Universidade de Aveiro Departamento de Eletrónica, Telecomunicações e Informática,
2016

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Sensores Passivos para Aplicações Espaciais

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requesitos necessários à obtenção do grau de Mestre em Engenharia Eletrónica e Telecomunicações, realizada sob a orientação científica do Professor Doutor Nuno Miguel Gonçalves Borges de Carvalho, Professor Catedrático do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro

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agradecimentos / acknowledgements

Começo por agradecer a quem me deu a possibilidade e todo o apoio para que chegar a este momento fosse possível, obrigado pai, mãe, sis, segundos pais, família.

Aos meus amigos, principais culpados por terem tornado todo este caminho uma aventura inesquecível, o meu muito obrigado.

Um agradecimento muito especial aos meus colegas, Ricardo Correia e Daniel Belo, pela disponibilidade, ajuda e companheirismo durante este último ano.

Muito obrigado ao meu orientador, Professor Doutor Nuno Miguel Gonçalves Borges de Carvalho, assim como, a todos os membros do Instituto de Telecomunicações, por todo o auxílio prestado.

Esforço, dedicação, devoção e glória...

Palavras-Chave

Radio Backscatter, Wireless Power Transmission, RF-DC, Antennas, RFID, WSN, Microcontrollers, Low-Power

Resumo

Uma das áreas, se não a principal área, com maior desenvolvimento nos últimos anos é a exploração espacial. A entrada de empresas privadas no negócio aliadas aos novos meios de comunicação reacenderam a curiosidade sobre o espaço.

Esta dissertação surge com o intuito de desenvolver um sistema de comunicação passivo, com capacidades de monitorização e de processamento para aplicações espaciais. Para tal quer-se utilizar conceitos tais como: antenas, projeto de formas de onda, transmissão de energia sem fios, circuitos de RF-DC, rádio retrodifusão , modulação e desmodulação de sinais.

Para se chegar a um sistema funcional, pretende-se analisar e testar diferentes soluções para cada uma das partes do sistema. Quer-se que o trabalho seja o mais abrangente possível, e que aborde todos as partes necessárias para o desenvolvimento do sistema. No entanto e devido à complexidade do mesmo, este trabalho é focado em quatro pontos: antenas, circuitos de RF-DC, circuitos de retrodifusão e microcontroladores. Os restantes aspectos são abordados mas superficialmente.

Para além de toda a parte hardware do sistema, também se pretende desenvolver uma solução otimizada a nível do software, de modo a que a solução final tenha o melhor rendimento possível.

Inicialmente o sistema será projetado para aplicações espaciais, no entanto espara-se que o mesmo possa ser usado em outras áreas.

Key-Words

Radio Backscatter, Wireless Power Transmission, RF-DC, Antennas, RFID, WSN, Microcontrollers, Low-Power

Abstract

One of the areas, if not the principal area, with higher development in recent year is space exploration. The entry of more private companies in the business allied with new ways of communication reignited the curiosity about the space.

This dissertation, appears with the intention of developing a passive communication system for spatial applications. The system should have sensing and processing capabilities. To achieve this, some concepts are important: antennas, waveform design, wireless power transmission, circuit RF-DC, radio backscatter, wave modulation and demodulation.

In order to design a functional system, each part of the system will be analysisd and tested. The work is designed to be the more embracing possible, however due to its complexity it is more focused in four points: antennas, circuit RF-DC, radio backscatter and microcontrollers. The other aspects are approached but with less details. Beyond all the hardware aspects, it is also intended to develop a optimized solution for software, trying to achieve a better general system efficiency.

The system is designed for spatial applications, however it is expected that it could be a solution for other areas.

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List of Acronyms

ADC	Analog to Digital Converter
ASK	Amplitude Shift Keying
CW	Continuous Wave
DAC	Digital to Analog Converter
DCO	Digitally Controlled Oscillator
EIRP	Equivalent Isotropically Radiated Power
ERP	Equivalent Radiated Power
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FET	Field-Effect Transistor
FSK	Frequency Shift Keying
HF	High Frequency
ICW	Intermittent Continuous Wave
ISM	Industrial, Scientific and Medical
LDO	Low Dropout Regulators
LF	Low frequency
NASA	National Aeronautics and Space Administration
OOK	On Off Keying
PAPR	Peak-to-Average Power Ratio
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
RF	Radio Frequency
RFID	Radio Frequency Identification

SAR Synthetic Aperture Radar

SNR Signal to Noise Ratio

SPI Serial Peripheral Interface

UART Universal Asynchronous Receiver/Transmitter

UHF Ultra High Frequency

UWB Ultra Wide Band

WISP Wireless Identification and Sensing Platform

WPT Wireless Power Transmission

WSN Wireless Sensor Network

Chapter 1

Introduction

The general challenge addressed in this work was the development of a passive system with sensing and processing capabilities using Wireless Power Transmission (WPT) and backscatter techniques.

In the first chapter the main objectives of this work are presented, as well as the motivation. Besides, some of the involved concepts essential for understanding the work are introduced.

Secondly, on the state of the art chapter, concepts and solutions related with the problematic in cause are explained. Some of the topics that are presented in this chapter are not explored in the work, however their understanding is important to have a clear vision about the whole system.

The next chapter is about the technologies used to develop the system. First with a general view about the whole system and after each part in detail. It shows how the system is constructed, which components are used and how it should work.

Chapter number four, give a detailed analysis related with microcontrollers, and software development.

The system results will be presented in chapter five.

Finally, on the last chapter, the conclusion about all the work is presented. A personal opinion about the future work that could be developed in order to improve the system can also be found there.

1.1 Motivation

Technology is everywhere around us, the frantic growth is not slowing down and each day there is a new discovery, a new product, a new idea being developed to change the way how we see and how we interact with the world. One of the areas, if not the principal area, that has been having an huge development in recent year is space exploration. The entry of more private companies in the business allied with the new ways of communication reignited the curiosity about the space. Some companies are already announcing that in some year spatial tourism will be a reality and an human foot on Mars, seems now more possible than ever, Space exploration and the hope to get answers to fundamental questions will maintain the need for developments in an high rate. To achieve major goals small steps need to be done, and the use of passive sensors to spatial applications can be an important improvement.

The use of sensors are generalized in spatial applications, temperature, pressure, oxygen levels, solar radiance are some examples. The massive use of sensors means more information and control, but at the same time it also means a huge amount of cables connecting them, or in some cases a big amount of batteries. Developing passive sensors can be one of the enablers to remove cables, which has direct impact in the space optimization and weight reduction key factors in satellites and spacecrafts.

The scientific fields involved in the developing of the project are trend line not only in spatial investigation but in a wide variety of science projects. WPT, backscatter techniques, low power sensors and microcontrollers, antennas, are all areas that will be even more in focus in the coming years.

1.2 Objectives

The main objective of this work is the development of a wireless powered system with sensing and processing capabilities using WPT and backscatter techniques.

The specific objectives purposed initially changed dynamically with the challenges and findings, some techniques that were suppose to be implemented, presented results not compatible with the main goal and needed to be adjusted. The decisions were always made with the intention to have a better final product, never compromising the scientific value of the work.

So the specific objectives can be listed as:

- Understand the general panorama in passive communications;
- Learn about backscater techniques and WPT capabilities;
- Make an analysis on types of antennas specially designed for WPT;
- Program and test low power microcontrollers, in order to fit it in the whole system with the lowest power consumption possible;
- Pack together WPT, backscatter and a microcontroller in one system;
- Make measurements on power transmitted, power received and distance;

With the complete understanding about all the process involved in this work, it is expected to generate valuable considerations about future developments and new possible applications for it.

1.3 Overview of Involved Concepts

To have a clear vision about the technologies involved in this work some concepts should be carefully presented before anything else. The work have a large number of concepts, however only the more important concepts will be dealt here in detail. Other concepts not so fundamental to the understanding of the work will be introduced on-the-fly.

The overview of involved concepts will start explaining the functionality of Radio Frequency Identification (RFID) systems, its operation mode and possible applications.

The second topic explains how Wireless Sensor Network (WSN) work, with a brief conclusion about its potential and limitations.

After, a description about the different ways of transmitting power without using wires, WPT. A general exposition about the concept using induction techniques will be done even though it is not used in this work, being followed by a more detailed explanation about WPT using electromagnetic radiation techniques.

The last subject is about processing units, which is essential to understand some concepts discussed in Chapter 4.

1.3.1 Radio Frequency Identification

RFID is a electronic system of identification using a product code, it appeared as an alternative to bar codes. RFID technology is based on the transmission of a carrier by a device usually called transceiver or reader, the transponder or tag receives the carrier where it is modulated and reflected. The carrier modulation can be done in amplitude, phase or frequency. The reader receives the modulated carrier that has the tag information in its modulation. Figure 1.1[1] is a illustration of how RFID works.

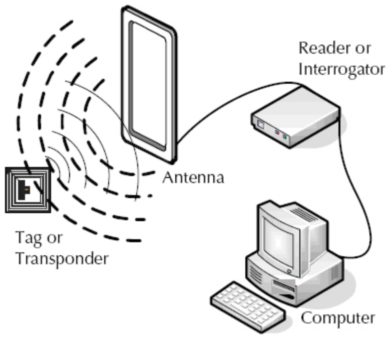


Figure 1.1: RFID concept

RFID tags operate at several different frequencies bands, however three of them are the most used bands, Low frequency (LF) 125 kHz to 134 kHz, High Frequency (HF) 13.56 MHz and Ultra High Frequency (UHF) 860 MHz to 960 MHz. The use of multiple frequencies is due to the different characteristics presented in each band, for example LF is better for omnidirectional requirements and HF is better for longer distances [1]. RFID spectrum is illustrated in Figure 1.2[2].

[1]Figure taken from: http://www.epc-rfid.info/rfid
[2]Figure taken from: http://rfid4u.com/rfid-basics-resources/the-rf-in-rfid/

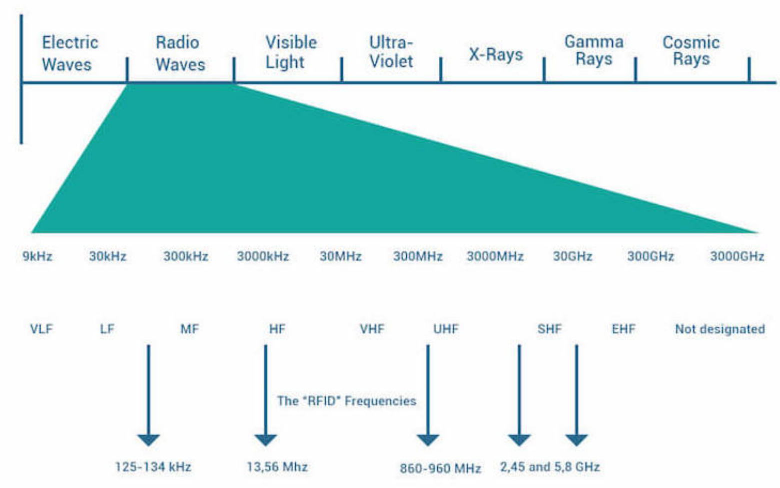


Figure 1.2: RFID spectrum

Other important point about this identification system is that usually the tag information is static, it is stored one time and it does not change [2].

A detailed description about the technical aspects involved in RFID will be done in Chapter 2. Section 2.1 will present information about RFID reader, Section 2.2 will explain tags features and Section 2.5 will be covering the carrier reflection known as radio backscatter.

In terms of applications, RFID appeared as the natural substitute for bar codes, nevertheless there are some important points that deserve a closer analysis[3]:

- RFID can be read from greater distances;
- RFID does not need a positioned line of sight with the reader;
- RFID has a faster reading process;
- Bar codes are smaller and lighter;
- Bar codes are less expansive;
- Bar codes are the worldwide identification system;

Comparing the systems there are some advantages and disadvantages in both systems. The big advantage for bar codes is its worldwide conditions, however since RFID with more applications, it will replace bar codes naturally. The applications for RFID are not limited at product identification, the technology can be also applied in others fields like logistics, asset management, access control, payments, product tracking, etc.

1.3.2 Wireless Sensor Networks

WSN is a concept with some years but in recent times advances in semiconductor, networking and material science technologies are driving them to a large-scale paradigm. WSN are finding their way into numerous applications in homes, industries or work places, bringing new sources of information, control and convenience to personal and professional lives [4].

These sensing networks are formed by multiple sensing nodes connected to one gateway or routing node. The communication between sensing nodes and gateway can be done directly, when the sensing node is reachable by the tag, or the information can jump between sensing nodes until it arrives at one node that can reach the gateway [5]. Figure 1.3[3] illustrates the process .

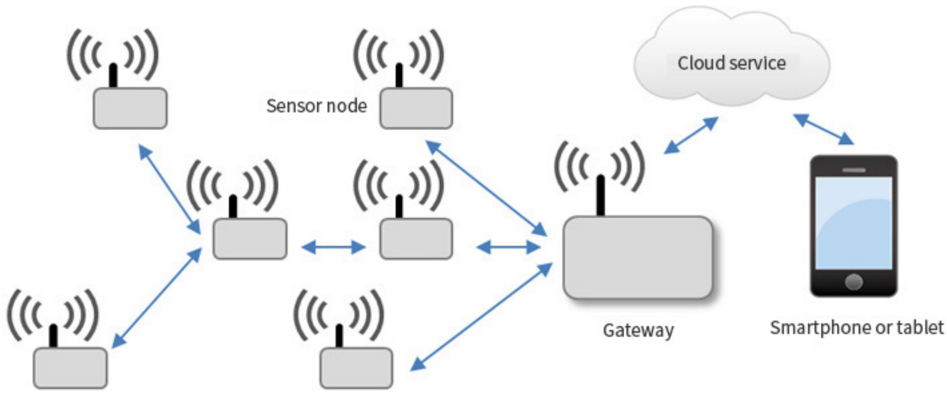


Figure 1.3: WSN concept

The WSN potential is huge, the amount of applications where these networks can be applied is not countable. However there are some issues that needed to be solved as the need of a battery for each sensing node. If the WSN has few sensing nodes and if they are on easy access locals there is no big problem with batteries, but if considered a networks with hundreds of sensing nodes and some in difficult access, replacing all the batteries becomes a big problem.

There is already some alternatives to the battery powered nodes, it is possible to find passive or semi-passive tags with sensing and processing units but due to its battery free technology they are very limited. The topic about different types of tags will be addressed in Chapter 2.2.

1.3.3 Wireless Power Transmission

The definition of WPT can be explained as the process involved in the transference of energy from one source to a load without conductive connections. The topic is not recent, the first discoveries can be dated to the beginning of the XIX century.

At that time, some inventors like Heinrich Hertz and Nicolai Tesla theorized the possibility of wireless power transmission. Tesla demonstrated it by powering fluorescent lamps. He also discovered that it is possible to increase the distance at which he could light a lamp, using a tuned resonant frequency between transmitter and receiver [6]. Even though that his attempt to commercialize the wireless transmission failed, due to its high cost compared to the cooper connections, his discovers are now fundamental.

Some years later, impulsed by the World War 2, the microwave technology had some developments. William C. Brown invented the rectenna that could efficiently convert microwaves to dc power, using his rectenna Brown made the first long distance WPT [7]. A

[3]Figure taken from: http://www.yuden.co.jp/ut/solutions/wsn/

more solid prove about the Brown invention appeared when he could power a aircraft by transmitting microwaves from the ground.

In the recent years the concept gained new importance, technological developments and new applications appeared. The idea of no physical connections to power systems is fascinating, since the costumer product until industry or even for space applications WPT is now a hot topic.

This type of energy transmission can be subdivided in two methods: resonant inductive coupling and electromagnetic radiation. The first is a technique mostly used in local applications for short distances and high needs of power, it is done using two inductive elements. On the other side electromagnetic radiation is used in long range and low power applications. In this work the WPT is done through electromagnetic radiation more specifically using Radio Frequency (RF), but both techniques are presented.

Resonant Inductive Coupling

To create a magnetic field, the only thing needed is an electrical current moving through a wire. With this, a circular magnetic field is created around the wire. When the intention is to use this technique in WPT, the magnetic field is highly increased if the wires are bent around a coil. Placing a similar coil near the first one will cause the opposite process, the magnetic field will induct a current. There are multiple aspects to consider if the goal is to ensure the maximum power transmission, for example number of loops and the coil form. Figure 1.4[4] illustrates the described system.

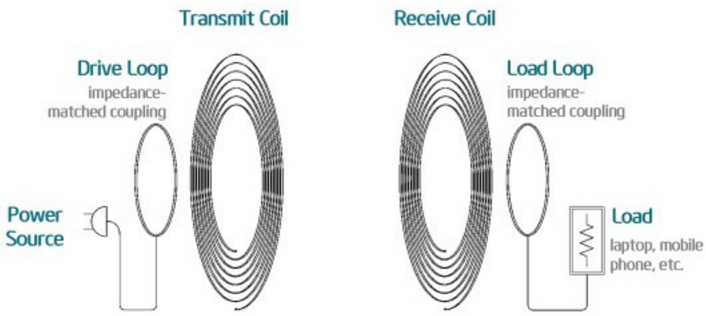


Figure 1.4: WPT resonant inductive coupling

This type of energy transmission has a big limitation in terms of efficiency, since the magnetic field spreads in all directions, the system is not efficient. However in some cases efficiency is not crucial, and this technology can be found in the market. Cellphone chargers, tooth brushes, electrical toys are some of the examples that can be found among many others products using resonant inductive coupling. Figure 1.5[5] shows how this technology is used to charge an electric car battery.

[4]Figure taken from: http://www.socialledge.com/sjsu/index.php

[5]Figure taken from: http://insights.globalspec.com/article/3003/wireless-power-transfer-a-key-technology-for-ev-adoption

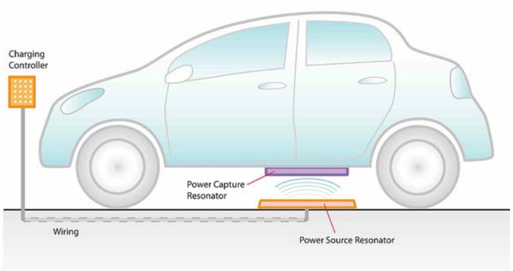


Figure 1.5: WPT resonant inductive coupling

Electromagnetic Radiation

Other WPT techniques are based on electromagnetic radiation, this method uses two different blocks to transmit and to receive the electromagnetic radiation.

The block responsible to transmit energy, has a signal generator, which is basically a local oscillator that generates a continuous wave at the determined frequency. Depending on the power that can be supplied by the generator, desired distance and power needed at the receiver, the system can have or not a power amplifier. The transmitter antenna can have multiple forms, since a directional antenna better to point-to-point connections, to a omnidirectional one, which is ideal when the application have multiple receivers in different places.

The receiver is a more simple model, it contains a receiving antenna, a rectifying circuit, a voltage regulator and a load or energy storage [8]. Figure 1.6[6] is a simplified illustration of the described process.

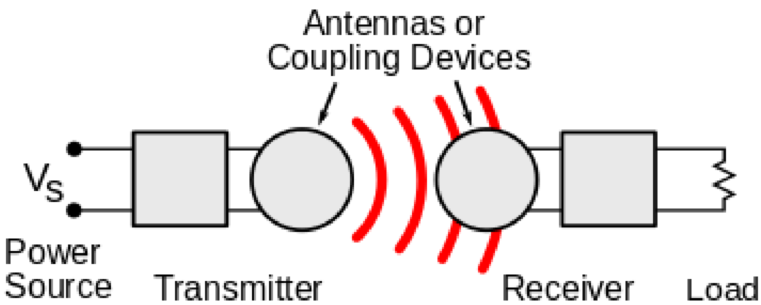


Figure 1.6: WPT electromagnetic radiation concept

The frequencies used in this method are usually radio or microwave frequencies. These frequencies make this model suitable for transmitting energy at large distances.

WSN is one of the examples where this method could be applied, sometimes these systems are placed in remote locations that makes the battery replacement an hard task. Using this technique to supply the sensors there is no need for batteries. Other application that use electromagnetic radiation is in space energy transference. It consists in a Satellite-Earth WPT with a multi-kilowatt transmission, the idea is represented in Figure 1.7[7].

[6]Figure taken from: https://en.wikipedia.org/wiki/Wireless-power-transfer

[7]Figure taken from: http://www.allaboutcircuits.com/news/wireless-power-transmission-of-solar-energy-from-space/

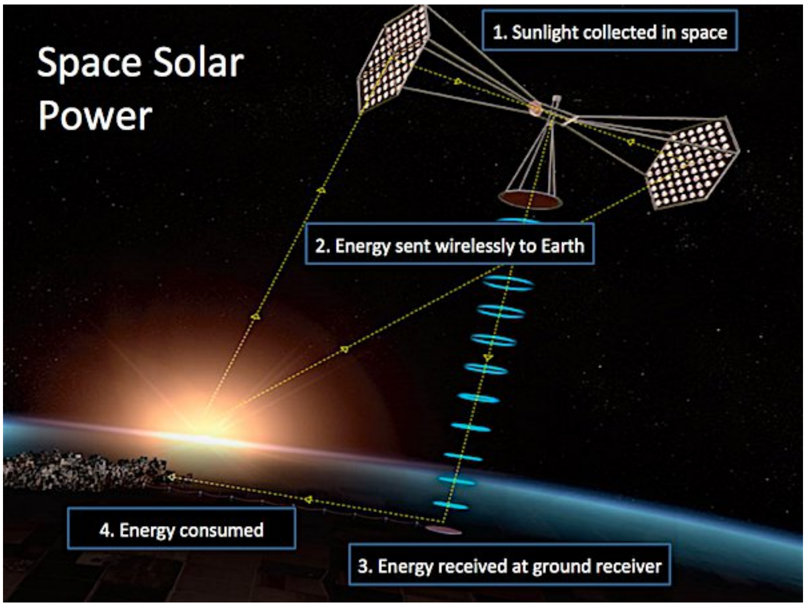


Figure 1.7: WPT electromagnetic radiation example

1.3.4 Processing Units

Microcontrollers are the brains of the electronic circuits, they are the process units of information and the part responsible to integrate others components. There are a countless ways to use microcontrollers. This diversity of uses makes the manufactures to produce different types of microcontrollers, ones more dedicated to a certain application than others. Although there is no defined classification for different types of microcontrollers, there are three big applications, where with more or less accuracy it is possible to divide them, for low-power, for high-performance and for communication.

Low Power Microcontrollers

These microcontrollers are specifically designed to have a low current consumption and a low operation voltage. This is achieved by using low frequency crystal clock as main clock source, dc-dc converters, sleep modes and others. Low power microcontrollers are chosen when the application involves energy harvesting system or batteries. The precision is not a requirement and the amount of features available is limited in this kind of microcontrollers.

Performance Microcontrollers

On the opposite side of the low power microcontrollers, the performance microcontrollers have no big concern about its consumption, its main feature is to ensure a high precision in multiple features. These are used when the application is industrial drivers, real time control or when it involves security systems. Beyond its high power consumption this class of microcontrollers is expensive.

Communication Microcontrollers

Communication microcontrollers are designed to integrate features that allow Bluetooth, Wi-Fi, ZigBee or others wireless communications technologies. It is possible to use low power or performance microcontrollers with external shields to make this communications, but when the microcontroller is already implemented and optimized for wireless use, it is a better choice than other microcontroller class.

Once the work objective is to create a passive system with sensing and processing capabilities, the low power microcontrollers are the natural choice. So it is important to describe in more detail some concepts about them.

The first important topic about low power microcontroller is its main clock options. Usually there are some clock options, providing different frequencies and different consumption. External low frequency crystals, like 12 kHz, are available and most of the time are the better choice in terms of energy efficiency. However it can bring big limitations in terms of processing time. Internal clock have higher frequencies but, as can be expected, have bigger power consumption. Even though some applications need a faster main clock, that can not be provided by low frequency crystals, it is a good policy to use them for secondary processes like timers, Digital to Analog Converter (DAC) or external components to reduce the overall power consumption.

Sleep modes are the other key feature about low power microcontrolers. These modes are software controllable and they can turn off some microcontrollers features until some interruption wakes the microcontroller to its normal state again. The interruption can be generated by multiple sources, since an external signal to a programmed timers. Figure 1.8 is a simplified sleep modes example [9].

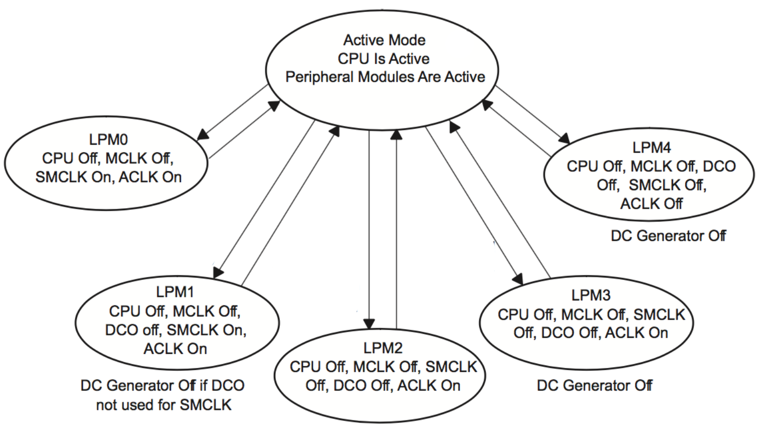


Figure 1.8: Sleep modes example

CPU should be read as Central Processing Unit, LPM as Low-Power Mode, MCLK as Master Clock, DCO as Digitally-Controlled Oscillator , SMCLK as Sub-System Master Clock and ACLK as Auxiliary Clock.

1.4 Conclusion

In this introductory chapter the motivational aspects behind the development of this work were presented.

The second topic, listed the objectives that are pretended to be achieved, and reinforces that the initially purposed objectives can change with the challenges and findings.

Next, some involved concepts important for contextualization were provided. Starting by an overview about RFID and WSN, two key definitions to understand the present work. It is followed by a WPT explanation, process that is used in the developed system.

For last point, processing units, approaching a general division between the microcontrollers. Some technical aspects also important in low power microcontrollers are also referred in this point.

Chapter 2

State of the Art

As said before, the goal with this work is the development of a passive communication system with sensing and processing capabilities. In the next pages a state of the art approach about the techniques needed to implement the system will be presented.

