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Development and Performance Evaluation of Wi-Fi Wake-up Radio

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by

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Abstract

This thesis illustrates all the phases to realize a switch system based on a Wi-Fi Wake Up Call. When a wake-up-call is generated, a receiver based on the Austria Microsystem AS3933 sends an interrupt to a microcontroller that immediately drives the switch system to turn on a Wi-Fi access point. A current measurement circuit communicates with the microcontroller in order to inform it when there is no user connected to the access point and it can be finally turned off, eliminating the standby power. Additionally, the system can be turned off remotely, by means of a second wake-up-call.

The aim of this work is to design, create and evaluate the performance of such a system so that it is possible to estimate how much power can be saved in several kinds of environments, like in an offices building, in a university campus or at home.

All the work is focused on the switch-on and switch-off of a specific model of access point, an implementation that serves as a proof of concept, but it is also our aim to provide a more universal solution: the design of an intelligent switch, which is activated from any Wi-Fi device, capable to turn on and off any electrical appliance. For this reason, all the chapters are divided in two sections: DC solution and AC solution.

The DC solution is powered with the 12 Volts provided by the power adapter of the access point. Then, it is suitable for the specific case of the selected access point but also for all the DC devices that are in the electrical ranges of the designed components.

The AC solution is powered directly from the mains voltage and can be considered as a universal solution within the limits of each designed component.

The current measurement circuit assesses when there is an operational mode (standby mode, for example) with the current consumption different from the active mode current consumption.

Moreover, both for the DC solution and the AC solution, a 3.3V power converter has been designed and created. For the DC solution, the conversion from 12V to 3.3V has been done with a voltage regulator. For the AC solution, a not-isolated capacitive power supply converts the mains voltage to 3.3V.

After a cost evaluation of the designed product, a return on investment analysis has been done in order to estimate after how much time it is possible to have back the money used to make this purchase, for three different scenarios.

Finally a market survey has been done in order to compare the designed switch system based on the WuC (with an estimated price of 15.2€) to similar products in the market.

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1 Introduction

The purpose of this thesis is to design and implement a switch system based on a Wi-Fi Wake-Up-Call (WuC), generated by a wake-up radio receiver, employing AS3933 chip by Austria Microsystem [1]. When a WuC is generated, a microcontroller (in our case, a MSP430F2350 by Texas Instruments) receives an interrupt and immediately drives the switch system to turn on/off a Wi-Fi access point. A current measurement circuit communicates with the microcontroller in order to inform it when there is no user connected to the access point, indicating it can be finally turned off, and eliminating the standby power.

The microcontroller and the Wake-Up Receiver can work thanks to a lithium battery of 3V but it is unhandy for a user to change it every time it is discharged. Therefore, some solutions for a 3.3V power converter will be also provided.

Figure 1 shows the board and its main components, i.e. the AS3933 receiver and the MSP430F2350 microcontroller.

In the following sections this board will be called "WuRx board".

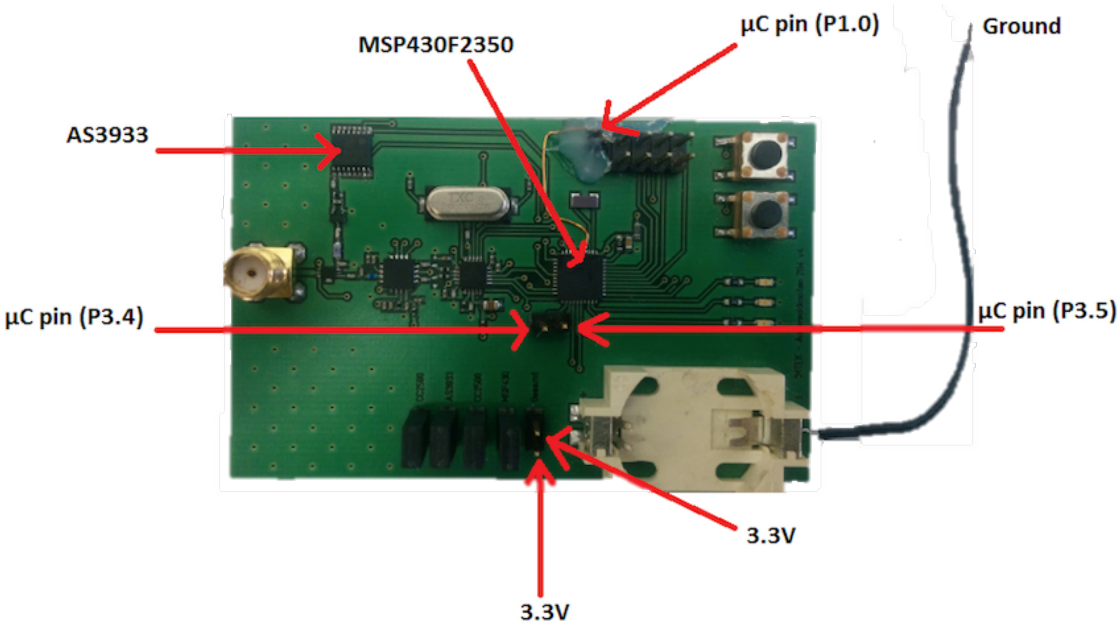

Figure 1. WuRx board

1.1 Wake-Up-Call generation

The AS3933 chip is a 15-150 kHz receiver that sends a Wake-Up interrupt when its address has been detected in a wake-up call. In order to generate the wake-up call, a protocol has to be followed [1]. An initial carrier burst, followed by a separation bit (a '0'), triggers the WuC-decoding procedure. Afterwards, a preamble, that is a 14-bit sequence of ones and zeros (1010..), delimits the bit length at the WuRx. Finally, a 16-

bit pattern is transmitted. If the pattern corresponds to the address of the intended receiver, the Wake-Up interrupt is generated.

Figure 2 shows the protocol to generate the Wake-Up call (WuC).

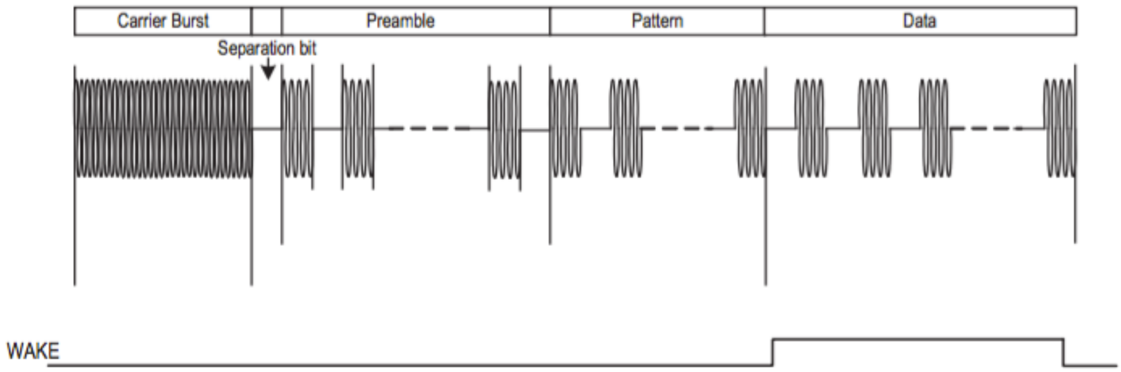

Figure 2. Wake-Up protocol

The AS3933 chip is an OOK receiver so that a carrier of duration of one bit corresponds to a ‘1’ and a no-signal time of duration of one bit corresponds to a ‘0’.

Figure 3 shows the time behavior of the received sequence when the receiver's address is 0xB3B3. The bit-rate has been set to 0.9kHz so that the bit duration is about 1.2ms.

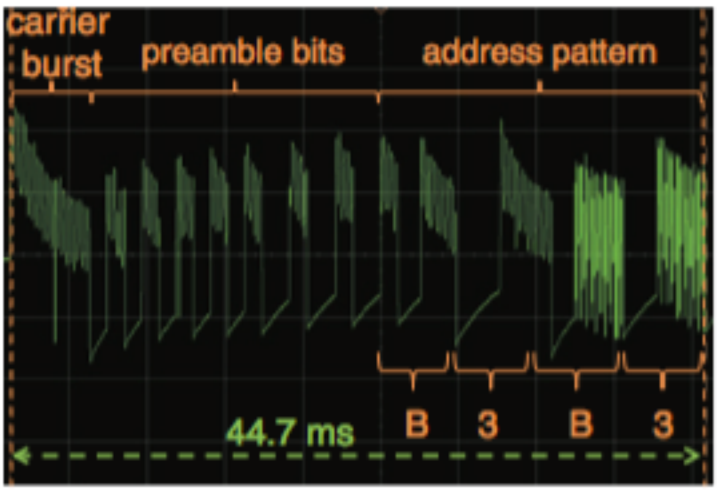

Figure 3. Time behavior of a WuC generation

The microcontroller will receive the interrupt caused by the Wake Up signal after a certain delay (1.17ms). Hence, the total wake-up latency is 45.87ms (44.7ms+1.17ms).

1.2 Wake-Up protocol generation

The data slicer in the WuRx is configured to operate at 0.9kbit/s, which corresponds to a single-bit duration of 1.12ms

The WuC signal is modulated by OOK. Then, a bit is received in the following way:

- ‘1’ -> a carrier of about 15kHz has to be received for about 20 periods;
- ‘0’ -> nothing should be received for the bit duration.

The carrier is generated with a subcarrier modulation technique. A 2.4GHz Wi-Fi signal is sent for about 34µs and a no-signal is sent for about 28µs. The AS3933 chip interprets the 2.4GHz signal as a ‘1’ and the no-signal as a ‘0’, obtaining a wave with a period of 62µs (16kHz). Then, as shown in *Figure 4*, to receive a ‘1’, that is the 16kHz carrier for the bit duration, the sequence formed by the 2.4GHz signal and a no-signal has to be sent about 22 times; conversely, to receive a ‘0’ only a no-signal for the bit duration is enough.

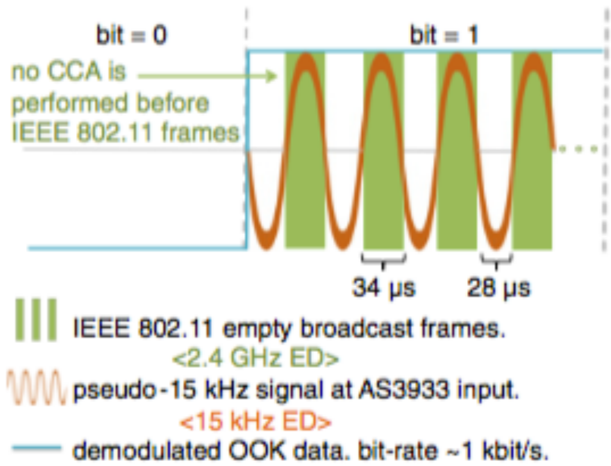

Figure 4. shaping 15kHz carrier by a 2.4GHz signal

1.3 Switch system

Figure 5 shows the switch system that we want to implement.

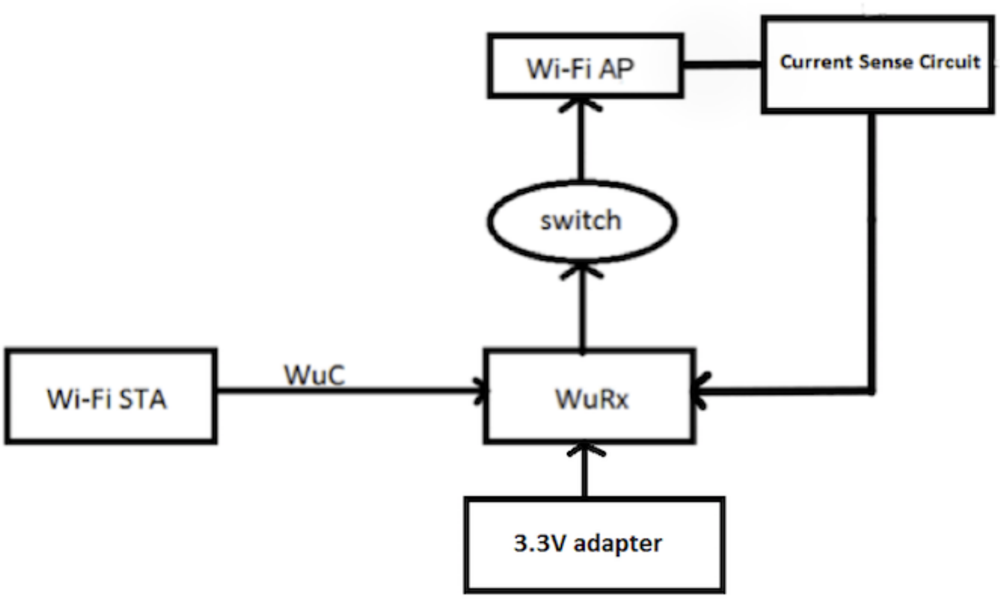

Figure 5. WuRx switch system overview

- Wi-Fi STA (WuTx): a Linux user-level application is used to generate the Wake-Up-Call using the Wi-Fi 2.4GHz signal by means of an off-the-shelf Wi-Fi device.
- WuRx: it is based on an AS3933 chip from Austria Microsystems and generates an interrupt to the microcontroller when the device's address is detected. The microcontroller will drive the switch when an interrupt is detected.
- Switch: the purpose of the switch is to turn on/off the access point after a WuC.
- Wi-Fi AP: a TP-LINK, TL-WR1043ND model has been used.
- Current sensing circuit: this circuit measures the current consumed by the AP and informs the microcontroller when no users are connected. The microcontroller then will drive the switch to turn off the access point.
- 3.3V adapter: a 3.3V converter has to power the WuRx board.

The thesis' work will focus mainly on the design of the switch, the current sensing circuit and the 3.3V power adapter.

1.4 Summary of the thesis's work

The thesis work has been developed following four chronological phases.

<u>Phase 1 (chapter 2-3)</u>

Design and implement the switch system in order to switch on/off the access point. Provide and compare different solutions in terms of performances and costs.

Phase 2 (chapter 4)

For each one of the different switch solutions, design and implement a current measurement circuit.

Phase 3 (chapter 5)

For each one of the different switch solutions, design and implement a 3.3V power converter.

Phase 4 (chapter 6)

Performance evaluation of the overall system, evaluation of the price of the designed product, impact on the electricity bill, return to investment analysis and comparison with the other products in the market.

2 Switch Circuit – Design

2.1 Configurations and technical specifications

The switch, used to turn on and turn off the access point, can be placed following two configurations, namely DC and AC configuration.

DC configuration

The switch is placed between the output of the power adapter and the electrical appliance (i.e. the Wi-Fi access point):

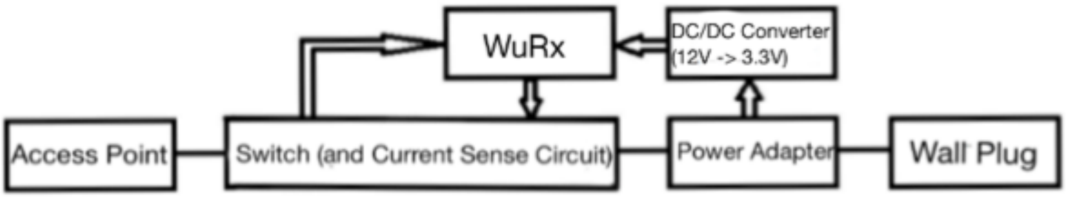

Figure 6. DC configuration

AC configuration

The switch is placed between the wall plug and the input of the power adapter:

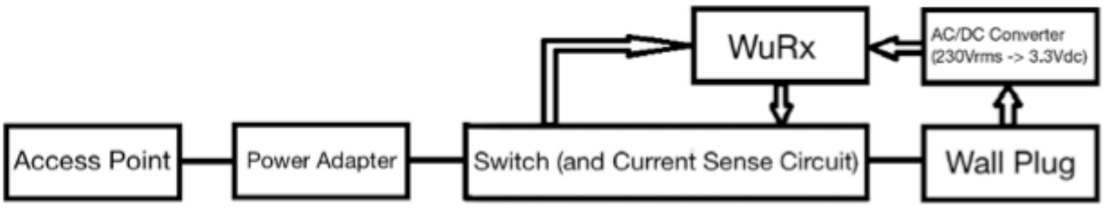

Figure 7. AC configuration

The design and implementation of the ``Current Sensing Circuit`` is provided in chapter 4.

The WuRx board has to be powered with a tension of about 3.3V. Then a DC/DC converter (DC configuration) and an AC/DC converter (AC configuration) will be designed and implemented (chapter 5).

Wall Plug: 100-240Vrms, 50/60Hz

- In Europe: 230Vrms, 50Hz

Power Adapter:

- Input: 100-240V, 50/60Hz, 0.6A (rms values)
- Output: 12V, 1.5A

  Note: the considered power adapter is the one included in the box of the *TP-LINK TL-WR1043ND* but its characteristics are common in most access point adapters.

2.2 Overview of the switch devices

In order to design a switch system that can work with 240Vrms or 12Vdc and that can be controlled from the microcontroller installed on the WuRx board, the switching circuit can make use of:

- a mechanical relay;
- a solid state relay;
- a high side switch.

The mechanical relay is a device that is able to open or close the circuit using an electromagnetic coil that, depending on the current that runs on it, will generate an electromagnetic field and will control the contacts. The main contribution to the power consumption will be at its input: the output of the microcontroller should provide enough current to power the relay's coil; at the output, the contact resistance should be very low and the power consumption should be negligible.

There are several kinds of mechanical relays. For our purposes, the no-latching relays and the latching relays have been considered. The no-latching type will consume power for the whole ON-state period, while the latching type will consume power only during the switching period. The latter option will need two I/O pin of the microcontroller in order to be controlled.

The solid-state relay is a device that is able to open or close the circuit thanks to solid-state devices and avoiding the use of mechanical components that can generate some contact failures. In our case, the system is not real-time and the contact failures can be managed easily via software. The main contribution to the power consumption will be at the output: in the ON-state its behavior is like a resistance that will consume power; at the input, the required current is very low and consequently also the input power consumption.

These two solutions provide also isolation between the microcontroller and the load: if there are some problems on the load, they will not affect the WuRx board.

The high side switch is a solution suitable only for the first configuration because it is an integrated circuit that generally works with low DC voltages. It does not provide any kind of isolation. It also uses a solid-state technology (MOSFET devices) and it also has an ON-state resistance that will contribute to the output power consumption. At the input, it requires a really low current and can be directly connected to the I/O pin of the microcontroller without using any transistor to amplify it.

The following solutions are the result of a long selection over the thousands of available components from the website http://www.mouser.es. For each of the different kinds of solutions, a trade off between the estimated power consumption and the price has been taken into account.

2.3 Chosen Switch Components: DC configuration

In the first configuration, the solution has to be able to switch 12 Volts DC, which corresponds to the voltage level after the power adapter.

2.3.1 First solution DC: mechanical relay (no-latching type)

http://www.mouser.es/ProductDetail/TE-Connectivity/IM21GR/?qs=%2fha2pyFadugbfSO99b0JVw4bqLEe6Jb%2fQ6DMPa4A7yg%3d

- Price: 4.37€
- Input power consumption: 50mW
- Switching voltage (max): 220V DC
- Switching power (max): 60W

In order to energize the coil we need a current of about 17mA that cannot be gotten directly from the microcontroller; for this reason we need also a transistor that amplifies the output current of the I/O pin. Moreover we need a resistance to limit the current on the transistor base and a diode that provides protection from the back electromotive force when the switch is turned off (the large dI/dt across the inductor induces a large voltage).

2.3.2 Second solution DC: solid-state relay

http://www.mouser.es/ProductDetail/Toshiba/TLP3107F/?qs=%2fha2pyFaduh%2fuNp7WSdztVV1nglNdqUxjtCQAfMkh30%3d

- Price: 5.09€
- Maximum output power consumption: 18mW
- Switching voltage (max): 60V DC
- Switching current (max): 6.6A

It needs an input resistance to regulate the required current.

