanical engineer in 10 days, 4h/day. A mechanical engineer salary is 15€/hour. Then, total salary is 600€.

Finally, adding all this costs, total price for six Serial Repeater prototypes is 10.359,00€. For more detailed information about price components and final price see ANNEX 9.

6. Conclusions and future development:

Main goal of this project is to develop in an industrial environment a PCB Repeater design in accordance to specifications provided by the client. Main blocks are Requirement's Documentation stage, Design stage and Validation stage, which includes functional and EMC tests.

As a result for this project it can be said that all the requirements specified in the Requirement's document have been fulfilled as expected. Functional and EMC tests are accomplished with the exception of Direct ESD and the tests that require firmware. But talking in hardware terms, all tests have passed successfully.

From my personal point of view, all work done has been very rewarding because:

- I had the opportunity of working in an industrial environment in the same conditions as if I were part of the enterprise staff.
- I dealt with all processes needed to carry out a product in an industrial and professional environment.
- I have learnt about Normative applied to electrical products that need to accomplish CE normative.
- I have been able to apply concepts learnt during university years.
- I have dealt with some software and tools that allowed me to design and simulate my work.
- I have learnt how to realize EMC tests with official equipment and I have applied this knowledge to check my shield.

Future work shall be:

- New shield iteration shall be built with all the corrections made.
- When firmware is developed, do the EMC remaining tests.
- Keypad implementation shall be done. This is the last step to be done in the design because it is customized (it is designed in an external enterprise).
- Send it to APLUS laboratory to obtain CE certificate.
- Send all the documents needed (Gerber's, schematic, housing files…) to industry to begin fabrication.

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8. Glossary

Acronym	Meaning
LCD	Lliquid Crystal Display
LED	Light Emmiting Diode
CPU	Central Processing Unit
uC	Microcontroller
SR	Serial Repeater
ESD	Electrostatic Discharge
EMC	Electromagnetic Compatibility
AWG	American Wire Gauge
ROHS	Restriction of Hazardous Substances
SMD	Surface Mount Device
WEEE	Waste Electrical and Electronic Equipment
IP	International Protection
JTAG	Joint Test Action Group
PCB	Printed Circuit Board
MTBF	Mean Time Between Failures
PS	Power Supply
DC	Duty cycle
GPIO	General pin input output
CDN	Coupling/Decoupling Network
TP	Test Point
EUT	Equipment Under Test
PL	Part List