2.1 Radio Frequency Identification / Wireless Sensor Networks readers

RFID and WSN are different systems with different goals, however he reader part of the system works in a similar way in both systems. Readers are strategically placed to interrogate tags where their data is required. For example a sports timing system locates its readers at starting and finishing line and a security system based on WSN would spread sensors in the control points.

Readers Structure

Typically a reader consist of a RF module, a control unit, and a coupling element to interrogate electronic tags. In addition, many readers are fitted with an interface that enables them to communicate their received data to a processing system [10]. Figure 2.1 illustrates the typical structure for a reader.

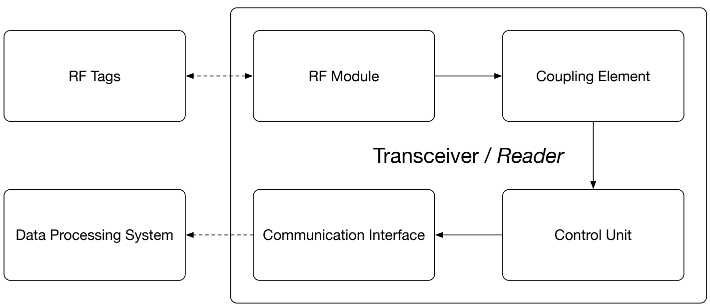


Figure 2.1: Transceivers / readers structure

The main structure between different readers does not have major differences.

Output Power

The output power is one of the most important features about readers, since it is related with distance, having bigger or lower output power represents different results in terms of distance. An increase of the output power can increase the distance at which the tags can be read.

As all the telecommunications system, the level of power radiated by the reader need to respect the legislation. This legislation is not universal and may change from country to country. Federal Communications Commission (FCC) and European Telecommunications Standards Institute (ETSI) are the regulator entities for different regions. To understand the power limits for RF transmission there are two important scales to know as Equivalent Radiated Power (ERP) and Equivalent Isotropically Radiated Power (EIRP).

ERP, corresponds to the amount of power that an ideal half-wave dipole antenna radiate in its peak power. EIRP, corresponds to the amount of power that a perfectly isotropic antenna radiate in its peak power [11].

The formula that relate ERP or EIRP is the same and is presented in Equation 2.1.

$$ERP/EIRP = PowerTransmitted - Losses + AntennaGain; \tag{2.1}$$

The gain of an ideal half-wave dipole antenna is 1.64 and the numeric gain of an ideal isotropic antenna is 1.0. Starting from this point the relation between ERP and EIRP is expressed in Equation 2.2.

$$\begin{aligned} 10\log 1.64 &= 2.15\,\mathrm{dBi}; \\ \mathrm{ERP} &= \mathrm{EIRP} - 2.15\,\mathrm{dB}; \\ \mathrm{EIRP} &= \mathrm{ERP} + 2.15\,\mathrm{dB}; \end{aligned} \tag{2.2}$$

To a better understanding, the legislation for RFID readers using the UHF band, $860\,\mathrm{MHz}$ to $960\,\mathrm{MHz}$ can be analysisd. In the countries covered by FCC norms the limit is $4\,\mathrm{W}$ EIRP by other hand under ETSI legislation the limit is $2\,\mathrm{W}$ ERP.

As it was demonstrated before there is a relation between EIRP and EIRP, so for clear analyses Equation 2.3 provides the values in equal units;

$$\begin{aligned} 2\,\mathrm{W} &= 2000\,\mathrm{mW}; \\ 4\,\mathrm{W} &= 4000\,\mathrm{mW}; \\ 2000\,\mathrm{mW} = 10\log_{10} 2000\,\mathrm{dBm} &= 33\,\mathrm{dBm}; \\ 4000\,\mathrm{mW} = 10\log_{10} 4000\,\mathrm{dBm} &= 36\,\mathrm{dBm}; \\ \mathrm{ERP} = 36\,\mathrm{dBm} - 2.15\,\mathrm{dB} \Leftrightarrow \mathrm{ERP} &= 33.75\,\mathrm{dBm}; \end{aligned} \tag{2.3}$$

Now it is easier to compare values, in FCC norms the limit is $33.75\,\mathrm{dBm}$ and in ETSI it is $33\,\mathrm{dBm}$.

Collisions

The readers can interrogate multiple tags, however if they answer at same time the signal that arrives to the reader can collide with one signal from other tag. In order to a reader communicate with multiple tags, a method for collision free tag communication must be employed [10]. This subject will be presented in the next topic, Section 2.2.

2.2 Radio Frequency Tags

RF tags are electronic circuits composed basically by a micro digital circuit and an antenna. This description meets the most used tag, passive tag. The tag information is saved on its digital circuit, the antenna is responsible for receive the carrier and reflect it with a modulation. There are tags that due to its high need of power, for example the ones that use power amplifiers, need to have a energy source, these tags are named active tags. The classification of RF tags is not well defined, some literature separates RF tag in three categories, passive, semi-passive and active, and other in two, passive and active, with semi-passive tags being a sub-category [2] [12].

In this work the classification in two categories was chosen because it is more clear to understand the developed system.

Passive tags

As mentioned before passive tags have essentially two parts a micro digital circuit and an antenna. In these kind of tags, the energy needed by the tag to activate its digital logic is provided by the carrier wave. The wave transmitted by the reader goes through a RF-DC circuit which generates output energy to supply the tag. Once supplied, its digital logic does the carrier modulation by reflecting it [1]. A more detailed explanation about the process of reflection can be found in Section 2.5. Figure 2.2[1] and Figure 2.3[2] correspond to a passive tag operation and a passive tag example respectively.

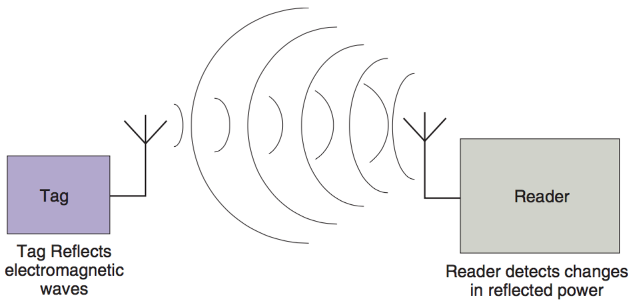


Figure 2.2: Passive RF tag operation

[1]Figure taken from: http://www.cisco.com/c/en/us/td/docs/solutions/Enterprise/Mobility/WiFiLBS-DG/wifich6.html

[2]Figure taken from: http://dir.indiamart.com/impcat/passive-rfid-tag.html

Figure 2.3: Passive RF tag example

Passive tags are excellent for many uses like product identification and human authentication, because they do not need any type of energy. Which means that there is no need for maintenance. However the distance from tag to the reader can not be bigger than a few meters [2].

Active tags

The electronic behind an active tag involves three main components: a micro digital circuit, an antenna and an amplifier. Beyond these main components, active tags can have more electronics, the tag is powered by a battery, or in alternative, by an energy harvester circuit. Active tags receive the wave from the reader but they work independently. They have their own radio and the communication tag-reader is done by radiating a signal [2]. Figure 2.4[3] illustrates an active tag operation and Figure 2.5[4] shows an active tag example.

Figure 2.4: Active RF tag operation

[3]Figure taken from: http://www.cisco.com/c/en/us/td/docs/solutions/Enterprise/Mobility/WiFiLBS-DG/wifich6.html

[4]Figure taken from: http://www.ns-tech.co.uk/blog/2010/02/active-rfid-tracking-system/

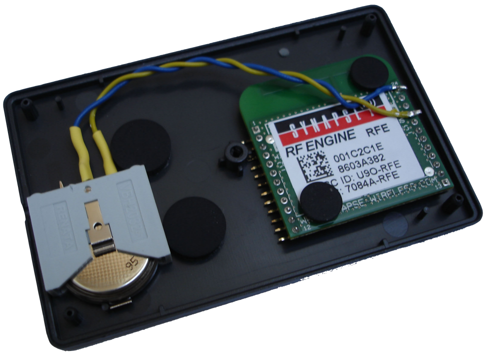


Figure 2.5: Active RF tag example

Active tags are normally used when the applications need long range WSN, medical equipment, electronic test gear, computer equipment or reusable shipping containers. The tag cost can vary significantly depending on the battery life required, and the sensors that are included. The distance in this case is limited by the power amplifier, it can be expected ranges of hundreds of meters [12].

The following Table 2.1 illustrates some aspects between passive and active RF tags.

Table 2.1: Active vs. passive RF tags

	Active tag	**Passive tag**
Tag Power Source	Internal (battery, energy harvester circuit)	Energy transferred from reader via RF
Tag Battery	Yes	No
Availability of Tag Power	Continuous	Only within field of reader
Communication Range	Long range (hundreds of meters)	Short range (few meters)
Data Storage	Large read/write	Small read/write

Semi-passive tags

As the own name indicates, semi-passive tags have features from both tag categories. It uses batteries or others supplies of energy to power its digital logic like an active tag, however the transmission of signal is done by reflecting the carrier wave like a passive tag. The antenna contained in a semi-passive tag is dedicated to backscatter modulation and there is no dependence on the semi-passive tag antenna to be a reliable channel of power for the tag [12]. Figure 2.6[5] shows the operation mode of semi-passive tags and Figure 2.6[6] is an example of a semi-passive tag.

[5]Figure taken from: http://www.cisco.com/c/en/us/td/docs/solutions/Enterprise/Mobility/WiFiLBS-DG/wifich6.html

[6]Figure taken from: http://www.dataloggerinc.com/products/RT0005-RFID-Temperature-Logger-SemiPassive-UHF-Tag/409/

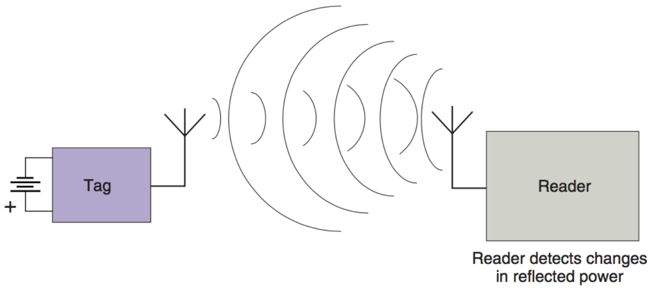


Figure 2.6: Semi-passive RF tag operation

Figure 2.7: Semi-Passive RF tag example

Semi-passive tags are manly used in electronic toll collections, besides that this technology can be found in security access systems, supply chain automation or hierarchical asset tracking systems. Even though, the reflecting process is the same than in passive tags, semi-passive tags can achieve longer distances than passive. As the antenna is fully dedicated to backscaterring it has greater efficiency, achieving distances of decades of meters [2].

Tags collision

When a signal from reader arrives at multiple tags at the same time, there is a chance that they will respond simultaneously creating an interference. This collision of responses typically result in a failed transmission.

In order to a reader communicate with multiple tags, methods to avoid collisions can be applied. These methods have a cost of time and processing capabilities, that is why they only should be implemented when there is a change of tags response collision.

It can be solved using probabilistic or deterministic algorithms. In probabilistic algorithms, the tags respond at randomly generated times. There are several variations of probabilistic protocols depending on the amount of control the reader has over the tags. Deterministic schemes involve a more complex system. The signal emitted by the reader have an ID that correspond to the tag that should respond, all the others that have a different ID should not respond [10] [13]. This solution requires the tags to have a signal demodulation, which means high power requirements. In practice this solution is only implemented when lots of tags can collide and active tags are used. Passive tags do not have enough power to implement this solution.

2.3 Wireless Power Transmission

WPT studies are divided into wave transmission, wave reception and RF-DC conversion. The transmitter emits radio waves that are received by a rectifying antenna known as rectenna. The received waves are converted into usable dc power. Due to legal restrictions and health recommendations the power transmitted is limited, an example of power limitation can be found in Section 2.1. This limitation is the reason why it is important to have an efficient RF-DC power conversion. Efficient rectennas have been implemented through a co-design of antenna, rectifier and front-end [14].

Structure

Figure 2.8 exemplifies the WPT stucture, transmitter antenna is connected to a power supply through a matching network to ensures the maximum power transferred. The receiver antenna is matched with a rectifier circuit, in turn it is connected to a power management unit and this one connected to a load [15].

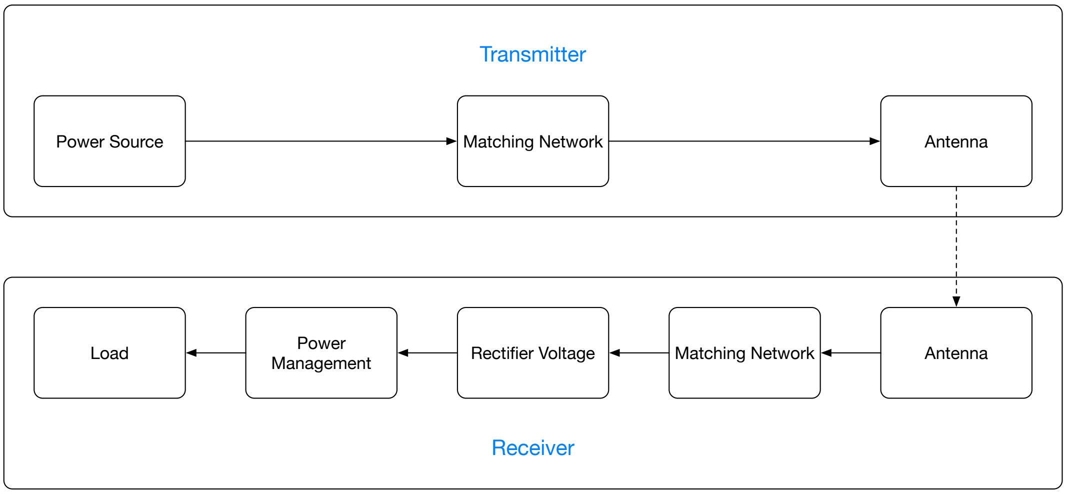


Figure 2.8: WPT structure

Antennas

There are many types of source or transmitter antennas, each one has its owns benefits. Dipole antennas, slotted wave guide, microstrip patch and parabolic dish antennas, are some examples of antennas for WPT due to its high directivity and efficiency [16]. Even though the antennas choice depends on the application, microstrip patch and dipole antennas have been used greatly in antennas for WPT. The simple process of manufacture, the reduced size and weight, as the easy process to construct an array circuit, are important characteristics in these antennas. The disadvantage of these types of antennas is mainly the low efficiency, however these aspects can be improved using antennas arrays. The following figures are examples of it, dipole array is illustrated in Figure 2.9[7] and microstrip patch array in Figure 2.10[8].

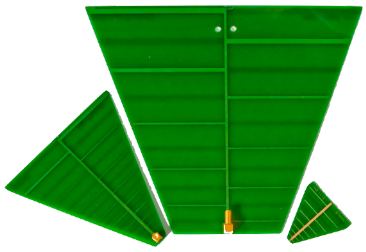


Figure 2.9: Antenna dipole array

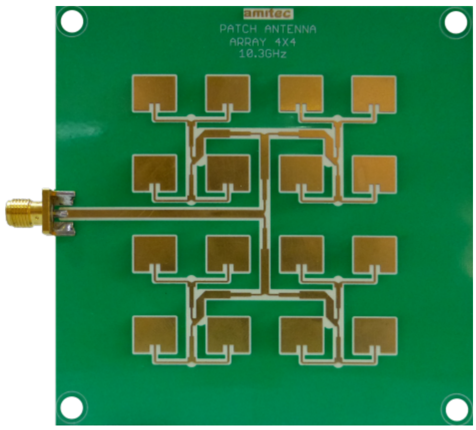


Figure 2.10: Antenna microstrip patch array

An important factor in WPT is the radiation pattern. There are techniques that allow steering radiation making the antenna beam more directive, focusing it in a specific area. It increases the antenna gain. Using this technique the radiation is no longer spread all over the room. Parameters like resonant frequency and polarization characteristics do not suffer any modification with this technique.

In order to obtain the desired radiation pattern there are some important parameters that should be taken into account type of element, the number of array elements, the distance between elements, geometrical arrangement and feeding type [16]. Figure 2.11[9] is an example of different radiation patterns.

[7]Figure taken from: http://www.electronicsbus.com/pcb-log-periodic-antennas/
[8]Figure taken from: http://amitec.co/home/antenna-positioner-transmission-line/rf-microwave-antenna
[9]Figure taken from: http://bpastudio.csudh.edu/fac/lpress/471/hout/wireless/omni.htm

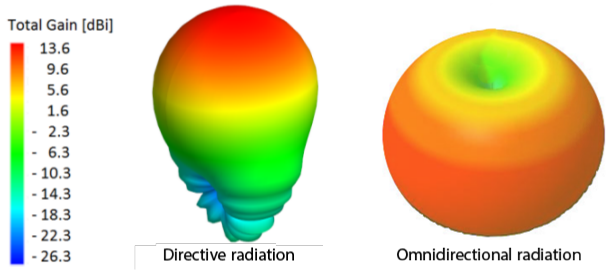


Figure 2.11: Directive vs. omnidirectional radiation pattern

Even though it is possible to do WPT efficiently in several frequencies, 2.45 GHz is the most used. Its low cost power components, its extremely low attenuation through the atmosphere (compared with higher frequencies like 100 GHz) and its location in the Industrial, Scientific and Medical (ISM) band are the factors that influenced this frequency choice [17].

Matching circuits are a key point in antennas efficiency, the circuits should be matched to ensure the maximum power transferred between the antenna and the power supply, in the case for the transmitter antenna. For the receiver antenna, the matching circuits are between the antenna and the RF-DC circuit. The maximum efficiency could be obtained by loading the antenna with its conjugate-matching impedance [18].

Waveform design

The waveform that is sent by the transmitter is an important aspect for WPT. Different waveform design produce different responses in the RF-DC circuit.

For many years, Continuous Wave (CW) have been used in WPT, however recently has been demonstrated that a proper wave design can improve the power transmittion efficiency, especially for low power levels .

The big majority of the RF-DC converters are simple peak detectors. The receiver detects the peak of the signal and charges the output capacitor. It has been found that signals featuring a high Peak-to-Average Power Ratio (PAPR) can provide an efficiency improvement when compared with CW signals [19] [20]. Figure 2.12 illustrates a CW and a high PAPR multisine.

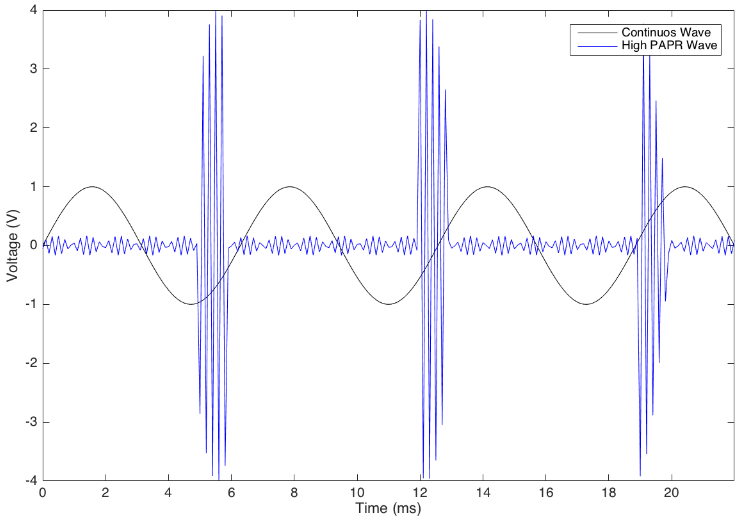


Figure 2.12: Waveform design

With the intention to discover the waveform that could have the maximum RF-DC efficiency, different waveform designs have been studied. Intermittent Continuous Wave (ICW), Ultra Wide Band (UWB), Chaotic Signals, Multisines and Harmonic Signal are some waveforms that were studied was alternatives to CW. Table 2.2 resumes some considerations presented in other works, [19] [21] about waveform analysis.

Table 2.2: Waveform for WPT analysis

ICW	It is spectral inefficiency; Low-pass filter should be applied to the intermittent pattern before transmitting the signal, it can reduce the PAPR;
UWB	Increased spectral bandwidth and the need for wide-band antennas and components;
Chaotic Signals	It is necessary to filter, to avoid radiating in restricted or not allowed frequency bands; Can be less complex than synthesizing other types of signals;
Multisines	It is necessary the generation of multicarrier components, increasing the complexity;
Harmonic Signals	Need for multiband circuit design at the receiver side; Probably the signals that achieve better results in conventional RF-DC converters;

As little improvements in antennas for WPT can mean great advances in the applications side, there are some specific approaches important to consider.

One study relates that employing more dipole elements, and applying a time-delay between the transmitted pulse trains, can work to position the maximum radiation point to any desired position in the horizontal plane [14].

Other study explains that circularly polarized antennas will help to obtain the same dc voltage irrespective of the rotation of the rectenna [22].

Some techniques to reduce the antennas size is other topic approached, studies claim that sizes reduction of more than 25% compared with traditional designs are possible without compromising the antenna's performance [17].

Transmission

The power received by the receiver antenna is much lower than the power transmitted by the transmitter antenna. There are multiple factors that influence the losses. The formula derived by Harald T. Friis, gives the power received by one antenna, under idealized conditions, given another antenna at some distance away transmitting a known amount of power. The Equation 2.4 represents the original formula and Equation 2.5 the formula where gain has units of dB, and power units of dBm.

$$Pr = Pt \times Gt \times Gr \times (\frac{\lambda}{4\pi \times R})^2 \tag{2.4}$$

$$Pr = Pt + Gt + Gr + 20\log(\frac{\lambda}{4\pi \times R}) \tag{2.5}$$

RF-DC

Due to the losses in the air, the power that arrives at the receiver antenna is very low. To avoid more losses, all the conversion steps needed to be adapted to ensure the maximum efficiency. The efficiency in RF-DC is defined as the ratio of the rectified dc output power and the RF incident power as follows in Equation 2.6 [23].

$$\eta = \frac{OutputPower(DC)}{InputPower(\mathrm{RF})} \tag{2.6}$$

The matching circuit between the antenna and the converter circuit is the first crucial point [24]. The impedance between antenna and circuit needs to be match otherwise the power loss can be huge. This matching circuit can be done with components (capacitors and inductors), however if the components have losses, the optimization will not lead to a optimal result. Alternatively, the matching can be done using lines representing the same capacitance and inductance values.

When the antenna and the RF-DC circuit are not in the same board, it is usual to match the parts to the impedance of $50\,\Omega$. Sometimes this separation is important to measure each component individually.

The circuit responsible to convert RF power into dc power is a voltage multipler. A voltage multipler is a circuit with switching elements, like diodes, and storing elements, usually capacitors. There is lots of voltage multipliers.

The Villard circuit is the most common voltage multiplier, and it consists just in a diode and a capacitor. The capacitor is charged up when the waveform goes negative (through the diode), and releases its charge when the waveform goes positive. The final result is that the negative peak disappears and the positive peak has its voltage doubled [25]. An improvement to Villard circuit was done by Greinacher, which put a peak detector after the Villard cell, it reduced dramatically the ripple. Figure 2.13[10] shows the combination of both circuits.

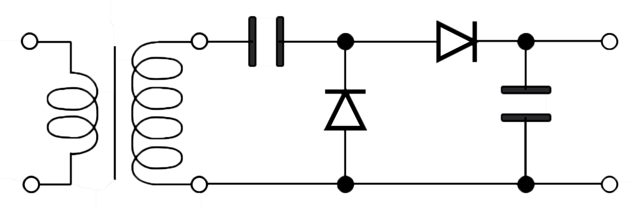


Figure 2.13: Villard circuit with Greinacher improvement

With the intention of power a particle accelerator John Cockcroft and Ernest Walton build a cascade of Greinacher. The result was a topology that can be seen as voltage quadrupler circuit that use two Greinacher cells. It is used to high-voltage applications and it is still used in particle accelerators. Figure 2.14[11] illustrates the circuit.

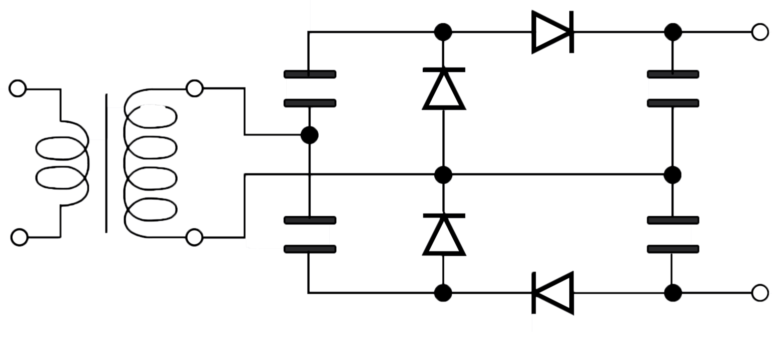


Figure 2.14: Cockcroft-Walton generator

Dickson charge pump is a modification of the Cockcroft-Walton generator. It consists in a cascade of diodes and capacitors with the capacitors being driven by a clock pulse. The clock pulse control each pair of diode and capacitor. The Dickson charge pump is intended for low voltage purposes [26]. Figure 2.15[12] show a Dickson charge pump with four stages which means that ideally the output produces five times the input voltage.

[10]Figure taken from: http://www.wikiwand.com/en/Voltage-doubler
[11]Figure taken from: http://www.wikiwand.com/en/Voltage-doubler
[12]Figure taken from: https://en.wikipedia.org/wiki/Voltage-multiplier

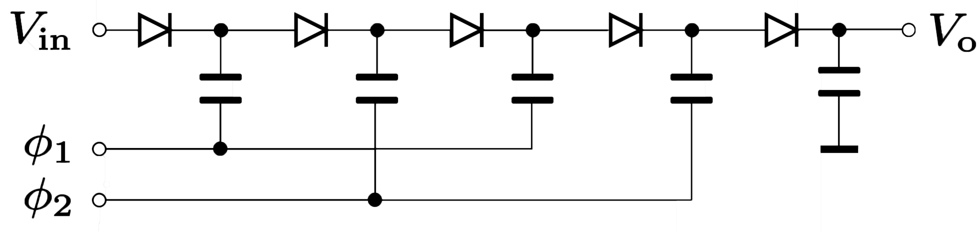


Figure 2.15: Four stages Dickson charge pump

When the clock signal is low on the first capacitor, the diode charge the capacitor until the input voltage. After, the clock signal goes high, the capacitor is pushed up to twice the input voltage. Next process is the clock supplying the second capacitor, going low, the second diode starts the charging process. This time, the diode has at its anode terminal twice the input voltage, so it will charge the capacitor until twice the input voltage. Again the clock that supplies the second capacitor goes high, going from twice the input voltage until three times the input voltage. The process is repeated in the following stages [27].