2.3.3 Third solution DC: smart high side switches

This high side switch has also a current sense pin that can be useful for the current measurement circuit.

http://www.mouser.es/ProductDetail/STMicroelectronics/VN5016AJ-E/?qs=sGAEpiMZZMuycWE%2fmH8IEiQ9rZtCLEnT

- Price: 2.61€
- Maximum output power consumption: 37.5mW
- Switching voltage (max): 41V DC
- Switching current (max): 65A

This device is CMOS compatible: this means that we can directly connect it to the I/O pin of the microcontroller.

2.4 Chosen Switch Components: AC configuration

In the second configuration the solution has to be able to switch 240 Volts AC (rms), in order to be universal.

2.4.1 First solution AC: mechanical relay (no-latching type)

http://www.mouser.es/ProductDetail/Panasonic-Industrial-Devices/PQ1A-3V/?qs=sGAEpiMZZMtSzCF3XBhmWw%2feQuZY3rqGRkMBi%2fF1Wmc%3d

- Price: 5.38€
- Input power consumption: 200mW
- Switching voltage (max): 250V AC
- Switching power (max): 1250VA

As for the mechanical relay of the first configuration, we need also a resistance, a diode and a transistor that will provide about 67mA in order to energize the coil.

2.4.2 Second solution AC: mechanical relay (latching type)

As already said, a latching relay maintains the contact position indefinitely without power applied to the coil. This means that the relay will consume power only during the switching instant.

http://www.mouser.es/ProductDetail/Panasonic-Industrial-Devices/ADW1103HTW/?qs=sGAEpiMZZMtSzCF3XBhmWz%252bafTQf0zMRjfejDynr1lE%3d

- Price: 6.82€
- Input power consumption: 200mW (during the switching period)
- Switching voltage (max): 277V AC
- Switching power (max): 4432VA

It needs two I/O pins in order to energize and de-energize the coil. For this purpose, rather than using the doubled amount of discrete components (with respect to the previous mechanical relay), it is possible to use an integrated circuit (MDC3105DMT1G) with the two transistors with the related two resistances and the diodes embedded:

http://www.mouser.es/ProductDetail/ON-Semiconductor/MDC3105DMT1G/?qs=HVbQlW5zcXWy6iE5QBzlyg%3d%3d

- Price: 0.434€

- Optimized to switch relays from a 3V to 5V coil

Other two PNP transistors with their base resistances are needed to give the correct voltage to the coil.

2.4.3 Third solution AC: solid-state relay

Contrary to the MOSFET-based solid-state relay of the first configuration, this relay should manage a very high AC voltage and the MOSFET is now substituted with a TRIAC.

http://www.mouser.es/ProductDetail/Fairchild-Semiconductor/MOC3023M/?qs=sGAEpiMZZMteimceiIVCB7OZToIkTRfkeqjFyqqZkaw%3d

- Price: 0.512€
- Switching voltage (max): 400Vpk

This optocoupler provide isolation between load and microcontroller but it cannot provide enough current to the load; then it will drive another more powerful TRIAC.

http://www.mouser.es/ProductDetail/NXP-Semiconductors/BT136-600127/?qs=sGAEpiMZZMuAO0%252bGuNbnQsYOkIrSb%2f6XuSHxirJJK%2f8%3d

- Price: 0.57€
- Output power consumption: 500mW
- Switching voltage (max): 600Vpk
- Switching current (max): 4Arms

As for the solid-state relay of the first configuration, a resistance will regulate the input current. Moreover, as suggested by the datasheet of the optocoupler, two snubber circuits, constituted by resistances and capacitors, have to be added in order to avoid breaking the circuit after a high dV/dt. These components will contribute to the output power consumption not only in the ON state but also in the OFF state because they add two more paths for the current.

2.5 Considerations about mechanical relays versus solid-state relays [7]

- A solid-state relay has a longer life than a mechanical relay and it is faster (please refer to the number of operations and the ON/OFF time in *Table 1*).
- A mechanical relay is more bulky (please refer to the size information in *Table 1*).
- The input power of the mechanical relay is the power that it needs in order to work correctly. In the solid-state relay the working principle is different and the input current determines the switching time. Anyway it is lower than the current required from a mechanical relay (see chapter 3).
- For the solid state solutions, a maximum output power consumption has been estimated considering the maximum ON-state current that the load (access point or access point – power adapter) consumes in the two different

configurations (1.5A and 0.6A rms); for the mechanical relay the datasheets do not provide enough information about the contact resistance and the exact output power consumption has been evaluated in the measurements phase (chapter 3).

- Contrary to the mechanical relays, in the OFF-state a solid-state relay is not an exact open circuit but it will have a leakage current of the microampere order and it will contribute to the power consumption but in a really low way.

2.6 Considerations about the first (DC) versus the second (AC) configuration

In the first configuration the found solutions lead to lower power consumptions compared to the second configuration. Actually, for the second configuration, the choice of a latching relay can be interesting if we have to provide the power for long periods; on the other hand, it is useless if the power has to be frequently switched (it would be more complicate to implement and would have the same performance of a no-latching type).

The second configuration has the advantage that eases the design of a more universal solution, beyond the particular case of the access point since many kinds of devices can use this mechanism in order to save power. Obviously, depending on the final chosen switch, it will have a maximum switching voltage value as well as a maximum switching current value.

2.7 Summary of the solutions and final chosen solutions

In the following table there is a summary of the several solutions. The final chosen solutions that will be better analyzed in chapter 3 are highlighted. In this table there are also more details about the turn on/off time, the size and the life of the components. The size of each component does not characterize the size of the complete switch system because in the circuitry there can be also resistances, capacitors or other transistors.

The datasheet of the components sometimes provides only maximum/minimum ratings and sometimes there is no information about some negligible data. For this reason in some boxes of the table the symbols “<” or ”>” (maximum/minimum rating) or “-” (there is no information) have been used.

Name	Price (€)	Rating	In. Curr (mA)	ON Time (ms)	OFF Time (ms)	Input Power (mW)	Out. Power (mW)	N° Oper	Size (mmxmmxmm)
DC Solution									
IM21GR	4.37	60W, 62.5VA	16.67	1 (typ.)	3 (typ.)	50.0 no-latching type	-	10^8	10x5.65x6
TLP3107F	5.09	60V, 6.6A	>5.0	0.6 (typ. @lin)	0.2 (typ. @lin)	16.5 @lin	18.0	inf	4.4x6.3x2.1
VN5016AJ-E	2.61	41V, 65A	<0.01	0.035 (typ.)	0.050 (typ.)	<0.033	37.5	inf	4.8x1.25x3.8
AC Solution									
PQ1A-3V	5.38	150W, 1250VA	66.7	<20	<10	200.0 no-latching type	-	2x10^7	10.4x20.8x15.6
ADW1103HTW	6.82	4432VA	66.7	<15	<15	200.0 latching type	-	10^6	10.4x25x18.8 (only relay)
MOC3023M + BT136-600	0.512 + 0.57	600Vpk, 4Arms	>5	-	-	>16.5	>500.0	inf	8.89x6.6x5.08 + 4.7x16x10.3

Table 1. Summary of the switch solutions

For the DC configuration, it is expected that the behavior of the mechanical relay will be worse than that of the solid-state relay or the high side switch. Then these last two solutions will be analyzed in detail and compared after a measurements phase.

For the AC configuration, the latching relay is a little bit more expensive than the no-latching relay, but the latching one can be perfect for our purposes (we estimate that a user will use the access point for a long time and there will not be a continuous switching). On the other side, the solid-state relay will consume more yet it is really low cost. For these reasons, the latching relay and the solid state solution will be evaluated in detail and compared after a measurements phase (chapter 3) also in terms of price: how much will be the price of the final product and how much will be the saving in the electricity bill?

2.8 Microcontroller's power problem

The microcontroller and the Wake-Up Receiver (WuRx) can work thanks to a lithium battery of 3V but it is unhandy for a user to change it every time it is discharged. For this reason, a DC/DC converter (first configuration) or an AC/DC converter (second configuration) will be introduced (chapter 5). For the first measurements phase, a switching 3.3V power supply has been chosen:

220 AC -> 3.3 DC	Price (€)	Rated Current (A)	Efficiency	No Load Power Consumption (W)
IRM-10-3.3 "Mean Well"	9.69	2.5	74.0%	<0.1W

The switching power supplies, as the one chosen, has a very high efficiency.

The efficiency should not be a problem in our case because when the WuRx is sleeping it will require a current of a µA order and the power waste will be negligible, while in the ON-state it will require a current of a mA order and the power waste will be also low with a low-efficiency power supply. For this reason, this power supply has been used only for a beginning measurements phase but a less efficient, cheaper and easy to design AC/DC converter have been implemented and analyzed in a chapter 5, as well as for the DC/DC converter.

3 Switch Circuit – Performance Evaluation

In order to analyze and compare the four solutions that we chose, the components have been purchased and, afterwards, a circuit for each solution has been designed to make them working according to the recommended operating conditions found on the datasheet of each device. Moreover, the final four circuits have been soldered on a board in order to make the measurements. A power meter (see appendix A for more details) has been used to measure the input and output power consumption.

Input current/power consumption (WuRx board)

For the input current/power consumption, the 3.3V adapter has been attached to the power meter as illustrated in the figure below. This test measures the power that is consumed by the WuRx board to make the switch working correctly.

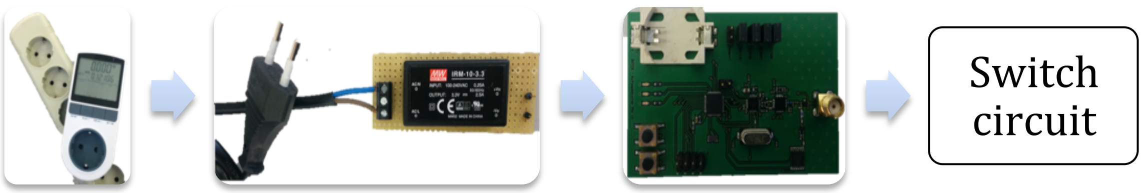

Figure 8. Input power consumption

Output current/power consumption (access point, switch and power adapter)

For the output current/power consumption, the system constituted by switch + power adapter + access point has been measured following the two configurations. This test measures the power that is consumed by the access point when the switch system is used.

DC configuration

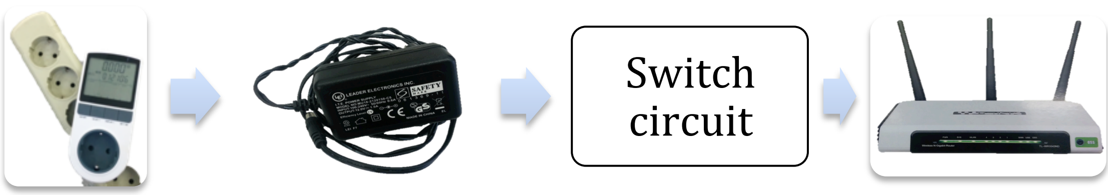

Figure 9. Output power consumption, DC configuration

AC configuration

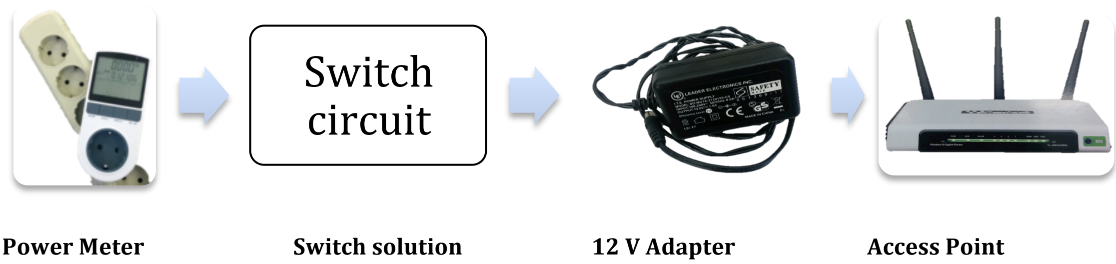

Figure 10. Output power consumption, AC configuration

3.1 Current/power consumption of the system alone without switch (access point + power adapter)

The measured current and power consumptions for the conventional system (without WuR + switch) is provided below, for comparison purposes.

<u>ON state, no user connected:</u>

Current consumption (rms value): between 42mA and 44mA (about 4W).

<u>OFF state (power adapter with the access point disconnected):</u>

Current consumption (rms value): about 7mA (about 0.3W).

Note: ‘power_adapter with the access point disconnected’ means that the power measure that has been done is referred to the only power adapter (how much the power adapter alone consumes?).

3.2 Implementation and performance evaluation

Each of the following sections starts with a design part to make each switch working correctly and is followed by the results of the power measurements. The results are commented in section 3.3.

3.2.1 DC configuration, solid-state relay

Figure 11 shows the circuit schematic of the DC – solid-state solution.

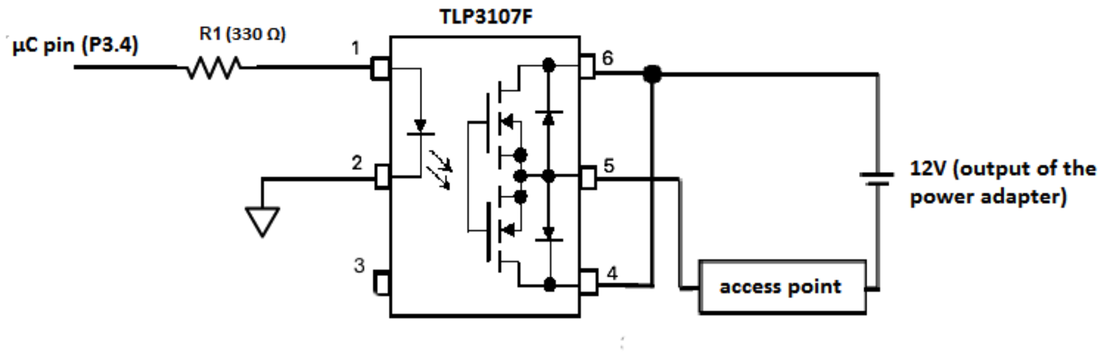

Figure 11. DC conf., solid-state relay - schematic

In order to have an input forward current at least of 5mA (minimum recommended current), a resistance R1=330Ω (E12 series, 5% of tolerance) has been chosen, based on:

- *µC pin voltage: about 3.28V*
- *Input Forward Voltage: max. 1.48V*

$$R1 < \frac{(3.28 - 1.48)V}{5mA} = 360\Omega \rightarrow \text{R1} = 330\Omega$$

Figure 12 shows the soldered circuit.

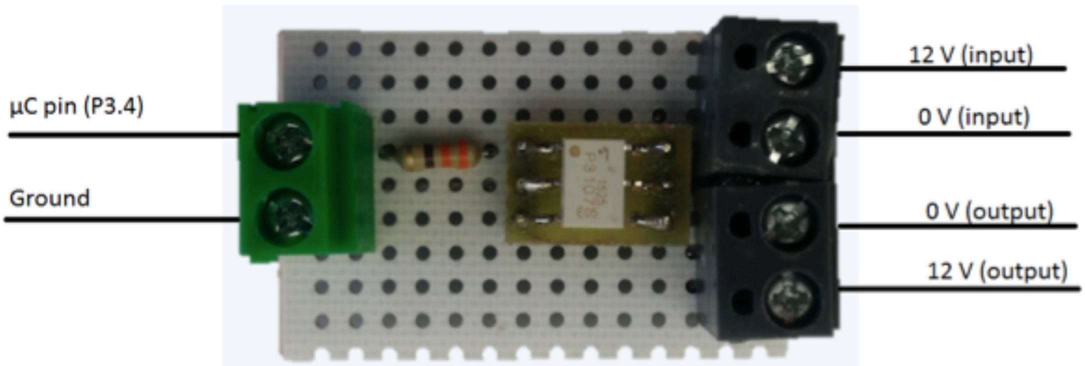

Figure 12. DC conf., solid-state relay - soldered circuit

Finally in *Figure 13* a picture of the measurement setup is showed.

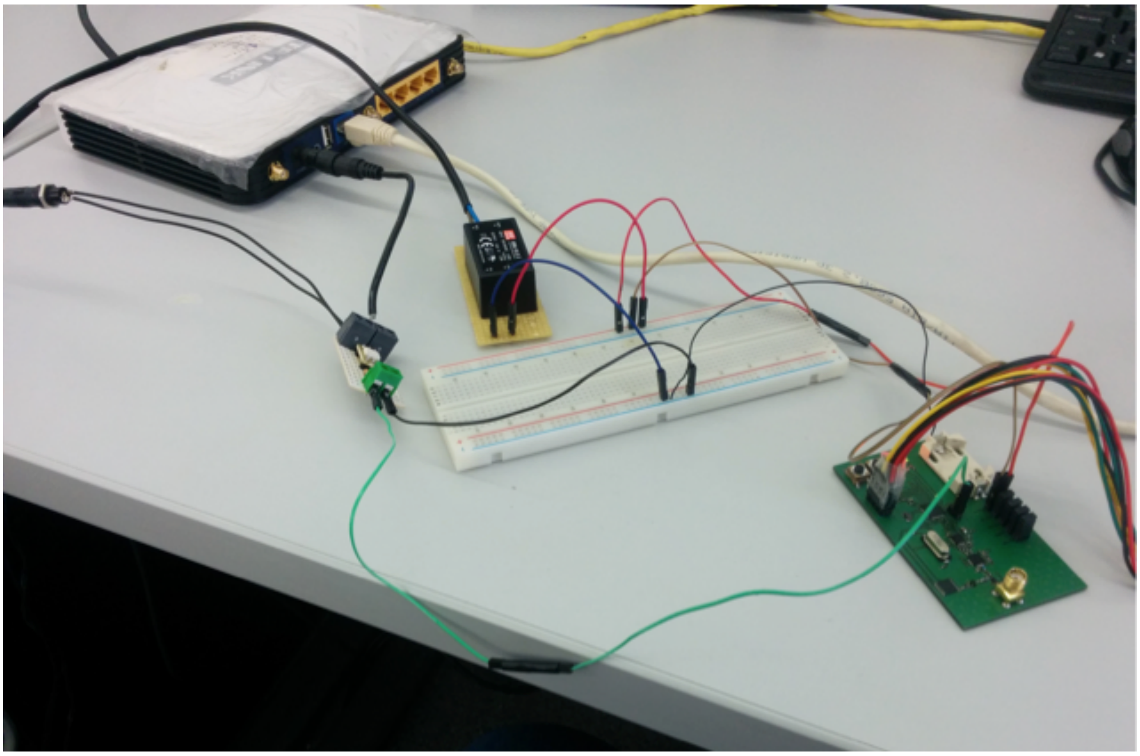

Figure 13. DC conf., solid-state relay - testbench

The measured current/power consumption values are given below.

<u>Input current/power consumption (ON and OFF state):</u>

- *Current consumption (rms value): about 0mA (about 0W).*

<u>Output current/power consumption:</u>

- Standby state; P3.4 pin to '1':
  - *Current consumption (rms value): between 42mA and 44mA (about 4W).*

- With a smartphone (connected via Wi-Fi) and a personal computer (connected via Ethernet); P3.4 pin to '1':
  - *Current consumption (rms value): between 46mA and 48mA (about 4.6W).*

- Off state; P3.4 pin to '0':
  - *Current consumption (rms value): about 7mA (about 0.3W).*

3.2.2 DC configuration, smart high-side switch

Figure 14 shows the circuit schematic of the DC – high-side solution.

