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TREBALL DE FI DE GRAU

TFG TITLE: Introduction to Radio-frequency Identification (RFID)

DEGREE: Bachelor's Degree in Air Navigation Engineering
Bachelor's Degree in Telecommunications Systems Engineering

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DATE: July 10, 2019

Títol: Introduction to Radio-frequency Identification (RFID)

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Data: 10 de juliol de 2019

Resum

En aquest projecte es presenten els aspectes fonamentals de la tecnologia RFID (Radio-frequency identification) que s'empra per establir comunicacions sense fils. El projecte se centra en el mode passiu de l'RFID, on el receptor no té cap font d'alimentació pròpia el que permet la seva miniaturització i baix cost.

Per altra banda, s'analitzen dos articles de diferents autors. El primer consisteix en el disseny d'un receptor passiu de molt baixa potència mitjançant diverses tècniques d'optimització en la fabricació del hardware.

En el segon, s'usa un dron com a element intermedi entre el transmissor i el receptor per estendre fins a 10 vegades el rang típic de l'RFID passiu. L'estudi se centra en el tractament de la senyal d'RF per eliminar considerablement les interferències i per localitzar precisament el receptor.

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Overview

This project presents the fundamental aspects of the RFID (Radio-frequency identification) technology used to establish wireless communications. The project focuses on the passive mode of RFID, where the receiver does not have any power supply, which allows its miniaturization and low cost.

On the other hand, two articles from different authors are analyzed. The first consists on the design of a very low power passive receiver through various techniques of optimization in the hardware's manufacture.

In the second, a drone is used as an intermediate element between the transmitter and the receiver to extend up to 10 times the typical range of passive RFID. The study focuses on the treatment of the RF signal to considerably eliminate the interferences and to precisely localize the receiver.

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INTRODUCTION

Radio Frequency Identification (RFID) is a low-cost wireless communication technique that requires no line of sight between the transmitter and receiver.

One of the first predecessors of RFID is considered to be Soviet listening device invented by Léon Theremin in 1945. This device retransmitted radio waves with an added modulation (audio information). Its purpose was to be a covert listening device instead of an identification device but it was as well passive and fed by an external power source.

Still in the late 40s, another paper by Harry Stockman stated that "considerable research and development work has to be done before the remaining basic problems in reflected-power communication are solved, and before the field of useful applications is explored".

In the next decades, investigation about reflected power communication kept ongoing until when in the early 70s the first modern RFID device was patented. Mario Cardullo's presented in 1971 and patented in 1973 a passive radio transponder with a 16-bit memory to be used as a toll device.

Nowadays what is known as RFID is used to keep track and identify objects and common applications are: tracking of objects at assembly lines and warehouses; identification of pets and livestock; automatic toll collection; and anti shoplifting of goods, among others.

This project is organized as follows:

- **Chapter 1** introduces the main definitions, concepts and classifications of RFID.
- **Chapter 2** describes all blocks of a passive RFID receiver (tag).
- **Chapter 3** reviews an article in which the authors design a low power tag by means of energy optimization techniques.
- **Chapter 4** reviews an article in which a drone is implemented in a RFID system to improve its range.

CHAPTER 1. CLASSIFICATION AND GENERAL DESCRIPTION

As it will be seen shortly, RFID applications can differ in several key parameters such as the operating frequency and intended use, but all have the next three elements.

- **Reader:** this device acts as master in RFID communications. It always starts the transmission and decides how to encode the data in both the downlink and uplink. It asks questions (queries) and process the response given by the tags.
- **Transmission channel:** typically only a few meters wide, it determines the behaviour of the transmission. Besides from the medium (air) it is also the frequency, modulation, and obstacles.
- **Tag:** it is the slave in the RFID system. It stores data (typically identification) which is asked by the reader. It processes the reader's queries and sends back the appropriate response.

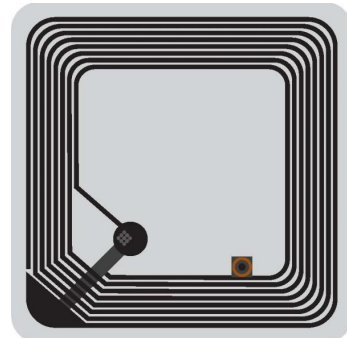


Figure 1.1: Elements of an RFID system: reader and tag.

1.1. Classification by power supply

RFID tags are usually passive (without own power source) although if range, data rate need to be increased or data be stored, they can be fed by an external power source (active).

1.1.1. Passive

Since they do not have any power supply, it must be acquired from the RF signal. Precisely, the signal is rectified and filtered to obtain a DC current that feeds the rest of the tag. To answer back to the reader a backscatter modulation is used, this means that the modulator

can be configured with two different impedances and thus, can send two different signals depending on the answer to send.

1.1.2. Active

It has a power source which is used both for feeding the tag's components and for transmitting the RF signal.

1.1.3. Semi-passive

It is a compromise between passive and active tags. It has a reduced power supply which is used to feed the tag's components but not for transmitting. Therefore, it also uses a backscatter modulation. This type of tags have an improved range compared to the passive tags while are not as expensive nor as big as the active tags.

1.2. Classification by frequency

Another way of classifying RFID tags is by its working frequency, which determines both the maximum data rate and range.

| Frequency | Usage |
|-------------|--|
| 120-150 kHz | animal identification, anti theft labels |
| 13 MHz | baggage tracking, e-Passport, access control |
| 430 MHz | defense applications |
| 860-930 MHz | inventory, labelling |
| 2.45 GHz | auto toll |

Table 1.1: RFID frequency usage.

Low frequencies have a range of a few centimeters and the communication is performed by induction of the magnetic field. In higher frequencies, as the attenuation is lower the communications is done by radiation and can achieve longer distances.