The Dickson charge pump requires that alternate cells are driven from clock in opposite phase, which is not common to find in RF circuits. However it is possible to modified the Dickson charge pump so it can be adapted for RF circuits. The solution is grounding the input and one of the clock signal. The RF power that arrives at the circuit will be the clock and the power source. Using this solution only half the capacitors are supplied by a clock which means that a stage of multiplication is only achieved after two diode stages. One stage doubles the voltage and the other is only responsible for smoothing the ripple [28]. Figure 2.16[13] represents the Dickson circuit adapted to RF situations.

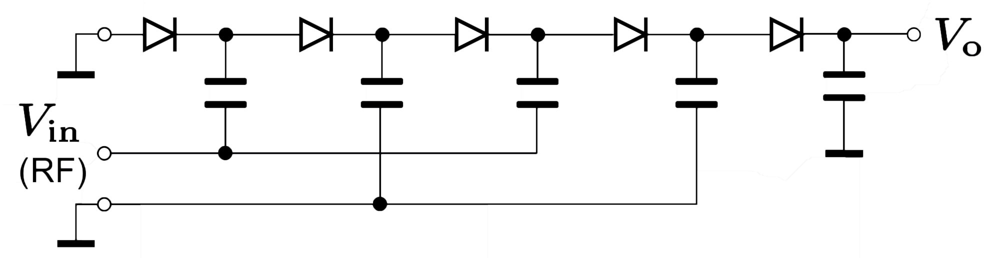


Figure 2.16: Dickson charge pump adapted for RF

Even though the voltage output increases at each stage, having multiple stages does not necessary mean better results. Each stage need a minimum amount of input power to switch the rectifying devices, multiple stages with low input power can make the circuit useless. Other important point related with the number of stages is the efficiency, for example for low power levels, the efficiency is low because the rectifying device is not completely switched on. The efficiency reaches the maximum right before the input voltage reaches the diode breakdown voltage. After this point, the diode reverse current is significant and the efficiency drops [19].

[13]Figure taken from: https://en.wikipedia.org/wiki/Voltage-multiplier

2.4 Voltage Regulators

A voltage regulator is a device that guarantees a fixed output voltage that remains constant for any changes in an input voltage or load conditions. It ensures a steady, reliable voltage protecting components from damages.

Basically, there are two types of voltage regulators: linear voltage regulator and switching voltage regulator.

Linear voltage regulator

Linear voltage regulators act like a voltage divider. They are continuously adjusting its ohmic region, dissipating the difference between the input and the output voltage.

The problem about usual linear voltage regulators is its efficiency, its voltage drop is too high. A standard linear voltage regulator, using a Darlington NPN or PNP as a pass element, can have a voltage drop as high as $2.0\,\mathrm{V}$ [29]. Equation 2.7 show the relation between voltages.

$$InputVoltage = DropoutVoltage + OutputVoltage \tag{2.7}$$

Due to this problem a more efficiency linear voltage regulators were build, Low Dropout Regulators (LDO) regulators. Most LDO use an N-channel or P-channel FET pass element and can have dropout voltages less than $100\,\mathrm{mV}$[30].

Linear voltage regulators are fast response, low noise interference, easy to use, cheap and give a low output ripple voltage.

Switching voltage regulator

Different from linear voltage regulators, switching voltage regulators work taking small chinks of energy from the input voltage. It is done using an electrical switch and a controller which regulates the rate at which energy is transferred to the output [30].

This kind of regulators are efficient and can drive high input voltages and drive loads over $200\,\mathrm{mA}$. However switching voltage regulators are complex and expensive circuits.

Choosing between a linear voltage regulator and a switching voltage regulator always depends on the device and on the application. For cases where there are low voltage variations and the current through the regulator is also low, linear voltage regulators can be the better choice. For applications like computers, digital cameras or robots where the input voltage and the current is high it is recommended to use switching voltage regulators.

2.5 Backscatter Radio

By definition a backscatter is associated with the reflection of waves or signals back to the direction from witch they came from. One of the first uses of backscatter techniques was in radar systems. It consist in sending a signal and wait for its reflection. With this method it is possible to have information about how far is the object that reflected the signal.

Today the radars are more evolved but the backscatter technique is still present. For example in weather radars, knowing the strength of the reflected signal it is possible to determine if there is ice or water, since the water is 4 times more reflective than the ice.

Backsatter techniques can be found in multiple areas, there are some examples:

- Many cities are placed in sedimentary soils, characterized by abrupt changes in materials. The diversity of materials makes the radar images very difficult to interpret. The correct characterization of the soil is crucial in seismic soil response. In the work [31], a evaluation of the Signal to Noise Ratio (SNR) caused by the backscatter energy is the method proposed to do the soil characterization.

- Personal luggage inspection at the airports can constitute a complex system to interpretation. The existing technologies are limited in detecting dangerous materials with X-ray image with overlapping objects. Conventional X-ray backscatter imaging utilizes the scattered radiation caused by the 'Compton scattering effect', this technique is not efficient and it has a large measurement time. A new technique for X-ray backscatter for this security application is described in the work referred in [32].

- Pocket size devices, like tablets or smartphones, have massive antenna arrays. It enhances the possibilty to map the surrounding environment by guaranteeing accurate localization. In the work refereed in [33] is investigated the capability of personal radar solution using real measured data collected at millimeter waves as input for the mapping algorithm.

- The forest degradation is a crucial issue in environmental studies, however this topic is not well defined in quantitative terms. To have a better understanding about the subject, it is important to obtain more data. Reference [34], approach a method using spatial statistics of Synthetic Aperture Radar (SAR) backscatter observations to provide new data.

The principle known as backscatter radio involves the transmission of waves by a transmitter, typically called reader, to a tag. The carrier wave that arrives at the tag is modulated and reflected, the modulation can be done in amplitude, phase or frequency. The reader receives the reflected wave that has the tag information in its modulation. Backscatter RF tags are designed to operate in the reader antenna far field [35].

The communications with backscatter radio only need a single RF transistor front-end, this simplicity makes the system with low energy requirements and low cost of production [36].

The most common use of backscatter radio is in RFID and WSN applications.

Modulation

The concept behind the simplest backscatter radio has an easy explanation, there are only two moments, a moment when the intention is to have the maximum reflection possible and other when it should not have any reflection. In RF systems reflection or no reflection corresponds to short circuit or open circuit. An antenna in short circuit or in open circuit will reflect the signal and an antenna adapted will have no reflection. Figure 2.17[14] illustrates this example and Figure 2.18[15] the correspondent Smith chart [35].

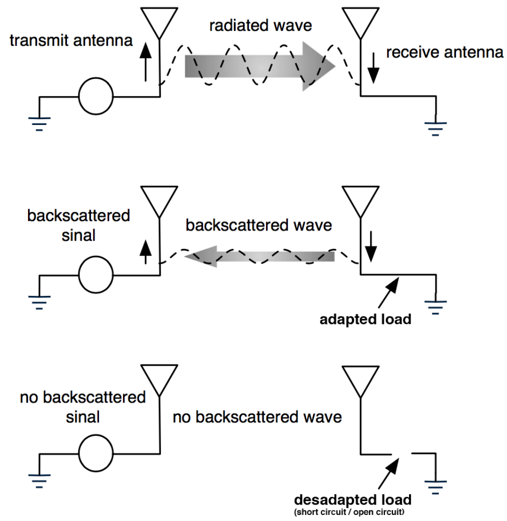


Figure 2.17: Backscatter radio basic fundament

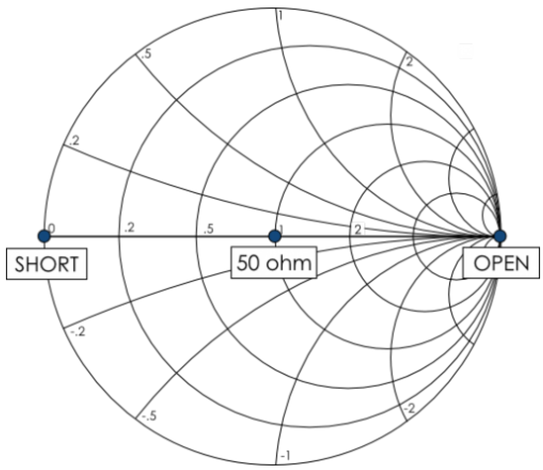


Figure 2.18: Backscatter radio basic smith chart

More complex backscatter systems can be implemented when different impedance terminations are applied to the antenna. In this case each different impedance correspond to a different point on the Smith chart, corresponding to different modulations.

One popular modulation used in radio backscatter is the simplest form of Amplitude Shift Keying (ASK), On Off Keying (OOK), which is a binary modulation. It is based in two different impedance with distinct real part. Ideally one is matched with the antenna and absorbs energy, the other is purely reflective. The system is powered when there is no reflection an the energy is absorbed. The different adaptations represent the logic ’1’ and the

[14]Figure taken from: http://www.eetimes.com/document.asp?doc-id=1276306
[15]Figure taken from: https://www.eeweb.com/electronics-quiz/smith-chart-basics/

logic ’0’. OOK is a modulation scheme suitable for the bandwidth limited regime, since it only needs one frequency [36]. Figure 2.19 illustrates the OOK modulation.

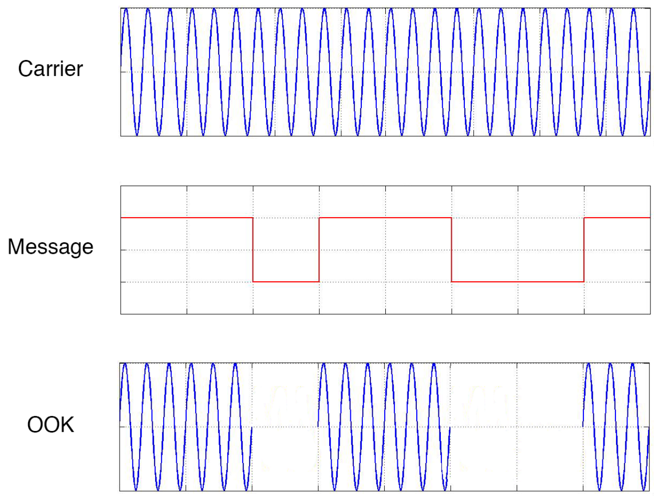


Figure 2.19: OOK modulation

Frequency Shift Keying (FSK) is another technique that can be applied to modulate the incoming signal. Like OOK, it is based in two different match circuits, one also responsible to power the circuit. In FSK modulation, the shifting between absorption and reflection is constant, the frequency at which it happens gives the information. The logic level ’1’ is represented by one frequency and the logic level ’0’ by another. FSK is more suitable for power limited regime, since, it is guaranteed that during half of the time the circuit is matched and absorbing energy. On the other hand, this modulation needs an extended range, and a increased receiver sensitivity [36]. Figure 2.20 shows all the process of FSK modulation.

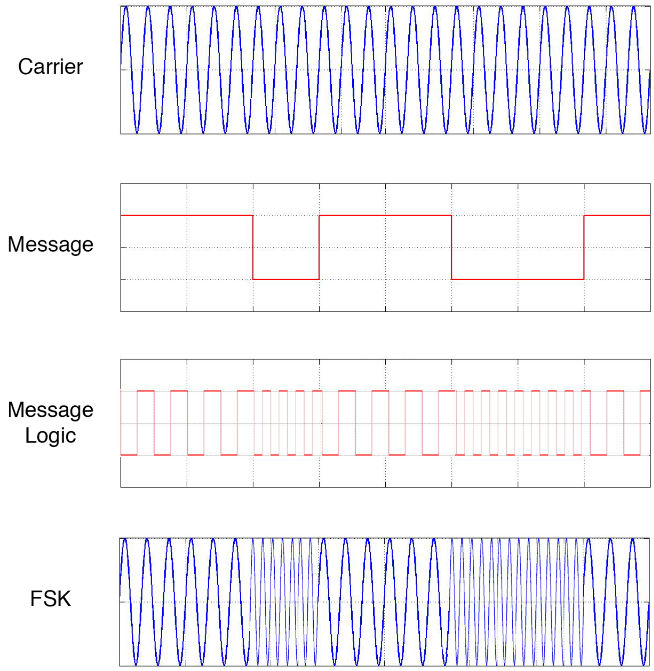


Figure 2.20: FSK modulation

Other modulation that can be used in backscatter radios is Phase Shift Keying (PSK). It works the same way as OOK but instead of modifications in the real part of the impedance, it modify the imaginary component. The attribution of logic levels is the same, each impedance corresponds to a logic level. In terms of results, when proper designed PSK modulation can allow more energy absorption that OOK [37]. PSK modulation is presented in Figure 2.21

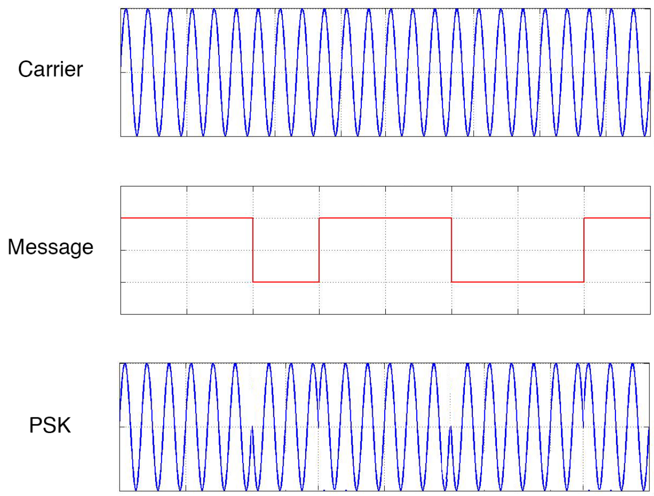


Figure 2.21: PSK modulation

The three modulations presented before are limited since they only transfer one bit per symbol period. With the intention of overcome these limitations more complex modulations based on combinations of these modulations were explored. One modulation that has been in focus for radio backscatters is the Quadrature Amplitude Modulation (QAM) modulation, that is combinations between ASK and PSK modulations. In [38], it is studied the application of backscatter based on 4-QAM modulation. Figure 2.22 demonstrates the 4-QAM modulation

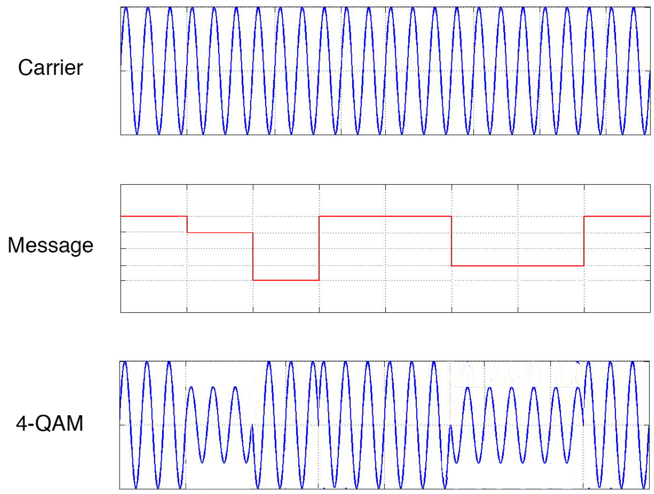


Figure 2.22: QAM modulation

Figure 2.23[16] illustrates how the points in a polar chart move with variations in amplitude and phase. It can be seen as a representation of QAM in a polar chart.

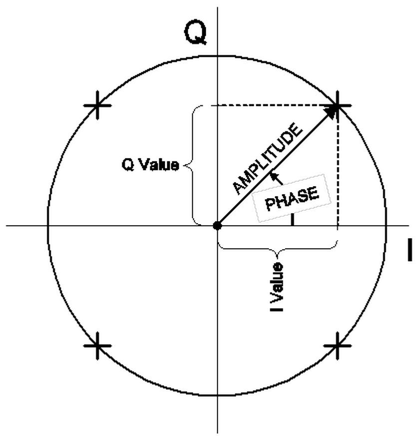


Figure 2.23: Polar chart - amplitude and phase variations

Modulation - Circuit Approach

The impedance termination control is done using a transistor that behaves as a switch. The microcontroller gives a pre-determined voltage to bias the gate of the transistor, and

[16]Figure taken from: http://www.tek.com/blog/whats-your-iq-about-quadrature-signals

each voltage will result in a different impedance for the antenna. Figure 2.24 represents the microcontroller and backscatter connection.

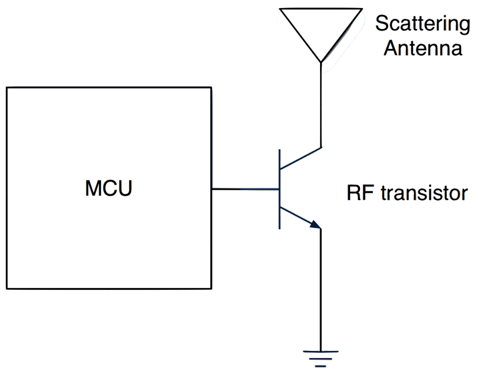


Figure 2.24: Backscatter radio control

In terms of circuit, a 4-QAM modulation is basically the transistor switching between four different impedance. Each impedance corresponds to a different reflected wave. Figure 2.25 illustrates it.

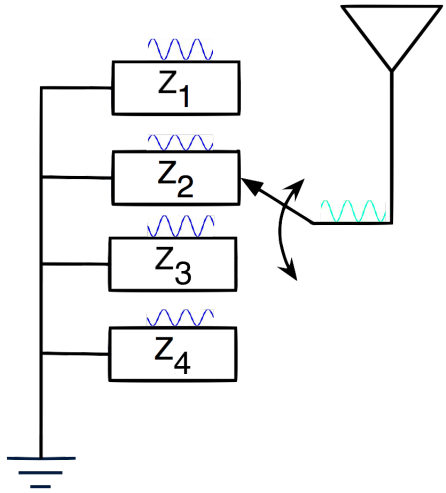


Figure 2.25: QAM modulation, circuit approach

2.6 Conclusion

This chapter pretended to be a theoretical approach, not only about the components involved in the system design, but also about some parts that are not developed in this work.

It started presenting features about the RFID or WSN readers, structures and legal restrictions.

After, RF tags, providing an understanding about the differences between tags, and their advantages and disadvantages. It also explained the problem about tags collision, and solutions about how it could be solved.

Following RF tags, the WPT subject was approached. Firstly a general understanding about the overall process, and after, with more details, antennas, waveform design and RF-DC circuits.

The fourth topic was voltage regulators, with an approach about different behaviors and solutions.

The last approached topic was backscatter radio, divided into backscatter applications, backscatter radio concept, modulations and modulations in terms of hardware.

Chapter 3

System Design

This chapter presents a complete description about the solutions developed to achieve the intended passive communications system. It goes through all the parts used to develop the final system.

To a better understanding about the choices made in this chapter it is important to consult the state of the art presented in Chapter 2.

3.1 Overall System

The proposed system is composed by two main blocks, it can be considered the same structure as RFID and WSN, a reader and a tag.

Ideally, the reader side has a wave generator, two antennas, a demodulator and a cloud gateway. In this work, the wave generator and the demodulator are replaced by a the Rohde & Schwarz SMW200A - Vector Signal Generator and Rohde & Schwarz FSP - Spectrum analysisr, and the cloud gateway is not used. The antennas were designed by the College Daniel Belo, PhD student at Instituto de Telecomunicações in Universidade de Aveiro, to work in the system.

The tag side has a dual band antenna, also designed by the college Daniel Belo, a RF-DC, a power management unit, a microcontroller, sensors and a backscatter. The RF-DC circuit and the backscatter are an hybrid solution once are built in a unique circuit. This circuit was designed by the College Ricardo Correia, PhD student at Instituto de Telecomunicações in Universidade de Aveiro. All these elements are used in the work.

Figure 3.1 shows the system diagram.

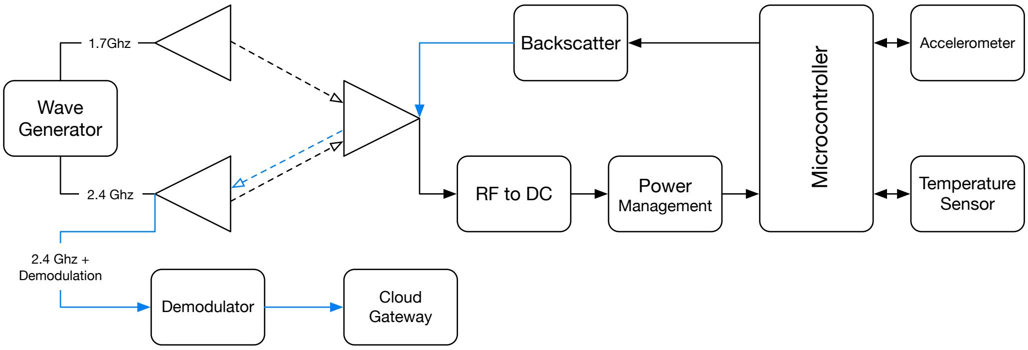


Figure 3.1: System overview diagram

3.2 Antennas

With the intention to have the first tests, commercial antennas were used. They were coupled with a RF-DC designed to match antennas frequency, 868 MHz to 960 MHz. These antennas were used mainly to test the WPT capabilities, the backscatter part do not work properly once the antennas frequency range is too narrow. These antennas are showed in Figure 3.2.

Figure 3.2: Commercial antenna

After initial tests, the antennas were designed and projected to match the maximum efficiency of the RF-DC and backscatter circuit. Due to the reasons presented in Section 2.3 a microstrip patch array antenna was chosen.

During the work two different RF-DC and and backscatter circuits were constructed, with different frequencies of operation.

The first designed antennas were projected to operate at 1.61 GHz and 2.29 GHz. These frequencies were chosen based on the simulation for the RF-DC and backscatter circuit. Figure 3.3 show the antennas used from transmission (reader side). The receiver antenna (tag side) is presented in Figure 3.4.

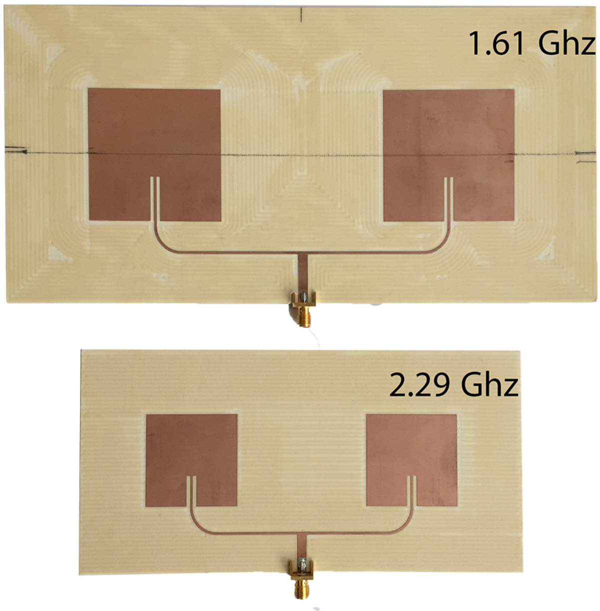


Figure 3.3: Transmitter antenna 1st version

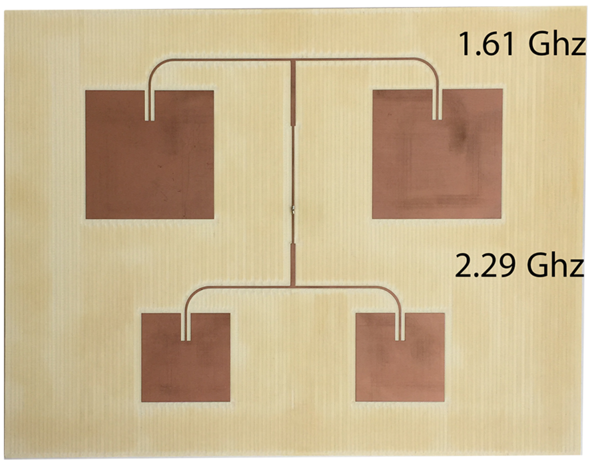
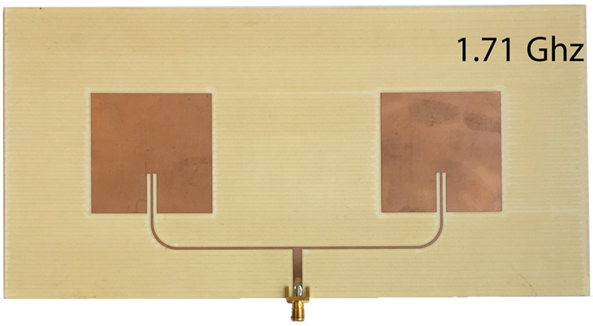


Figure 3.4: Receiver antenna 1st version

The antennas used in the final system were projected to operate at 1.71 GHz and 2.40 GHz. Like the previous antennas, these were also built based on RF-DC and backscatter circuit simulation. Figure 3.5 show the antennas used from transmission (reader side). The receiver antenna (tag side) is presented in Figure 3.6.



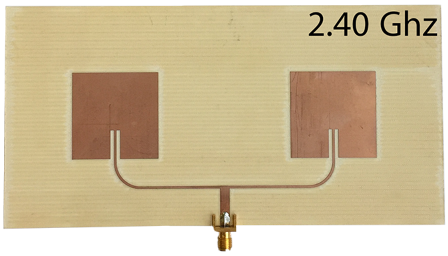


Figure 3.5: Transmitter antenna 2^{nd} version

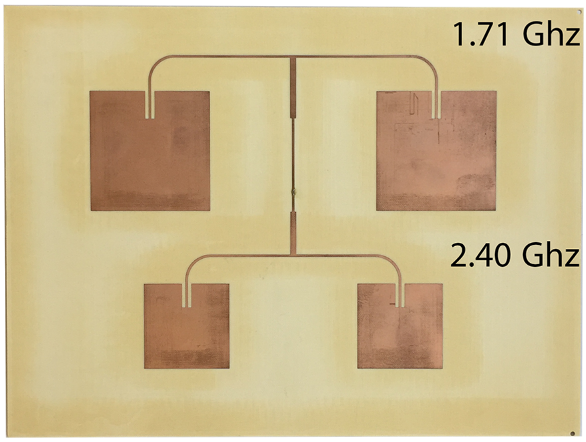


Figure 3.6: Receiver antenna 2^{nd} version

3.3 Rectifier and Backscatter

As the rectifier and the backscatter are a hybrid solution, the components are presented together.