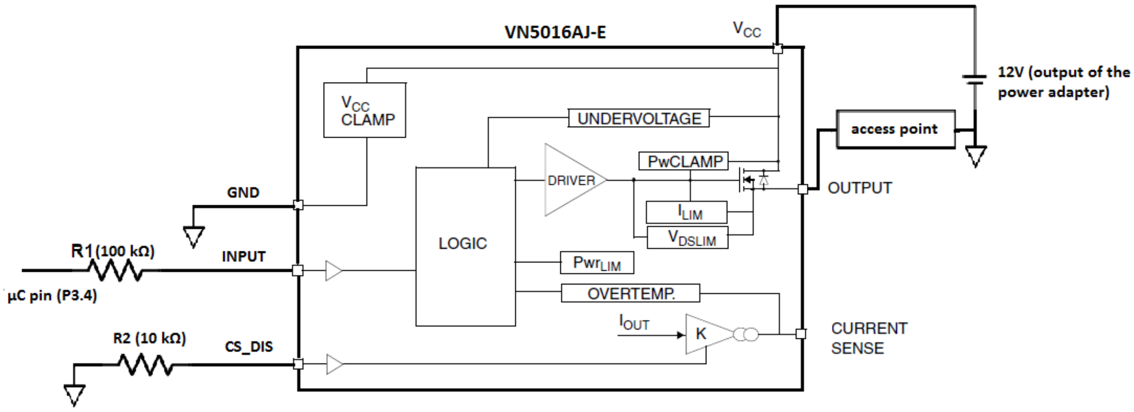

Figure 14. DC conf., high-side switch - schematic

In order to have a high level input current of a maximum of 10µA (maximum recommended current), the resistance R1=100kΩ (E12 series, 5% of tolerance) has been chosen.

- *µC pin voltage: about 3.3V*
- *Input High Level Voltage: min. 2.1V*

$$R1 < \frac{(3.3 - 2.1)V}{10\mu A} = 120k\Omega \rightarrow \mathrm{R1} = 100\mathrm{k}\Omega$$

The value of R2 is recommended by the datasheet in order to put the *CS_DIS* pin to '0'.

Figure 15 shows the soldered circuit.

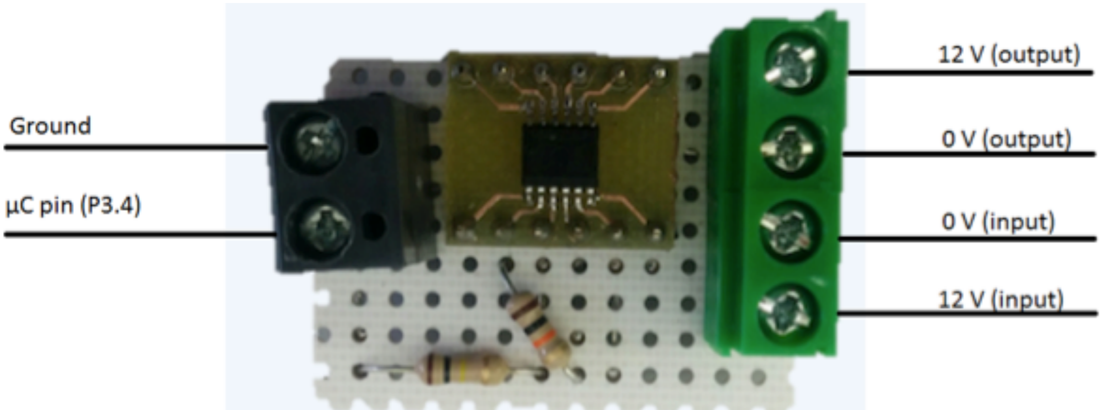

Figure 15. DC conf., high-side switch - soldered circuit

Finally in *Figure 16* a picture of the measurement setup is shown.

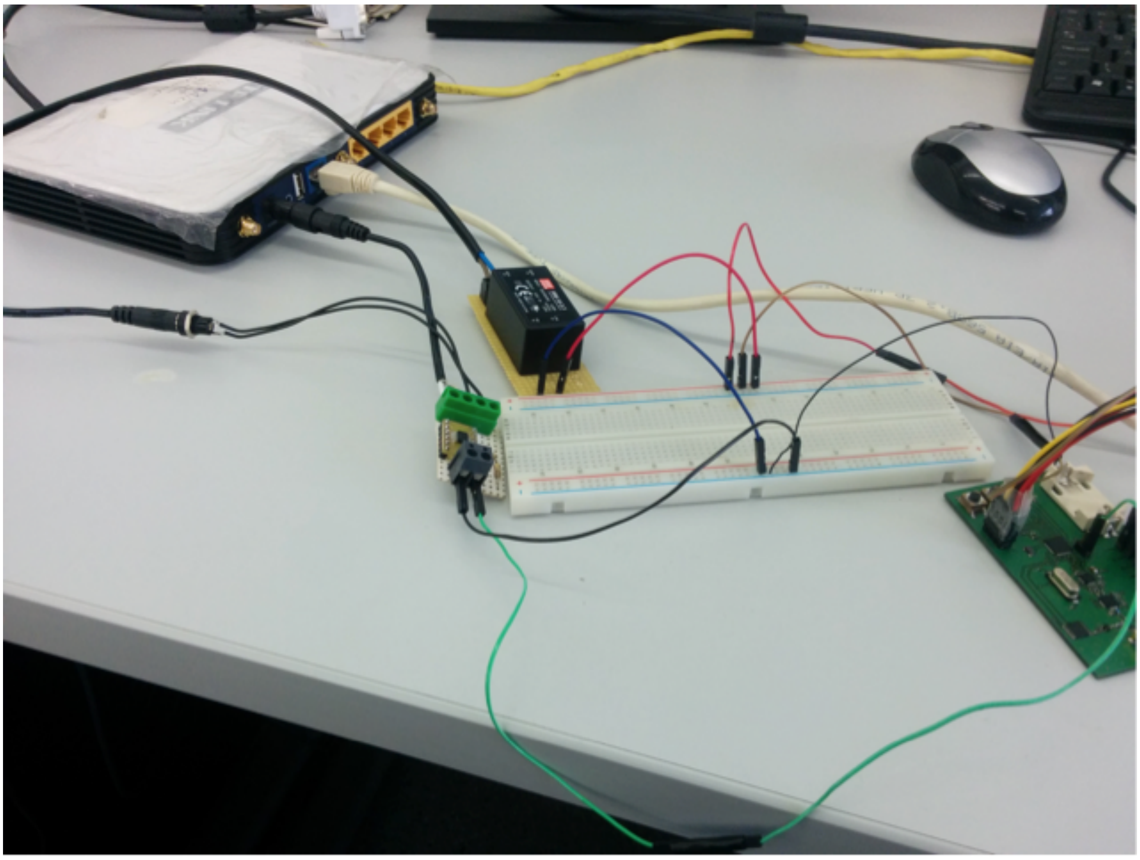

Figure 16. DC conf., high-side switch - testbench

<u>Input current/power consumption (ON and OFF state)</u>

- *Current consumption (rms value): about 0mA (about 0W).*

<u>Output current/power consumption</u>

- Standby state; P3.4 pin to '1':
  - *Current consumption (rms value): between 42mA and 44mA (about 4W).*

- With a smartphone (connected via Wi-Fi) and a personal computer (connected via Ethernet); P3.4 pin to '1':
  - *Current consumption (rms value): between 46mA and 48mA (about 4.6W).*

- Off state; P3.4 pin to '0':
  - *Current consumption (rms value): about 7mA (about 0.3W).*

3.2.3 AC configuration, mechanical relay (latching type)

Figure 17 shows the circuit schematic of the AC – mechanical relay solution.

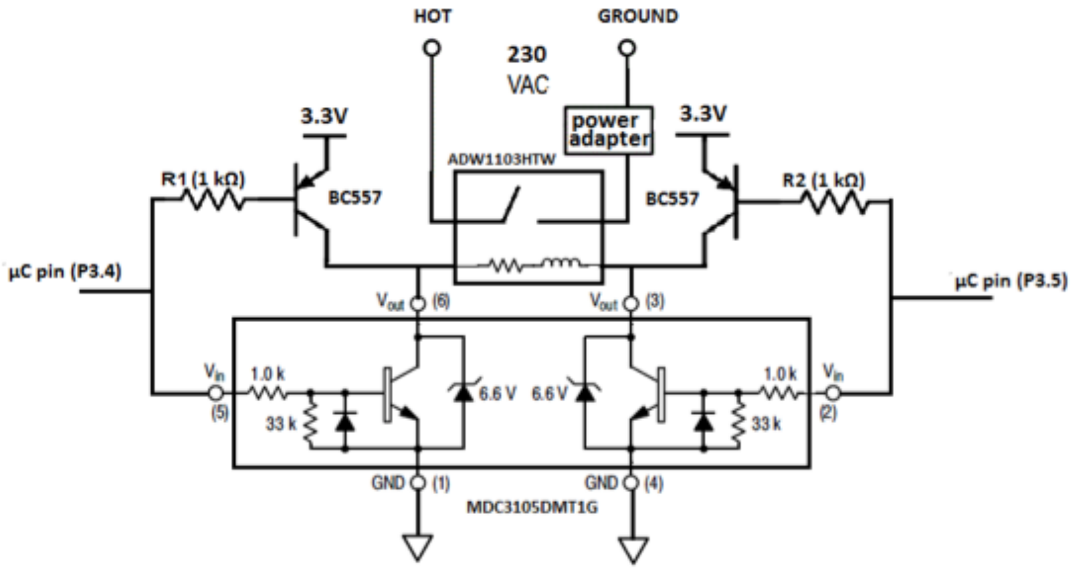

Figure 17. AC conf., mechanical relay - schematic

In order to energize/de-energize the relay's coil, a circuit that can provide 67.5mA has been designed. In fact, the maximum current that the microcontroller's I/O pin can output is 6mA. Then the PNP and NPN transistors have the purpose to amplify the output current of the microcontroller. This current will be the base current of each transistor and it will be really low thanks to the 1kΩ input resistances. Moreover the diodes integrated in the *MDC3105DMT1G* chip provide protection from the back electromotive force during the switching period (the large dI/dt across the inductor induces a large voltage).

- Switch on (P3.4 to '1' and P3.5 to '0' for at least the turn on time):
  - NPN transistor on the left and PNP transistor on the right - ON
  - NPN transistor on the right and PNP transistor on the left - OFF
- Switch off (P3.4 to '0' and P3.5 to '1' for at least the turn off time):
  - NPN transistor on the left and PNP transistor on the right - OFF
  - NPN transistor on the right and PNP transistor on the left - ON

Figure 18 shows the soldered circuit.

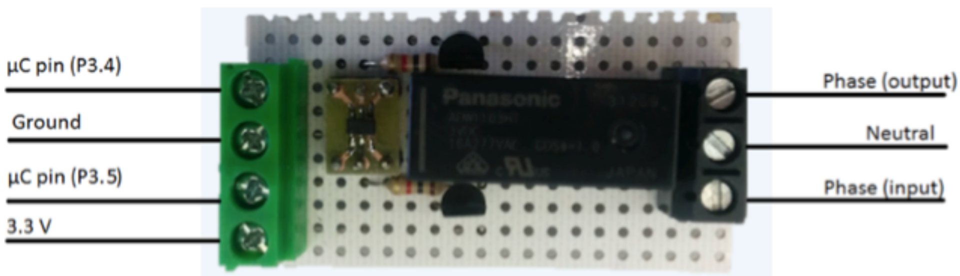

Figure 18. AC conf., mechanical relay - soldered circuit

Finally in *Figure 19* a picture of the measurement setup is shown.

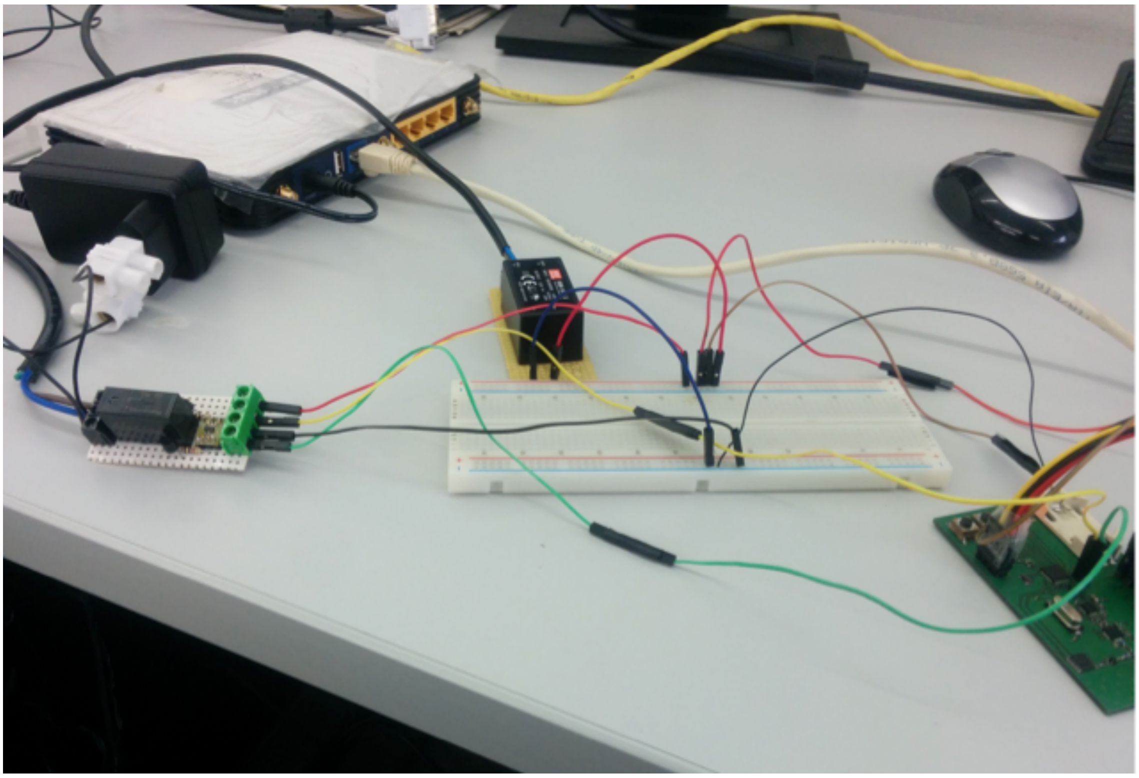

Figure 19. AC conf., mechanical relay - testbench

Input current/power consumption (ON and OFF state)

- *Current consumption (rms value): about 5mA (about 0.35W) for a max of 15ms (max. turn on/off time); exactly 0mA (exactly 0W) after the turn on/off time.*

Output current/power consumption

After the switching time, the two I/O pin are both to '0'.

- Standby state:
  - *Current consumption (rms value): between 42mA and 44mA (about 4W).*

- With a smartphone (connected via Wi-Fi) and a personal computer (connected via Ethernet):
  - *Current consumption (rms value): between 46mA and 48mA (about 4.6W).*

- Off state:
  - *Current consumption (rms value): exactly 0mA (exactly 0W).*

3.2.4 AC configuration, solid-state relay

Figure 20 shows the circuit schematic of the AC – mechanical relay solution.

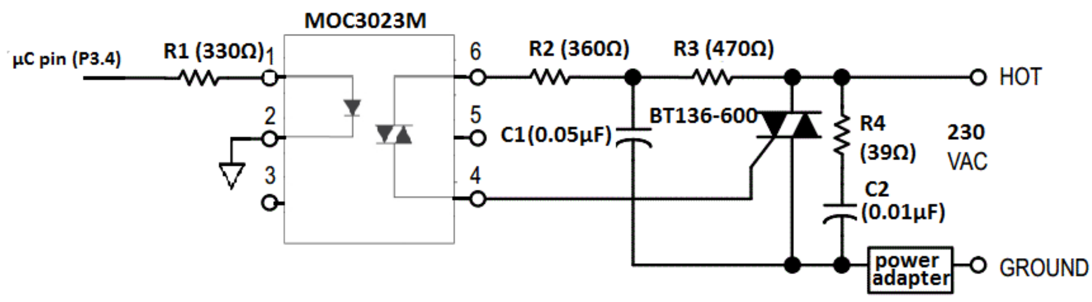

Figure 20. AC conf., solid-state relay - schematic

In order to have an input forward current at least of 5mA (max. trigger current), the resistance R1=330Ω has been chosen (E12 series, 5% of tolerance).

- *µC pin voltage: about 3.3V*
- *Input Forward Voltage: max. 1.5V*

$$R1 < \frac{(3.3 - 1.5)V}{5mA} = 360\Omega \rightarrow \mathrm{R1} = 330\Omega$$

The resistances and capacitances used on the right of the *MOC3023M* chip are for snubbing the coupler and the TRIAC; the used values are recommended by the datasheet.

Figure 21 shows the soldered circuit.

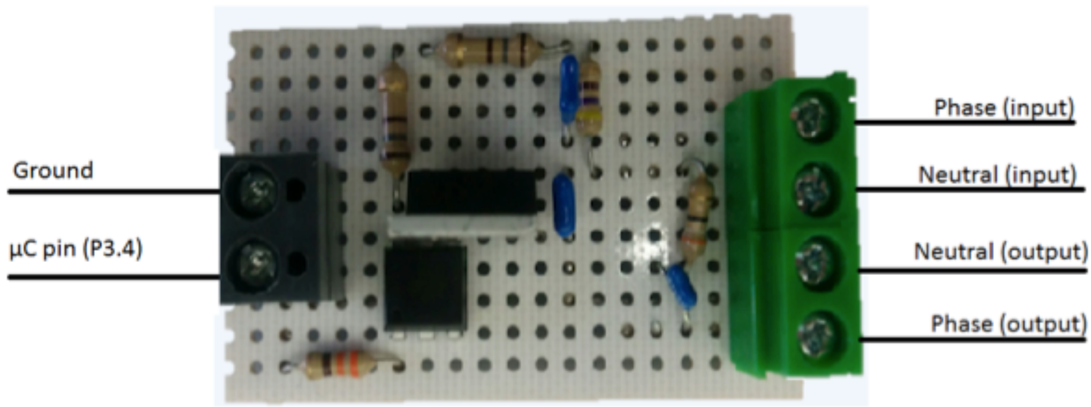

Figure 21. AC conf., solid-state relay - soldered circuit

Finally in *Figure 22* a picture of the measurement setup is showed.