1.2.1. Near field

In near field, as the tag is close to the reader both inductive and capacitive effects take place. This means that just because the tag interacts with the RF signal, it affects the current back in the reader antenna, thus, modifying the impedance.

Due to the high attenuation, this behavior can exist up to 1-2 wavelengths. It can be used in applications that require a very small antenna since using a loop antenna is enough.

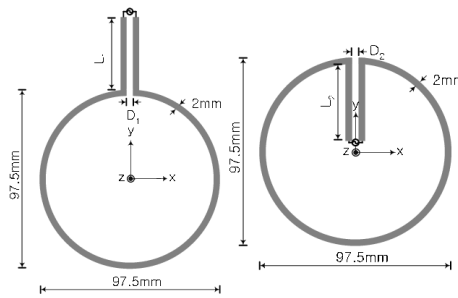


Figure 1.2: Loop antenna. The tag's antenna with its center frequency at 911.25 MHz ($\lambda = 329$ mm) adopts a parallel transmission line feed method to match the impedance.

1.2.2. Far field

In the other hand, in far field the RFID tag does not affect the reader's antenna. As the tag's antenna has to emit an RF signal, it is more appropriate to use a dipole rather than a loop. Nevertheless, the standard dipole might be too big for an RFID tag so it is usually modified.

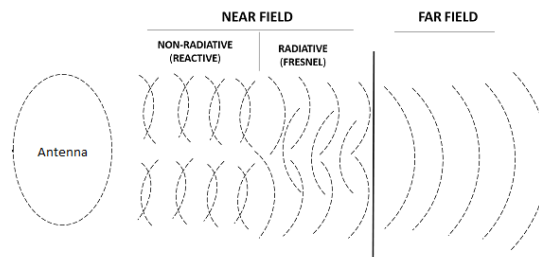


Figure 1.3: Electromagnetic field regions.

1.3. Regulation

Currently, there is no global standardization for RFID and instead every country sets its own regulations. Therefore, parameters as allowed bandwidth or maximum RFID reader power differ between countries.

Even though there are several standards, the most common is ISO 18000 which regulates RFID communications, in its part 6 (860-960 MHz). This standard, ISO 18000-6C, also incorporates the regulation called EPC Gen2 Class1 UHF which is broadly used by RFID technology manufacturers.

In Europe, the regulations set an usable band at 865-868 MHz and maximum power of 2 W ERP, subchannels of 200 kHz wide and a mandatory "listen before talk" wait of at least 5 ms.

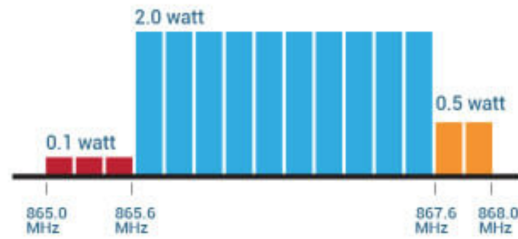


Figure 1.4: Power profile in the 865-868 MHz band.

1.4. Communication

The communication in RFID systems is always started by the reader and afterwards the tag responds. According to the EPC standard, both the modulation and data encoding are different in the downlink and uplink.

1.4.1. Downlink

The modulation either can be

- Double sideband ASK.
- Single sideband ASK.
- Phase reversal ASK.

With a modulating frequency comprised between 40 and 160 kHz.

To encode the data, a Pulse Interval Encoding (PIE) is used. This encoding technique is based on transmitting the '0' and '1' on different durations, being the first one well defined and called TARI and the second 1.5 or 2 times longer than it. Also, when a '1' is sent it corresponds to the full level of the RF signal while the '0' corresponds to the lower level.

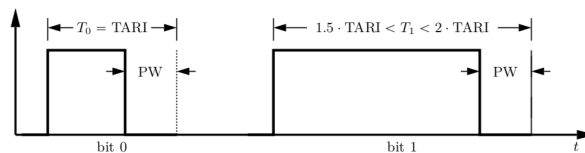


Figure 1.5: PIE symbols.

1.4.2. Uplink

The modulation can be ASK, PSK or a mix of both and the modulation frequency is comprised between 40 and 640 kHz, although it is established by the reader.

In the other hand, the data encoding is also decided by the reader and can be whether FM0 or Miller. In the Miller encoding (which is similar to FM0) each bit time is divided in half and each symbol has two representations, as shown in the next picture.

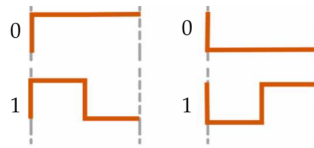


Figure 1.6: Miller symbols.

Which version of the symbol is sent depends on the previous symbol: if two consecutive are the same, the phase is inverted (left representation or right in the picture above) while if they are not, it is kept the same.

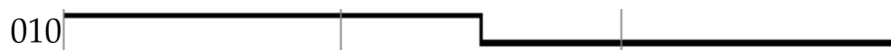


Figure 1.7: Example of message under Miller encoding.

1.5. Link budget

In all radiolinks a link budget must be done to determine whether the connection is feasible. This computation determines the power margin (how much excess power respect to the minimum needed) and which leads to obtain the Bit Error Ratio (BER) and the Signal to Noise Ratio (SNR) among other key parameters.

In addition to this, propagation models give an idea of extra attenuations in different scenarios. For instance, models like Okumura, Okumura-Hata or COST231-Hata provide accurate mathematical models that take into account effects such as diffraction and reflection for rural, suburban and urban areas.

Although there also exist models for indoor conditions, the standard Friis model will be used.

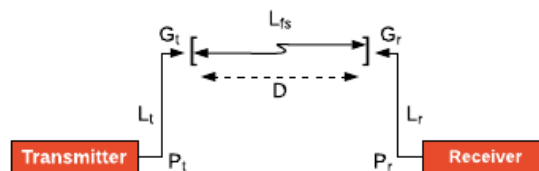


Figure 1.8: Standard radio link.