The first circuit used to convert RF-DC is based on a two stages rectifier. The electronics behind the backscatter system are basically a Field-Effect Transistor (FET) which has a external pin directly connected to the gate so it can change the circuit impedance. More details about the behavior of the backscatter radio can be found in Section 2.5. The RF-DC was initially projected to work at 868 MHz, the frequency choice was to adapt the system with the commercial RFID antennas. Figure 3.7 shows the first model tests.

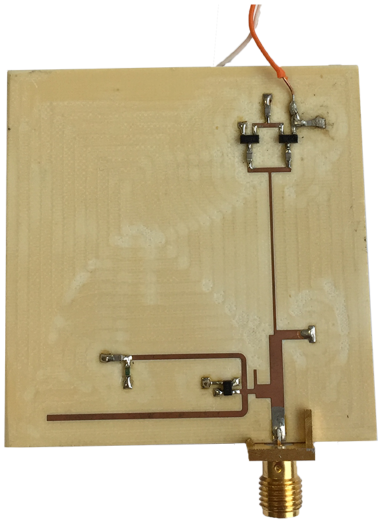


Figure 3.7: Rectifier and backscatter circuit 1st version

The second circuit was projected independently from the antennas, in this case the circuit was the starting point. The antennas should be projected to match the circuit and not the opposite. Due to reasons of maximization of efficiency and based on simulations, the project frequencies were 1.61 GHz to WPT and 2.29 GHz to backscatter. It is important to refer, that the frequency used for backscatter also produces a dc power, however it is lower than the power produced by the frequency specially chosen to power transmission. Using the knowledge adquired from the previous circuit it was possible to use a Dickson multiplier as RF-DC circuit with five stages, instead of two stages used in the first approach. The model is presented in Figure 3.8.

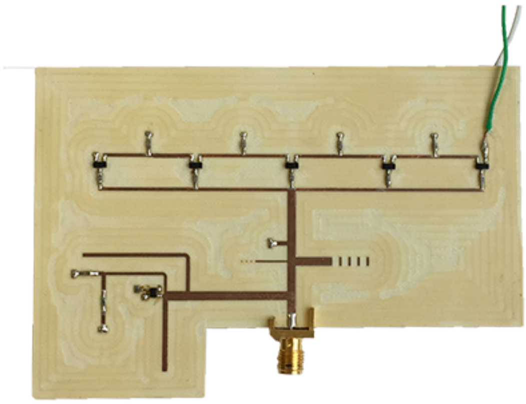


Figure 3.8: Rectifier and backscatter circuit 2nd version

When the microcontroller was connected to the circuit, it started to have a current consumption, which does not happen in normal conditions. To solve these problems the circuit needed to be re-designed. The new circuit kept the five stages and the majority of its features, however the frequencies shifted a little bit. In this new circuit the optimal simulated frequencies are 1.71 GHz to WPT and 2.40 GHz to backscatter. Figure 3.9 illustrates the final circuit.

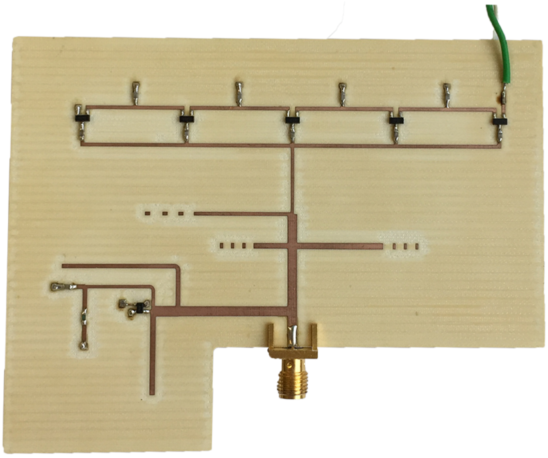


Figure 3.9: Rectifier and backscatter circuit 3rd version

3.4 Voltage Regulator

The output voltage produced by the RF-DC circuit depends on the power that arrives at the receiving antenna. The power that arrives at the receiving antenna is unstable since the power transmission process can be affected by multiple variables. The microcontroller is a element that is sensible to voltage variation, it presents different behaviors to different input voltages, and if the voltage is to high it can even burnout. That is why it is extremely important to regulate the voltage that supplies the microcontroller. The solution need to have a low power consumption, once it is a crucial point to enable the overall system.

As the application is low power and taking into account the considerations presented in Chapter 2.4, the NCP583 of On Semiconductor was chosen.

In Attachment A can be found the Figure A.1 presenting the schematic of the circuit used to regulate the input voltage.

3.5 Microcontrollers

The process to incorporate a microcontroller in the system involved at the same time code development, measurements and analysis. It was not possible to choose a microcontroller only based on the datasheet information. To find a solution that could satisfy all the requirements, monitoring and processing having a low power consumption, tests needed to be made. For that reason, it was decided to create the Chapter 4 that describes all the process.

3.6 Conclusion

This chapter described the multiple systems built during the work with the intention to achieve purposed objectives.

The first topic showed a system overview, it provided an understanding about how the multiple blocks of the work are connected to each other.

Following the first topic, all the parts of the system were presented in details: antennas, rectifier and backscatter and voltage regulator. Due to the multiple aspects to analysis in the microcontroller choice, the section about the topic pointed to Chapter 4.

The reasons behind all design choices were supported by the state of the art approach, available Chapter 2.

Chapter 4

Microcontrollers

Microcontrollers have been developed by two sides, one is the processing capabilities and the other is energy efficiency, this last introduced the low power microcontrollers solution in the market

As all the system is based on energy efficiency, it is mandatory to use low power microcontrollers. Besides low power the microcontrollers need to have some others features like I/O ports, timers, Analog to Digital Converter (ADC) and DAC. Some of these features are not available in the microcontroller and the solution is the use of external components.

In the following pages a closer look to three different low-power microcontrollers will be presented. The analysis includes hardware specifications, code developed, additional peripherals, current consumption, results and conclusion.

4.1 Silicon Labs C8051F912

The C8051F912 is a development board made by Silicon Labs that has been designed to be highly power-effective. Its minimum voltage is $0.9\,\mathrm{V}$, the current consumption in active mode, at $32.768\,\mathrm{kHz}$, is $84\,\mu\mathrm{A}$ and using its low frequency oscillator in sleep-mode it has a consumption of $0.3\,\mu\mathrm{A}$ [39]. The microcontroller has an internal temperature sensor and the other features like I/O ports, Timers, ADC, do not present any limitation to the work. In terms of components the microcontroller is only missing an output voltage controller, for example a DAC. The importance of a controlled output voltage is explained in Section 2.5.The Silicon Labs microcontroller was the first option due to its excellent performance in current consumption, a key point to the work, its low minimum voltage and its ready to use development board. The Figure 4.1[1] shows the used board [36].

[1]Figure taken from: https://www.element14.com/community/docs/DOC-79668/l/development-kit-for-c8051f912-ultra-low-power-mcu

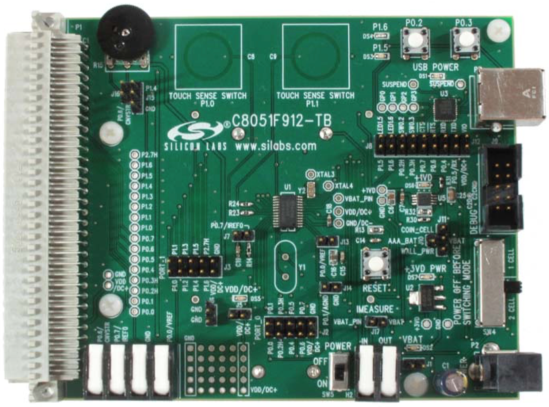


Figure 4.1: Silicon Labs C8051F912 development board

4.1.1 Code Development

To take full advantage of the microcontroller low power features, the code efficiency is extremely important.

When the microcontroller turns on, it starts by executing the configuration block. It selects the internal low power oscillator as clock source, it turns the ADC into low power mode, and it sets the sleep-mode. Within the configuration block is done the I/O Ports assignment and the configuration of Universal Asynchronous Receiver/Transmitter (UART) communication. The UART protocol is used in tests to display information while programming, important to ensure that processes like sensors calibrations are well done.

After the initial block the system starts a loop, the first block inside the loop is the ADC that converts data that arrives from the internal temperature sensor.

The ADC generates an output with a decimal format, which can not be sent by a digital output port. Before that, the decimal format is converter in binary, decimal to binary block. Sending the information is a basic process, when the bit is '1' the output is high, when it is '0' the output is low. Immediately after each bit is sent the microcontroller enters in sleep-mode, if the message is not completed it sleeps during $1.96\,\mathrm{ms}$, if it is already completed the sleep time is $98.4\,\mathrm{ms}$. The referred time periods are demonstrative, they may change in the final application. When the process of sending the message with the respective sleep time finishes, the microcontrollers starts the loop again reading the ADC. The blocks diagram presented in the Figure 4.2 are the process description.

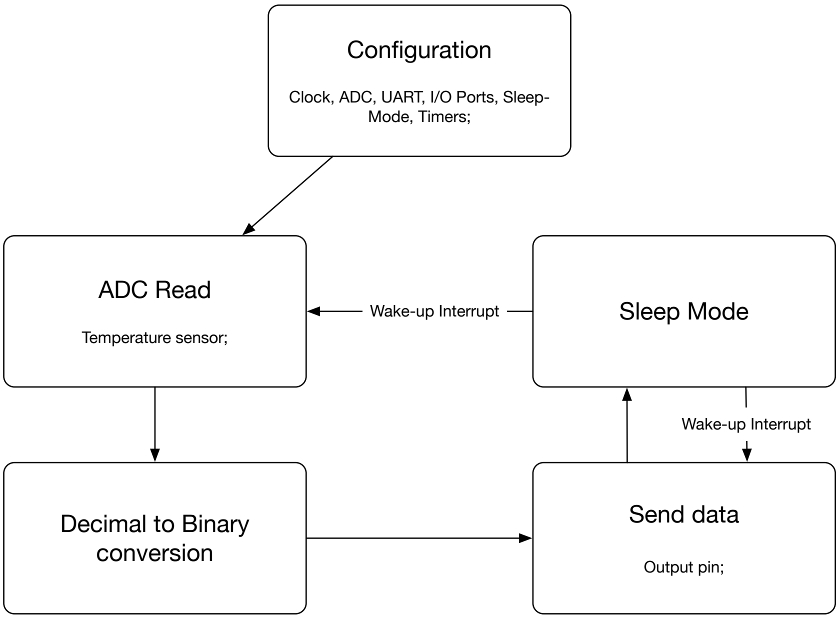


Figure 4.2: C8051F912 code diagram

Figure 4.3 shows the development board sending multiple messages and Figure 4.4 illustrates one detailed message.

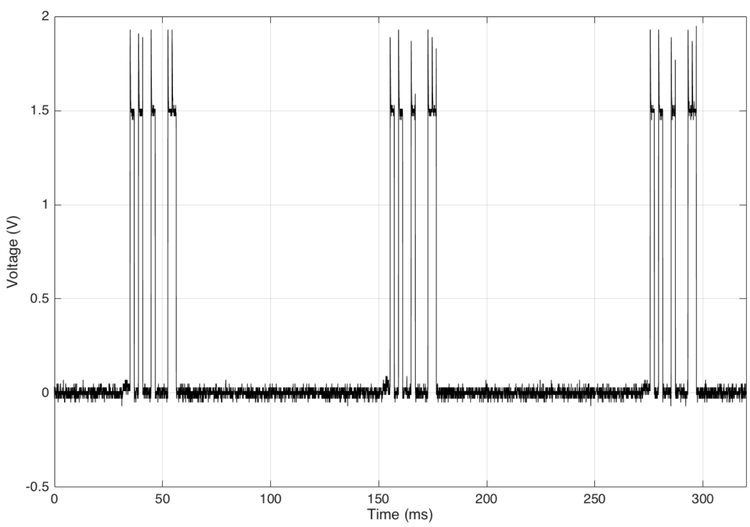


Figure 4.3: C8051F912 sending multiple messages

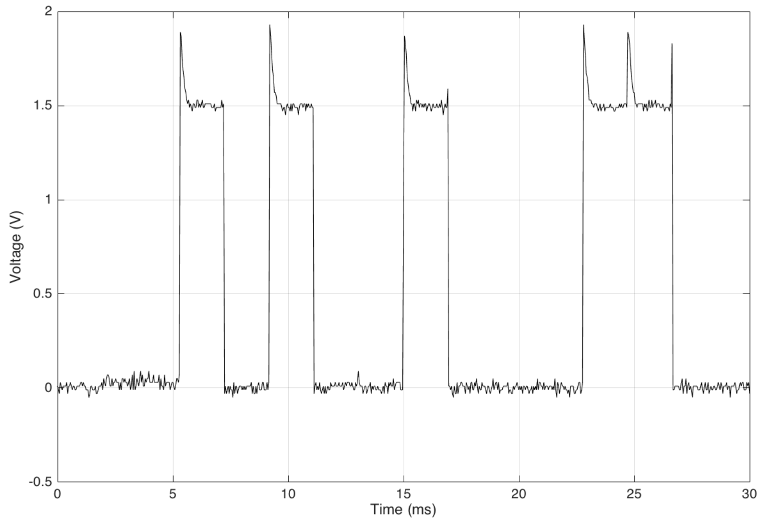


Figure 4.4: C8051F912 send one message

4.1.2 Temperature Sensor Calibration

For reasons of convenience the sensor used to perform the initial tests is the internal temperature sensor. To minimize the error that it could have, a process of calibration is made:

- Measure the temperature with a calibrated device;
- Turn on the microcontroller and wait some seconds;
- Read the internal temperature sensor data using the ADC;

The calibration process lead to the Equation 4.1:

$$temperature = calibrationtemperature + \frac{(voltage - offset)}{slope} \tag{4.1}$$

The *calibrationtemperature* is the temperature measured by the calibrated device, the *offset* is the voltage generated in calibration and the *slope* is the division between voltage and the temperature measured during calibration. The *voltage* is the value that ADC needs to read each time the temperature is calculated, with these variables it is easy to calculate the actual *temperature*.

4.1.3 Current Measurement

After all software configurations, the next step is to measure the current consumption. The setup represented in Figure 4.5 uses an amperemeter between the power supply and the C8051F912 board. It is used to measure the current consumption varying the input voltage when the microcontroller is off and to measure the average consumption when it is on. The Figure 4.6 shows the result of voltage variation before microcontroller turns on.

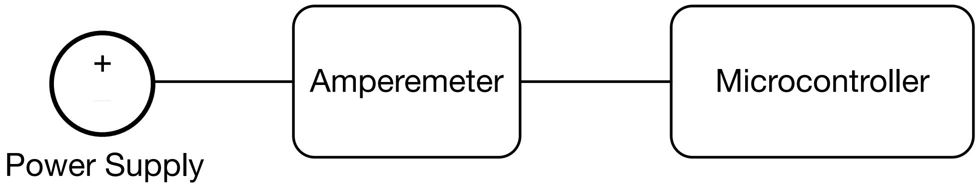


Figure 4.5: Amperemeter setup

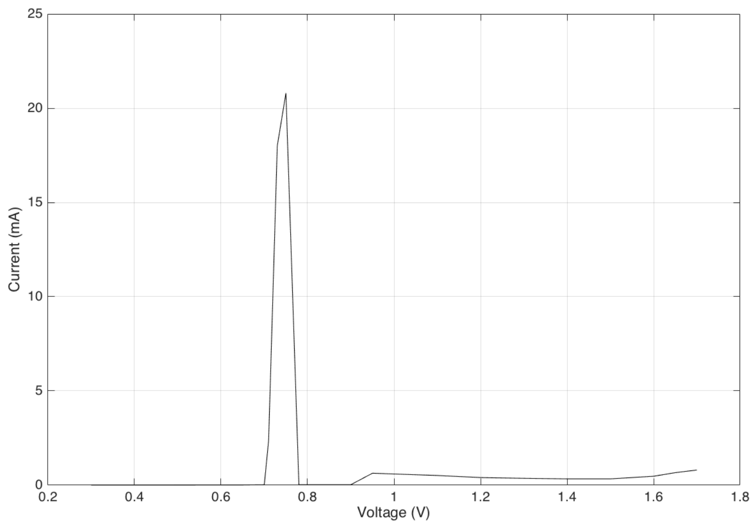


Figure 4.6: C8051F912 current consumption

When the microcontroller is in operation mode, the value of current consumption depends on the running process, meaning an unstable current. In order to have a value susceptible to be compared, the average current consumption is measured. The amperemeter has a mode that allows the measurement of average current. To minimize the measurement error, each measurement was done during 30 seconds. Table 4.1 exhibits the values.

Table 4.1: C8051F912 consumption

Code Specifications	Current Consumption
Bit Period = 361 µs; Sleep Period = 6.3 ms; All working;	36 µA
Bit Period = 61.5 µs; Sleep Period = 6.3 ms; All working;	72 µA
Bit Period = 44.1 µs; Sleep Period = 6.3 ms; All working;	104 µA

4.1.4 Microcontroller Analysis and Conlusion

Analyzing the code implementation in the microcontroller, it can be said that it fulfilled all requirements. The output has the required format, and the periods associated with messages intervals can easily be changed to a required rate. It is possible because all interval mechanisms work with timers, allowing modifications only changing the timer variable. All the programming part features are fully functional without providing any limitation to the objectives.

As the sensing element does not need to be extremely precise, the internal temperature sensor can be used. To improve its accuracy the calibration process was implemented and it worked as expected.

The current consumption is the key point of the microcontroller, if it has an high consumption it is impossible to ensure that the system can be powered by the WPT at desired distances. In the first analysis to the microcontroller consumption, Figure 4.6, it is possible to see that near the turn on point there is an high peak of current, about 20 mA. The values about its consumption when turned on are available in Table 4.1.

The general behavior of the microcontroller is excellent, however its current peak before it turns on, makes it not suitable for the desired system. The WPT needed to be adjusted to fulfill the current peak what in terms of distance would mean a significant loss. Note that for systems working with batteries the Silicon Labs microcontroller has excellent energetic consumption after it is turned on [36].

4.2 Texas Instruments MSP430F4250

Comparing with others microcontrollers, Texas Instruments MSP430F4250 is not the the most efficient in terms of power consumption. In running mode it consumes about 250 µA using a main clock of 1 MHz and an auxiliary clock of 32.768 kHz. In sleep-mode the consumption is around 1 µA [40]. However it has internally, a very precise DAC that is fundamental to the integration with the backscatter, more details can be seen in Section 2.5.

Other special feature about this microcontroller is the use of sigma-delta converter instead of the normal ADC. In a conventional ADC, an analog signal is integrated, or sampled, with a sampling frequency and subsequently quantized into a digital signal. This process introduces quantization error noise. In sigma-delta converter it is performed filtering and decimation, process of reducing the sampling rate of a signal, bringing benefits in resolution and noise mitigation. However it is a complex process, slower and less power efficient than the usual ADC [41].

Excluding the absence of SPI communication ports, that are used for some sensors, the chip fulfill all the I/O ports requirements. Figure 4.7[2] shows the MSP430F4250 microcontroller and the Figure 4.8 its implemented circuit. The complete description about the circuit is presented in the Chapter 4.2.3.

Figure 4.7: Texas Instruments MSP430F4250

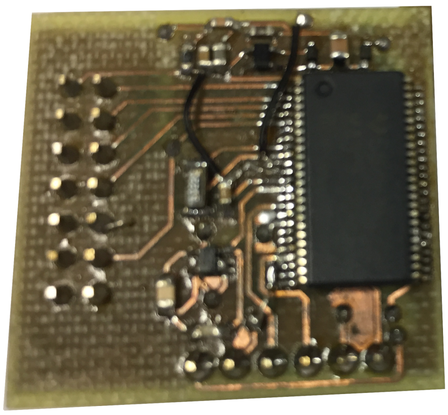


Figure 4.8: Circuit with MSP430F4250 microcontroller

4.2.1 Code Development

After the microcontroller starts, the first step is the configuration process. During this process the Digitally Controlled Oscillator (DCO) is defined as the system clock supply, the sleep-mode is established and the sigma-delta converter is configured to read the external temperature sensor. The reason to use an external temperature sensor is presented on Sub-Section 4.2.2. Other important process that occurs during the configuration block is the definition of DAC parameters. It can have a resolution of 8 or 12 bits and the voltage reference can be multiplied by 1 or 3, depending on the choice of these parameters the output voltage equation differs. The parameters were set to a resolution of 8 bits and the voltage reference multiplied by 1 that lead to Equation 4.2.

$$Voutput = Vreference \times \frac{(DAC12DAT)}{256} \tag{4.2}$$

[2]Figure taken from: http://www.ti.com/graphics/folders/partimages/MSP430F4250.jpg

Next step is responsible to do the sensing part, in this case the sigma-delta converter converts analog data given by the temperature sensor in digital data. The process of decimal to binary conversion is the same explained in Sub-Section 4.1.1 and consists in convert the decimal format into binary, the result of the conversion goes to the next process.

For a proper integration with the backscatter the output voltage needed to be $0.6\,\mathrm{V}$ and $0.0\,\mathrm{V}$. Equation 4.2 gives the value that when programmed in the register DAC12DAT ensures the pretended voltage at the output. The voltage reference is $1.8\,\mathrm{V}$, the same voltage that supplies the microcontroller. The process of solving the equation is demonstrated in the Equation 4.3.

$$DAC12DAT = \frac{(Voutput \times 256)}{Vreference} \Leftrightarrow DAC12DAT = \frac{(0.6 \times 256)}{1.8} \Leftrightarrow DAC12DAT \approx 85 \tag{4.3}$$

Sending data is basically the process of combining the DAC result with the message information. When the bit information is '1' the output voltage is $0.6\,\mathrm{V}$, when is is '0' the output voltage is $0.0\,\mathrm{V}$. After each bit is set, the system enters in sleep-mode during a defined period, when it wakes up it sends another bit. This sleep time is used to reduce the power consumption but it is also important to give time to establish the output voltage.

Completed the process of sending the message, the microcontroller enters in sleep-mode until a defined timer wakes it up to start the loop again. Figure 4.9 illustrates the code diagram.

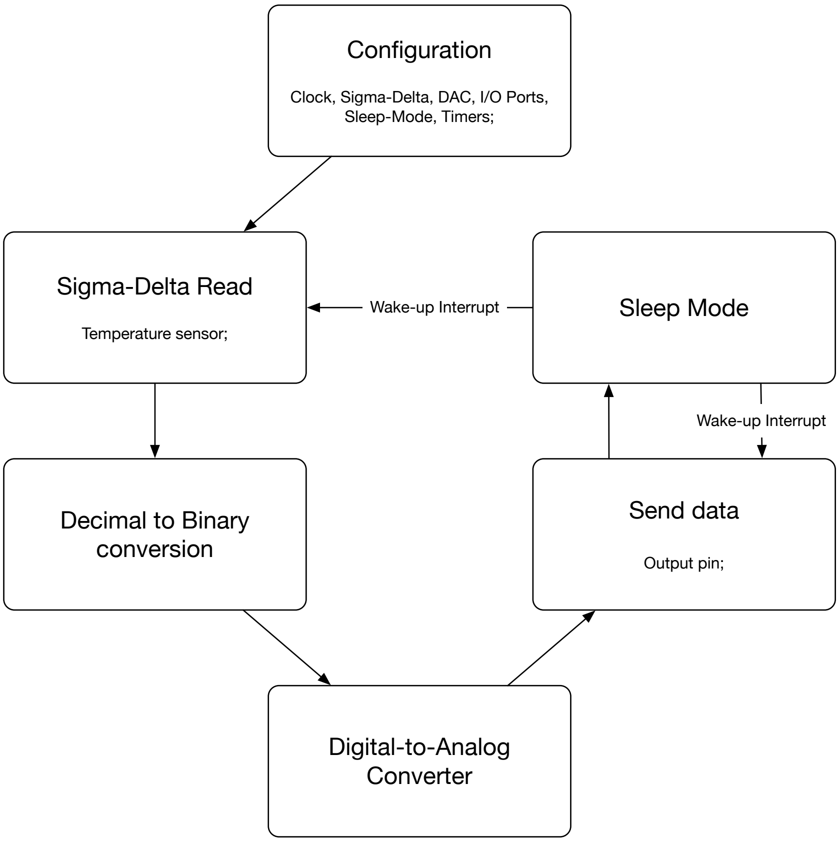


Figure 4.9: MSP430F4250 code diagram

Figure 4.10 shows the result of the circuit board sending multiple messages, Figure 4.11 is one detailed message.

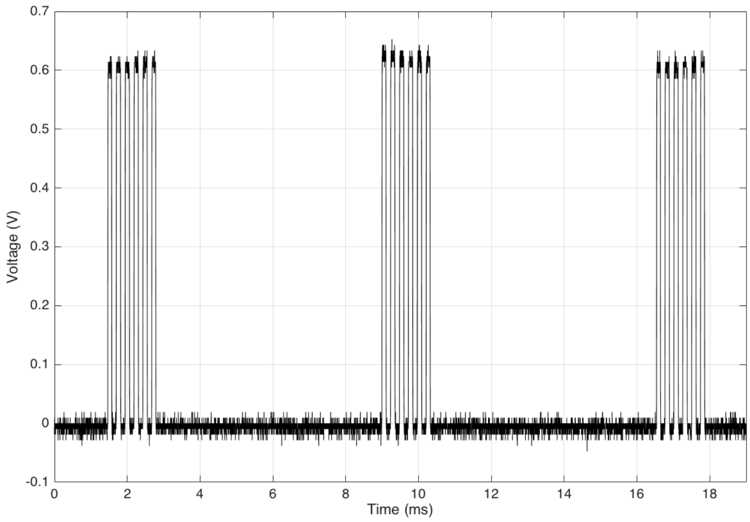


Figure 4.10: MSP430F4250 sending multiple messages

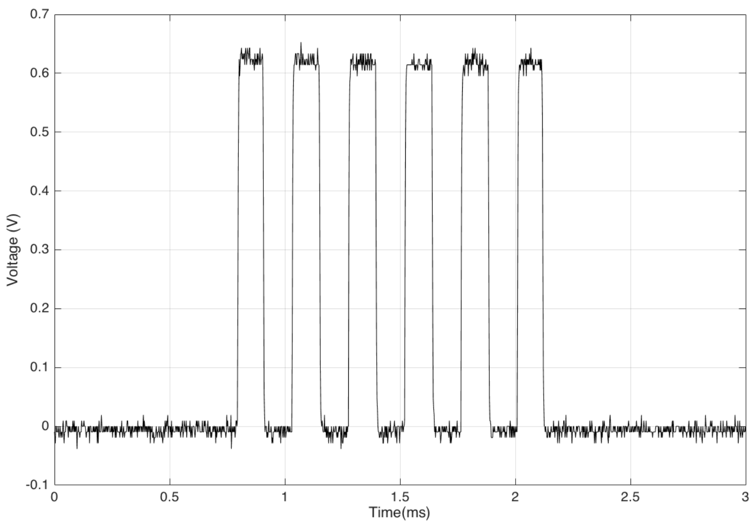


Figure 4.11: MSP430F4250 send one message

4.2.2 Temperature Sensor Calibration

To reduce the influence of microcontroller temperature in the measured temperature, it is used an external temperature sensor. The Texas Instruments LM94021 was chosen due to its low consumption, its precise measurements and its simple calibration process. Its image is showed in Figure 4.12[3].