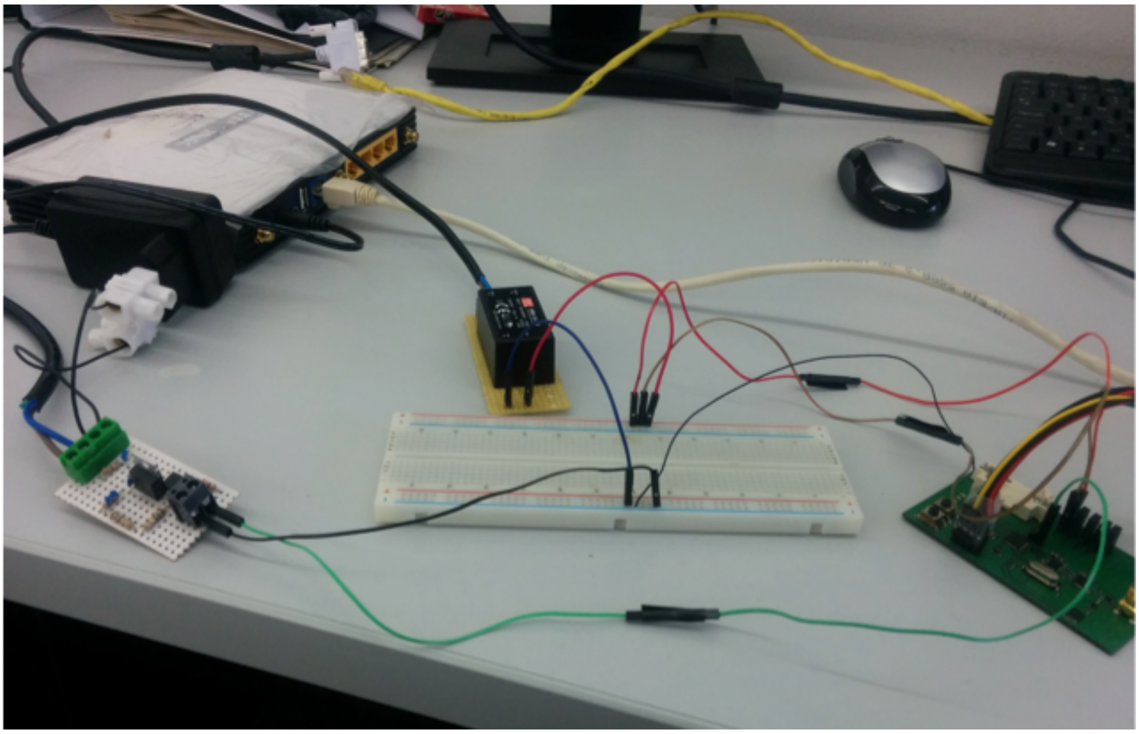

Figure 22. AC conf., solid-state relay - testbench

<u>Input current/power consumption (ON and OFF state)</u>

- *Current consumption (rms value): about 0mA (about 0W).*

<u>Output current/power consumption</u>

- Standby state; P3.4 pin to '1':
  - *Current consumption (rms value): between 77mA and 79mA (about 4.05W).*

- With a smartphone (connected via Wi-Fi) and a personal computer (connected via Ethernet); P3.4 pin to '1':
  - *Current consumption (rms value): between 83mA and 85mA (about 4.65W).*

- Off state; P3.4 pin to '0':
  - *Current consumption (rms value): about 0mA (about 0W).*

3.3 Summary and comparison of the four solutions

	DC conf. (solid-state relay)	DC conf. (high-side switch)
Input Current/Power cons.	about 0mA, 0W	about 0mA, 0W
Output Current/Power cons. (standby)	42mA - 44mA, ≈ 4W	42mA - 44mA, ≈ 4W
Output Current/Power cons. (cell.+comp. connected)	46mA - 48mA, ≈ 4.6W	46mA - 48mA, ≈ 4.6W
Output Current/Power cons. (OFF)	about 7mA, 0.3W	about 7mA, 0.3W
	AC conf. (mechanical relay)	AC conf. (solid-state relay)
Input Current/Power cons.	about 5mA, 0.35W for max. 15ms; exactly 0mA/W after this time	about 0mA, 0W
Output Current/Power cons. (standby)	42mA - 44mA, ≈ 4W	77mA - 79mA, ≈ 4.05W
Output Current/Power cons. (cell.+comp. connected)	46mA - 48mA, ≈ 4.6W	83mA - 85mA, ≈ 4.65W
Output Current/Power cons. (OFF)	exactly 0mA/W	about 0mA, 0W

Table 2. Summary of the switches performance

As expected, there is an evident contribution to the input power consumption only in the case of the mechanical relay, which requires more input current to work. However, it does not mean that it consumes more: it consumes about 0.35W, but only during the turn on and off time while for the rest of the time it will consume exactly 0W. Conversely, the input power of the other devices is apparently 0W for the whole ON-state period: the accuracy of the power meter does not allow detecting a current of less than 1mA and consequently the average input power consumption during the ON period can be more than the case with the mechanical relay.

Because of the same accuracy problem, it is impossible to detect the real differences in the output power consumption between the DC configurations and the mechanical-relay solution of the AC configuration. It is evident, however, that the solid-state solution of the AC configuration consumes more than the others: as already estimated, the snubber circuits required by this solution add two more paths for the signal so that the consumption at the output is higher.

Finally, there is a relevant difference between the DC and the AC configuration. In the OFF-state the access point does not consume power in any case; however, with the switch after the power adapter there will be always the power consumption of the power adapter itself (7mA). Contrarily, in the AC configuration, the power consumption will be exactly 0W in the case of the mechanical relay (its behavior is exactly as an open circuit), while it is close to 0W in the solid-state case because of the leakage current and for the snubber circuit's paths. Also in this latter case, the accuracy of the power meter does not allow a good estimation of this power consumption: it's only possible to say that it's less than the device's accuracy (0.5W).

4 Current Measurement Circuit

In this section a solution for a current measurement circuit, both for the two configurations, will be provided.

First, in order to better understand the behavior of the access point in terms of current, the current consumption of the access point during different modes of operation will be measured by means of the DC power analyzer (the details of the power analyzer is given in Appendix A). Then this information will be exploited for the design of the current measurement circuit.

4.1 Current consumption behavior

Three operating modes of WiFi access point are evaluated:

A. AP ON and no user connected
B. AP ON and one user connected via Wi-Fi
C. After the 'poweroff' command

The meaning of the 'poweroff' command will be explained before its analysis.

A. <u>AP ON and no user connected</u>

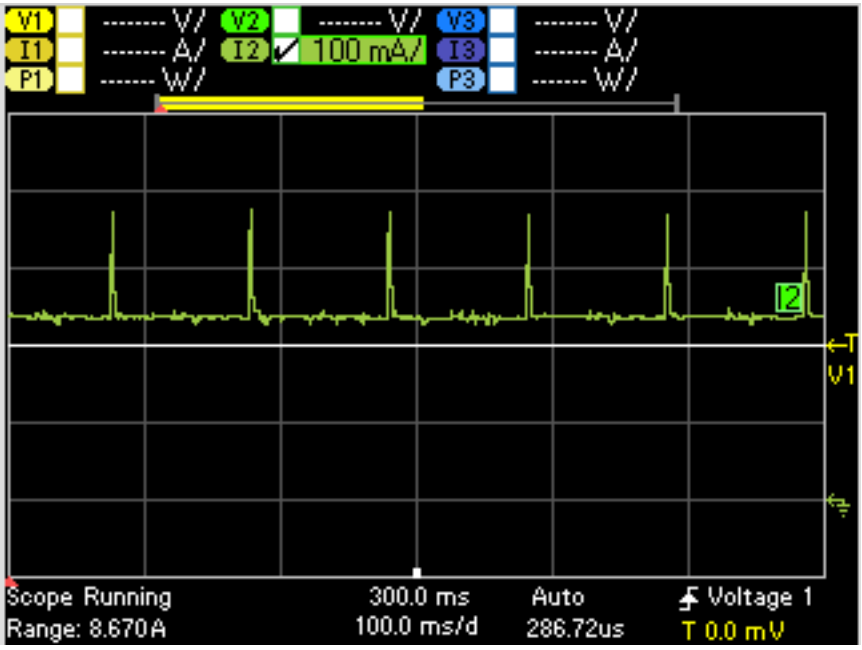

Figure 23. AP ON and no user connected - current consumption

The behavior of the current is periodic with a frequency of 10Hz (due to the transmission of beacon frames each 100ms) and an average value that oscillates between 0.23A and 0.25A (measured by the instrument).

B. AP ON and one user connected via Wi-Fi

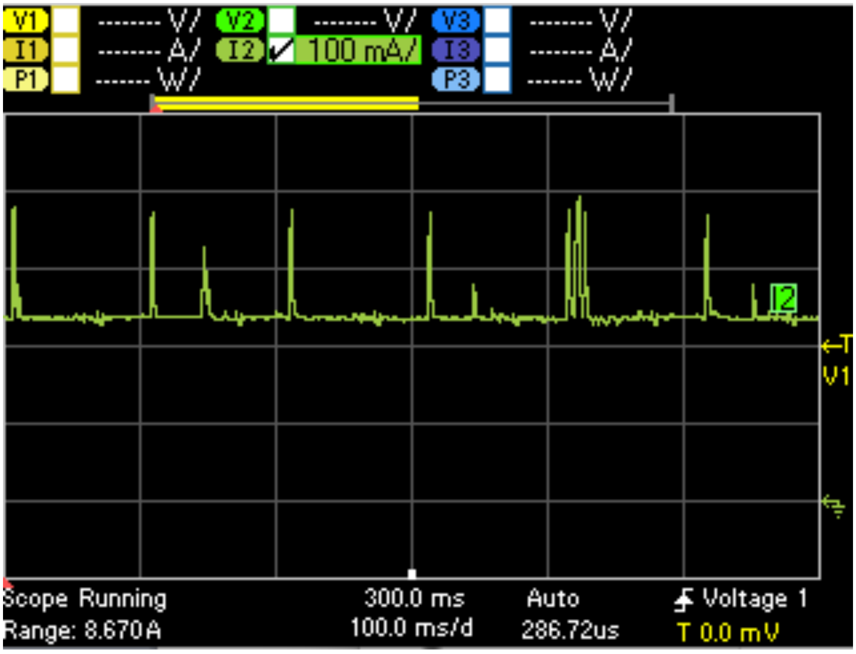

Figure 24. AP ON and one user connected via Wi-Fi – current consumption

The behavior of the current is not periodic anymore but in some periods (for example the first grid in the figure) it is like in the previous case so that the average value in that period is the same of the case with no user connected. In other periods (for example the second one) there are more pulses (due to reception/transmission of Wi-Fi frames) and the average value is higher. It oscillates between 0.23A and 0.26A (measured by the instrument).

As consequence, only a current measurement circuit is not enough to understand when there are no users connected to the access point; the idea to fix the problem is to put a program into the Linux based access point that automatically sends a 'poweroff' command when there are no packets received and transmitted for a given time. The 'poweroff' command deactivates all the communications but the access point continues to be ON.

C. After the 'poweroff' command

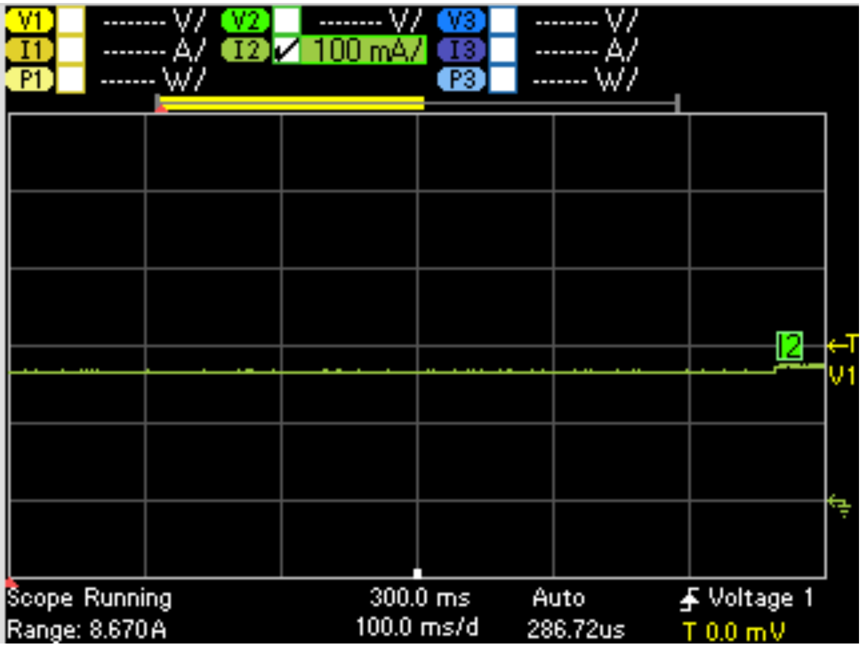

Figure 25. After the 'poweroff' command - current consumption

After the 'poweroff' command the wave has no pulses and the current oscillates between 0.16A and 0.17A (measured by the instrument). Then after a 'poweroff' command a current measurement circuit can inform the microcontroller to completely switch off the device.

In the following two sections, a solution for each configuration is provided. For the DC configuration, the design and the measurements have been done using the high side switch. For the AC configuration, the design and the measurements have been done using the mechanical relay. The other two switches have not been taken into account but a similar circuit to the one designed for the AC configuration can be implemented for each switch. In the following sections the operating modes of the access point will be differentiated as:

- OFF mode: the access point is completely OFF;
- ACTIVE mode: the access point is completely ON;
- POWEROFF mode: a 'poweroff' command has been sent.

4.2 DC Configuration - current measurement circuit

For the DC configuration, as already said, one of the two solutions has a current sense pin that provides a current proportional to the output current. Then adding a resistance at the output of the current sense pin, we can get a voltage proportional to the output current. In particular, with a resistance of 33Ω, the voltage on it is:

- OFF state: 0V
- ACTIVE state: 1.37V
- POWEROFF state: 0.95V

A voltage divider has been implemented in order to obtain a voltage between the active state one and the poweroff state voltage.

$$Vref = \frac{150k\Omega}{150k\Omega + 330k\Omega} \cdot 3.3V \approx 1V$$

A voltage comparator, powered with the 3.3V, can provide a '1' when the voltage on the current sense pin is less that 1V.

Figure 26 shows the schematic of the DC - current measurement solution developed.

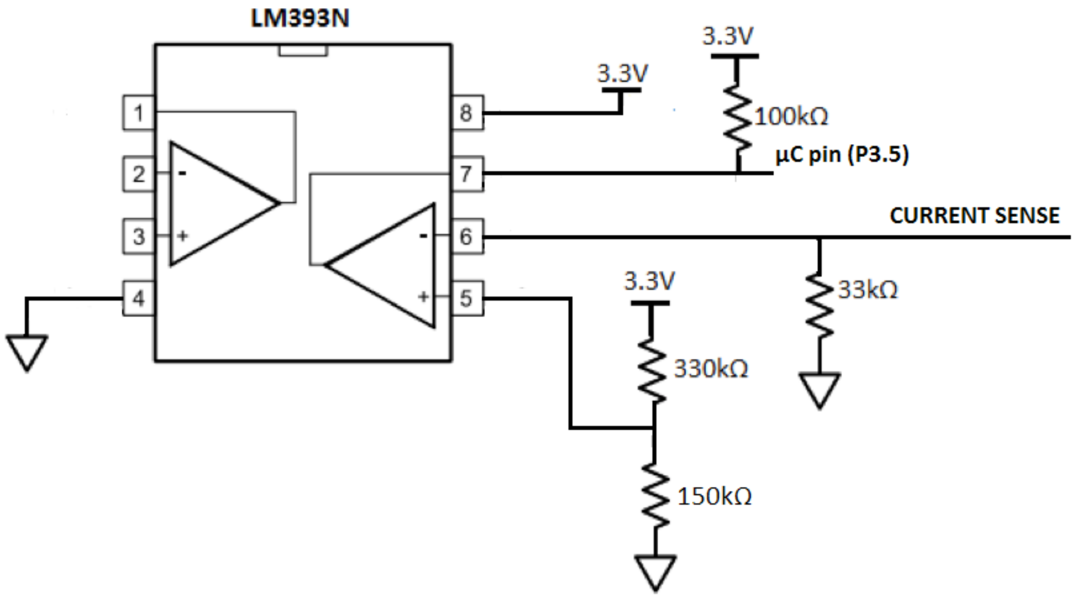

Figure 26. DC current measurement - schematic

Figure 27 shows the soldered circuit.

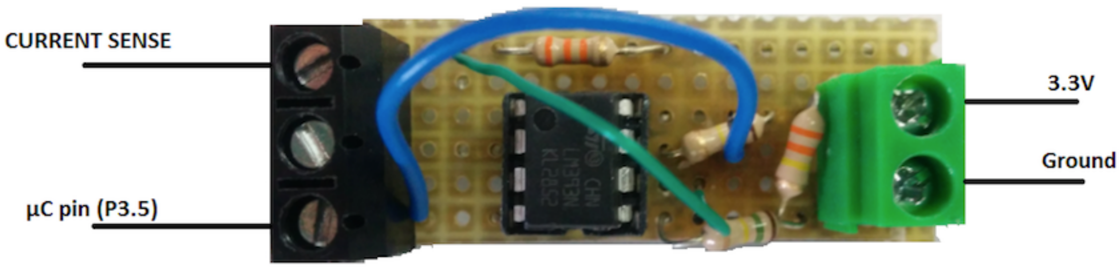

Figure 27. DC current measurement - soldered circuit

For the other DC solution, a current measuring circuit similar to the one designed for the AC configuration (next section) can be used.

4.3 AC Configuration - current measurement circuit

Depending by the kind of application, there are several ways to measure a current [3]. In our case, the use of a shunt resistance represents a cheap and easy-to-implement solution. The use of a shunt resistance is a problem in high current application for the heat dissipation or in the high frequency application when the series inductor starts to not be negligible. In our application the heat dissipation is very low because of the low current (less than 100mA) and also the working frequency is low (50Hz) so that the inductive component is negligible.

The shunt resistance is a very low resistance, generally some mΩ, that should not modify the load current and it just creates a very low voltage drop on it. Theoretically, from the measurement of the voltage drop and knowing the value of this resistance, it is possible to find the value of the load current from the Ohm's law (I=V/R).

The voltage drop on the shunt resistance can be measured thanks to a differential amplifier that outputs a voltage proportional to it.

In this application we don't want to measure the exact value of the current that flows in the access point, but we just want to design a measuring system that is accurate enough to understand when the system is OFF, active or if a 'poweroff' command has been sent. For this reason the linearity errors, like the offset voltages, are not taken into account. Moreover the current difference between the active mode and the POWEROFF mode is really low, so that the differential amplifier should be more efficient as possible. Good performances can be achieved with an instrumentation amplifier in the following configuration [4]:

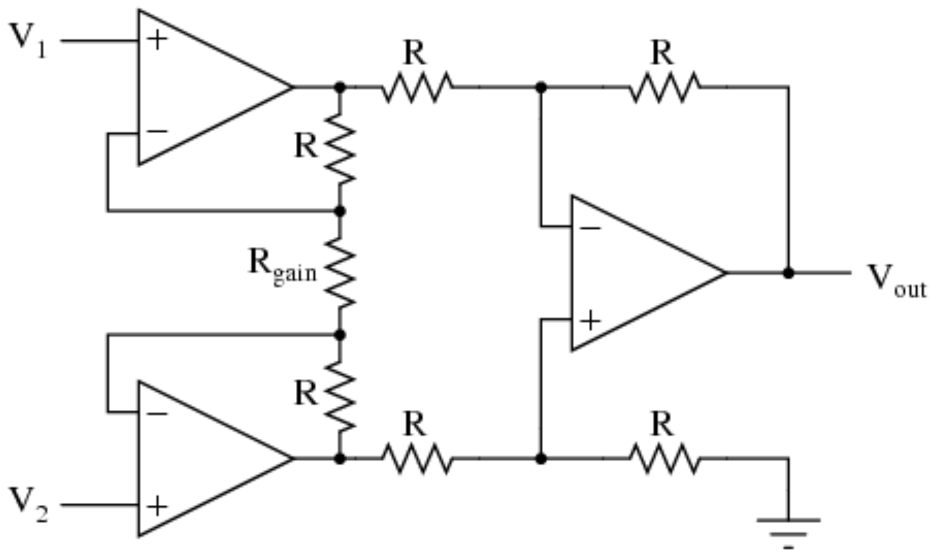

Figure 28. Instrumentation amplifier circuit

$$V_{out} = \left(1 + \frac{2R}{R_{gain}}\right)(V_+ - V_-)$$

4.3.1 Instrumentation amplifier

The LM324N quad-opamp has been used to implement the instrumentation amplifier. As suggested by the datasheet (examples of typical applications – instrumentation amplifier) the value of the resistances R of *Figure 28* has been chosen to be R = 100kΩ. With the oscilloscope, the output has been observed with different values of R_{gain}. An appreciable output (Figure 29) can be obtained with $R_{gain} = 1k\Omega$.

$$R_{gain} = 1k\Omega$$

$$V_{out} = 201(V_+ - V_-)$$

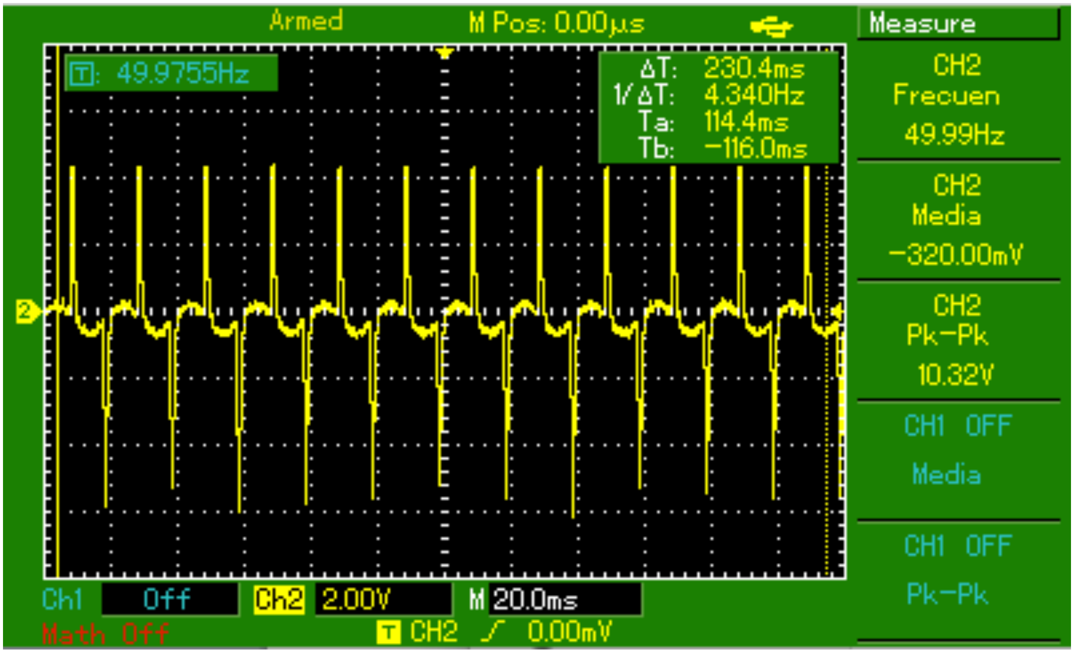

Figure 29. Instrumentation amplifier output with the gain 201

Figure 30 shows the schematic of the implemented instrumentation amplifier.