The power emitted by the transmitter antenna (EIRP) is radiated as an EM wave. It propagates through the medium and gets to the receiver antenna as density power. How much power gets into the receiver depends on the ability of its antenna to capture (effective area).

This, translated into an equation means:

$$P_r = \frac{EIRP}{4\pi d^2} \cdot A_{eff} \quad (1.1)$$

Since the effective area can be expressed as:

$$A_{eff} = \frac{\lambda^2 G}{4\pi} \quad (1.2)$$

The first expression finally results in:

$$P_r = EIRP \cdot G_r \cdot \left(\frac{\lambda}{4\pi d} \right)^2 \quad (1.3)$$

Feeding this link budget with an EIRP of 500 mW (maximum power allowed at 868 MHz by the standard), a half-wave dipole gain of 1.64 (2.15 dBi) and a distance between the reader and the tag of 5 m, it results on a $P_r = 24.81 \mu W$ or -16.05 dBm.

As it can be seen, in only 5 meters the power gets attenuated by a factor of about $2 \cdot 10^5$. Thus, RFID tags must be able to detect and work with very low signals.

CHAPTER 2. PASSIVE RFID TAG STRUCTURE

A RFID tag can be divided in several blocks, which are: antenna and its matching network, power harvesting section, demodulator, modulator, and the digital controller.

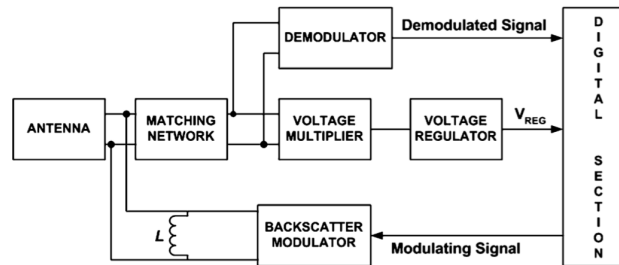


Figure 2.1: Scheme of a passive RFID tag.

2.1. Antenna

The antenna is the biggest and outermost element of the RFID tag and is responsible of extracting the RF signal from the channel and also of backscattering it back to the reader. It must be carefully designed to avoid RF losses.

- Working frequency and bandwidth: the signal uses a specific band of the electromagnetic spectrum. Partial or total losses occur if the antenna is not tuned to the same band.
- Gain: maximizing the antenna amplification will improve the tag capabilities.
- Polarization: the EM wave and the antenna must have similar polarizations in order to prevent losses.

The size of the antenna must be of the order of the wavelength to work properly and the simplest and cheapest way to achieve this is using a dipole. This type of antenna presents an omnidirectional radiation pattern which is appropriate for a tag. Directive antennas are more suitable for the RFID reader.

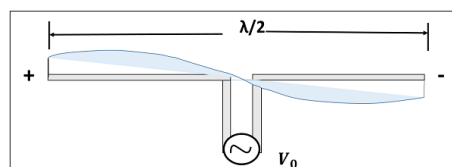


Figure 2.2: Dipole antenna.

Nevertheless, if using low frequencies (wavelength of the order of meters) or having strict size constraints the use of a dipole becomes unfeasible and other types of antennas such as circular, rectangular and spiral coils can be used.

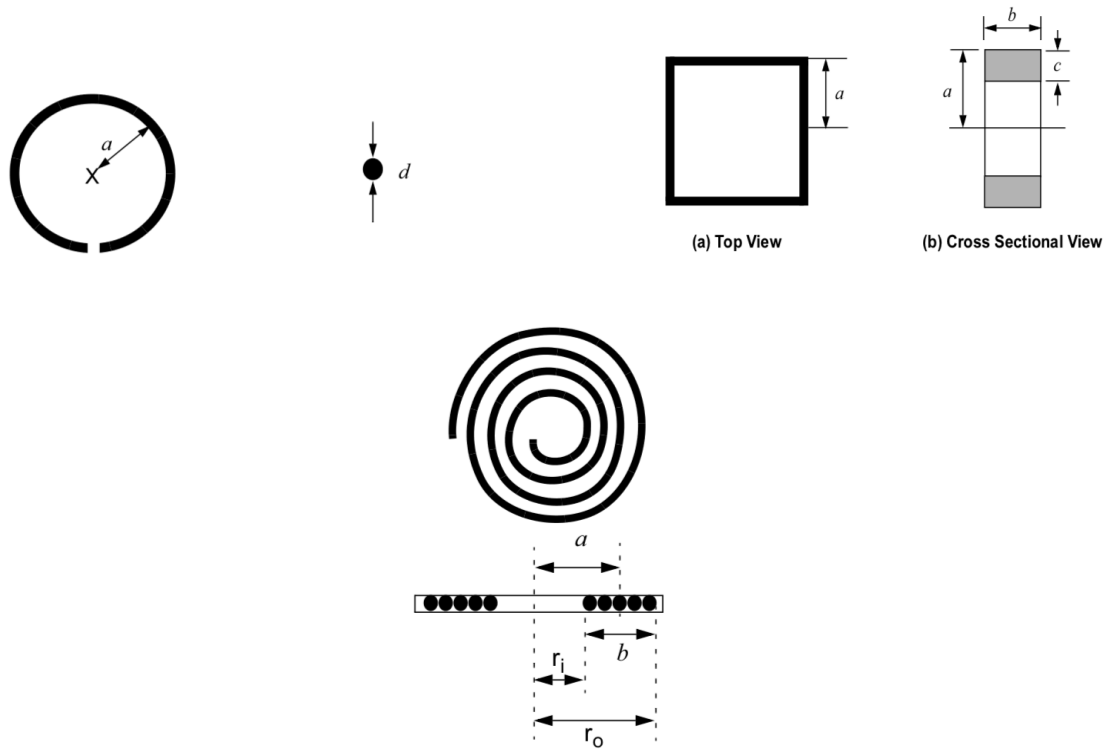


Figure 2.3: Size reduction of antennae: circular loop, square loop and spiral.