[3]Figure taken from: http://www.ti.com/product/LM94021

Figure 4.12: Texas Instruments LM94021

To convert the voltage at the sensor output in valid temperature information a table available in the sensor technical information was used [42]. The table relates the output voltage with temperature, it starts from -50 °C and ends at 150 °C. As the goal is to measure ambient temperature and some small variations of it, there is no need of having such a wide range. The selected operating range is between 0 °C and 40 °C, the linearization should be done between these values. On the table, these values correspond to 1.034 V and 0.816 V respectively. The linearization process is reproduced in Equation 4.4.

$$V - V1 = \frac{(V2 - V1)}{(T2 - T1)} \times (T - T1)$$
$$V = -5.45 \times T + 1.034 \tag{4.4}$$
$$T = -\frac{(V - 1.034)}{5.45}$$

4.2.3 Circuit Design

Figure 4.13 shows a block schematic of the circuit. The J-TAG Programming module is a debug and programming tool that implements a serial communication interface allowing direct external access to the system address and data buses. The block relative to the voltage regulator is explained in detail in Section 2.4. In Attachment A can be found the Figure A.2 with more details about the board.

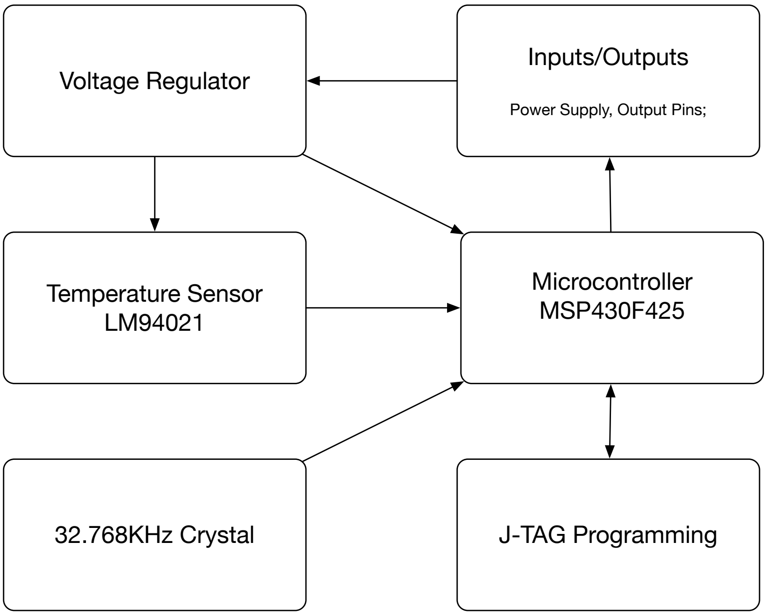


Figure 4.13: MSP430F4250 circuit board schematic

4.2.4 Current Measurement

Repeating the measurement process described in Sub-Section 4.1.3 it was possible to measure the current consumption of the MSP430F4250 board. Results are presented in Figure 4.14 showing the current consumption varying the input voltage until the microcontroller turns on.

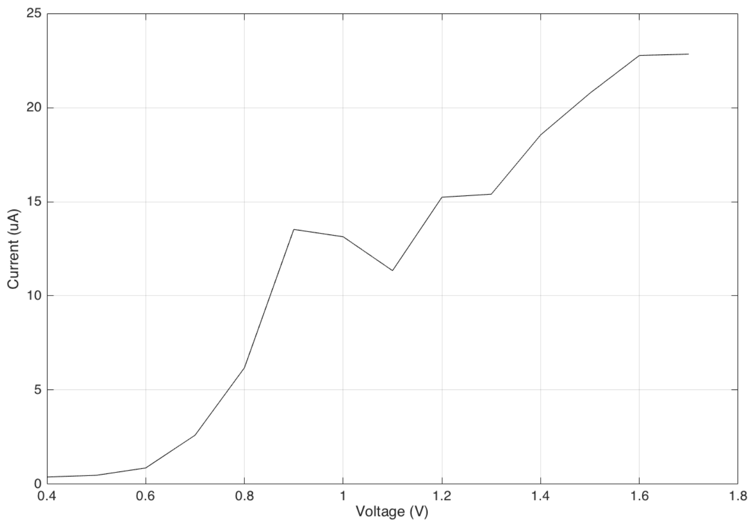


Figure 4.14: MSP430F4250 current consumption

After the microcontroller turns on the current consumption at each moment depends on the process that it is running. The best way to have perception about how much current it consumes is doing its average consumption. Table 4.2 exhibits the measured values for different programming setups.

Table 4.2: MSP430F4250 consumption

Code Specifications	Current Consumption
Bit Period = 61.5 µs; Sleep Period = 6.3 ms; Sigma-Delta Off; DAC On;	87 µA
Bit Period = 61.5 µs; Sleep Period = 6.3 ms; Sigma-Delta On; DAC Off;	260 µA
Bit Period = 61.5 µs; Sleep Period = 6.3 ms; Sigma-Delta On; DAC On;	266 µA

4.2.5 Microcontroller Analysis and Conlusion

Starting by doing an appreciation on the code development, the microcontroller performs as it was expected. It is important to refer that the DAC voltage output is very precise, Figure 4.11 shows it. This aspect is very important to ensure a good connection between microcontroller and backscatter. The only limitation about the microcontroller is the absence of SPI communication that could be important to implement sensors like accelerometers.

The sensing element, Texas Instruments LM94021, proved to be easily usable with low power consumption.

About current consumption, the microcontroller proved to have a very optimized turn on process, its maximum consumption is less than 23 µA before the microcontroller turns on, details in Figure 4.14. However doing an analysis on Table 4.2 it is possible to understand that the sigma-delta converter has a big current consumption. Even though it is only turned on every 7 ms (approximated value that corresponds to bit period plus sleep period), it has an average consumption of 266 µA. The same code with the converter turned off has an average consumption of 87 µA.

As final conclusion about the behavior of the microcontroller, it proved that the DAC is the correct choice to do the connection between the microcontroller and the backscatter. Yet it has limitation on terms of sensing, the sigma-delta converter is the only way to receive sensing information and it has an high current consumption. It is important to note that the system is completely functional. It proved to be a consistent solution to use with WPT and backscatter, however an improvement in the current consumption would mean longer distances what is a strategic point for the project.

4.3 Texas Instruments MSP430F2132

Developed by Texas Instruments MSP430F2132 is one of the most efficient microcontrollers in terms of power consumption. Its consumption in active mode using the external 32.768 kHz crystal is about 2 µA and in sleep-mode it can go as low as 0.3 µA. The microcontroller fulfill all the requirements, I/O ports, ADC, timers and communications protocols [43].

Using the same microcontroller that can be seen in the Figure 4.15[4], and using the substrate FR-4, two boards were made. The 1st board represented in Figure 4.16 was built in first place to validate the microcontroller power consumption and the 2nd as a more complete version with external elements like DAC, accelerometer and temperature sensor, Figure 4.17 shows the board.

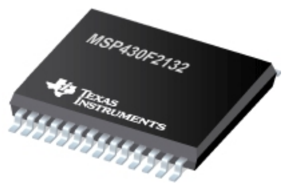


Figure 4.15: Texas Instruments MSP430F2132

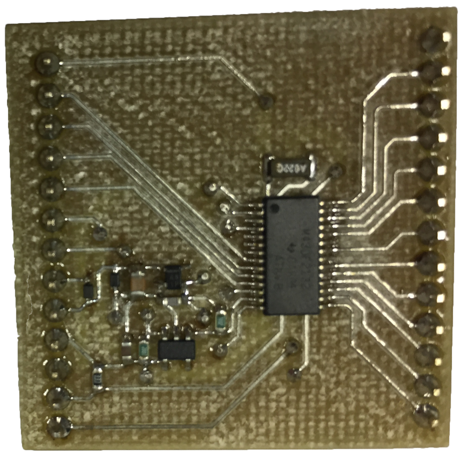


Figure 4.16: Circuit with MSP430F2132 microcontroller 1st version

[4]Figure taken from: http://www.ti.com/product/MSP430F2132

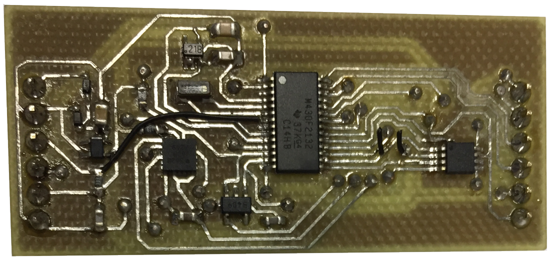


Figure 4.17: Circuit with MSP430F2132 microcontroller 2nd version

4.3.1 Code Development

The microcontroller starts processing the configuration block, it configures the crystal with 32.768 kHz to be the source of main and auxiliary clock, I/O ports, timers, ADC and the sleep-mode.

After configuration it enters in the sensing block, while in the first version of the board it reads the internal temperature sensor, in the second it reads the external temperature sensor and the accelerometer. In both cases, first and second version, the reading process is done using ADC to read the temperature. The communication between accelerometer and microcontroller, only available in second version, is done through Serial Peripheral Interface (SPI).

The same process used in Sub-Section 4.1.1 and Sub-Section 4.2.1 was used to convert decimal data in binary data.

Sending data is different in first version and second version. In the first version, it just does the match between an output port and the binary value, example: if the binary value is '1' the port is in high level (1.8 V) if it is '0' the port does not present voltage. In the second version the data is sent through SPI protocol to the external DAC where it is converted in 0.6 V or 0.0 V. It is important to refer that the 0.6 V / 0.0 V is the perfect voltage values to connect the microcontroller with the backscatter.

After each bit, the microcontroller enters in sleep-mode. When all the bits were sent, it enters in a sleep-mode again, but this time for a longer period. Finished the sleep time, it starts again the process from the beginning with the sensing block.

Figure 4.18 is representative of the code diagram of the first board, and Figure 4.19 represents the second board. Figure 4.20 and Figure 4.21 are representative of both versions, the only difference is that in the second model the voltage level is 0.6 V instead of 1.8 V.

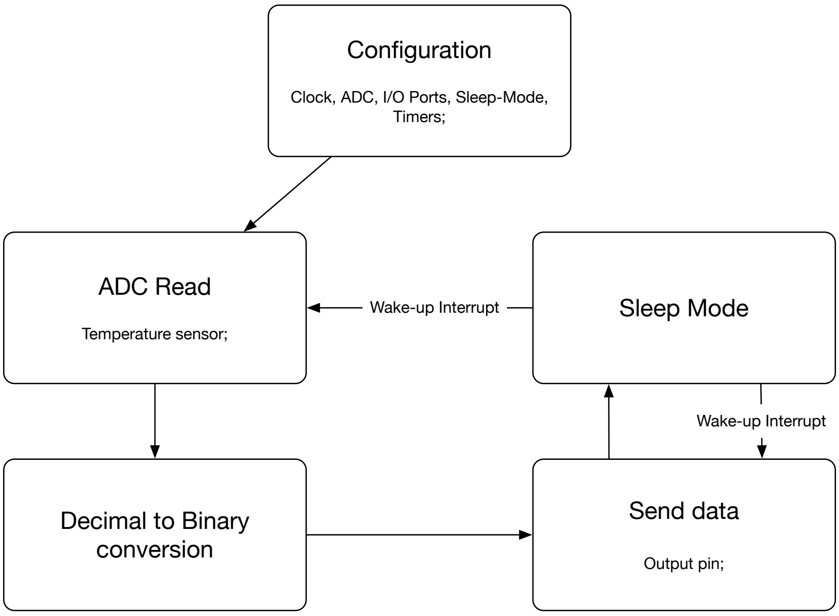


Figure 4.18: MSP430F2132 Code diagram 1st version

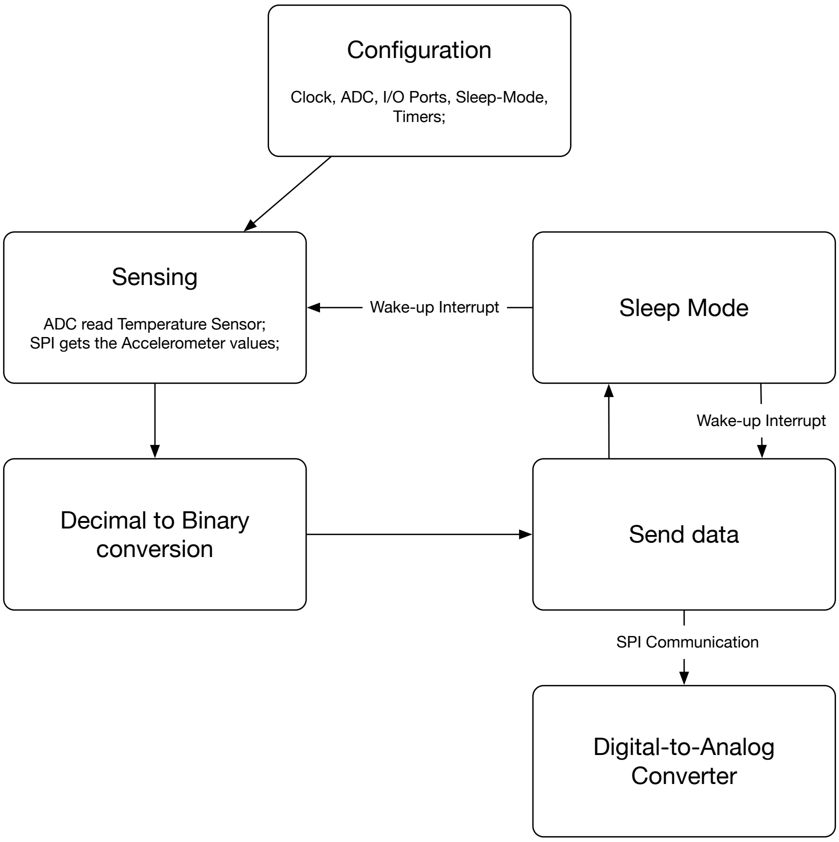


Figure 4.19: MSP430F2132 Code diagram 2nd version

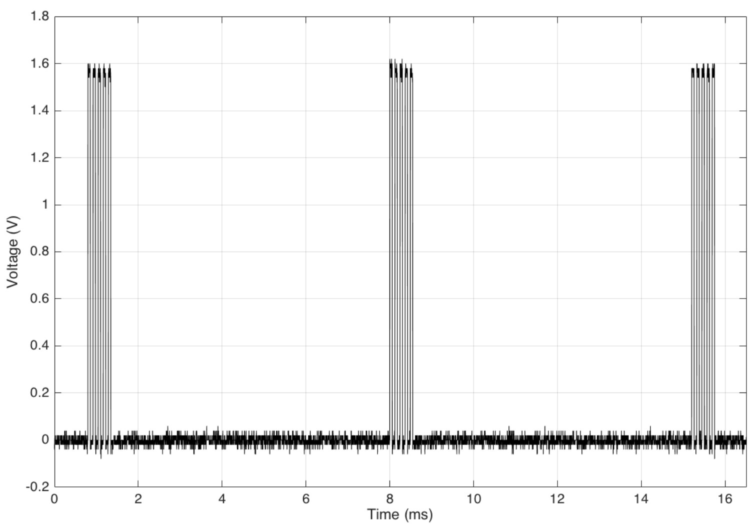


Figure 4.20: MSP430F2132 sending multiple messages

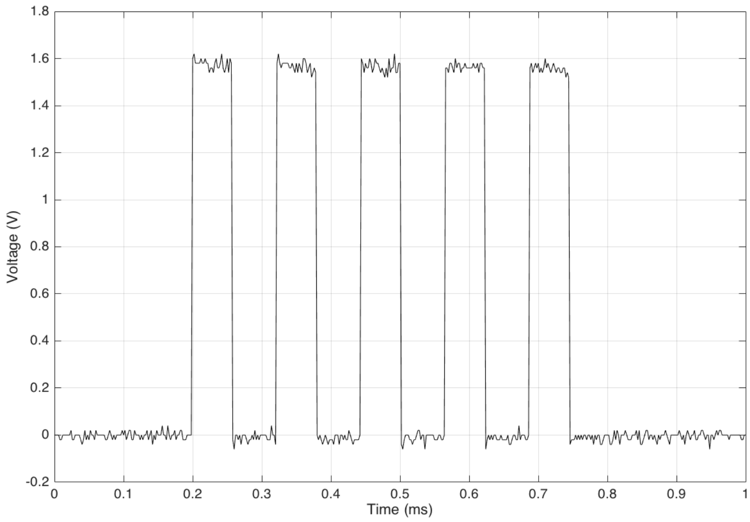


Figure 4.21: MSP430F2132 send one message

4.3.2 Temperature Sensor Calibration

The temperature sensor and the calibration process is the same as the one described in Sub-Section 4.2.2

4.3.3 Accelerometer

In order to prove that the system can work with multiple sensors an accelerometer was added to the system. This type of sensor was chosen because usually accelerometers are low consumption sensors, and because it allows an human interaction with the system. The human interaction with the system is very important to show the various applications that the system may have.

The Analog Devices ADXL362 was chosen because it has a very low power operation mode, $1.8\,\mu A$ at $100\,Hz$, and an ultra low stand-by current, $10\,nA$. The accelerometer has others interesting features like the possibility to generate an interruption when there is movement. The communication with the microcontroller is done using SPI digital interface. Figure 4.22[5] shows the accelerometer.

[5]Figure taken from: https://ebv.avnet.com/wps/portal/ebv/products/highlights/ebv-and-adi-enabling-the-internet-of-things/

Figure 4.22: Analog devices ADXL362

4.3.4 Circuit Design

Figure 4.23 is the schematic of the first board. The main goal in this first version is the microcontroller validation in terms of power consumption.

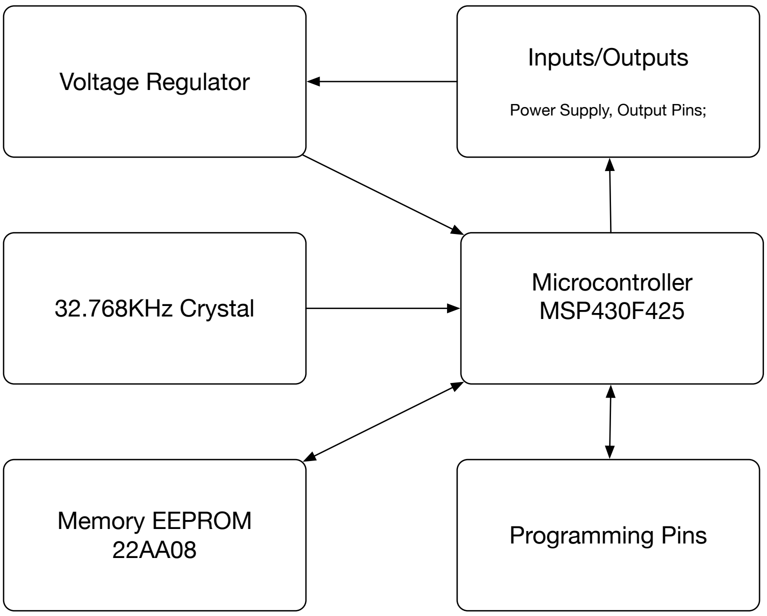


Figure 4.23: MSP430F2132 circuit board schematic 1st version

The next figure, Figure 4.24 presents the schematic of the second board. This new version integrates new sensors and one DAC. With these new elements the board is complete and can fulfill all the requirements.

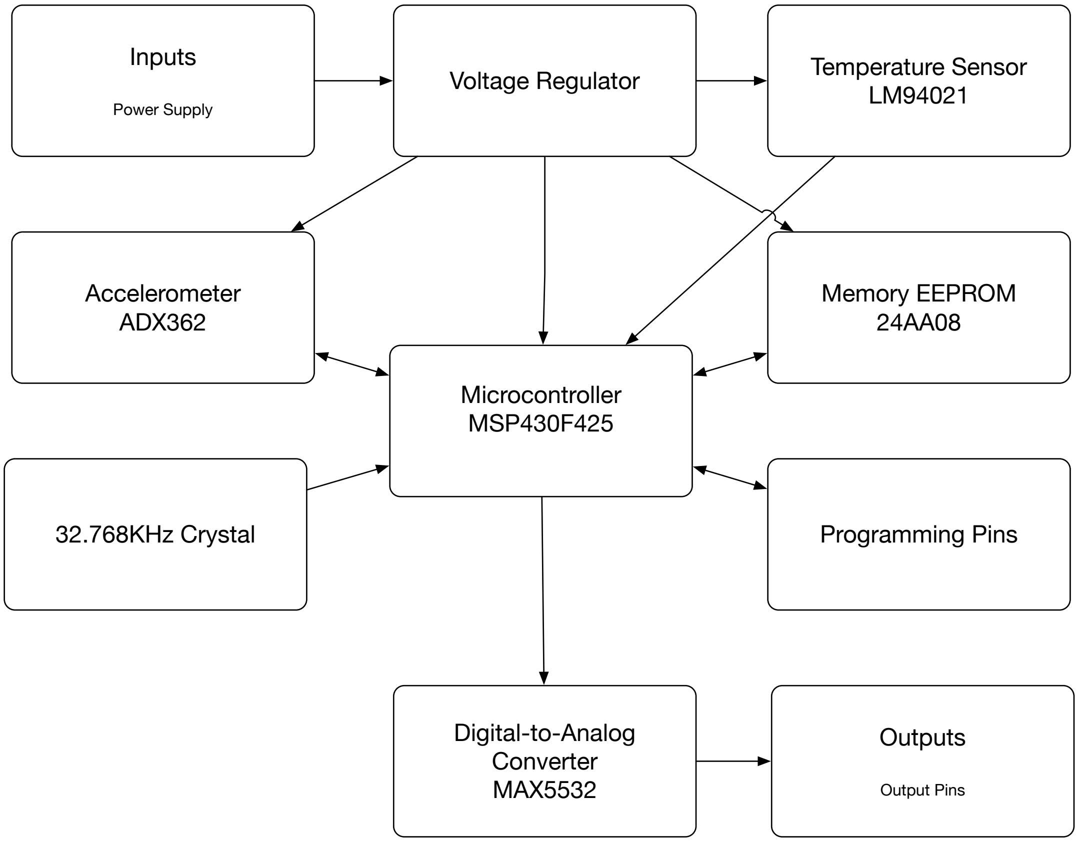


Figure 4.24: MSP430F2132 circuit board schematic 2nd version

More details about the design circuit in both versions can be found in Attachment A, Figure A.3 and Figure A.4 respectively.

4.3.5 Current Measurement

Figure 4.25 illustrates the current consumption during the microcontroller turn on process. The voltage is varied from $0.0\,V$ until the microcontroller turns on. This turn on process is the same for both board versions.

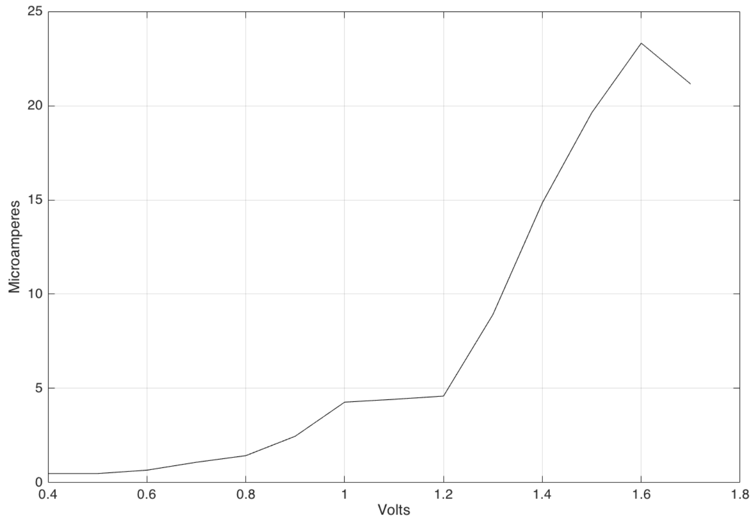


Figure 4.25: MSP430F2132 current consumption 1st version

As in the previous microcontrollers, the current consumption depends on the running process. The average consumption for the first board is presented in Table 4.3 and for the second is presented in Table 4.4.

Table 4.3: MSP430F2132 consumption 1st version

Code Specifications	Current Consumption
Bit Period = 366 µs; Sleep Period = 6.3 ms; All working;	39 µA
Bit Period = 61.5 µs; Sleep Period = 6.3 ms; All working;	68 µA
Bit Period = 42.6 µs; Sleep Period = 6.3 ms; All working;	138 µA

Table 4.4: MSP430F2132 consumption 2nd version

Code Specifications	Current Consumption
Bit Period = 1.105 ms; Sleep Period = 4.890 ms; All working;	39 µA
Bit Period = 1.105 ms; Sleep Period = 11.910 ms; All working;	41 µA
Bit Period = 1.105 ms; Sleep Period = 8.834 ms; All working;	45 µA
Bit Period = 444 µs; Sleep Period = 7.786 ms; All working;	51 µA
Bit Period = 366 µs; Sleep Period = 6.312 ms; All working;	59 µA

4.3.6 Microcontroller Analysis and Conclusion

As the first board developed was with the intention of testing the basic parameters of the MSP430F2132, and the second a more complete version with all the requirements, without any change on the microcontroller, the following analysis will be only about the second board.