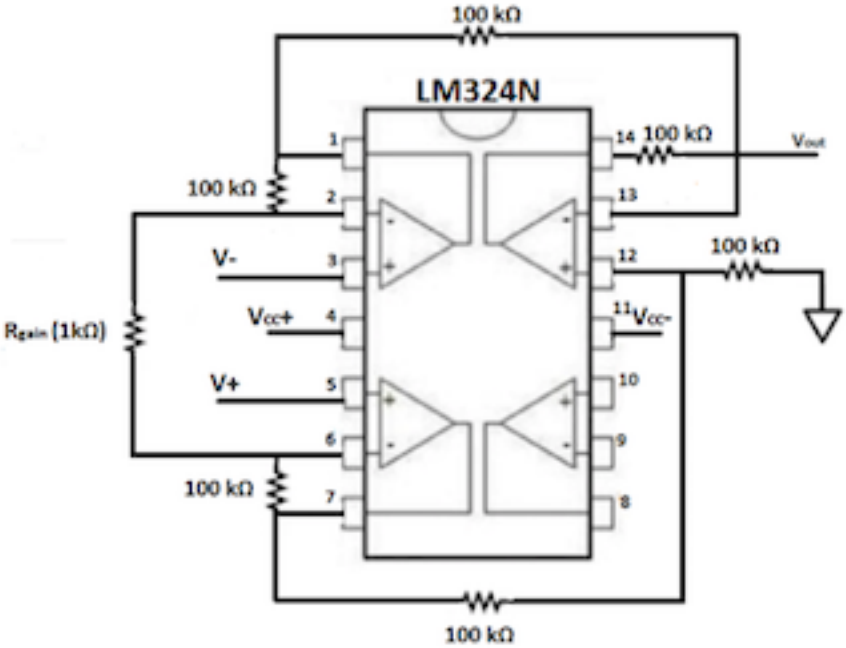

Figure 30. Instrumentation amplifier - schematic

Figure 31 shows the soldered circuit.

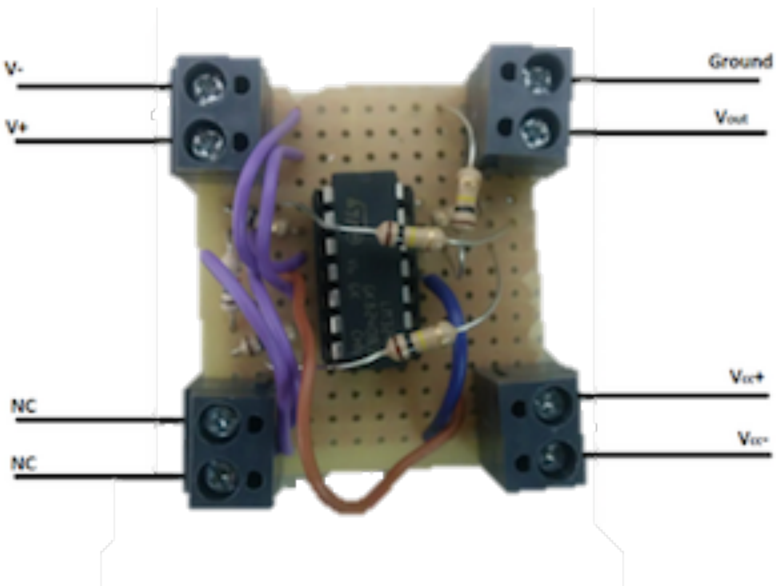

Figure 31. Instrumentation amplifier - soldered circuit

4.3.2 RFI filter

At the input, an RFI filter is added, in order to attenuate the high frequency noise.

Figure 32 shows the schematic of the implemented RFI filter.

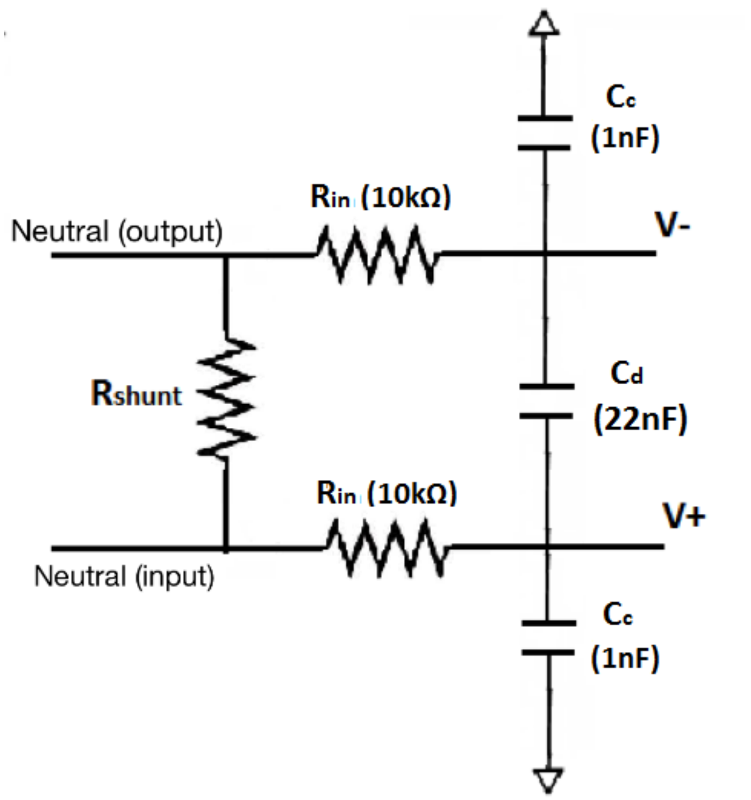

Figure 32. RFI filter - schematic

$$Differential\ filter\ cutoff = \frac{1}{2\pi R_{in}(2C_d + C_c)} \cong 350Hz$$

$$Common - mode\ filter\ cutoff = \frac{1}{2\pi R_{in} C_c} \cong 16kHz$$

The instrumentation amplifier should reject the common-mode component so that the cutoff frequency of the common-mode contribute can be higher. Contrarily, the instrumentation amplifier amplifies the differential contribute so that if it has some noise, it would be also amplified.

Figure 33 shows the soldered circuit.

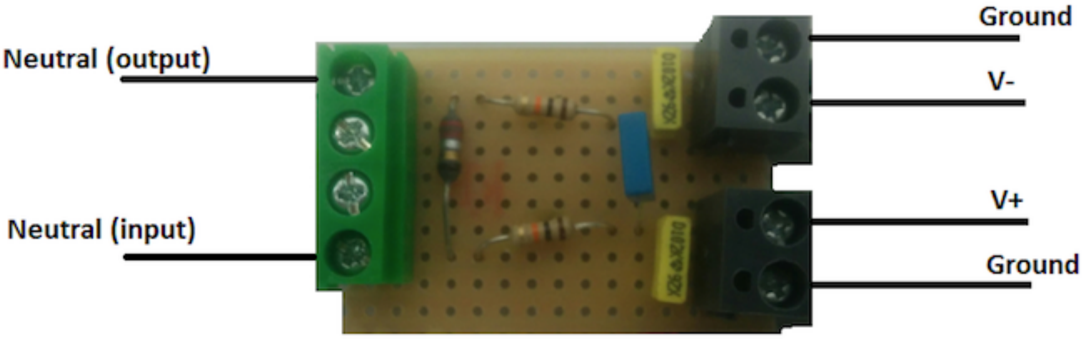

Figure 33. RFI filter - soldered circuit

The voltages on the V- pin and on the V+ pin have been observed with the oscilloscope:

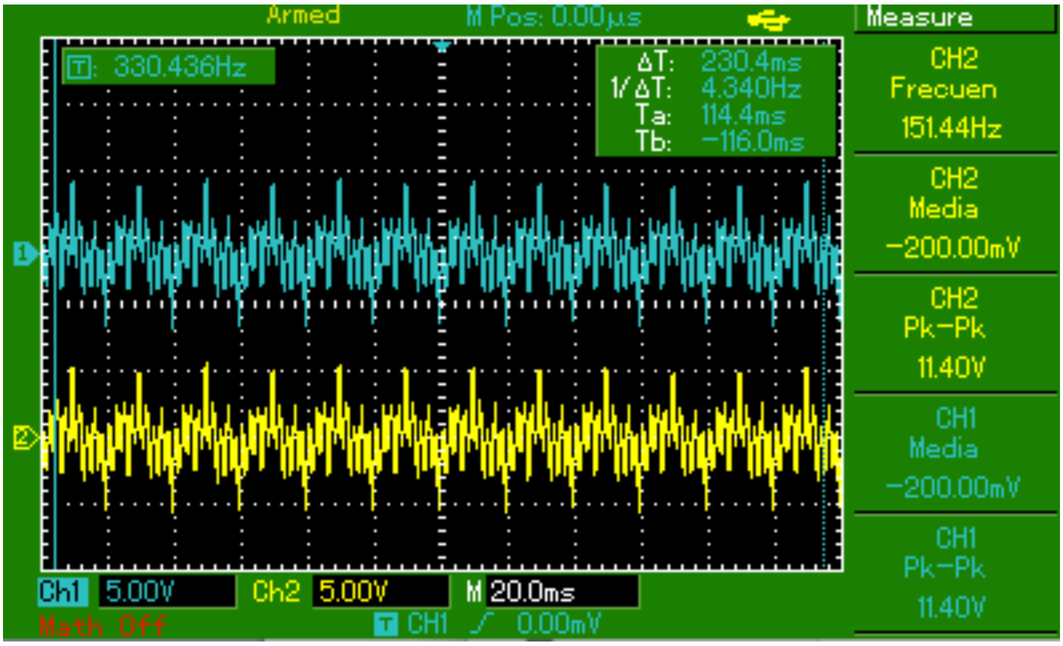

Figure 34. V- and V+ behavior

4.3.3 Conditioning circuit and final comparator

Finally the output of this circuit is a 50Hz wave with a different peak-to-peak voltage depending by the operation mode as shown in the following figures.

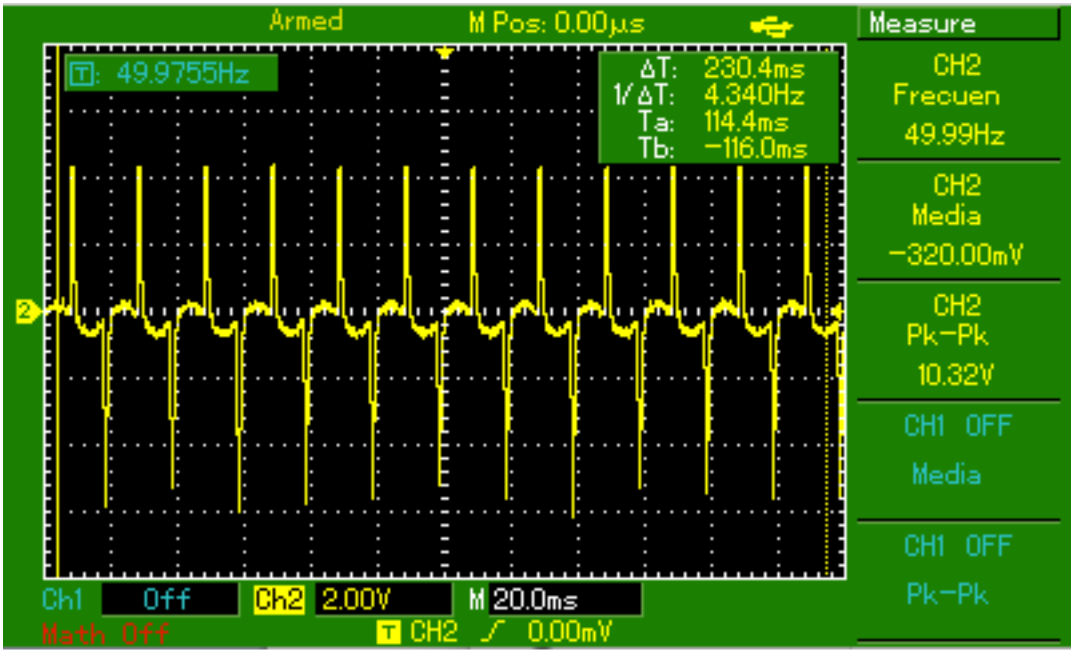

Figure 35. Vout - ACTIVE mode

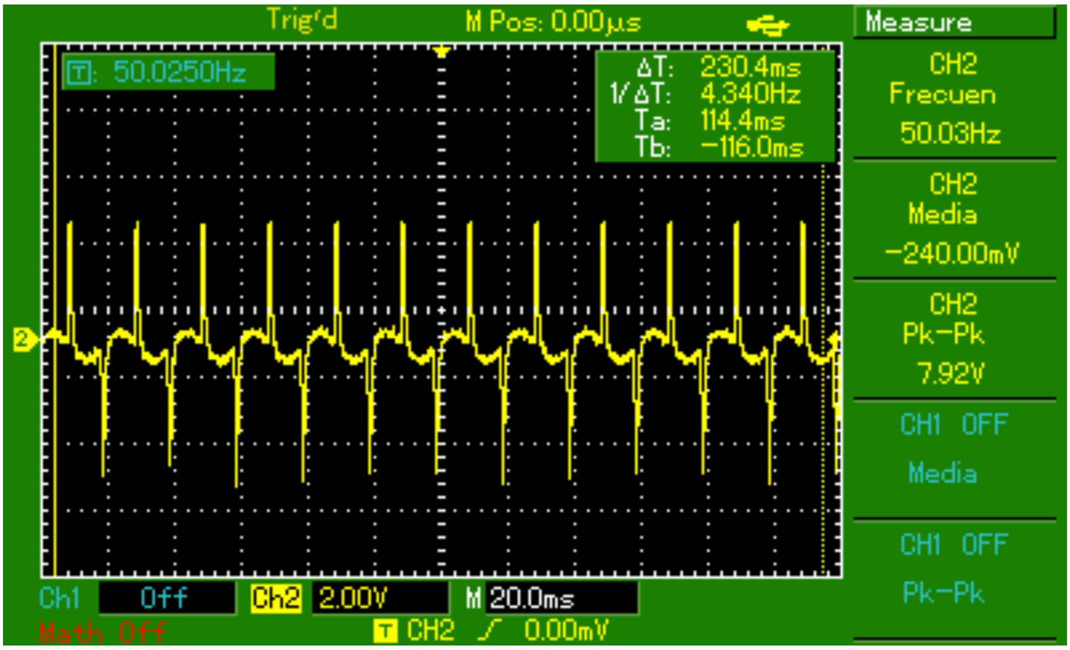

Figure 36. Vout - POWEROFF mode

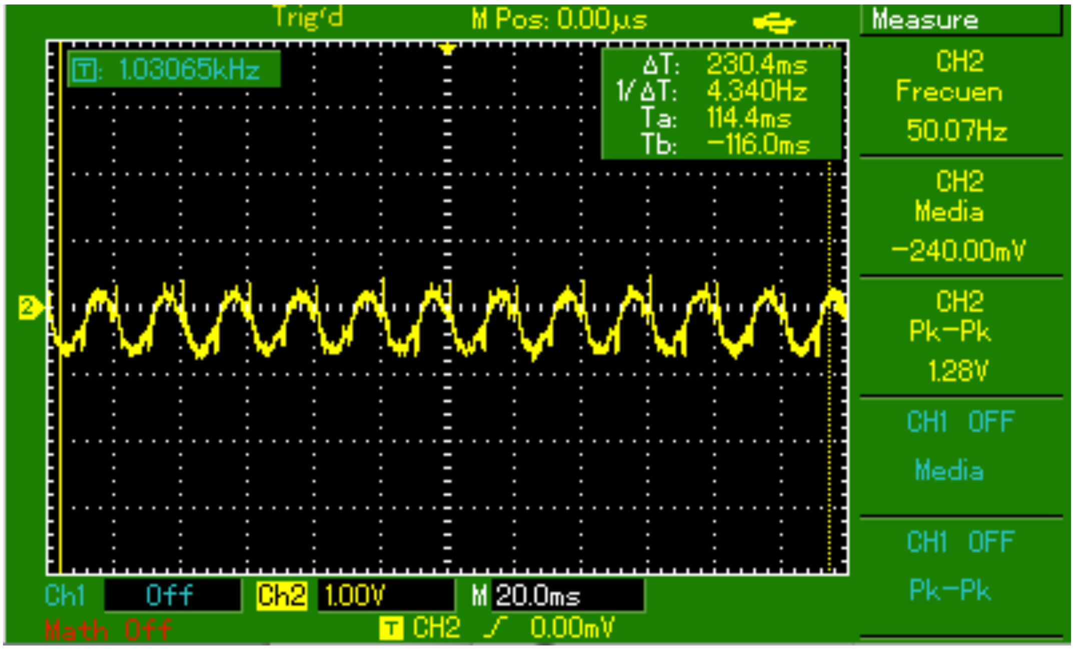

Figure 37. Vout - OFF mode

The next design step was to exploit this output wave and create a '1' for the microcontroller when the peak voltage is less than the active mode one.

A peak detector circuit is added at the output in order to detect the DC peak voltage of the signal at the output of the instrumentation amplifier. Moreover, it is divided by two to be lower than 3.3V: it will be the input of a voltage comparator.

The output of the divider has been observed with the oscilloscope.