2.1.1. Antenna matching

As described in all basic electromagnetic literature, since the antenna is a power source and the rest of the tag a load, their impedances must be matched in order to maximize the power transfer.

The RFID reader is an active device which usually leads to the maximum range get determined by the tag's sensitivity. Therefore a proper impedance matching is critical since any power reflected back to the antenna will reduce the RFID system's range.

One way to make the matching network is to use lumped elements between the antenna and the rest of the tag. Nevertheless, for a commercial tag it would be unsuitable due to the big size and price.

On the other hand, by modifying the printed dipole a reduction in size and output impedance can be achieved. Some of these techniques are the T-match and the inductive coupling feeding which provide a highly inductive impedance to match the mostly capacitive tag's impedance.

2.1.1.1. T-match

As explained here [1], the T-match consists of two dipoles: the antenna of length L_1 which instead of being directly fed, it is fed by the second and smaller dipole of length L_2 .

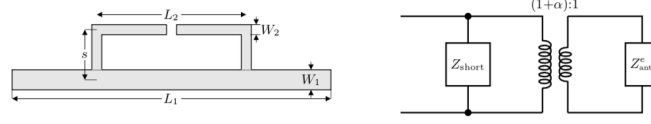


Figure 2.4: T-match scheme and equivalent circuit.

By analyzing using the odd and even method, the impedance is found as:

$$Z_{ant} = \frac{2Z_{short}Z_{ant}^e(1+\alpha)^2}{2Z_{short} + Z_{ant}^e(1+\alpha)^2} \quad (2.1)$$

Where alpha measures the asymmetry in the dipoles width ($\alpha = 1$ if $W_1 = W_2$), Z_{short} is the impedance of the radiating dipole and Z_{ant}^e the impedance from the feeding dipole.

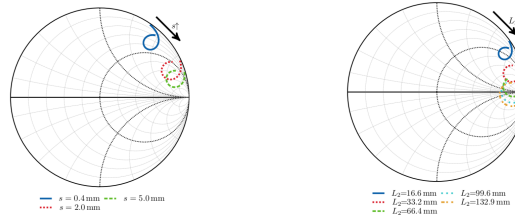


Figure 2.5: T-match results on tuning s and L_2 .

The results of simulations show that a high inductive impedance is achieved by whether reducing the separation between the dipoles or by reducing the feeding dipole's length.

2.1.1.2. Inductive coupling feeding

In this case the feeding dipole is replaced by a rectangular loop that couples with the antenna dipole.

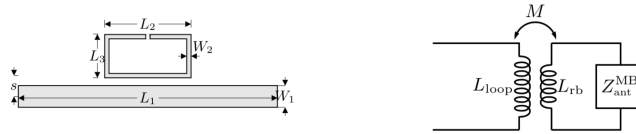


Figure 2.6: Inductive coupling scheme and equivalent circuit.

$$Z_{ant} = Z_{loop} + \frac{(2\pi fM)^2}{Z_{ant}^{MB}} \quad (2.2)$$

Where Z_{loop} and Z_{ant}^{MB} are the uncoupled loop and dipole impedance, respectively and M is the coupling.

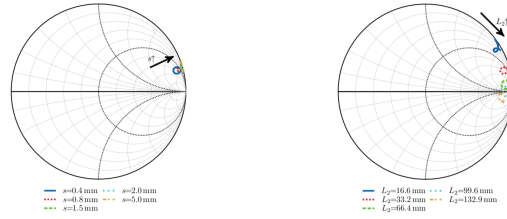


Figure 2.7: Inductive coupling results on tuning s and L_2 .

The simulations show that the inductance is determined by the loop (L_2) while the resistance by the coupling (separation) between the two elements.

2.2. Power harvesting section

Since passive RFID tags have no power supply, it must be extracted from the RF signal to power the tag components. As the input power will typically be very low, it is required an efficient way to collect DC current. The input impedance is nonlinear due to the high frequency conversion. High quality capacitors and Schottky diodes (very low threshold) are commonly used.

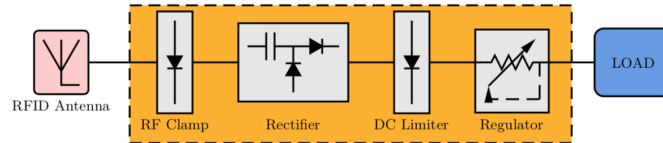


Figure 2.8: Power harvesting block scheme. The RF clamp and DC limiter protect the components against signal peaks. The regulator assures a stable DC current.

2.2.1. Rectifier

The main block of this system is the rectifier. The next picture will be used to explain its principle of work.

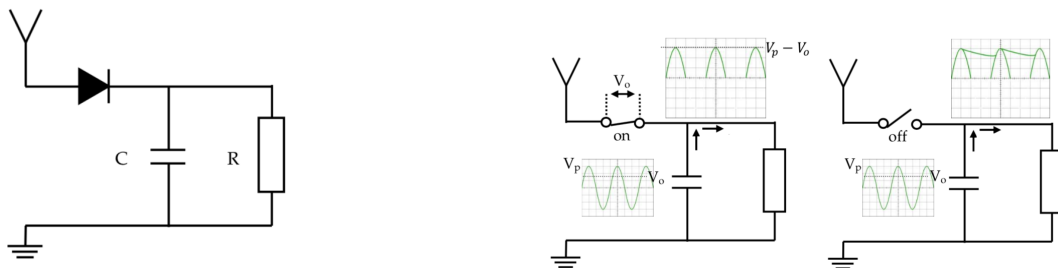


Figure 2.9: Rectifier scheme and analysis.