The first point to appreciate is the code development, in this point with the inclusion of the external components (accelerometer, temperature sensor and DAC) all the requirements were fulfill. All the processes are working, the accelerometer and the temperature sensor are acquiring data to the microcontroller, this same data that after converted is sent using the DAC. The DAC output voltage can easily be controlled by software.

Power consumption reveled to be the very low in the turn on process and also during the time when the microcontroller is on. Table 4.4 shows its consumption with different bit and sleep periods. With all the components working and even with a short time of sleep the circuit only consumes 59 µA. It means that the board working consumption is very good. In terms of power consumption it does not have any limitation.

Concluding, the microcontroller behavior is very good. It fullfil all the requirements: support external sensing components, have a low power consumption and variables like output time and bit rates can easily be changed by software.

4.4 Conclusion

During this chapter a complete analysis to three different microcontrollers was done. The analysis process starts by the perception of the microcontrollers features, it is important to understand if there is need for external components. After, the programming part, to ensure that it can do all the software requirements. In the microcontroller that needed to build a board, its blocks are explained. Before the general analysis it was done measurements to understand the microcontrollers consumption.

To evaluate which microcontroller can better serve the solution three parameters are essential: power consumption, crucial to integrate the microcontroller in the WPT system; sensing components, the microcontroller need to have the capability of read different external sensors; software flexibility, it is important that the maximum number of aspects could be changed by software, with this it is possible to adapt the system for different applications only adapting the code, maintaining the hardware;

Looking to the aspects presented before the Texas Instruments MSP430F2132 appear as the best choice.

Chapter 5

System Measurements and Analysis

During this chapter, will be presented all the tests made during the work to the different system components.

5.1 Antennas Scattering Parameters

As it was showed in Section 3.2, during the work multiple antennas were tested. One of the key points to analysis in antennas, is its adaptation. It can be measuring the scattering parameter (S11), that represents the reflected power radio. As the intention is to have the lowest reflection possible, the antenna is more adapted in the frequencies where this parameter has lower values.

Figure 5.1 shows the scattering parameter of the commercial antenna.

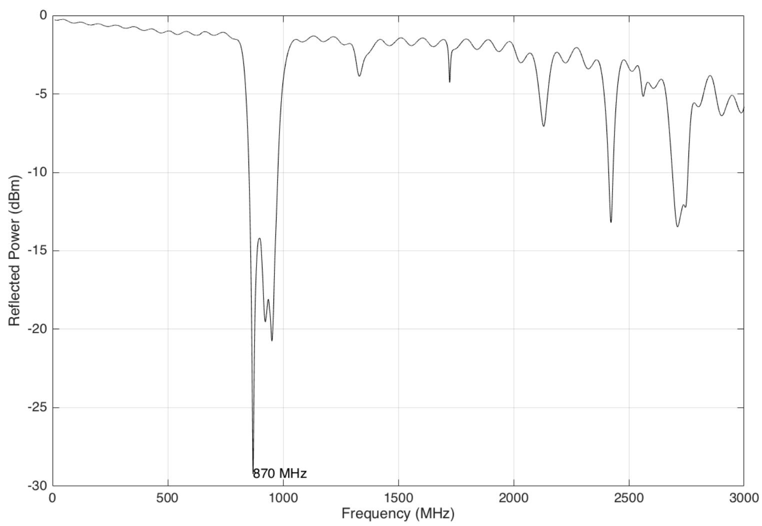


Figure 5.1: Scattering parameter - commercial antenna

The measurements about the commercial antenna indicate that it can operate properly between $860\,\mathrm{MHz}$ and $970\,\mathrm{MHz}$, once all this range is below $-10\,\mathrm{dBm}$. The frequency where the antenna reflect less power is at 870 MHz.

Figure 5.2 refers to the scattering parameters of the transmitter antennas, one was projected to transmit at 1.61 GHz and other at 2.29 GHz. Figure 5.3 presents the same parameters for the receiver antenna, it was projected to the work at the same frequencies.

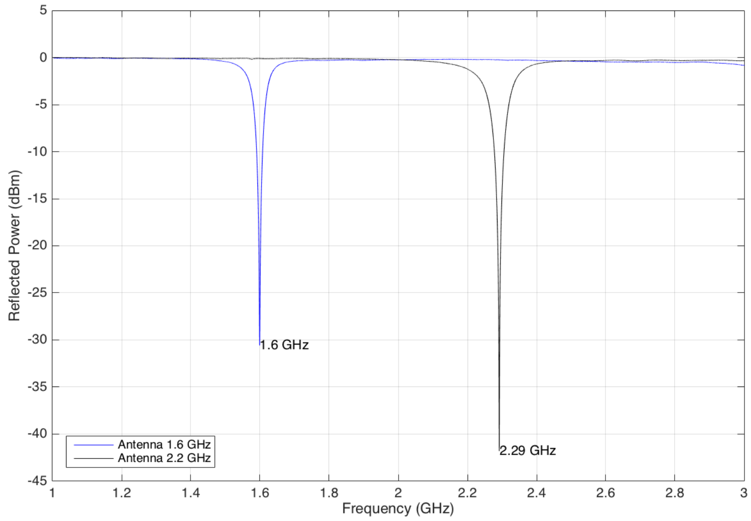


Figure 5.2: Scattering parameters - transmitter antennas 1st version

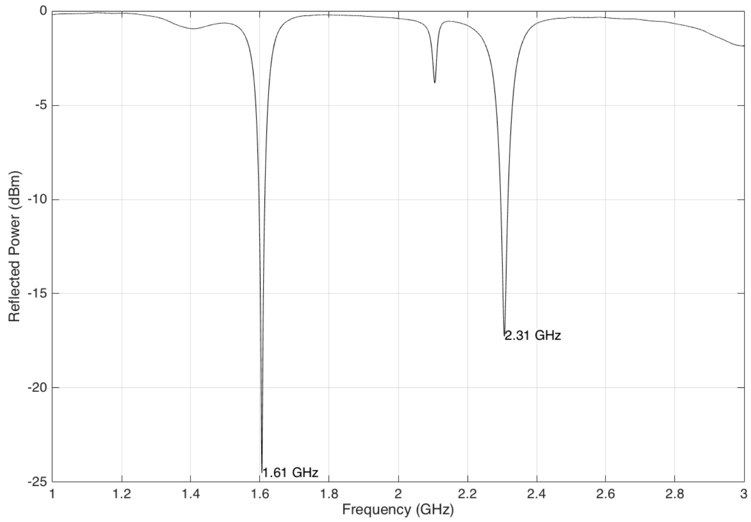


Figure 5.3: Scattering parameter - receiver antenna 1st version

The first pair of antenna specific built to this work, has its best adaptation at 1.60/1.61 GHz and 2.29/2.31 GHz. The power reflection values quickly increase when there is a deviation from the optimal frequencies, which means more power reflected. It is important to operate these antennas at frequencies close to its most adapted points. Even though there are differences between the optimal frequencies for the transmitter antennas and for the receiver antennas, these differences are not significant.

The scattering parameters of the antennas projected to work at 1.71 GHz and 2.40 GHz were presented in Figure 5.4 to the transmitter antennas, and in Figure 5.5 to the receiver antenna.

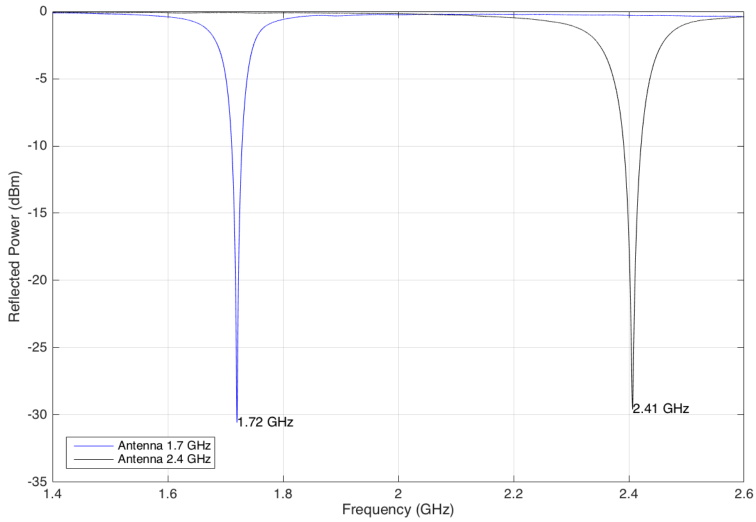


Figure 5.4: Scattering parameters - transmitter antennas 2nd version

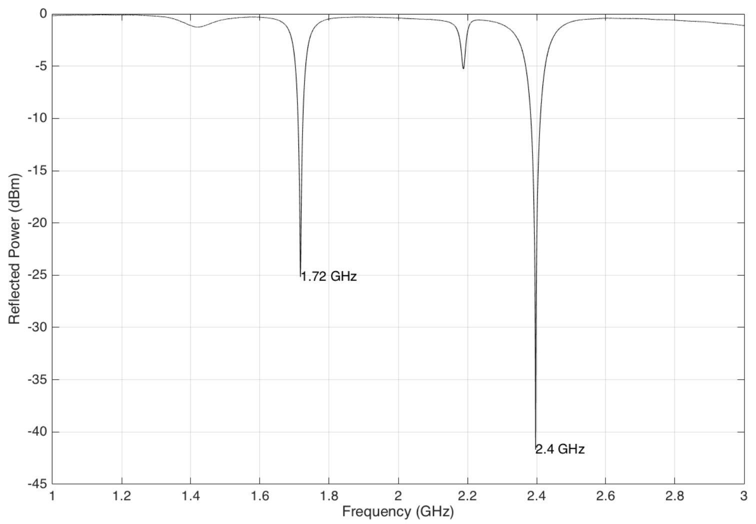


Figure 5.5: Scattering parameter - receiver antenna 2nd version

The last pair of antennas built, has optimal operation frequencies at 1.72 GHz and 2.40/2.41 GHz. The 2.40 GHz is the optimal operation frequency to the receiver antenna, for the transmitter antenna it is 2.41 GHz. As the difference is very small, it does not jeopardize the communication between them. Like the first pair, the adaptation value quickly increase with frequencies deviation.

5.2 RF to DC

During the work three different rectifiers were developed. They can be seen in Section 3.2, the first example in Figure 3.7, the second in Figure 3.8 and the third in Figure 3.9.

The RF-DC circuit were projected to operate at a specific frequency. The first circuit was projected to match the commercial antenna, however is easier to match the antenna frequency than the circuit frequency, the second and the third were built before the correspondent antennas. As the circuits present different efficiency levels for different frequencies, it is crucial to understand how it varies. For each circuit, two different input powers (-11 dBm and -8 dBm) were tested. The tests consisted in a fixed input power, a frequency variation, and a measurement of the output voltage. In these tests the RF-DC circuits have no load.

The measurement corresponding to the first RF-DC is showed in Figure 5.6.

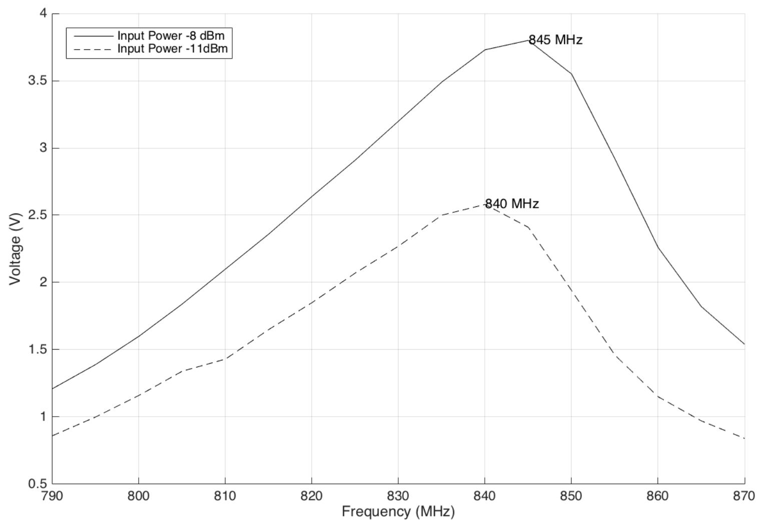


Figure 5.6: Voltage, varying frequency - 1st RF to dc circuit

The figure shows a RF-DC presenting an optimal frequency slightly lower when the input power is -11 dBm than when it is -8 dBm. However it presents small variations in the neighborhood of the optimal frequencies. Inside the range of 835 MHz and 845 MHz the voltage variations are lower than 0.5 V.

The second RF-DC result is presented in Figure 5.7.

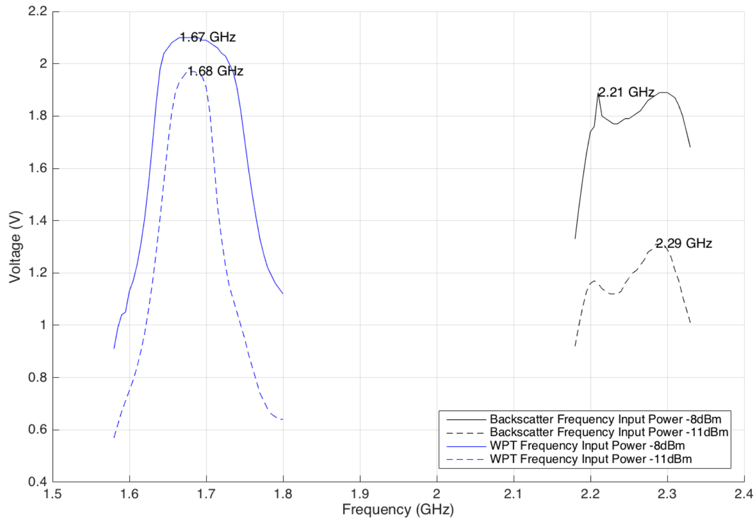


Figure 5.7: Voltage, varying frequency - 2nd RF to dc circuit

From the Figure 5.7 can be seen that there is almost no variation in the first frequency. It presents a good flat zone when the input power was $-8\,\mathrm{dBm}$ or $-11\,\mathrm{dBm}$, with a range between $1.66\,\mathrm{GHz}$ and $1.70\,\mathrm{GHz}$. The second frequency, the backscatter frequency, has the most efficient points in different frequencies for the different inputs powers. A closer look can show that the line corresponding to the backscatter frequency, at $-8\,\mathrm{dBm}$, has a sub-optimal peak at the frequency of $2.29\,\mathrm{GHz}$. That is the frequency at which the backscatter frequency presents best results when the input power is $-11\,\mathrm{dBm}$. This frequency shift does not present a big efficiency loss, it produce an output value near the output produced by the optimal frequency.

Figure 5.8 represents the measurement made in the third RF-DC.

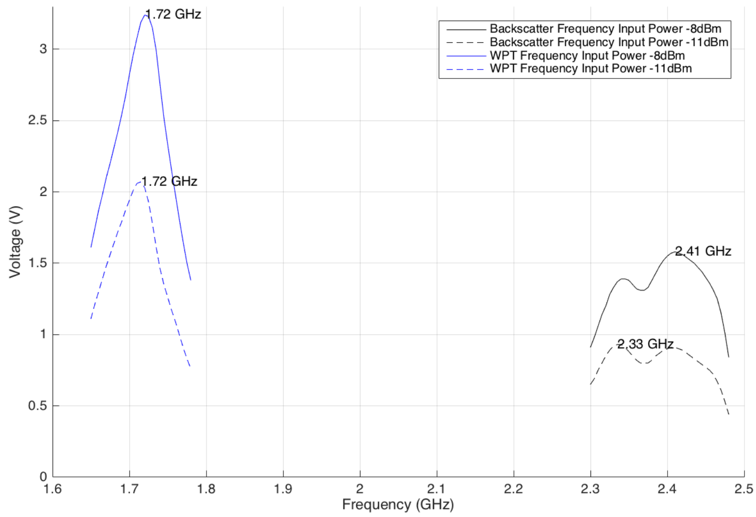


Figure 5.8: Voltage, varying frequency - 3rd RF to dc circuit

The efficiency of the third RF-DC circuit, presents a peak at $1.72\,\mathrm{GHz}$ for the first frequency. In this case the peak is narrow, in order to maintain the efficiency the operational frequency should not have huge variations. In the second frequency the most efficient points have different optimal frequencies for different power inputs. However both shapes are identical, choosing frequencies near $2.41\,\mathrm{GHz}$ produce good results for both input powers, $-8\,\mathrm{dBm}$ and $-11\,\mathrm{dBm}$.

As it can be seen in the previous figures, the optimal operational frequency in the RF-DC circuits varies with different inputs. However, in most cases, the difference between the optimal frequency and the frequencies surrounding, in terms of efficiency, is not huge. This means, that the circuits can be operated at frequencies that are not exactly the most efficiency frequency, without major losses.

With the information about the antennas scattering parameters available on Section 5.1 and the information about the RF-DC efficiency, it can be established the operation frequency for each par of antennas and rectifier. Figure 5.9 crosses the information of the commercial antennas and the first RF-DC.

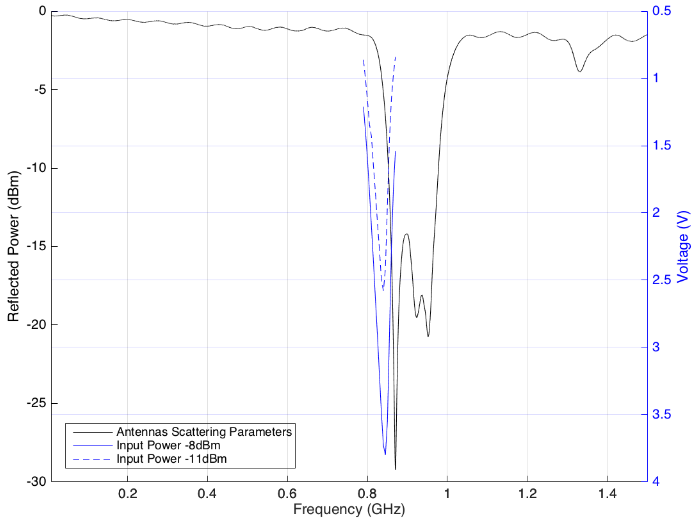


Figure 5.9: Optimal operational frequency 1st set

Analyzing the figure it is possible to see that there is not a optimal frequency for the set. The optimal frequency to the RF-DC is slightly to the left compared with the antenna adaptation. However between the two optimal frequencies, in a interception point, it is possible to identify a frequency that does not compromise the system.

Figure 5.10 is relative to the second set of antennas and RF-DC.

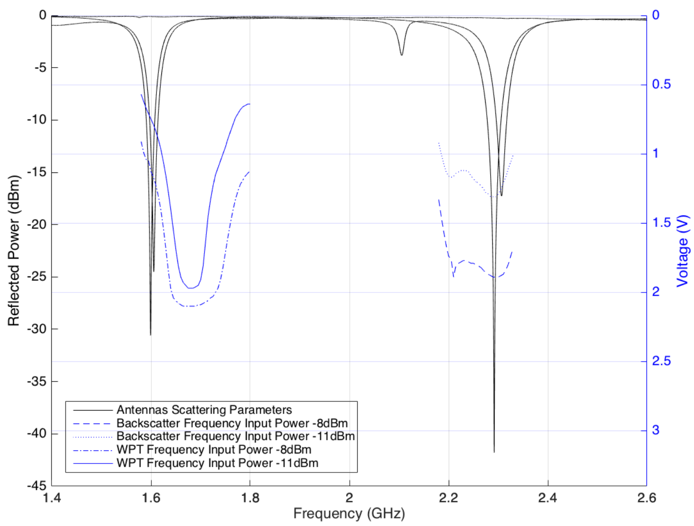


Figure 5.10: Optimal operational frequency 2nd set

In the second set, on the first analysisd frequency, there is a clear difference between the optimal frequencies for the RF-DC and the antenna adaptation. To minimize losses the operation frequency needed to be between the optimal points. However as the correspondent reflected power is high it can not be expected a big yield. This frequency deviation could be caused by multiple factors. For example, the no characterization of the components used in the simulation of RF-DC circuit , or variations on the substrate parameters used to produce the antennas. In the second frequency the optimal frequency is the same for RF-DC and antennas adaptation.

The third set is represented in Figure 5.11

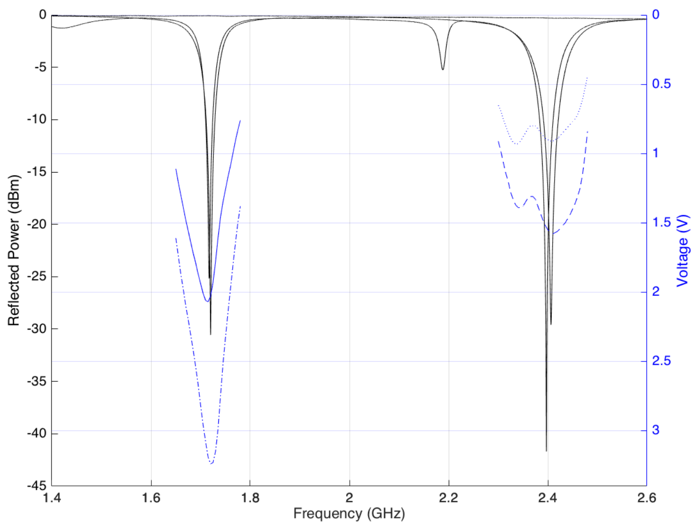


Figure 5.11: Optimal operational frequency 3rd set

By the figure it is possible to see that there is a very good relationship between the RF-DC most efficient points and the antennas adaptation. The optimal frequencies for both are on the same frequencies, this means that can be expected a system working with a good efficiency.

The operation frequencies for each set, were established based in the information available in the previous analysis. From them can be confirmed that, antennas adaptation has big variations with small frequency changes, and RF-DC efficiency do not suffer big losses with small frequencies variations. Table 5.1 shows the established operation frequencies for each set.

Table 5.1: Operation frequency established

Sets	Operation Frequencies
1st set	860 MHz
2nd set	1.612 GHz and 2.300 GHz
3rd set	1.720 GHz and 2.405 GHz

The proposed technology is a hybrid between RF-DC and backscatter. This means that the backscatter state can have influence in the produced voltage. The developed backscatter has two states, one where it is absorbing and other where it is reflecting (more information about backscatter operation is available in Section 2.5). Other aspect to have in attention is the connected load, in this case, the load is the microcontroller MSP430F2132 chosen as the processing unit of the system (more information available in Section 4.4).

The following measurements pretend to evaluate the input power and output voltage after the RF-DC circuit in different conditions. Figure 5.12, Figure 5.13 and Figure 5.14, correspond to the first, second and third set respectively.

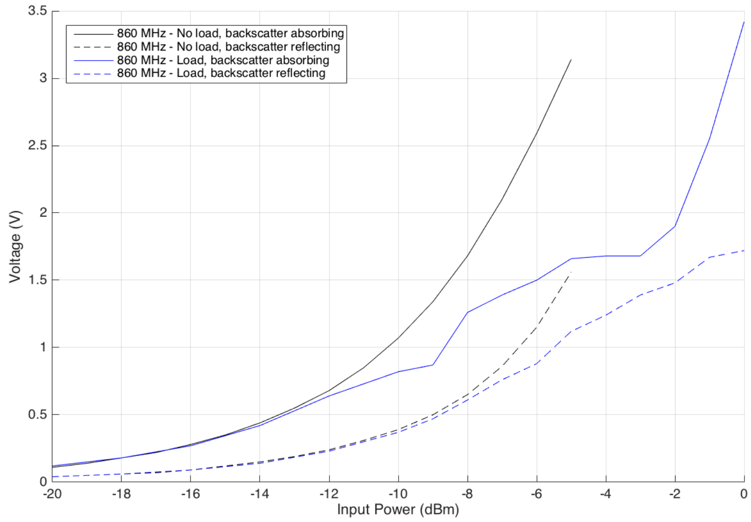


Figure 5.12: Input power vs. output voltage, 1st set

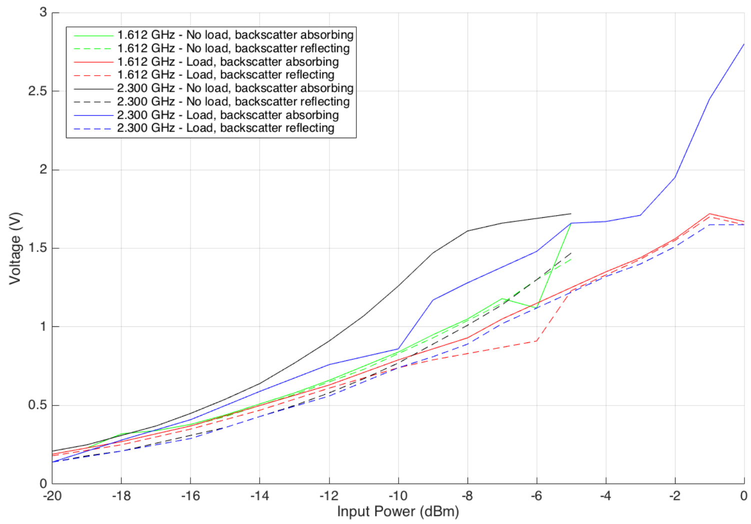


Figure 5.13: Input power vs. output voltage, 2nd set

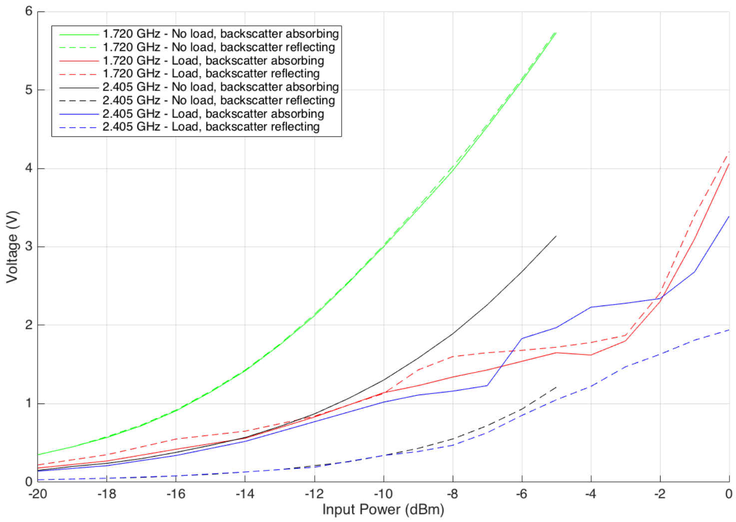


Figure 5.14: Input power vs. output voltage, 3rd set

Even though that there is differences in the values, all the three sets present the same behavior. In this case, a generic analysis can be done.