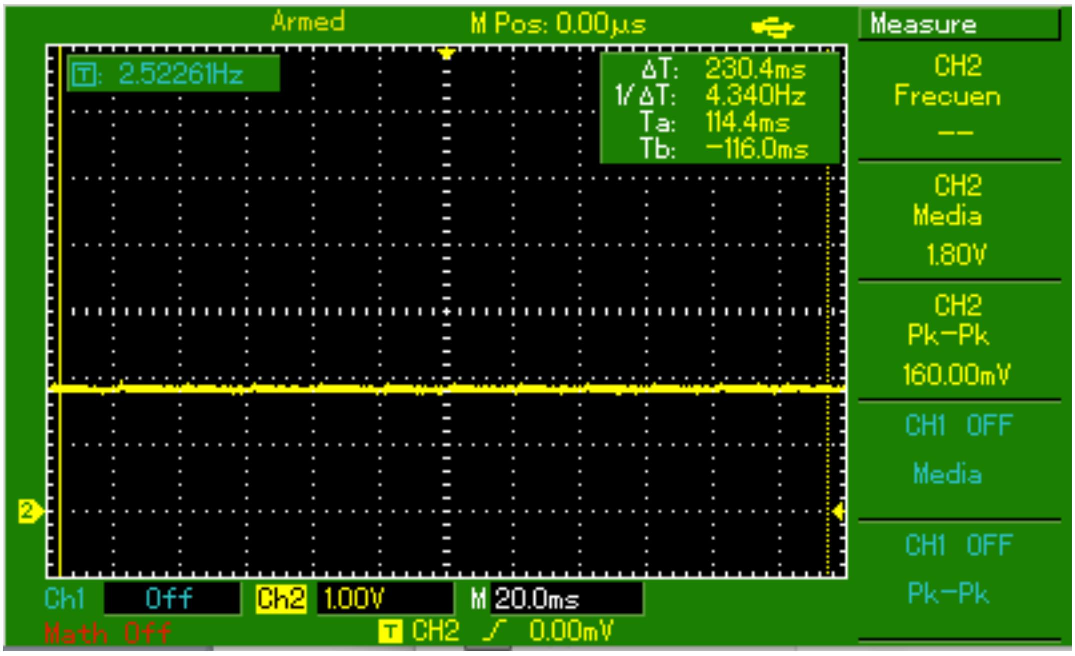

Figure 38. Divider output - ACTIVE mode

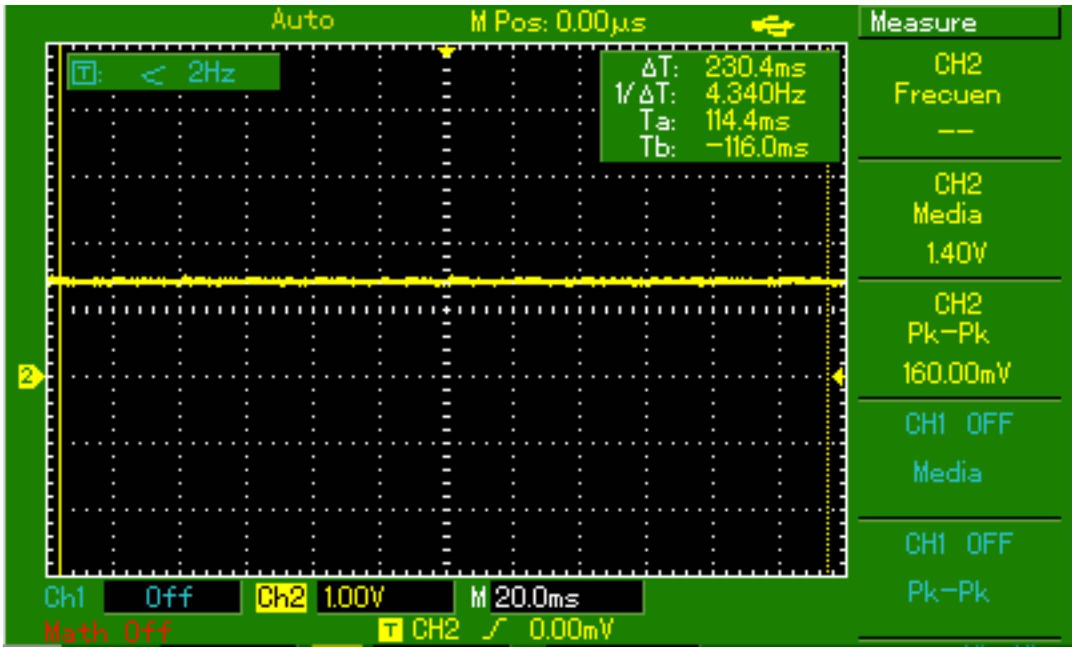

Figure 39. Divider output - POWEROFF mode

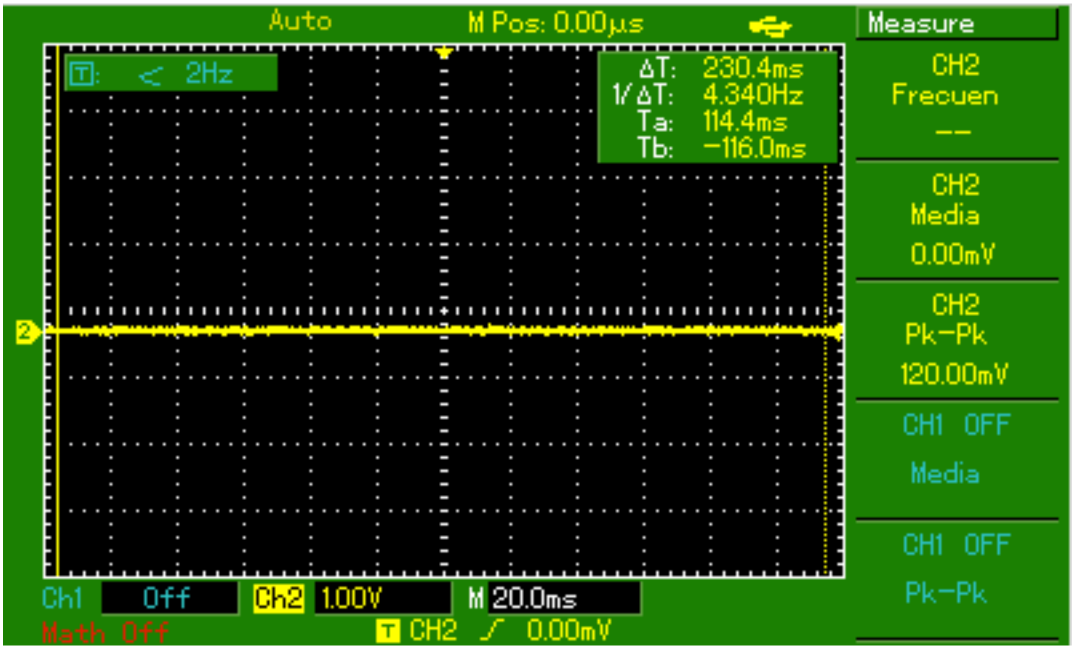

Figure 40. Divider output - OFF mode

The output of the comparator should be '1' when the latter voltage is less than the one of the ACTIVE mode.

$$Vref = \frac{12k\Omega}{(12k\Omega + 15k\Omega)} 3.3V = 1.47V$$

When a ‘poweroff’ command has been sent, the input voltage of the comparator will be less than 1.47V and will output a ‘1’. The microcontroller will read this ‘1’ and will switch off all the system.

Figure 41 shows the schematic of the implemented conditioning circuit followed by the output comparator.

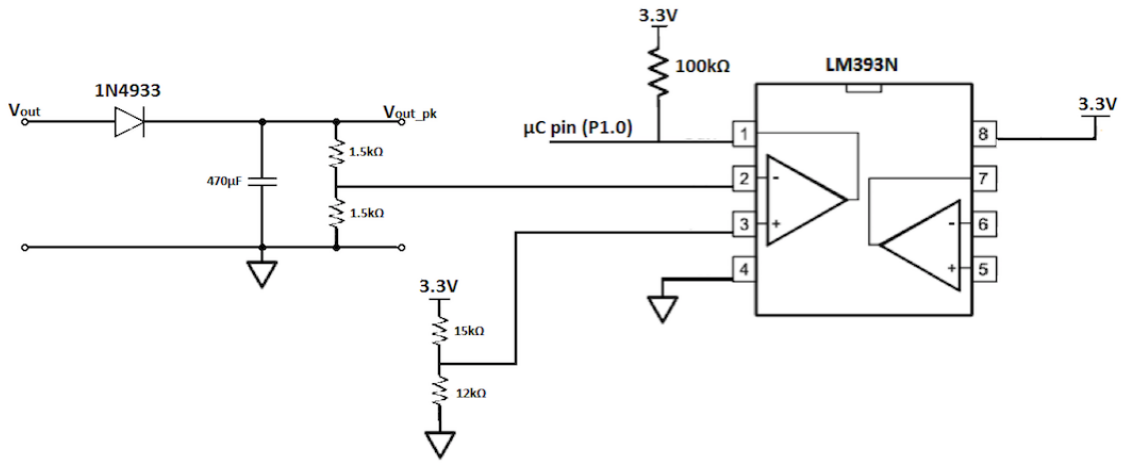

Figure 41. Conditioning circuit + comparator – schematic

Figure 42 shows the soldered circuit.

Figure 42. Conditioning circuit + comparator - soldered circuit

4.3.4 Instrumentation amplifier - power problem

In order to make everything working correctly, the instrumentation amplifier should be supplied from a dual voltage supply of about ±10V. The main problem was to create a negative voltage. In the market there are some cheap circuits that have an integrated charge pump circuit and it can be exploited to create a higher voltage and its negative value voltage (see section 5.3).

5 Power Conversions

5.1 DC Configuration

5.1.1 Design

In order to obtain a stable 3.3V from 12V, the idea is to use a voltage regulator. Mainly there are two kinds of voltage regulator [5]:

- linear regulator;
- switching regulator.

In general, linear regulators represent an easy-to-use and cheap solution compared to the switching ones that, on the other hand, have the advantage to be more efficient.

In our case, the 3.3V converter has to power some very low power devices, such as the Texas Instrument microcontroller (few hundreds of microamperes in the active mode and less than 1 microampere in the standby and OFF state) and the Austria Microsystems chip (few microamperes). For this reason, the power loss due to a linear regulator is not critical and the choice has then been the LM1117T-3.3:

- http://www.mouser.es/ProductDetail/Texas-Instruments/LM1117T-33-NOPB/?qs=sGAEpiMZZMsGz1a6aV8DcCERHZHPu4lvF5Bk6xMWlHo%3d
- Price: 1.27€

The power dissipated by such a device is:

$$P_D = (V_{IN} - V_{OUT})I_L + V_{IN}I_G$$

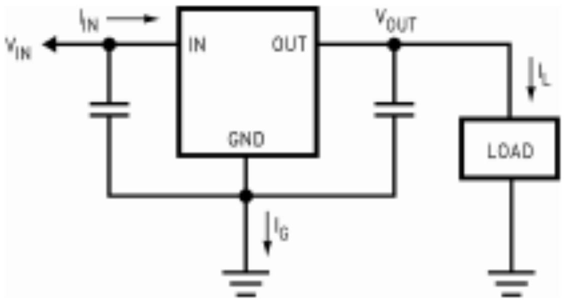

Figure 43. Power dissipation diagram of a low-dropout regulator

With $V_{IN} = 12V, V_{OUT} = 3.3V, I_L \cong 318\mu A$ (typ. In active mode at 1MHz) and $I_G = 5mA$ (typ.), the resulting dissipated power is about 62.7mW (the most contribution is given by the quiescent current).

As suggested by the device's datasheet, two capacitors to ground have been added at the input and at the output to maintain the regulator stability.

Figure 44 shows the schematic of the implemented DC converter.

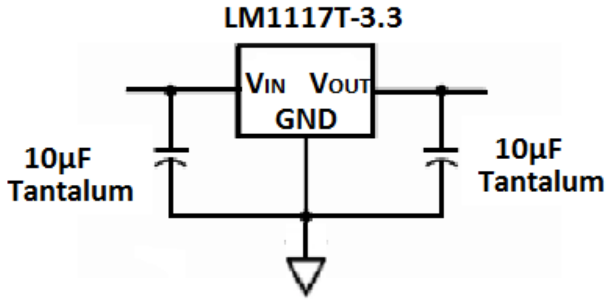

Figure 44. 3.3V DC converter – schematic

Figure 45 shows the soldered circuit.

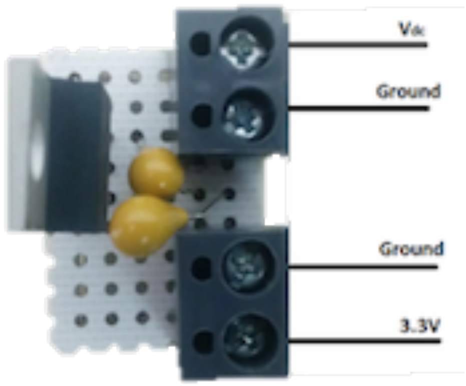

Figure 45. 3.3V DC converter - soldered circuit

5.1.2 Measurements

The above circuit output a stable 3.28V (measured with the multimeter).

5.2 AC Configuration

5.2.1 Design

The design of a 3.3V power supply, starting from the wall-outlet AC voltage, can be done in a lot of ways. For this specific application (to power mainly a microcontroller) we focused on a transformerless power supply [6], a low cost solution suitable for applications that require low supply current.

There are mainly two kinds of transformerless power supplies:

- resistive transformerless AC supply;
- capacitive transformerless AC supply.

The capacitive one is more efficient compared to the resistive supply but it is physically larger and is a little bit more expensive. Because of the so high voltage difference between the input and the output, the low efficiency of the resistive power supply can be critical and the choice fell on the capacitive one as in the following configuration:

Figure 46. Capacitive power supply

The reason for the higher efficiency is exactly the presence of the capacitances that can be charged and discharged without losses; a resistive loss is still added (R_{in}) to limit the inrush current and to avoid a possible short circuit due to the large voltage that can rapidly charge up the input capacitor producing a high current that can exceed upstream circuit breaker current limits. Common household circuit breakers are typically rated for 15A so that R_{in}=33Ω limits the short circuit current, for example, to 3.6A in the USA (120Vac/33Ω) or to 7A in Spain or Italy (230Vac/33Ω).

The zener diode regulates the output voltage and the output diode provides a half wave rectification; the output capacitance will output the DC peak voltage. This DC voltage will be equal to the zener reverse voltage less the diode voltage drop. The same voltage regulator, designed in the DC section, will be then added at the output in order to obtain exactly 3.3V.

In order to consume less zener power as possible and obtain a DC voltage as close to 3.3V as possible to minimize the regulator power consumption, a zener of 6.2V has been chosen.

$$I_{out\_max} = 0.318 \frac{V_{pk} - V_{zener}}{\sqrt{(R_{in})^2 + \left(\frac{1}{2\pi f C_{in}}\right)^2}}$$

With a bench power supply (see Appendix A), the current that the system needs has been measured: it oscillates between 0.01 and 0.02A. Then, choosing to have a maximum output current of about 50mA, we need an input capacitor of 1.5µF.

A varistor provides transient protection and ferrite beads with a capacitor to ground attenuate EMI.

Figure 47 shows the schematic of the implemented AC power converter.

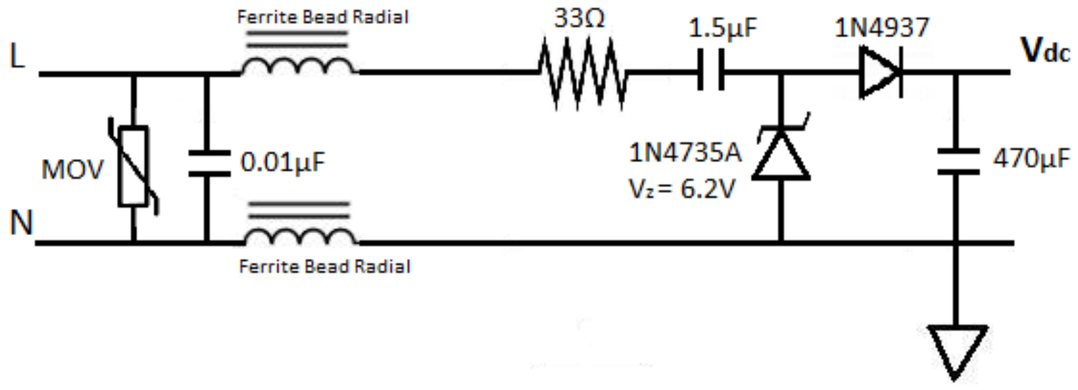

Figure 47. 3.3V AC converter – schematic

Figure 48 shows the soldered circuit.

Figure 48. 3.3V AC adapter - soldered circuit

5.2.2 Measurements

With the oscilloscope the output of the capacitive power supply has been observed As expected from the diode+capacitor – peak detector, it has a 50Hz ripple so that its minimum value is 5.6V and the peak-value is 6V.

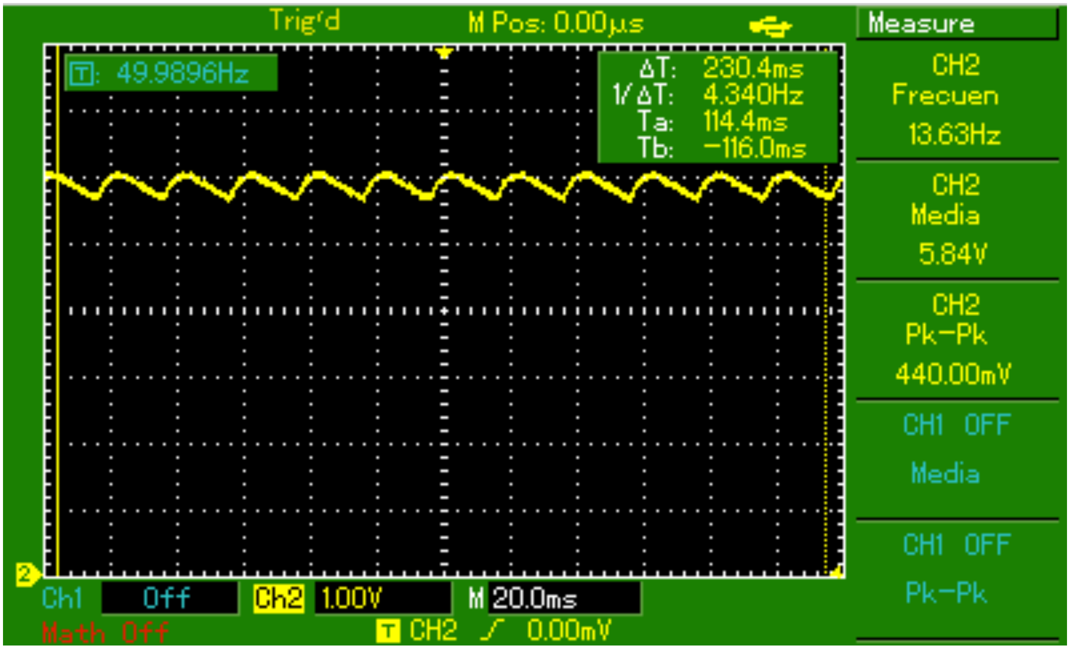

Figure 49. Time behavior of the capacitive power supply

5.3 Vcc+ and Vcc- generation for the instrumentation amplifier

5.3.1 Design

In order to make everything working correctly, the instrumentation amplifier should be supplied from a dual voltage supply of about ±10V. The main problem was to create a negative voltage. In the market there are some cheap circuits that have an integrated charge pump circuit and it can be exploited to create a higher voltage and its negative value voltage. The MAX232N has been chosen, which can be supplied from 4.5V to 6V.

Our system has only a 3.3V of power but, as explained in section 5.2, the designed voltage converter has an output voltage of 5.9V that will be the input of a 3.3V voltage regulator. The 5.9V has been used to supply the MAXIM chip creating at the output 9.6V and -10.4V.

It has been implemented exactly as suggested by the datasheet.

Figure 50 shows the schematic of the circuit that generates Vcc+ and Vcc-.