When the signal is higher than the threshold (V_o) the capacitor and load are fed with an amplitude of $V_p - V_o$ and the capacitor is charged. In the other case, the diode acts as an open circuit and the capacitor discharges feeding the load. To properly rectify the signal, the discharge time must be much greater than the signal's period.

2.2.2. Voltage doubler

Since this configuration would require a very small capacitor, other options like the voltage doubler are used. As it can be seen in the figure, this configuration uses two diodes and two capacitors.

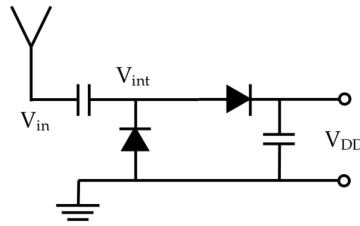


Figure 2.10: Voltage doubler scheme.

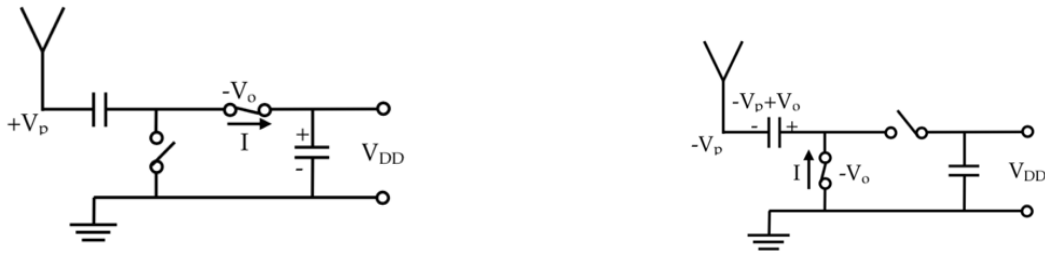


Figure 2.11: Voltage doubler analysis.

When the signal is negative, it flows from the ground through the left diode and charges the left capacitor, as the right diode is in blocking state.

In the other hand, when the signal is positive, the right diode is off and both the signal from the antenna and the charge at the left capacitor flow to the other capacitor through the right diode.

The output voltage is approximately the input's double:

$$V_{DD} = 2 \cdot (V_p - V_o) \approx 2 \cdot V_p \quad (2.3)$$

2.2.3. Voltage multiplier

If it is required more voltage than the one provided by the voltage doubler, several doublers in cascade can be used. The configuration below is known as Dickson voltage multiplier.

The number of stages directly impacts on the output:

$$V_{out} = N \cdot (V_p - V_o) \quad (2.4)$$

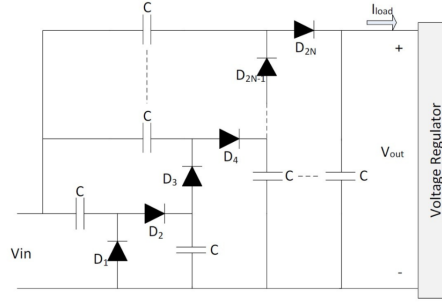


Figure 2.12: Voltage multiplier scheme.

Nevertheless, the more stages there are, the worse the efficiency is. This can be shown by analyzing the power throughout the circuit. As the current flows by every diode, a power reduction is observed. It might seem negligible since both voltage and current values are small but comparing to the output voltage which is about 2-5 V, the power loss becomes remarkable.

$$\eta = \frac{P_{output}}{P_{total}} = \frac{V_{out}}{V_{out} + 2NV_o} \quad (2.5)$$

Where N is the number of stages and V_γ the diode's activation voltage.

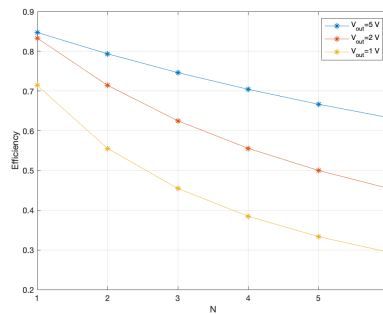


Figure 2.13: Voltage multiplier efficiency vs number of stages.

2.3. Demodulator

The demodulator is in charge of translating the analogic ASK signal at the input into a digital signal containing the transmitted information. In order to get this, it basically must first extract the envelope of the modulation and then compare it to the average RF signal.

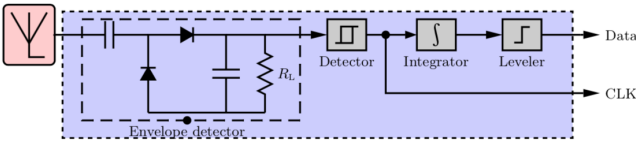


Figure 2.14: Demodulator scheme.

A simple circuit like the shown below can obtain the signals. To design the envelop-related capacitor, it must be taken into account its discharge time. It must be longer than the RF signal period in order to be flat but shorter than the data pulses to properly generate the envelope.

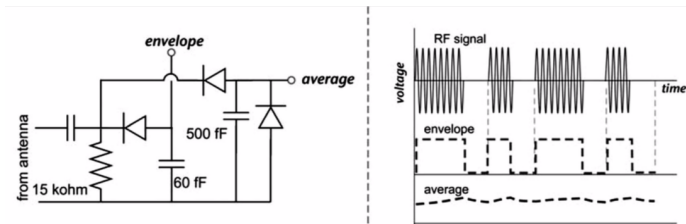


Figure 2.15: Demodulator implementation and i/o signals.

Then the digital signal can be generated: when a long RF signal is detected it is translated as a '1' and a short signal as a '0'.