In the frequencies only project for WPT, 1.612 GHz - second set and 1.720 GHz - third set, the results are not influenced by the backscatter. It can be absorbing or reflecting that the voltage produced do not suffer big variations, as it could be expected.

By other side, in the frequencies projected for WPT and backscaterring, 860 MHz - first set, 2.300 GHz - second set and 2.405 GHz - third set, the voltage produced is highly influenced by the backscatter state. In the tests the differences reached differences of 1.5 V.

When connected to the load, all the sets present less output voltage than when they are not connected. The received power is the same in both situations, however when the set is connected to a load, it consumes current. As the Equation 5.1 shows, maintaining the power and increasing the current, the voltage necessary drops.

$$Power(\mathrm{W}) = Amplitude(\mathrm{V}) \times Current(\mathrm{A}) \tag{5.1}$$

Overlaying the figures of the three sets, it is possible to do a comparison. To do it with a realistic environment, only the measurements with connected load (microcontroller connected) are used. Figure 5.15 represents all the sets when they are absorbing, Figure 5.16 shows the results when they are reflecting.

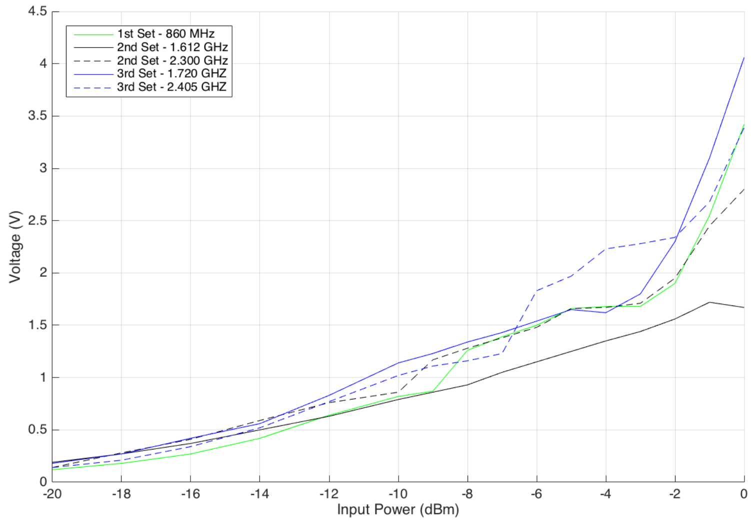


Figure 5.15: Sets comparison, backscatter absorbing

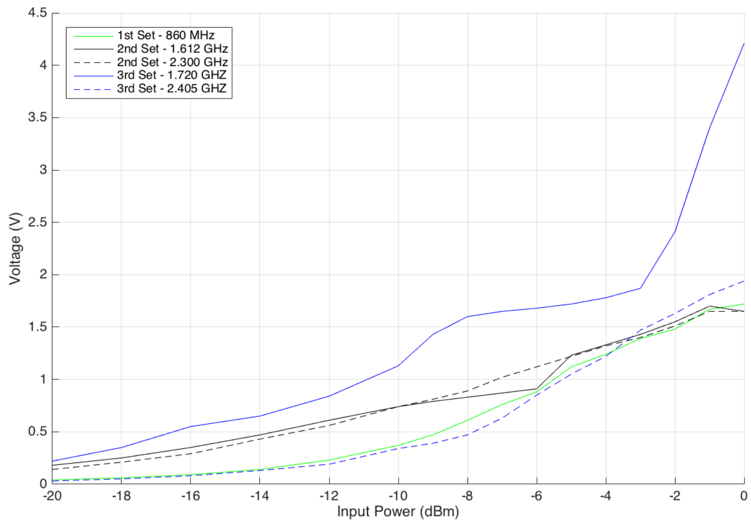


Figure 5.16: Sets comparison, backscatter reflecting

As expected the third set is the one that presents the best results. The precise match between the most efficient frequency for the RF-DC and the frequency where the antennas reflect less power is the main factor to the good results.

5.3 Wireless Power Transmission

The following measurements provide information about the transmitted power, power received in both frequencies and the correspondent output voltage. The tests were done with a fixed distance, 100 cm, 200 cm and 300 cm, and with transmitted power varying. Figure 5.17 presents the results when the antennas were separated 100 cm.

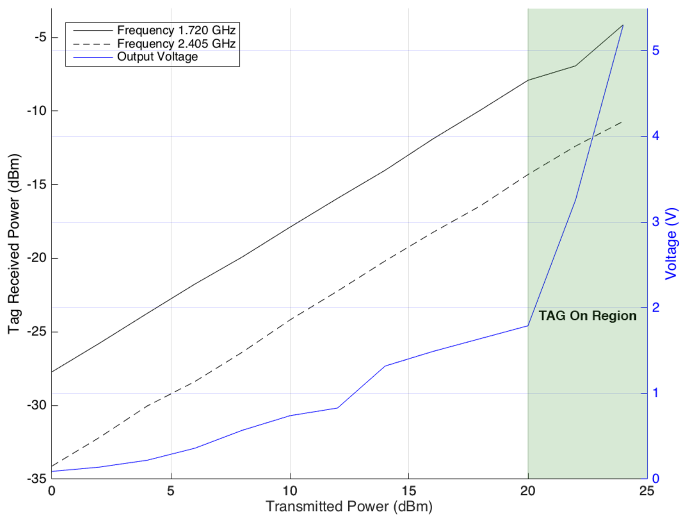


Figure 5.17: WPT at 100 cm

From the measurements, it can be seen that there is a considerable difference between the power received at 1.720 GHz and the power received at 2.405 GHz. Even though the transmitted power and the distance are the same, the multiple reflection on the tests scenario can have influence in the power received by the receiver antenna. This explain the observed differences. At a distance of 100 cm the microcontroller turns on when the transmission power is 20 dBm, the received power is approximately −8 dBm for 1.720 GHz and approximately −15 dBm for 2.405 GHz.

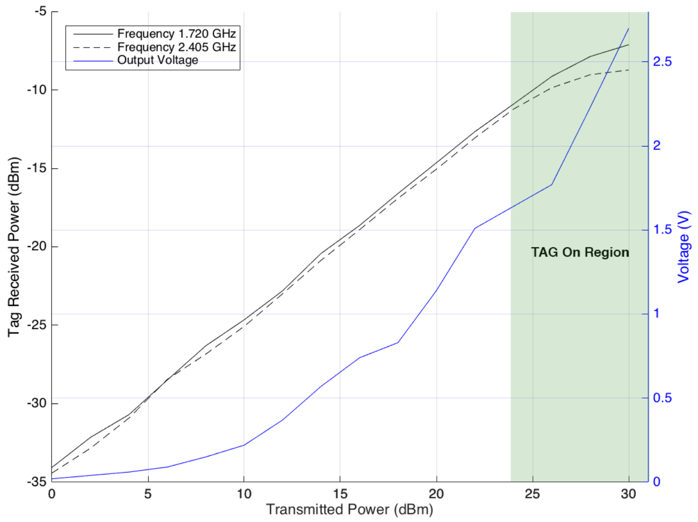


Figure 5.18: WPT at 200 cm

Figure 5.18 show a linear increase in terms of received power in both frequencies. When the microcontroller turns on it is possible to see that the backscatter frequency 2.405 GHz does not match the power increase of the WPT frequency. It happens because when the microcontroller turns on the backscatter starts working and consequently less power is absorbed in the backscatter frequency. At a distance of 200 cm, the microcontroller turns on when the transmission power is 24 dBm, the received power for both frequencies is approximately −12 dBm.

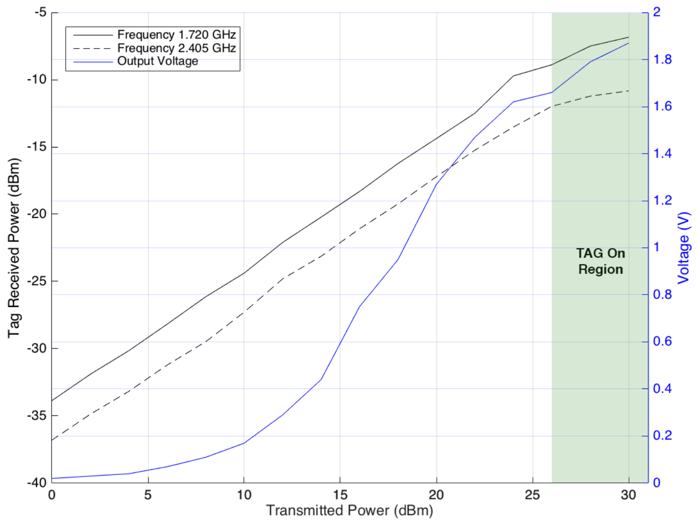


Figure 5.19: WPT at 300 cm

The third set presents a linear behavior during the increment of transmitted power. As it happens on Figure 5.18, when the microcontroller starts working, the backscatter starts reflecting, consequently the gap between the power received in the different frequencies increases. At a distance of $300\,\mathrm{cm}$, the microcontroller turns on when the transmission power is $26\,\mathrm{dBm}$, the received power is approximately $-9\,\mathrm{dBm}$ for $1.720\,\mathrm{GHz}$ and approximately $-12\,\mathrm{dBm}$ for $2.405\,\mathrm{GHz}$.

Figure 5.20 illustrate the results on the tests made to measure the maximum distance at which the microcontroller turns on varying the transmitted power since $10\,\mathrm{dBm}$ until $30\,\mathrm{dBm}$.

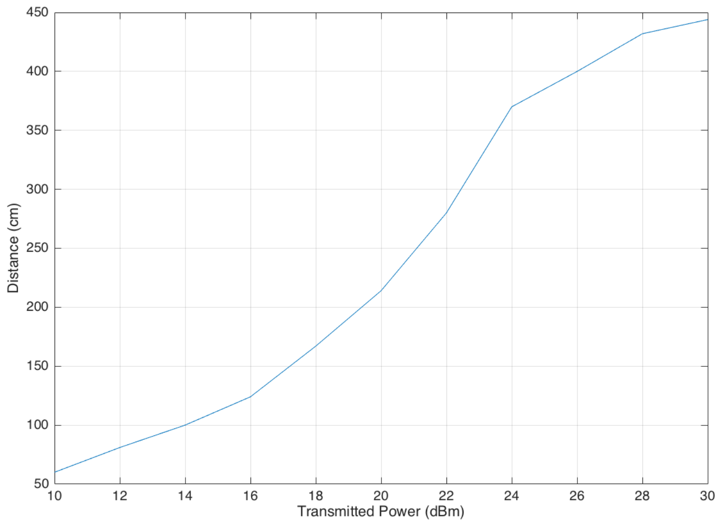


Figure 5.20: Transmitted power vs. maximum distance

5.4 Overall System

The following tests involve the system completely working. The tag is powered by WPT, the microcontroller turns on, does the sensing and processing work, and the backscatter sends the information by modulating the receiver carrier. This information should be demodulated by the reader. Figure 5.21 shows the scenario and all the components involved in the measurements.

Figure 5.21: Overall system scenario

The results of all the process are presented in Figure 5.22. Having as reference the transmitted power it was measured the received power in both frequencies, the reflected power, the power received by the reader and the distance.

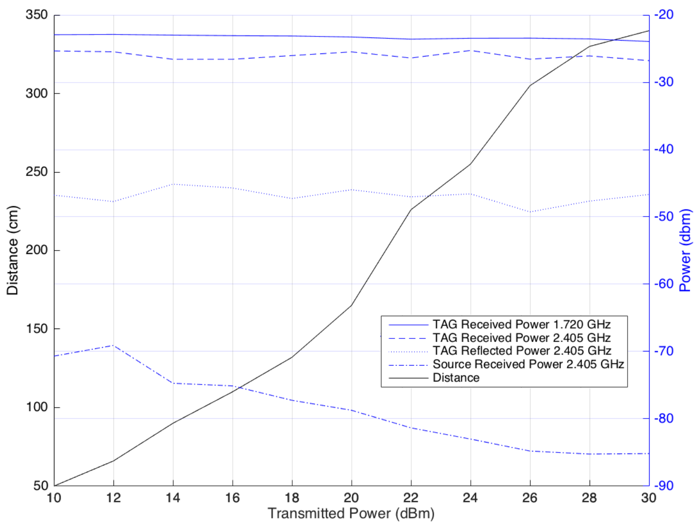


Figure 5.22: Transmitted power vs. maximum distance

All the measurements are made when the microcontroller is on, backscatter working, and the power that is received by reader is enough to distinguish the signal from the noise, allowing its demodulation.

As can be proved by the measurements, the power received, by the receiver antenna does not suffer big variations. It is natural once the minimum received power to ensure that the tag is on, is constant. If the power received is constant, and if the reflection is always done in the same way, it is logical that the tag reflected power presents a value without big variations. However, being the tag reflecting the same amount of power and the distance increasing it will result in a decrease on the power received by the reader. All this conclusions are supported by the previous figure.

The next figures show the measurements in each one of the points analysisd when the transmitted power is 30 dBm and the distance is 340 cm. These conditions correspond to the maximum distance at which is possible to see the system working properly, from this distance beyond, the signal received by the reader is difficult to distinguish from the noise.

Figure 5.23 illustrates the power received by the tag, in the frequency dedicated to the WPT, 1.720 GHz.

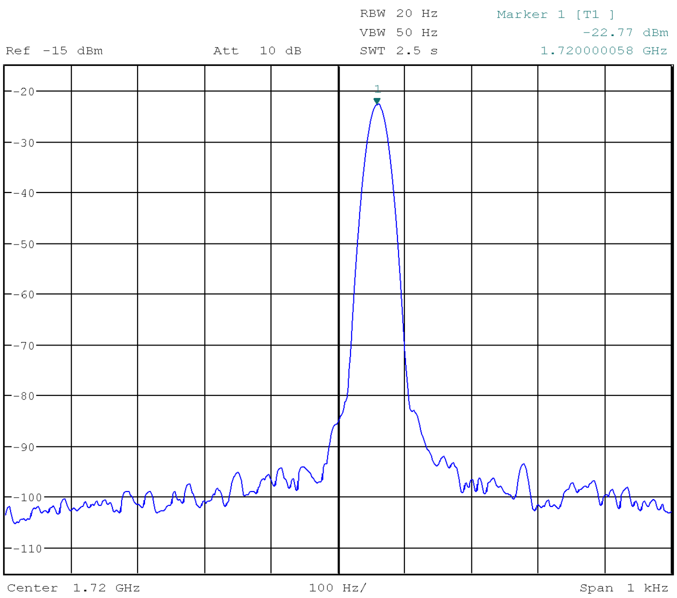


Figure 5.23: TAG received power at 1.720 GHz

Figure 5.24 shows the power received by the tag at the frequency of 2.405 GHz.

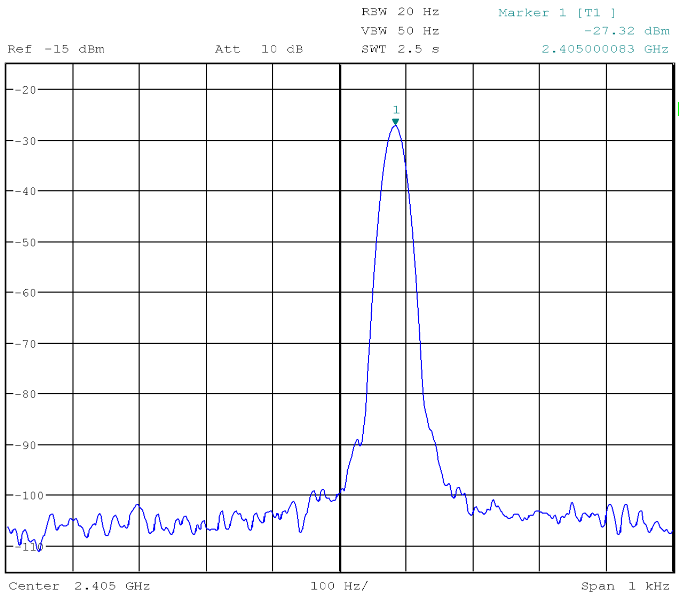


Figure 5.24: TAG received power at 2.405 GHz

The tag reflected power can be seen on Figure 5.25. The rate used by the microcontroller to control the backscatter reflection is the responsible by the frequency shifting. This rate need to be balanced, if it is too high the microcontroller consumption increases, if it is too low the modulated signal can not be distinguished from the carrier.

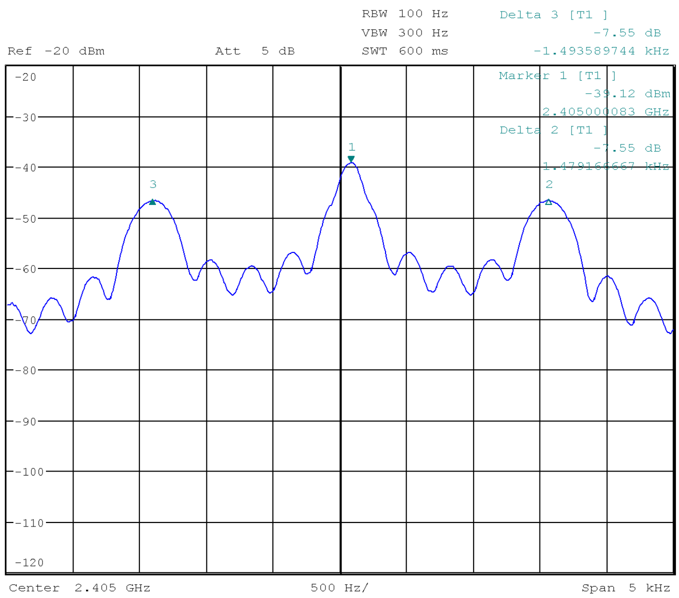


Figure 5.25: TAG modulation and reflection

The final element is presented in Figure 5.26, it shows the power received at the reader.

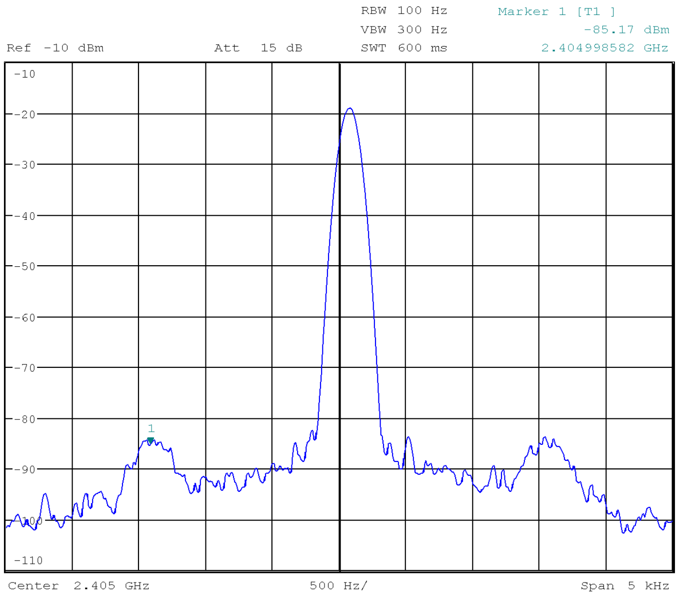


Figure 5.26: Reader received information

5.5 Conclusion

The first conclusions are about the antennas and the RF-DC circuits. The first set, was projected to prove some concepts about WPT. It presented a good behavior and it was important to understand some possible improvements. The second set had good results when the components are tested individually, however due to the frequency deviation the general behavior of the set was below expected. The last set projected presented a good behavior in all the tests.

Looking to the influence of the backscatter and the load on the overall system, it can be said that the results prove what was already expected. When the load is connected the voltage decreases and when the backscatter is reflecting the received power at the backscatter frequency is lower.

In terms of WPT the results are satisfactory, the microcontroller can be turned on at a distance of $4.40\,\mathrm{m}$.

Due to the power losses when the tag is reflecting at $4.40\,\mathrm{m}$, it is not possible to see clearly the signal modulated at the reader. The maximum distance at which the system can operate properly is at $3.40\,\mathrm{m}$.

Chapter 6

Conclusion and Future Work

This chapter intends to give an overall conclusion about the final system. A more detailed conclusion about specific parts of the work can be found in the end of each chapter. Besides the final conclusion, some ideas about the future work that could be developed are presented.

6.1 Conclusion

The main objective defined for this dissertation was clearly achieved. The system allows communication between the reader, and the passive tag, using WPT and backscatter techniques. The tag has processing capabilities and can be connected to multiple sensors. The message format can be fully controlled by software and the bit rate can also be easily modified.

An important feature about the system is the distance at which it can properly operate. The distance of $3.40\,\mathrm{m}$ between the reader and the tag can be considered a good result for space applications. The spacecraft that has been being built by National Aeronautics and Space Administration (NASA) to do human exploration of Mars, only has $3.3\,\mathrm{m}$ of height [44]. In other applications like, smart homes, smart cities, or industrial applications, the developed system continues to be a viable solution. In application that need a longer range, the solution is not suitable anymore.

The system was tested in a scenario with multiple objects, and consequently with different reflections. It can mean that with a different scenario the results can be slight different.

The work was focused in four points: antennas, RF-DC circuit, radio backscatter and microcontrollers. However, superficial knowledge about others subjects related with the system, was acquired. Topics like readers, tags collisions or waveform design were approached during the work.

6.2 Future Work

For future work, it is important to try to explore some techniques to improve the distance at which the system can operate. Waveform design is one of the topics that can have an important impact in the maximum distance. By other hand to make the system suitable for more application it is important to reduce its dimensions. The use of different substrates for antennas, or the the use of components in the RF-DC circuits can be topics that can worth exploring.

About the concrete application, for space, it would be interesting to understand the best frequencies at which the system could have better performances in a spatial application. In terms of the sensing unit, a detailed research about the sensors used in space, and its implementation on the circuit would be a good complement to the work.

Appendices

Appendix A

Circuits schematics and designs

A.0.1 Voltage Regulator

Figure A.1 represents the schematic of the voltage regulator circuit. It was done in the software tool Eagle.

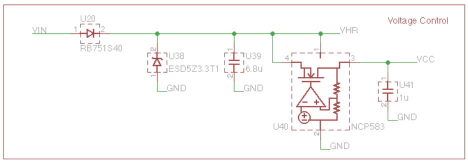


Figure A.1: Voltage regulator

A.0.2 MSP430F4250 schematic

Figure A.2 shows the schematic produced by the software tool Eagle, used to design the produced the board.

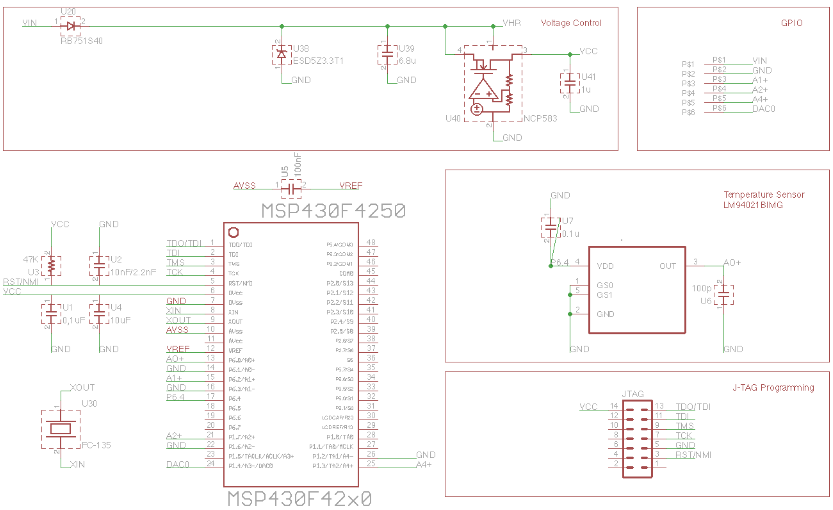


Figure A.2: MSP430F4250 circuit board design

A.0.3 MSP430F2132 schematic

Figure A.3 shows the 1st version of the schematic produced by the software tool Eagle used to design the produced board. Figure A.4 shows the 2nd version.