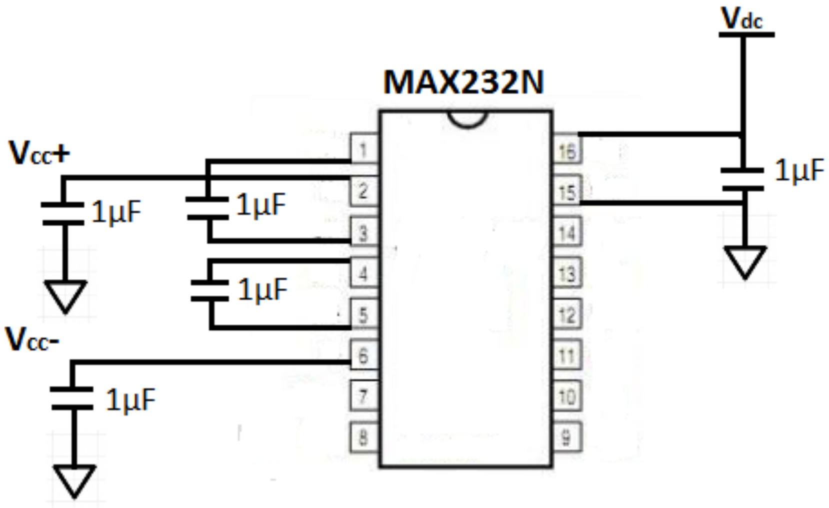

Figure 50. Vcc+ and Vcc- generation – schematic

Figure 51 shows the soldered circuit.

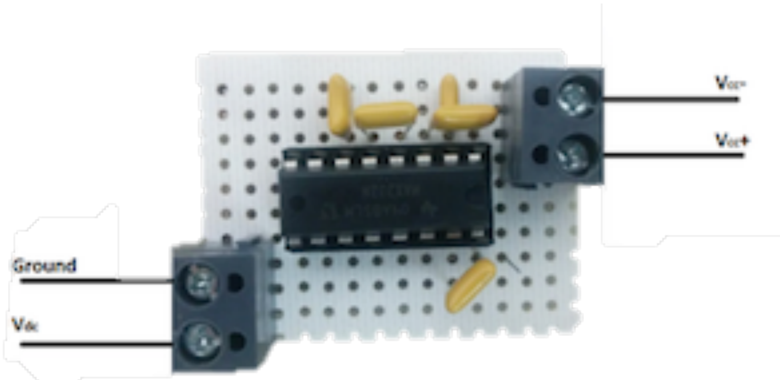

Figure 51. Vcc+ and Vcc- generation - soldered circuit

5.3.2 Measurements

The output of the MAX232N chip has been observed with the scope.

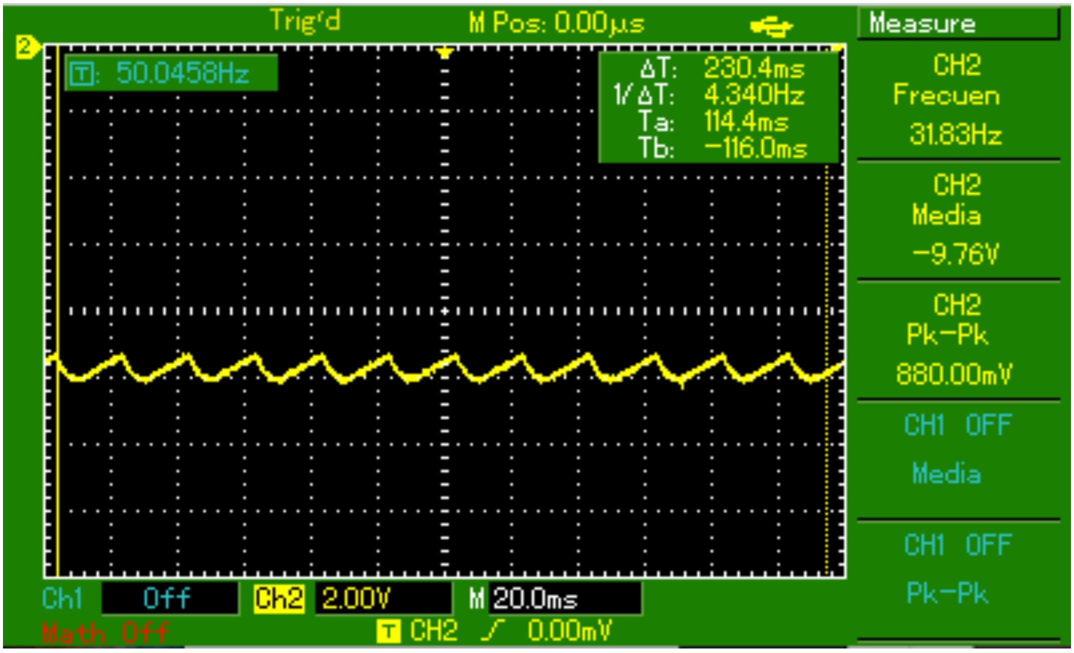

Figure 52. Vcc-

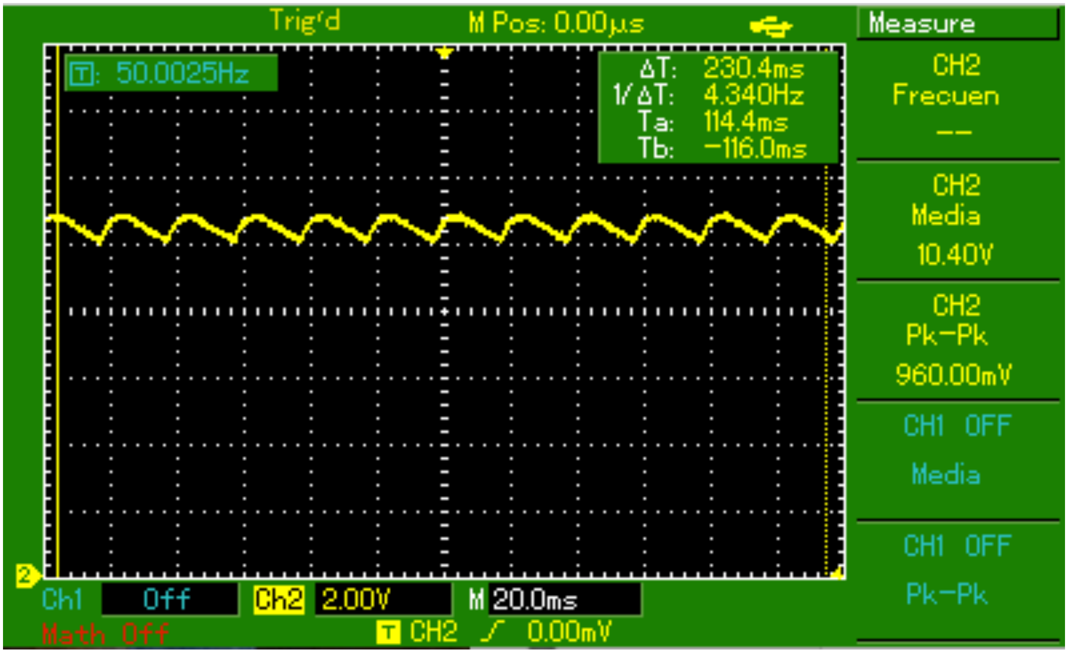

Figure 53. Vcc+

At the output, a 50Hz ripple can be observed. The waves are always in the range of LM324N chip so that this ripple doesn't create problems to it.

6 Overall System Performance Evaluation

In this section we provide performance measurements of the complete system: for both AC and DC switch configurations, the performance of the system is observed now with the addition of the current measurement circuit and the power converter.

In this section two cases have been considered:

- the case with a user connected via Wi-Fi (ACTIVE mode);
- the OFF mode.

As stated in chapter 4, the consumption between the standby state (no users connected) and the case with one user connected is more or less the same. Then, the ACTIVE mode case can be comparable to the standby-case values of chapter 3.

6.1 DC configuration – performance evaluation

ACTIVE mode

- *Current consumption (rms value): between 43mA and 45mA (about 4.3W).*

OFF mode

- *Current consumption (rms value): about 8mA (about 0.5W).*

In the ACTIVE mode, with the added circuitry, it consumes 0.3W more than the case evaluated in the section 3.2.2.

In the OFF mode, it consumes 0.2W more than the case evaluated in section 3.2.2; in fact the OFF state power consumption of the regulator is now added.

6.2 AC configuration – performance evaluation

ACTIVE mode

- *Current consumption (rms value): about 0.122A (about 4.5W).*

OFF mode

- *Current consumption (rms value): about 0.115A (about 1W).*

With respect to the section 3.2.3, in the ACTIVE mode the system consumes 0.5W more, while in the OFF mode it consumes 1W (rather than 0W). We already said that the capacitive power supply is not so efficient, so it can be used only with low current load values. In this case, the consumption of 1W can be considered acceptable if compared to the power that the system would have if it was always ON (at least 4W).

6.3 Comparisons between the several performances

As said in chapter 3, the AC solution has the advantage to save the power consumed by the 12V power adapter in the OFF state. Now the problem is overturned because the 3.3V power adapter designed for the AC configuration consumes more than the 12V power adapter. The only solution to avoid this waste of power is to use a high-efficiency 3.3V power adapter, exactly as the one used in chapter 3. The compromise is in the price. The switching one costs about 9€ against a less of 1€ capacitive adapter.

Then with the capacitive power supply, the AC-configuration performance are worse than the DC-configuration ones, but it can be also used with larger current loads and the OFF mode power consumption will be the same. For example, with a load that consumes 15W during the standby, with the addition of our system, the OFF mode power consumption will be 1W, saving about the 94% of the ACTIVE mode (or standby). Moreover, it is important to note that the AC configuration can be considered universal and comparable to a lot of products in the market. A market survey (to have more details see Appendix C) has been done in order to compare the universal AC solution to the products in the market. *Table 3* shows a comparison between the designed switch system based on the WuC and the other products in the market.

Name	Price	Communication technology	Max. Ratings	Power Consumption
Orvibo S20 Smart Socket	20.00€	Wi-Fi	2000W	-
Belkin Wemo Insight Switch	59.99€	Wi-Fi	1800W	-
EGO Efergy Smart Wi-Fi Socket	47.90€	Wi-Fi	100-240 V, 16A	-
Witenergy E100 Energy Meter Socket	29.99$	Bluetooth 4.0	1800W	-
ISOCKET Ecoswitch	99.00€	GSM (call/SMS)	4000W	< 1W
Valta Starter Kit	149.00$	ISM (921MHz)	1800W	> 0.6W, < 1.1W
Samsung Smartthings Outlet	153.99$	Zigbee	120V, 12A	-
Loxone Smart Socket Air	70.48€ + 361.79€	868MHz	85-265 V, 16A	< 500mW
AC solution	15.20€	Wi-Fi WuC	4432VA	≈ 1W

Table 3. Comparison between the designed switch system and the products already in the market

All the above products can be controlled remotely from a smartphone. In our test a Linux user-level application is used to generate the Wake-Up-Call using the Wi-Fi 2.4GHz signals but any off-the-shelf Wi-Fi enabled device (e.g. smartphone, smartwatch, tablet, etc.) can control the switch with just a software modification.

The designed current measurement circuits work only with this access point because the V_{ref} of each comparator has been chosen looking the behavior of this specific access point in the different operating modes. However, a universal current sensing circuit can also be designed. It is enough to have a microcontroller, with an integrated ADC that can read and save the different voltage values after a certain conditioning circuit. In our work, it was not possible to read from the microcontroller because the used one does not have any ADC at the input pins (a similar microcontroller with the ADC at the input pins costs only 1€ more).

6.4 Return on Investment analysis

The following table summarizes the performances of the two solutions.

	ACTIVE mode	OFF mode
DC solution	4.3W	0.5W
AC solution	4.5W	1W

Table 4. Performances - summary

The impact of the use of a switch system based on the Wake-Up-Call on the electricity bill can be estimated. *Figure 54* shows the price of the electricity in Europe in the year 2014.

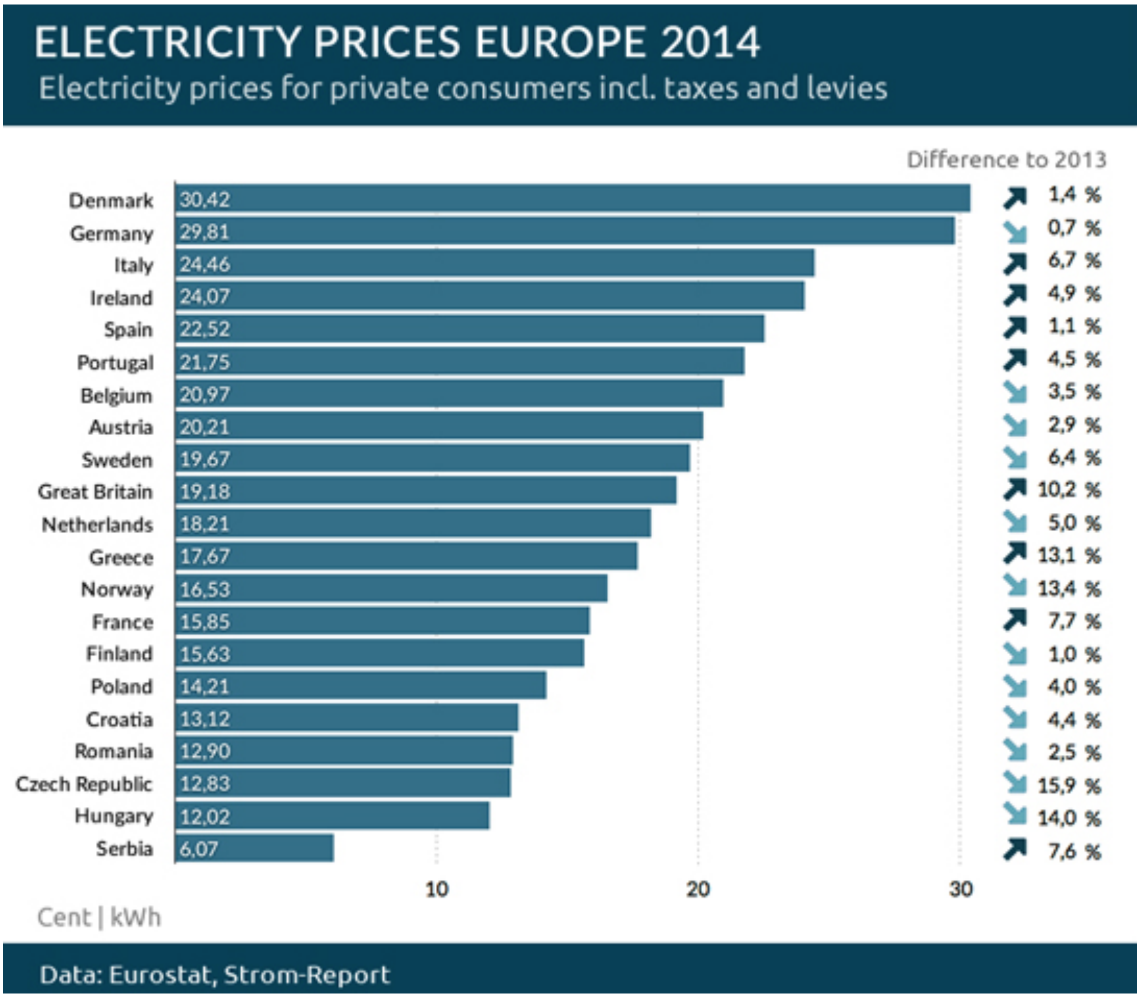

Figure 54. 2014 - electricity price in Europe

If we take into account, for example, the price of the electricity in Italy (24.46 cents of euros for kWh), the money saving per month can be evaluated in different scenarios [7] (*Table 5*).

	Offices building	University Campus	Family home
ACTIVE hours	08:00 - 18:00	08:00 - 22:00	18:00 - 00:00
Number AP	100.0	2000.0	1.0
Power Consumption without switch	4W x 24h x 100	4W x 24h x 2000	4W x 24h x 1
Power Consumption with DC solution	(4.3W x 10h + 0.5W x 14h) x 100	(4.3W x 14h + 0.5W x 10h) x 2000	(4.3W x 6h + 0.5W x 18h) x 1
Power Consumption with AC solution	(4.5W x 10h + 1W x 14h) x 100	(4.5W x 14h + 1W x 10h) x 2000	(4.5W x 6h + 1W x 18h) x 1
Price - electricity bill in Italy	24.46 cents/kWh	24.46 cents/kWh	24.46 cents/kWh
Power Saving with DC solution	1656kWh x year	22176kWh x year	22.032kWh x year
Money Saving with DC solution	405€ x year	5424.25€ x year	5.4€ x year
Power Saving with AC solution	1332kWh x year	16560kWh x year	18.36kWh x year
Money Saving with AC solution	325.8€ x year	4050.6€ x year	4.5€ x year

Table 5. Money saving in different scenarios

Then the question is: how much is convenient to buy a switch system based on the WuC? It depends by the price of the solid device constituted by the WuRx board, the switch, the current measurement circuit and the 3.3V power adapter. Both for the two configurations, an overall price can be estimated. The WuRx board is mainly constituted by the AS3933 chip and the MSP430F2350 microcontroller:

- AS3933: 4.60€
- MSP430F2350: 3.88€

The other components of the WuRx board are very cheap and them price is not taken into account.

6.4.1 DC configuration

In the DC configuration, the most expensive components have the following prices:

- High side switch (VN5016AJ-E): 2.61€
- 3.3V regulator (LM1117T-3.3): 1.27€
- Current-measurement circuit (LM393N): 0.35€

Then the overall system price to product a single device will be of about 13€; if the manufacturer produces 1000 devices the price will be, for example, a 60% less, that is 5.2€ per device. With a profit of 100%, the price per unit can be 10.4€. A big-quantity purchase can make you save a 40% of the unity-price so that a big-quantity price can be 6.25€. Then, referring to *Table 4,* each scenario should spend:

A. Offices building: 6.25€ x 100 = 625€
B. University campus: 6.25€ x 2000 = 12500€
C. Family home: 10.4€

Finally you can have back the money of the purchase after:

A. 1.48 years
B. 2.3 years
C. 1.9 years

6.4.2 AC configuration

In the AC configuration, the most expensive components have the following prices:

- Latching relay (ADW1103HTW): 6.82€
- Capacitive power supply (the high voltage capacitors are the most expensive): about 2€
- Current-measurement circuit (LM393N+LM324N+MAX232N): about 1.7€

Then the overall system price to product a single device will be of about 19€; if the manufacturer produces 1000 devices the price will be, for example, a 60% less, that is 7.6€ per device. With a profit of 100%, the price per unit can be 15.2€. A big-quantity purchase can make you save a 40% of the unity-price so that a big-quantity price can be 9.2€. Then, referring to *Table54,* each scenario should spend:

D. Offices building: 9.2€ x 100 = 920€
E. University campus: 9.2€ x 2000 = 18400€
F. Family home: 15.2€

Finally you can have back the money of the purchase after:

D. 2.8 years
E. 4.5 years
F. 3.4 years

7 Conclusions

A switch system based on the WuC has been developed following two kinds of configurations (DC and AC). The idea was to save power during the time when, for example, there is no user connected to an access point. Therefore, the mechanism of receiving a Wake-Up-Call to drive a switch has been designed and implemented providing several solutions, as well as a current sensing circuit, which has the purpose to detect the time when there are no users connected to the AP. Finally a 3.3V power converter has been implemented.

The designed 3.3V power converter can be used not only for the WuRx board, but it is a solution for a lot of low power applications.

Everything is working as expected and it has been demonstrated that, depending by different scenarios, it represents a solution to save power.

In section 6.4, the impact of such a system on the electricity bill has been calculated, as well as the reasonable cost that the overall device can have in the market. Then a return on investment analysis has been done. *Table 6* summarizes the return on investment analysis that represents the amount of time required to have back the money used for the purchase.

	Offices building	University Campus	Family home
DC solution	1.48 years	2.3 years	1.9 years
AC solution	2.8 years	4.5 years	3.4 years

Table 6. Return on investment analysis

The AC solution can be universal because it is attached directly to the main voltage and can work with a current load up to 19Arms (with a main voltage of 230Vrms). Then on a more powerful load the amount of years to have back the money used to purchase the product can be lower.