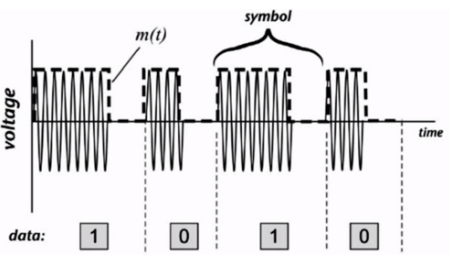


Figure 2.16: Example of unencoded message.

2.4. Modulator

A backscatter modulator consists on sending information by reflecting the incident power rather than radiating a signal.

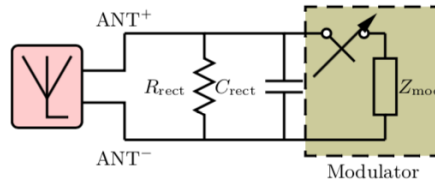


Figure 2.17: Modulator's equivalent behaviour with the antenna.

The modulation used in RFID is typically ASK or PSK and it is achieved by changing the input resistance or the reactance, respectively. This extra component must be added along with the rest of the circuitry in a such a way that the efficiency is not modified.

Also, this load is added in a switch configuration (using varactors), letting the digital controller decide whether to connect it and thus having two different modulations.

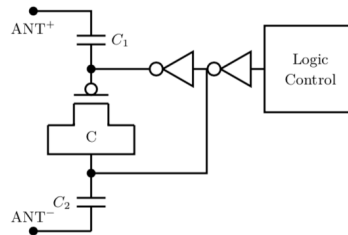


Figure 2.18: Modulator diagram.

The picture above is a simplified version of a PSK modulator. This reactive load increases the input admittance (inverse of impedance) by $j2\pi(C_1 + C + C_2)$. When required to switch the input impedance, the varactor's feed is changed shifting its capacitance C to $C + \Delta C$ and thus, changing the overall impedance.

If an ASK is desired, the varactor must be used with a resistance to modify the signal's amplitude. Nevertheless, it can decrease the rectifier's efficiency since this resistance is connected in parallel with it.

2.5. Digital control unit

The control unit rules over the other systems of the tag. One of its functions is to process the digital input from the demodulator.

The simplest version of the control unit controls the backscatter response when the reader asks about the tag identification. If the reader asks about a different tag ID, the modulator (impedance switch) is not activated and if the ID matches the tag's it is activated.

More advanced control units can store data other than the ID and be programmed by the reader. Typically, the more functions it can perform, the more consumption it has. For this reason, digital control units with optimized low consumption shall be used.

CHAPTER 3. REVIEW OF A LOW POWER RFID TAG

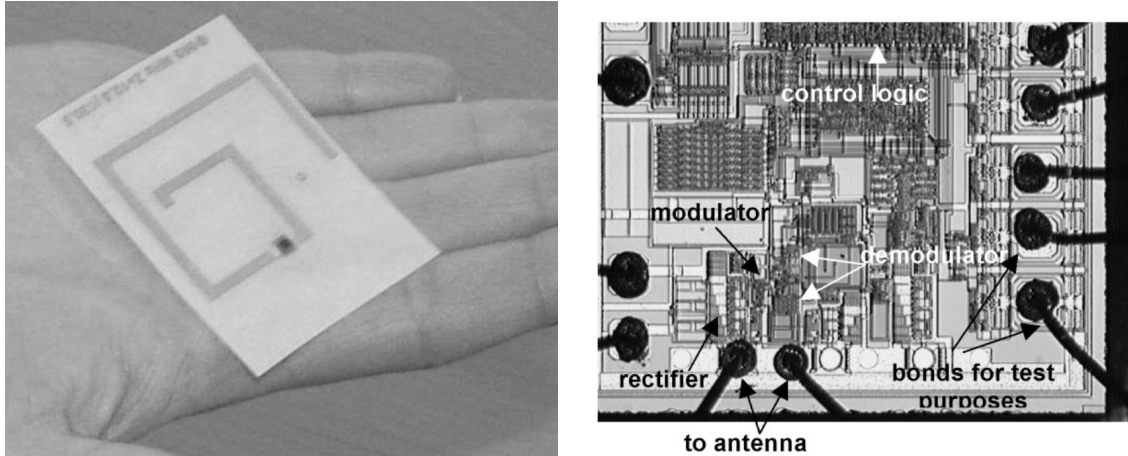


Figure 3.1: View of the RFID assembled tag and IC.

In this paper [2], the authors present a miniaturized passive RFID tag able to operate at the 868/915 MHz bands with a range of 4.5 and 9.25 m, respectively. The integrated chip includes all blocks described in previous sections besides the antenna.

To get these results, the authors have used several low consumption techniques, including the control logic design, the use of a very well designed Schottky diodes and an efficient modulation.

3.1. Architecture

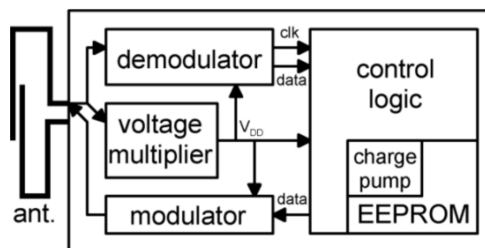


Figure 3.2: Scheme of the tag.

3.1.1. Antenna

The antenna used is a printed loop that has low losses and is adapted to the average input impedance of the voltage multiplier block.

3.1.2. Voltage multiplier

The voltage multiplier block is formed by 10 Silicon-Titanium Schottky diodes whose model includes a low series resistance ($< 300\Omega$) and a junction capacitor of about 12 fF, and 250 pF poly-poly capacitors to store the charge.

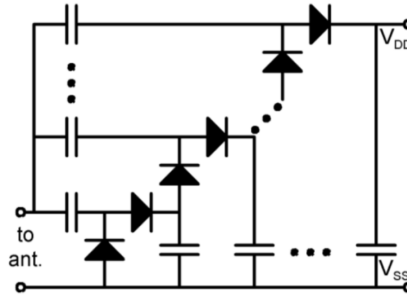


Figure 3.3: Voltage multiplier scheme.