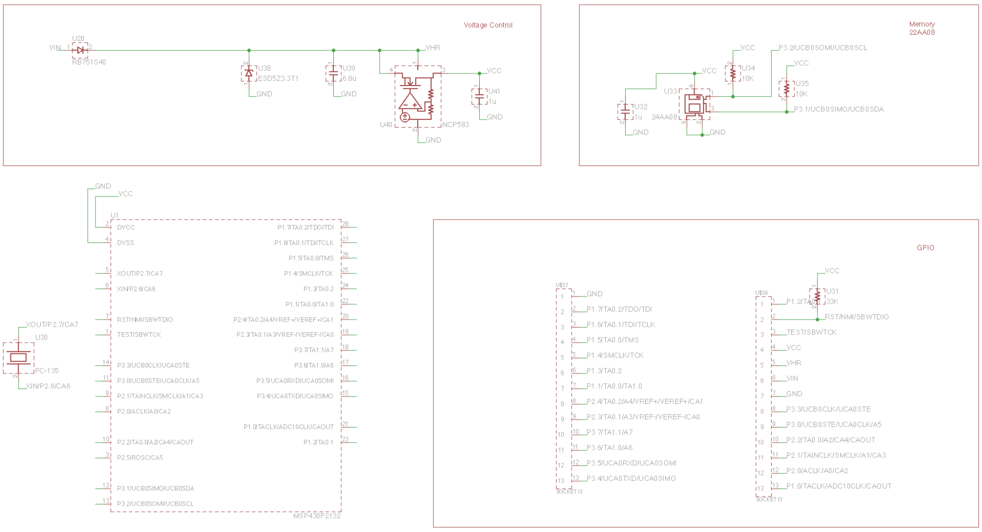


Figure A.3: MSP430F2132 circuit board design 1st version

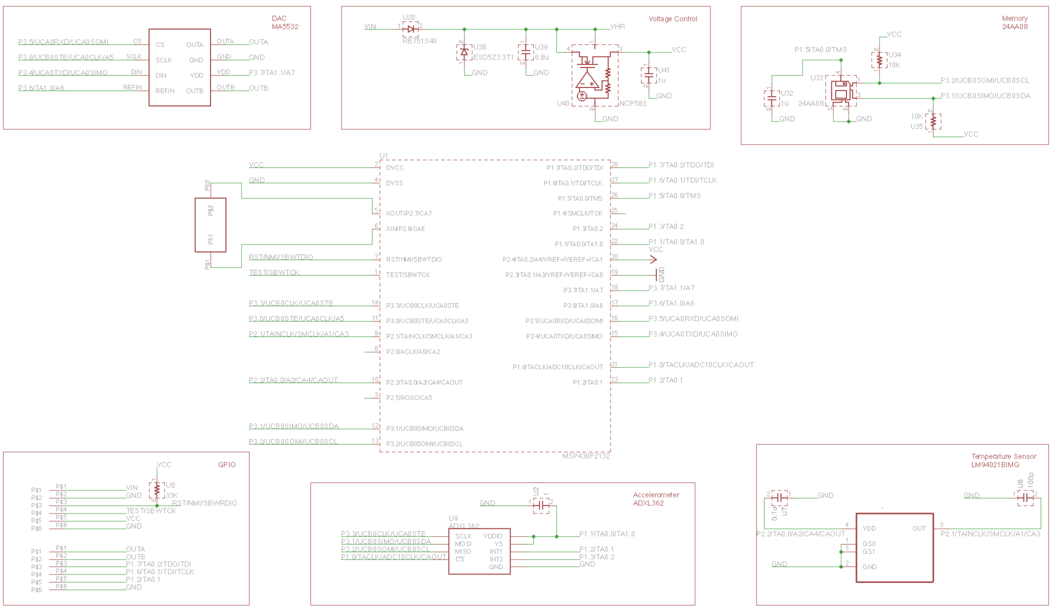


Figure A.4: MSP430F2132 circuit board design 2nd version

Appendix B

Article for RWW2017 — IEEE Radio Wireless Week

Dual Band Wireless Power and Data Transfer for Space-Based Sensors

Daniel Belo, Ricardo Correia, Felisberto Pereira and Nuno Borges de Carvalho

Instituto de Telecomunicações, Departamento de Electrónica, Telecomunicações e Informática
Universidade de Aveiro

***Abstract*— Wireless sensor networks can be used in many ways including article tracking, position location, passive temperature sensors, passive data storage, and in many other systems which require information exchange between an interrogator and a small, low-cost transponder with little-to-no transponder power consumption. Yet, almost all of them operate on batteries that normally deplete long before the predicted life span of basically all the other hardware components.**

In this work we propose a solution for a fully passive sensor to be used inside a spaceship. By using this approach, data and power can be transferred simultaneously, allowing the sensor to be continuously wirelessly powered.

***Index Terms*— Wireless Power Transfer, Passive sensors, dual band antenna, backscatter communications.**

I. INTRODUCTION

Nowadays, the use of conventional sensors on a medium sized spacecraft has increased and there are several potential applications for smart sensor technologies that have not been explored yet. The realization and development of space travel at rational cost demands a reusable spacecraft that can assume frequent missions. The success of space missions depends on performance, supervising and controlling an extensive amount of functions on-board of any spacecraft. For the supervisory, multiple information is needed and it is obtained by sensors. These sensors not only control the function on satellites, but they are also needed for the mission objective itself. For space applications, the conventional approach for the communications is to use wired sensor networks that contributes significantly with weight [1]. Nevertheless, in the last years, wireless communication systems have been investigated in order to overcome some limitations about the maintenance and the weight [2].

The function of the satellite is based on the structural support, attitude and orbit control, thermal control, power supply, on-board data handling and the communication. To monitor all these tasks, the spacecraft needs to contain a lot of sensors. Almost half of them are temperature sensors that are required for the thermal control of the satellite. The rest of them are to measure angles or positions (magnetometers, star sensors and gyroscopes). Some additional sensors can be needed such as accelerometer to track the position, pressure gauges and flow meters.

Due to the limitation of using wires inside the spacecraft for the sake of saving weight for other useful payloads, there is the need of using wireless sensor network (WSN) powered by wireless power transfer (WPT) technologies. Some work in these concepts has been applied in some terrestrial application [3], [4], where it was used a low power communication (backscatter) combined with WPT. The backscatter radio frequency identification is a type of RFID technology employing tags that do not generate their own signals but reflect the received signals back to the readers with some kind of carrier modulation.

For this purpose, this paper describes a wireless sensor system that can be wirelessly powered while being able to transfer data, simultaneously. Moreover, a dual band microstrip patch antenna array is considered as the sensors antenna.

II. PASSIVE SENSOR FOR SPACE APPLICATION

Fig. 1 presents the block diagram of the proposed system. This system is composed by two main blocks, which are the backscatter modulator (switch transistor) and the RF harvesting circuit with a power management unit. The main objective of the RF harvesting block is to generate dc output power to supply the microcontroller to modulate the information acquired from a temperature sensor, by means of switching ON and OFF the transistor.

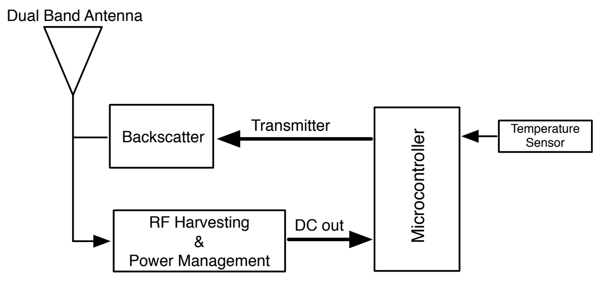


Fig. 1. Block diagram of the proposed system

Our proposed system was based on the circuit presented in [3] with an increase of stages in the Dickson multiplier and a different matching network. The system is illustrated in Fig. 2 and includes a switch transistor to modulate the impedance of the antenna to cause a change in the reflection coefficient. It also includes a five-stage Dickson multiplier to maximize the dc output voltage collected. RF Schottky diodes (SKYWORKS, SMS7630-006LF) were employed. The designed matching network has an important role in this circuit, since it was designed for the backscatter load modulation in one frequency and for the continuous energy beam for the WPT in other frequency. The frequency selected for the communication was 2.3 GHz and for the WPT was 1.6 GHz.

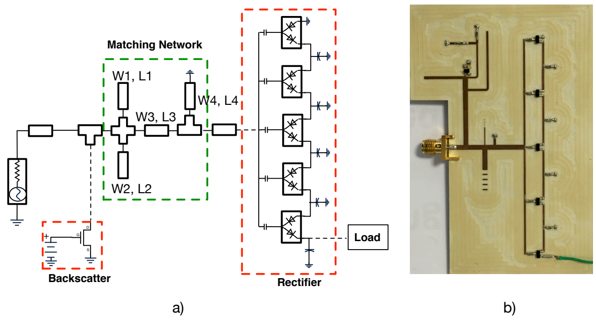


Fig. 2. a) Configuration of the proposed system. b) Photograph of the proposed system. Element values are L1 = 7 mm, W1 = 0.4 mm, L2 = 8 mm, W2 = 1.9 mm, L3 = 2.48 mm, W3 = 1.87 mm, L4 = 3.15 mm, W4 = 0.94 mm. Substrate for the transmission lines is Astra MT77, thickness = 0.762 mm, ε_r = 3.0, tan δ = 0.0017.

III. Dual Band Patch Antenna

To achieve continuous power and data transfer, a dual band antenna should be employed at the receiver in order to avoid additional losses from combining processes if two separated antennas are used. Many dual band designs have been proposed such as microstrip-fed [5], probe-fed [6] or planar inverted F antennas [7].

For this system, a microstrip patch antenna subarray (1x2) composed by square patches with inset-fed was considered and optimized for each frequency of operation. To achieve the dual band operation, each subarray should be matched at the operating frequency while presenting an open circuit for the other frequency. To accomplish this, the length of the main feed line of each subarray (L1 and L2 in Fig. 7) was varied until the condition above was verified. After this process, the subarrays can be joint together to produce a dual band patch array. Fig. 3 presents the CST MWS simulated and measured reflection coefficient.

Fig. 4 and Fig. 5 represents the simulated radiation patterns for both y-z and x-z planes, respectively. As each subarray is not centered at the ground plane, the radiation pattern deviates from the ideal one in the y-z plane, as it can be seen a tilted main beam in Fig. 4. The maximum gain achieved for both operating frequencies is around 9 dBi. Moreover, from Fig. 4, a low front-to-back ratio at

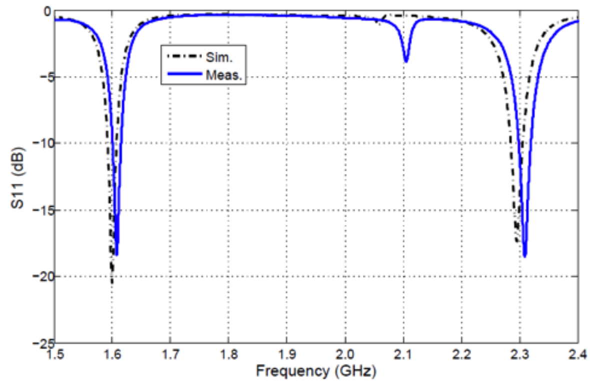


Fig. 3. Measured and simulated reflection coefficient for the dual band antenna array.

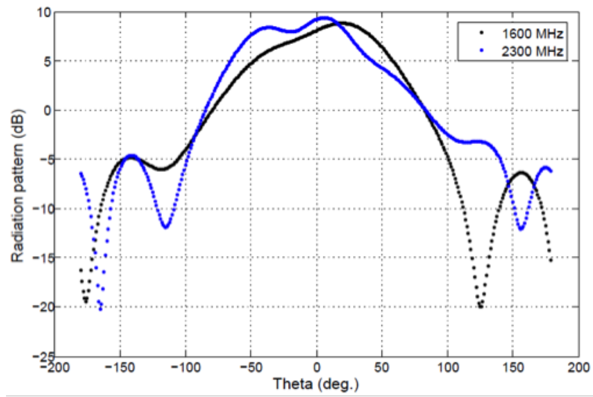


Fig. 4. Simulated radiation patterns for both operation frequencies for the y-z plane.

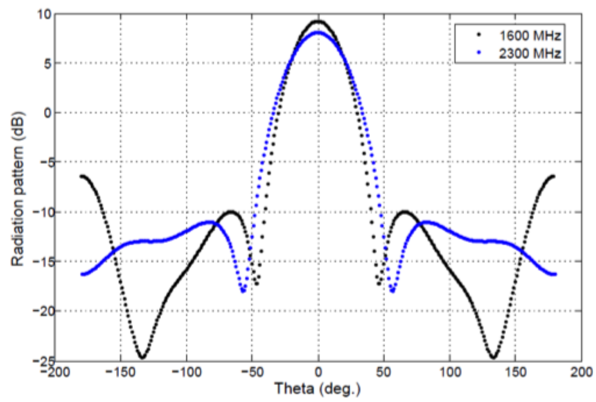


Fig. 5. Simulated radiation patterns for both operation frequencies for the x-z plane.

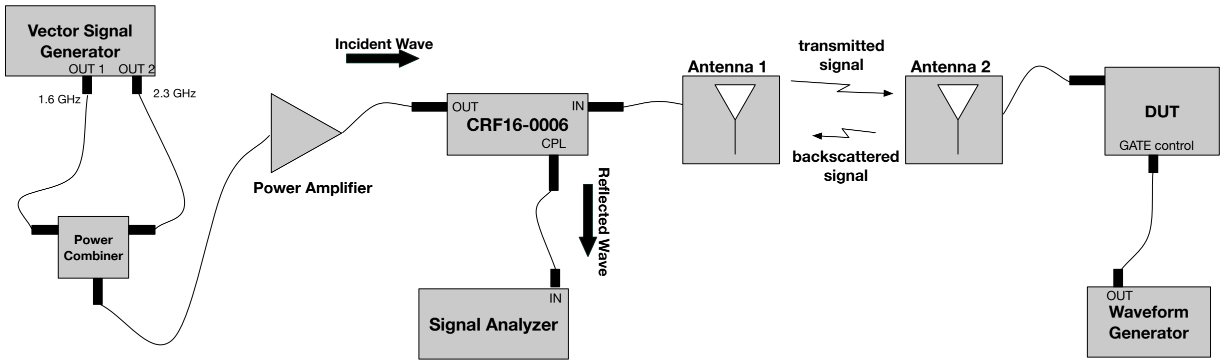


Fig. 6. Block diagram of the measurement setup

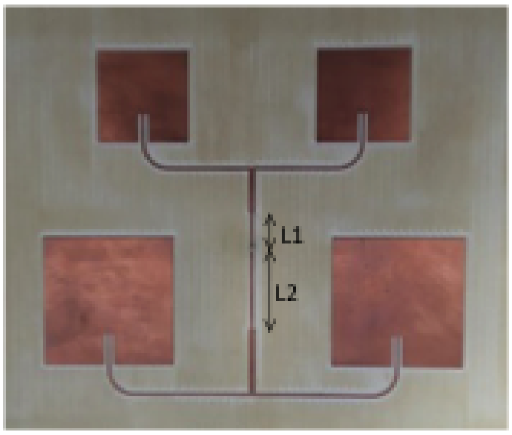


Fig. 7. Dual band patch antenna array prototype.

the lower operation frequency was obtained. One of the most important parameters in our designing process is the simplicity of the antenna and its feeding structure so that the antenna can be fabricated easily and be accurate in practice. Fig. 7 shows the manufactured antenna prototype. By adopting this strategy, it is simple to design a relatively high gain dual band antenna, in the expense of the occupied area when compared with other techniques, such as the conventional "U" slotted patch antenna approach [8] that usually has less efficiency.

IV. MEASUREMENTS

Fig. 6 presents the block diagram of the measurement setup used to acquire the reflection wave from our proposed circuit with the antennas. We used a vector signal generator (ROHDE&SCHWARZ, SMW200A) to generate 1.6 GHz and 2.3 GHz. At the output of the vector signal generator we used a power combiner (Mini-Circuits, ZFRSC-183-S+) to combine 1.6 GHz and 2.3 GHz to the input of the power amplifier. A coupler (Marki, CBR16-0012) was used to measure the reflected backscattered signal, using a signal analyzer (ROHDE&SCHWARZ, FSQ). A waveform generator (Agilent, 3325OA) was used to switch the transistor's gate voltage to provide the backscatter modulation.

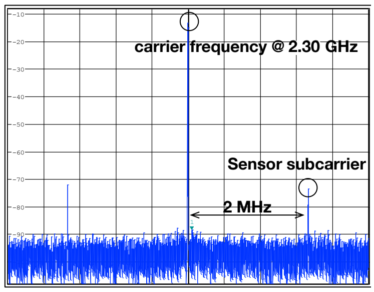


Fig. 8. Backscattered signal obtained in signal analyzer

With the measurement setup presented in Fig. 6 it was possible to acquire the signal presented in Fig. 8 by the signal analyzer. As can be illustrated by Fig. 8, the sensor subcarrier is spaced 2 MHz from the carrier. In the Fig. 9 is represented the distance at which is possible to supply the microcontroller and the sensors for different values of transmitted power. The measures were made for the frequency of 1.6 GHz. For a maximum transmitted power of 30 dBm, the microcontroller can be supplied at a distance of 3.4 m.

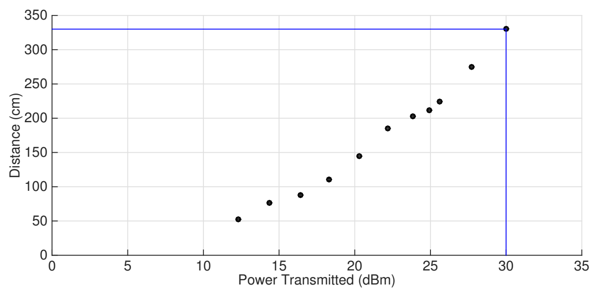


Fig. 9. Power transmitted as function of distance.

V. Conclusion

A fully passive sensor for space applications has been proposed that operates at 1.6 GHz for wireless power transfer and at 2.3 GHz for data transfer. A dual band microstrip patch antenna was designed as the sensor?s antenna showing around 9 dBi of maximum gain at each operating frequency. By following this approach, data and power can be transferred simultaneously, allowing the sensor to be continuously wirelessly powered.

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Appendix C

Poster for Research Day University of Aveiro

Enabling IoT technologies with Backscatter Radio

engineering

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Felisberto Pereira, Nuno Borges Carvalho

Department of Electronics, Telecommunications and Informatics,
Instituto de Telecomunicações (IT), University of Aveiro

Abstract

Nowadays, the wireless sensor networks (WSNs) depend on the battery duration and there is a lot of interest in creating a passive sensor network scheme in the area of internet of things (IoT) and space oriented WSN systems. Radio frequency energy harvesting enables the control and the delivery of wireless power to radio frequency (RF) devices. All the devices made with this technology can be sealed, embedded with this structures, or made mobile, so that can be battery independent.
One of the possibilities for the passive network implementation is to use backscatter radio combined with wireless power transmission (WPT).

The rapid increase in the progress and development of wireless communications and identification made possible to track and sense some materials wirelessly. The use of RFID technology as an effective and reliable way for tracking and sensing has gain a lot of importance in recent years. RFID is a short range wireless communication system that comprises a tag, reader, data transfer and processing subsystems. This technology has been applied in many areas such as industrial and automation, transportation control management, access control, and has an enormous potential for the future applications (structural health monitoring, human health monitoring, etc.). Some potential scenarios for the optimization of power are the passive sensors (humidity, temperature, light, etc.) where the sensing needs more power than in the normal situation.

Passive or battery-free RFID tags are an attractive option for WSN and RFID applications because they do not need any maintenance requirements. This is due to the fact that passive RFID do not use a battery for power storage, since energy is harvested for several sources. Examples of this sources are solar, motion or vibration, ambient RF, or an RF signal generated by the RFID reader.

The difference between passive and the active RFID wireless transceivers is the backscatter modulation for the uplink. In the backscatter communication, shown in Fig.3, the tag reflect a radio signal transmitted by the reader, and modulate the reflection by controlling their own reflection coefficient. The load modulator is usually a transistor switch that changes between two different impedances.

Our system proposal is based on Fig.4 and it is composed by two matching networks, a backscatter modulator and a dual band rectifier. The goal is to harvest electrical energy with one tone (1.8 GHz) and with the other tone (2.45 GHz) transfer data by backscatter means. The RF power harvester employs a receiving antenna, an impedance matching network, DC power conditioning and the sensor to be powered. The backscatter modulator employs the receiving antenna, an impedance matching network and a semiconductor to control the reflection coefficient.

As illustrated in Fig.8, we purpose an example of application in wireless powered sensors combined with backscatter modulation. This solution presents a potential performance improvement when compared with conventional battery powered sensors network, since eliminates the need of battery replacement or recharging. Nevertheless, the use of WPT reduces the operational cost and increases the communication performance. Wireless sensors need to harvest enough energy before transmitting data, and this novel solution intends to demonstrate the need of this work in achieving continuous power delivering to the passive backscatter WSN, increasing the communication performance. It is important to denote that this solution uses two different frequencies for different purposes, one is used for WPT and the other for backscatter modulation. Therefore, we envision that this solution will have an important role in many popular commercial and industrial systems in the future including the IoT or space oriented WSN systems.

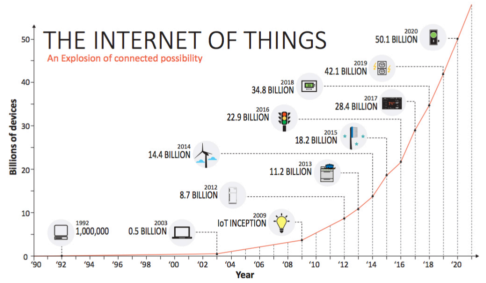

Fig 1 The Internet of Things evolution

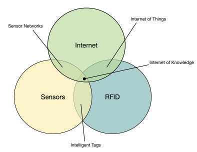

Fig 2 Relation of the internet with sensors and RFID

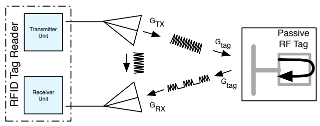

Fig 3 Schematic of backscatter communication

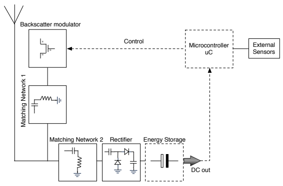

Fig 4 Block diagram of system proposal based on backscatter with WPT

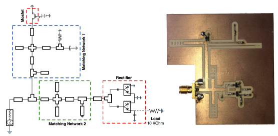

Fig 5 Configuration of proposed backscatter modulator and dual band rectifier circuit

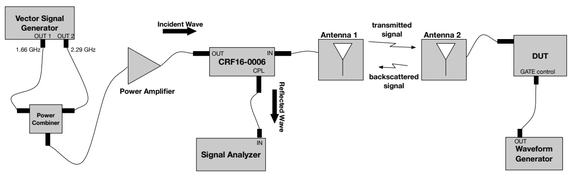

Fig 6 Block diagram of the measurement setup

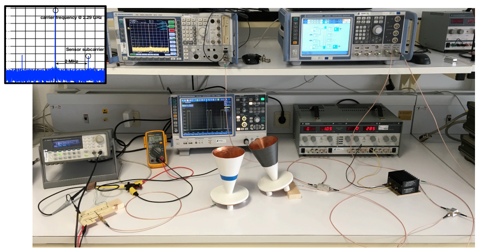

Fig 7 Photograph of the measurement setup

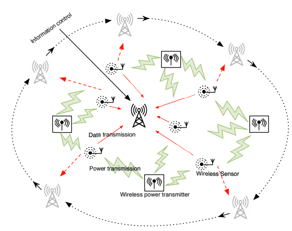

Fig 8 Example application of WPT combined with backscatter modulation

Conclusion

This work received 3rd prize award for the best student paper on the International Conference "Wireless Power Transfer Conference", that took place in Boulder, USA, from 13th to 15th May 2015.

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Acknowledgements

This work is funded by FCT/MEC through national funds and when applicable co-funded by FEDER – PT2020 partnership agreement under the project UID/EEA/50008/2013 and project CReATION (ref. EXCL/EEITEL/0067/2012)

Appendix D

Poster for Students@DETI

instituto de telecomunicações

Passive Sensors for Spatial Applications

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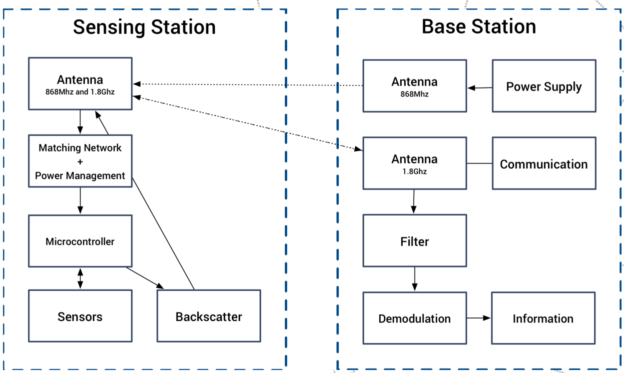
Abstract

In spatial applications, sensors are one of the key components for obtaining essential data to manage the system. Temperature, pressure, oxygen levels, solar radiance sensors are some examples of it. The number of sensors in one spatial application can be enormous what means a huge amount of cables connecting sensors to the base station. Developing passive sensors can be one of the enablers to remove the cables witch has direct implication in the space optimization and weight reduction for spatial applications. This work present the passive sensor solution, that is composed by two main blocks, the base station and the sensing station. The work is focused in the sensing station and in its sub-systems: antenna, wireless power transmission, microcontroller, sensors and backscatter communication.

General Description



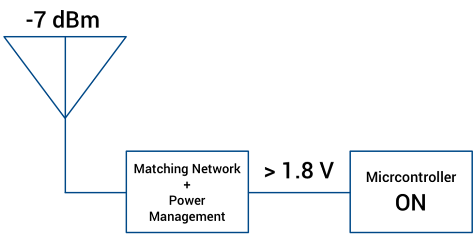
The base station transmits two radio waves that are going to the sensing station. One used in low power communication (backscatter), the other to power the system;

The sensing station is battery less, it is completely powered by radio-frequency wireless power transmission.

Microcontroller is ultra low power, it enters in "sleep mode" when it is not in use.

The system can afford to have multiple sensors connected to it.

Wireless Power Transmission



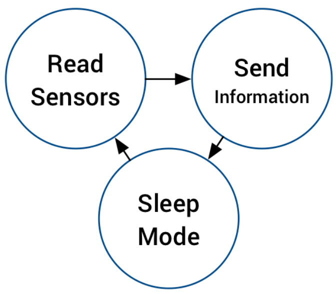
▹ The minimum power that ensures that all the system works is **-7dBm**;

▹ The matching network is adapted to the 868Mhz wave;

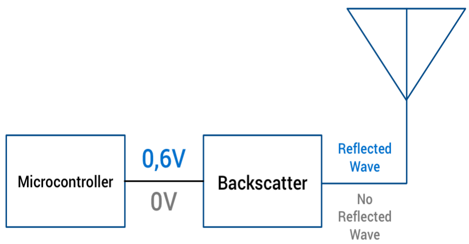
Microcontroller

▹ Microcontroller is programed to obtain the maximum power efficiency;

▹ Sensors are adapted to the special requirements of spatial applications and low power consumption;



Backscatter



▹ When the system is adapted (0V) there is no reflected wave. When it is not adapted (0,6V) there is reflected wave;

▹ No reflecting and reflecting the wave is the information being transmitted to the base station (ASK modulation);

Conclusion

In this work it was presented a proposal to improve the way how sensors communicate with base stations. The whole system is complete functional with a reasonable power, which indicates that good distances between the sensing station and the base station can be obtained. The backscatter is fully controlled by the microcontroller, it ensures that the scattering parameters (S-parameters) can be controlled by software. The shown solution is not limited for spatial applications and it can be used in others applications.

Healthcare

Smart Cities

Industry

Transports

Agriculture

universidade de aveiro

instituto de telecomunicações

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