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[2] *Solid-State Relays (SSRs) vs Electromechanical Relays (EMRs),* Crydom

[3] *Current sensing for energy metering,* W. Koon, Analog Devices, Inc.

[4] *A Designer's Guide to Instrumentation Amplifiers,* 2nd edition, Analog Devices

[5] *Basic concepts of linear regulator and switching mode power supplies*, Henry J. Zhang.

[6] *Transformerless power supply design,* DESIGNER CIRCUITS, LLC.

[7] How bad are the rogues's impact on enterprice 802.11 network performance? Kaixin Sui, Youjian Zhao, Dan Pei ∗, Li Zimu

Appendices

Appendix A: Instrumentation and warning

The following measuring devices have been used:

- Multimeter: BRYMEN BM907s
  It has been used to measure the voltages and the real values of the used resistances.

  - DC Voltage - accuracy:

RANGE	ACCURACY
60.00 mV	0.6% + 3d
600.0 mV	0.3% + 3d
6.000 V	1.2% + 3d
60.00 V	0.6% + 3d
600.0 V	1.0% + 3d

  - Resistance - accuracy:

RANGE	ACCURACY
600.0 Ω	0.8% + 8d
6.000 $k\Omega$, 60.00 $k\Omega$, 600.0 $k\Omega$	0.6% + 4d
6.000 $M\Omega$	1.5% + 5d
60.00 $M\Omega$	2.5% + 5d

- Power meter: ALDI GT-PM-04
  It has been used to measure the current/power consumption of the system at.

  - Current - accuracy: 3% + 0.001A
  - Power - accuracy: 3% + 0.5W

- Power Analyzer: Agilent Technologies N6705A
  It has been used to observe the behavior of the current consumed by the access point.
- DC Power Supply: Tenma 72-8690

It has been used during the tests when the power converters were not ready and also, during the design phase of the 3.3V power converters, to understand how much current the system needs.

- Oscilloscope: Tenma 72-8705
  It has used to observe the behavior of the designed circuits for the AC configuration.

Every time a measure has been done with the scope to test all the circuits of the AC configuration, a 1:1 transformer has been used in order to protect the scope.

Moreover all the neutral and phase connections should be done after a check of the correct phase and neutral holes of the wall plug. In fact, it is important to remember that the AC circuits are not isolated and phase and neutral cannot be interchanged.

For this check a screwdriver – phase tester is enough.

Appendix B: Script

MSP430F2350 - software

The MSP430F2350 microcontroller has been programmed in order to read/write from/to three I/O pin.

DC configuration

Figure 55 describes the algorithm used to drive the DC switch.

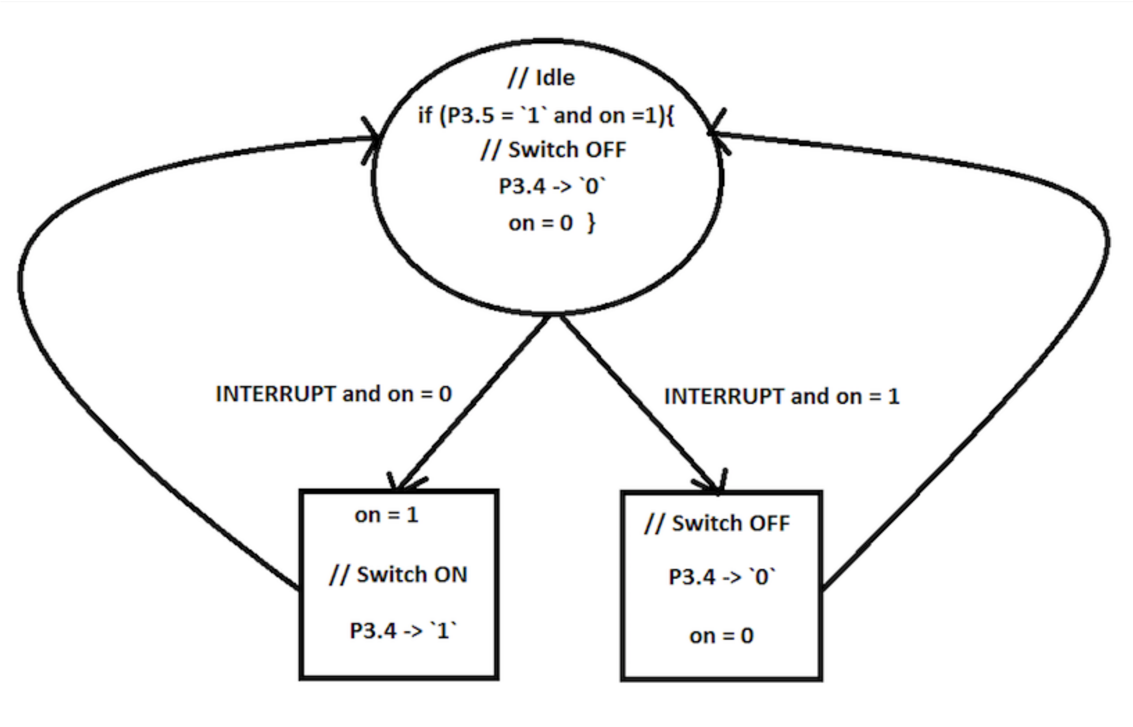

Figure 55. DC algorithm

AC configuration

Figure 56 describes the algorithm used to drive the AC switch.

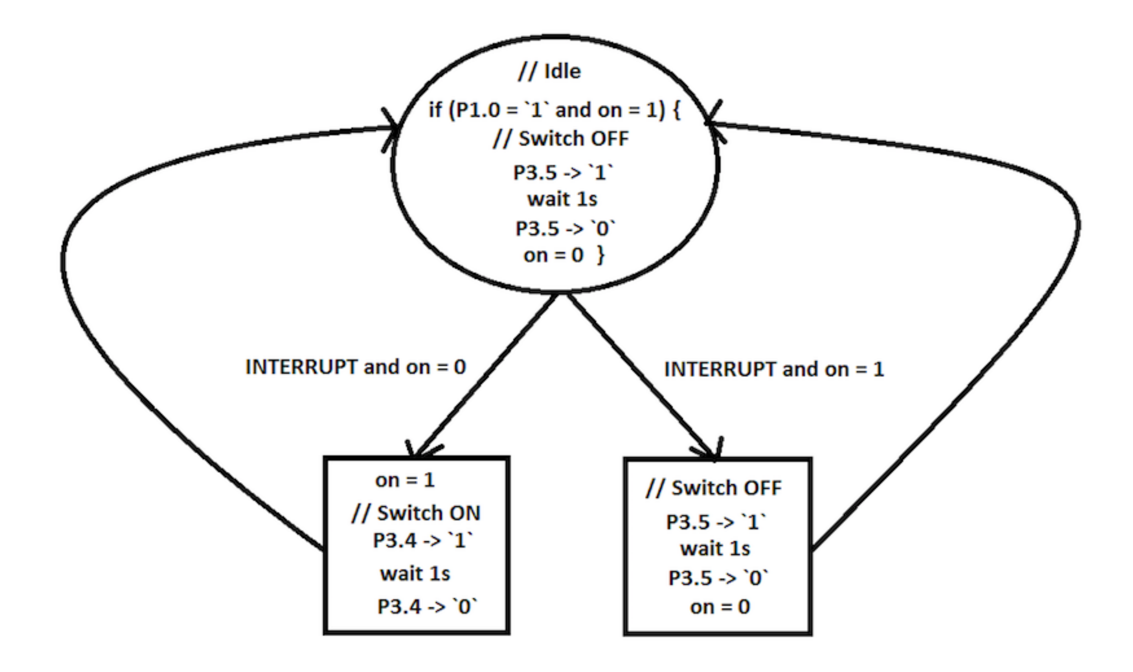

Figure 56. AC algorithm

LINUX script

The following script has been installed in the access point in order to calculate the transmitting/receiving traffic and, finally, send a 'poweroff' command when there are no users connected.

```
#!/bin/sh
# Script for ...poweroff... if there is no traffic

sleep 30

/sbin/ifconfig wlan0 > out.tmp

rxp1=`grep "RX packets" out.tmp | cut -d ':' -f 2 | cut -d ' ' -f 1`
txp1=`grep "TX packets" out.tmp | cut -d ':' -f 2 | cut -d ' ' -f 1`

period=5

exitLoop=true

while $exitLoop

do
	sleep $period
	/sbin/ifconfig wlan0 > out.tmp
	rxp2=`grep "RX packets" out.tmp | cut -d ':' -f 2 | cut -d ' ' -f 1`
	txp2=`grep "TX packets" out.tmp | cut -d ':' -f 2 | cut -d ' ' -f 1`
	incrementrx=$((rxp2-rxp1))
	incrementtx=$((txp2-txp1))
	echo "$incrementrx RX packets and $incrementtx TX packets in the last
	$period seconds"
	if [ $incrementrx -eq 0 -a $incrementtx -eq 0 ]; then
		exitLoop=false
	fi
	rxp1=$rxp2
	txp1=$txp2

done
poweroff
```

Appendix C: Market Survey

A market survey has been done in order to understand how much our final product can be useful and if it can compete with the devices that are already in the market.

The idea to put the switch directly to the wall plug already exists and there are several "smart switches" that eliminate the standby power in a remote controlled way. The list of IR remote controlled sockets is really long, but nowadays they are being replaced by the RF remote controlled sockets that allow a longer range, non-line-of-sight use as well as lower transmitter power consumption. For this reason I focused on the latter: remembering that our product works with the 2.4GHz frequency and choosing the second configuration (with the switch attached directly to the wall plug), it can be included in the category of RF remote controlled sockets.

I've chosen eight devices to highlight because each one has at least one interesting feature that makes it different from the others.

1. Orvibo S20 Smart Socket

   http://www.orvibo.com/product_24.html

   - Price: €20.00

Product-Overview:
S20 connects an electronic device to Internet, so that it's possible to control it through 2G, 3G or Wi-Fi. Thanks to the app for smartphones, it is also possible to set a timing schedule.

Features:

- Voltage range: 100-240V AC
- Max current: 10A
- Max power: 2000W (resistive load)

- Wireless frequency: 2.412~2.484GHz
- Wireless IEEE standards: 802.11b/g/n
- Security: WPA-PSK/ WPA2-PSK /WPA/WPA2/WEP/WPS2/WAPI
- Encryption type: WEP/TKIP/AES
- Wireless consuming: ≤0.3W

2. Belkin Wemo Insight Switch

http://www.belkin.com/us/F7C029-Belkin/p/P-F7C029/

- Price: €59.99

Product-Overview:
The Wi-Fi enabled WeMo Insight Switch connects an electronic device to the Wi-Fi network, allowing to turn it on or off, program customized notifications and change device status. WeMo Insight Switch can monitor the device and send information about its energy usage directly to the smartphone or tablet.

With the WeMo App, it is possible to create rules and custom schedules.

IFTTT is a service that lets create powerful connections with one simple statement: if this then that. IFTTT works with the WeMo collection of products to connect the home electronics to some online apps.

Features:

- Max 120 V / 15 A
- Max Power: 1800 W
- Wi-Fi: 2.4Ghz, 802.11n

3. EGO Efergy Smart Wi-Fi Socket

http://efergy.com/uk/products/ego

- Price: €47.90

Product-Overview:
With the ego smart Wi-Fi socket it is possible to control the home appliances and devices, turn them on and off and monitor their energy use from the smartphone.

The ego uses a cloud to collect and store the data. It's also possible to set timers for automatic switching of devices or set the ego to turn off appliances left on standby for too long.

Features:

- Voltage: 100-240V.
- Current: 13A(UK)/16A(EU)/10A(AU)/15(US)
- Frequency: WiFi 2.4GHz b/g/n

4. Witenergy E100 Energy Meter Socket

http://wittech.net/WiTenergy.html

- Price: $29.99 (approximately €26)

Product-Overview:
E100 is a Bluetooth 4.0 Energy Meter Socket that can control and monitor the energy usage of the electric appliance connected with the App provided. User can program the socket to turn on/off at desired time schedule.

Features:

- E100S: 120 VAC, max 15A, 1800W
- Wireless Standard: Bluetooth 4.0
- Frequency Range: 2400 – 2480 MHz
- Operation Range: up to 30 meters

5. ISOCKET Ecoswitch

https://www.isocketworld.com/en/iSocket-EcoSwitch-ISGSML706EU/

- Price: €99.00

Product-Overview:
iSocket EcoSwitch is designed to switch electrical equipment remotely via a mobile

GSM network using standard mobile phone SMS-commands from traditional phones or from smartphones with apps. There is no payment for the call/SMS service.

Features:

- Power Input (Supply Voltage): 100-240VAC, 50-60Hz
- Max. rating 4000W (16A at 250VAC); continuous resistive load
- Three security levels: password, list of phone numbers, limited configuration interval
- Support several security numbers to limit access to management and configuration
- 4-band worldwide GSM 850MHz/900MHz/1800MHz/1900MHz
- Stand-by power <1W

6. Valta Starter Kit

http://www.amazon.com/Valta-A001001011-Starter-Kit/dp/B00EP78BDM/ref=sr_1_1?ie=UTF8&qid=1462006748&sr=8-1&keywords=valta

- Price: $149.00 (approximately €129), hub + 2 sockets

Product-Overview:
Valta is a remote energy management system that can detect unused devices, identify energy waste, and send notification to help the user to save energy.

The Valta interface will also provide connected devices' energy usage data.

The Valta app has three setting options.

- Schedule: Schedule the device to turn on.
- Timer: Decide how long the device has to be turned on for.
- Grouping: Control multiple devices.

The energy information is stored on the Valta cloud.

Valta sockets use a proprietary communication with industrial grade encryption.

The Valta control hub enables communications with all components of the Valta ecosystem with the Valta cloud server.

Features (socket, North America version):

- Electrical rating - 120V/ 15A/ 60Hz/ 1800W
- Power consumption - 0.6w (min.)/ 1.1 watt (max.)
- Communication - ISM (industrial scientific and medical) frequency band (921MHz)
- High resolution chipset to measure standby power

Features (Valta Hub):

- Input power - DC 5V@1A
- Power consumption - 1.0 watt (min.)/ 1.75 watt (max.)
- Communication - ISM (industrially scientific and medical) frequency band with minimum 100M point-to-point signal range
- Feature - Pair up to 16 sockets

7. Samsung Smartthings Outlet

http://www.amazon.com/Samsung-SmartThings-Hub-2nd-Generation/dp/B010NZV0GE/ref=sr_1_1?s=electronics&ie=UTF8&qid=1462008275&sr=1-1&keywords=smartthings

- Price: $153.99 (approximately €133), hub + outlet

Product-Overview:
This outlet allows a remotely control of an electronic device thanks to a ZigBee communication. Using the Samsung SmartThings app it's possible to set timers for the device plugged into the Samsung SmartThings Outlet to automatically turn on and off based on a schedule or in response to other activities.

- Save energy by restricting power to electronics or appliances or receive alerts if lights or electronics were accidentally left on.
- Acts as a ZigBee repeater, extending the range of the ZigBee devices, when plugged into a wall outlet.
- Additional Requirements: Samsung SmartThings Hub

The SmartThings Hub connects wirelessly all the compatible smart devices.

Features (outlet):

- Communication protocol: ZigBee
- Max General Purpose Load: 120V, 12 Amps
- Range: 50-100 feet

Features (hub):

- Power: In-wall power adapter with about 10 hours of backup power from 4 AA batteries (included)
- Communication Protocol: ZigBee, Z-Wave, IP
- Range: 50-130 feet

8. Loxone Smart Socket Air

http://shop.loxone.com/enuk/smart-socket-air.html

- Price: €70.48
- Requires a miniserver: (€361.79, Miniserver Go)

Product-Overview:
The intelligent wireless plug uses Loxone Air technology and can be integrated with either the Air Base Extension for the Miniserver, or alternatively with the Miniserver Go. The Smart Socket Air has an in-built temperature sensor and power meter, so it’s possible to track the energy usage.

The Smart Socket Air allows the appliances’ control either automatically from the Miniserver’s schedules and logic, or manually from the Loxone apps.

Every 5 minutes, information about the energy and power is sent to the Miniserver. If a 5% change in the data occurs this update is sent immediately to the Miniserver. The Miniserver offers an intelligent control of a smart home. Loxone Air is a proprietary wireless technology. The Miniserver saves all data locally so that all statistics and other data are not passed on to third parts.

Features (socket):

- Suitable for a voltage of 85 - 265VAC
- Max. switching capacity: 16A
- Integrated measurement of energy (kWh), power (kW) and temperature (-20 to 50°C)
- Frequency: 868MHz
- Power consumption: <500mW
- Protection: IP20
- Safety shutdown: If the CPU temperature increases over 92°C, the relay is turned off. Once the temperature drops below 77°C, the relay is turned on. The CPU temperature is updated on startup and if there is a temperature change of more than 5°C.

Features (Miniserver Go):

- Voltage supply: 5VDC (via micro USB charger)
- Loxone OS operating system with built-in webserver
- Fully integrated Air Base Extension with internal antenna
- Frequency: 868MHz (SRD Band EU) / 915MHz (ISM Band Region 2)
- Power consumption**:** 1.3W
- Onboard microprocessor and memory
- Stand-alone - no additional servers or hardware required
- Protection: IP20

Summary and Comments

All the above sockets are characterized by the same purpose that is to remotely turn on/off plugs (and hence devices) thanks to an embedded switch system remotely controlled and they also have the feature to set a timing schedule thanks to a free app for smartphones (note that each device has different system requirements). These are the basic functions that characterize the first device by Orvibo; it is the cheapest one and works with the 2.4GHz Wi-Fi band. The following two devices (by Belkin and Efergy) work conceptually in the same way and with the same wireless band but they have more features and consequently they are more expensive. First of all they can monitor the energy usage of the attached electronic devices; it's a very useful feature that also the other devices of the list have. Moreover the *Belkin Wemo Insight Switch* has the possibility to set rules that trigger the power according to preset times and it's also possible to receive custom notifications. These features are missing in the *Ego* by Efergy but this one has the feature to learn the standby power of the attached electronic device (thanks to the learn button of the app) and to turn off the system after a given time. This one is exactly the feature that we want to put inside our product in *Phase 2*; also the Valta socket can measure the standby power but this feature is present in very few products of the market.

While the products I've just talked about work with the Wi-Fi protocol, the others make use of different ways to communicate with consequences on the range and on the transmitter power:

- *Witenergy E100* is a Bluetooth based socket;
- *iSocket* is driven by free calls or SMS;
- The *Smartthings Outlet* communicate via the Zigbee protocol;
- Valta and Loxone have developed a proprietary communication that makes use of some ISM frequencies.

iSocket is very interesting in terms of power saving but it's also expensive.
Also Valta, Samsung and Loxone have really expensive solutions and they require a hub/miniserver to work but they can be a good solution for a smart home, thanks to the possibility to communicate with the other compatible smart devices.

Finally, the following table summarizes price and technical characteristics of these eight smart sockets.

Name	Price	Communication technology	Max. Ratings	Power Consumption
Orvibo S20 Smart Socket	20.00€	Wi-Fi	2000W	-
Belkin Wemo Insight Switch	59.99€	Wi-Fi	1800W	-
EGO Efergy Smart Wi-Fi Socket	47.90€	Wi-Fi	100-240 V, 16A	-
Witenergy E100 Energy Meter Socket	29.99$	Bluetooth 4.0	1800W	-
ISOCKET Ecoswitch	99.00€	GSM (call/SMS)	4000W	< 1W
Valta Starter Kit	149.00$	ISM (921MHz)	1800W	> 0.6W, < 1.1W
Samsung Smartthings Outlet	153.99$	Zigbee	120V, 12A	-
Loxone Smart Socket Air	70.48€ + 361.79€	868MHz	85-265 V, 16A	< 500mW

Table 7. Market products summary