The voltage generated at the output is approximately:

$$V_{DD} = n \cdot (V_{p,RF} - V_{f,D}) \quad (3.1)$$

Where n is the number of diodes, $V_{p,RF}$ the amplitude of the RF signal and $V_{f,D}$ the activation voltage for the diodes (about 200 mV at $7\ \mu\text{A}$).

The input impedance of this block, which is the main contributor to the total tag's impedance, is principally determined by the capacitances of the Schottky diodes. The authors show that in an operation point of $V_{DD} = 1.5\ \text{V}$ and $I_{DD} = 1.5\ \mu\text{A}$, the reactance is about 30 times higher than the resistance. Thus the quality factor Q is also about 30 which leads to the need of a very good adaptation with the antenna to obtain a good power efficiency.

3.1.3. Modulator

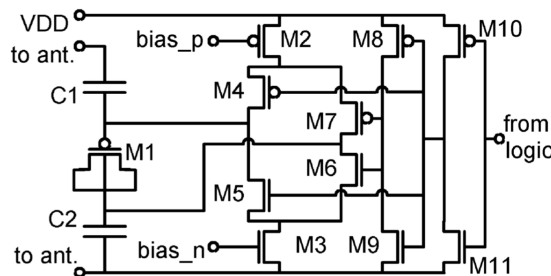


Figure 3.4: Implementation of the modulator.

The modulator is implemented as a backscatter. As explained before, it modulates the continuous wave from the reader by switching between two input impedances. The authors have decided to use a variable capacitance which implies a modulation on the phase (PSK) instead of on the amplitude (ASK).

The capacitance is changed by feeding in different ways the varactor M1. This is achieved with the capacitors C1 and C2 that set the varactor's feeding to $\pm V_{DD}$. M2 and M3 decide how fast the varactor is charged and discharged which determines the bandwidth of the signal. M4, M5, M6 and M7 are switched on or off depending on the logic state and M8, M9, M10 and M11 are inverters for the logic signal.

3.1.4. Demodulator

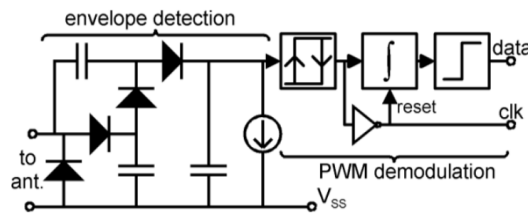


Figure 3.5: Demodulator scheme.

The demodulator block consists on an envelope detector and a pulse-width demodulator. The first part also uses a voltage multiplier circuit but with 4 diodes instead of 10. The capacitors along with the sink current determine the minimum width of the gaps that can be detected, which typically are around $4 \mu s$ long.

The inverted output is used as a clock signal for the digital part. Every rising edge corresponds to a new bit. The integrator is used to determine the duration of each pulse and a discriminator decides if each pulse is short ('0') or long ('1').

3.1.5. EEPROM

The tag includes an EEPROM (electrically erasable programmable read-only memory) which allows to store data, that works at a frequency of about 300 kHz which is generated by an RC oscillator

Approximately 14 V are needed for programming the EEPROM. A charge-pump using almost the same architecture as the voltage multiplier is used to raise the voltage.

3.2. Optimization techniques

3.2.1. Voltage supply

The key parameters of a voltage multiplier block are the power efficiency, its input impedance and the working point. Since they all affect each other, a tradeoff must be achieved. Designing the Schottky diodes, the coupling capacitors and the number of stages will determine the overall behavior.

To optimize the power the voltage drop and the parasitic effects at the diodes must be minimized. Larger Schottky diodes have smaller voltage activation and series parasitic

resistance but larger junction parasitic capacitance and substrate capacitance. Therefore, an optimum size has to be found.

In the other hand, the parasitic resistance and capacitance of the coupling capacitors must be small as well. While the resistance can be reduced by using a large aspect ratio, the parasitic capacitance cannot be reduced a lot because it is directly related with the actual coupling capacitance.

Finally, the substrate losses can be determined by the following equation:

$$P_{loss} = \frac{1}{2} v^2 \frac{R_{sub}}{R_{sub}^2 + (\omega C_{sub})^{-2}} \approx \frac{1}{2} v^2 (\omega C_{sub})^2 R_{sub} \quad (3.2)$$

Where v is the RF peak voltage, C_{sub} the capacitance to the substrate and R_{sub} its series resistance.

It can be seen that the losses are dependent on the capacitance to the substrate and on the frequency. Thus, there is much better power efficiency on the 868/915 MHz band than in the 2.45 GHz's.

3.2.2. Modulator

To review the efficiency of the modulation process, two effects have to be considered. These are the backscattered power efficiency in on hand, and the efficiency of the modulation used, in the other.

The first, depends on the impedance matching with the antenna and it is important to be considered since the modulator will switch between two different impedances.

The RF in power is calculated as follows:

$$P_{RF,in,1,2} = \frac{1}{2} Re(v_{in} \cdot i_{in}^*) = \frac{v_0^2}{8R_{ant}} \cdot \left(1 - \left| \frac{Z_{1,2} - Z_{ant}^*}{Z_{1,2} + Z_{ant}^*} \right|^2 \right) \quad (3.3)$$

Which by using the following definitions:

$$P_{avail} = \frac{v_0^2}{8R_{ant}} \quad \rho_{1,2} = \frac{Z_{1,2} - Z_{ant}^*}{Z_{1,2} + Z_{ant}^*}$$

Gets simplified to:

$$P_{RF,in,1,2} = P_{avail} (1 - |\rho_{1,2}|^2) \quad (3.4)$$

Introducing the fractions of time p_1 and p_2 that account when each impedance is used, the equations results in:

$$P_{RF,in} = p_1 P_{RF,in,1} + p_2 P_{RF,in,2} = P_{avail} (p_1 (1 - |\rho_1|^2) + p_2 (1 - |\rho_2|^2)) \quad (3.5)$$

In the other hand, the efficiency of the modulation is reviewed. They demonstrate that the power of the two sidebands can be computed as follows:

$$P_{bs} = \frac{v_0^2 R_{rad}}{32 R_{ant}^2} |(1 - \rho_2) - (1 - \rho_1)|^2 = \frac{P_{avail}}{4 L_{ant}} |\rho_1 - \rho_2|^2 \quad (3.6)$$

Where L_{ant} is defined as:

$$L_{ant} = \frac{R_{rad} + R_{loss}}{R_{rad}} = \frac{R_{ant}}{R_{rad}}$$

Then, they analyze three different modulations which are:

1. ASK with power match in one state and total reflection in the other.
2. PSK with equal mismatch in both states.
3. ASK with equal mismatch in both states.

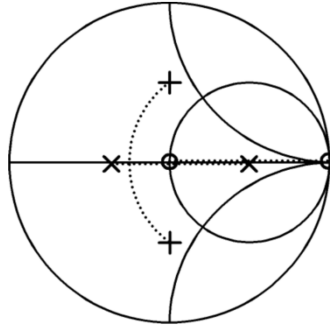


Figure 3.6: Representation of the three modulations on a Smith chart.

Case 1: the modulator is disconnected or shorted in one state ($|\rho_1| = 1$) and adapted to the antenna ($\rho_2 = 0$) in the other. Therefore, the power is only reflected in the first state while in the second it all gets to the voltage multiplier.

$$P_{RF,in,ask,on-off} = p_1 P_{avail} \quad (3.7)$$

One possibility is that one state is active most of the time. This allows a high power efficiency but needs a larger bandwidth that is usually against the standardization.

Another is to use $p_1 = p_2 = 50\%$ which leads to

$$P_{bs,ask,on-off} = \frac{P_{avail}}{4 L_{ant}} \quad (3.8)$$

In this case, if there are no antenna losses ($L_{ant} = 1$), 25% of the input power is backscattered, 50% is available to rectificate and the remaining 25% is wasted.

Case 2: the reflection coefficient is constant in magnitude but with opposite sign, while keeping the real part to zero. That is $\rho_{1,2} = \pm jm$, being m the modulation index.

$$P_{bs,psk} = m^2 \frac{P_{avail}}{L_{ant}} \quad (3.9)$$

$$P_{RF,in,psk,1} = P_{RF,in,psk,2} = (1 - m^2) P_{avail} \quad (3.10)$$

Considering again $L_{ant} = 1$, it can be seen that the power is never wasted since it is always used whether for rectification or for backscattering (the sum of both equations equals the total available power).

Case 3: the reflection coefficient is real and both states have the same amount of mismatch, thus, $\rho_{1,2} = \pm m$. This configuration is easily achieved by switching a resistor in series or parallel. Nevertheless, the power loss in that resistance is the main disadvantage of this option.

When considering the resistor power losses and the switching between the states, the optimal RF power is found as follows:

$$P_{RF,in,ask} = \frac{1}{2}(1 - m^2) P_{avail} + \frac{1}{2}(1 - m^2) \left(\frac{1 - m}{1 + m} \right)^2 P_{avail} = \frac{1 - m^4}{(m + 1)^2} P_{avail} \quad (3.11)$$

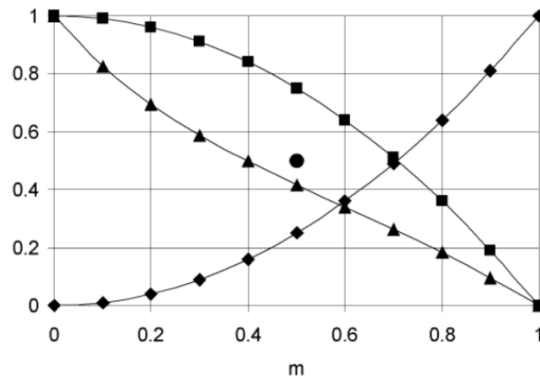


Figure 3.7: Efficiency vs modulation index. Diamonds: backscattered modulated power. Power available to the rectifier in case 1 (circles), case 2 (squares) and case 3 (triangles).

When evaluation the last equations for the whole range of m , the results show that the PSK outperforms the ASK. Comparing the three cases at $m=0.5$, it is found that the efficiencies are 50%, 75% and 42%, respectively, while the rectifier efficiency is 25%.

| Test conditions | $\text{Re}(Z_{1,2})$ [Ω] | $\text{Im}(Z_{1,2})$ [Ω] | Vdc [V] | Idc [μA] | Efficiency [%] | RF input power [μW] |
|------------------|--------------------------------------|--------------------------------------|------------|--------------------------|-------------------|-------------------------------------|
| 869 MHz, idle | 5.7 / 4.5 | -218 / 203 | 1.5 | 0.95 | 14.5 | 9.8 |
| 869 MHz, active | 6.7 / 5.5 | -218 / 203 | 1.5 | 1.5 | 18 | 12.5 |
| 2.45 GHz, active | 4.0 / 3.8 | -89 / -84 | 1.5 | 1.5 | 5 | 45 |

Table 3.1: Test results.

Experimental tests performed in an anechoic chamber show that under the conditions of 868 MHz and 500 mW ERP a maximum range of 4.5 m is achieved which corresponds to an input RF power of 30 μW . Under the US conditions (915 MHz and 4 W ERP) for the same power the range achieved is 9.25 m.

In another hand, when there is not antenna loss and the mismatch can be measured and eliminated, the minimum input power for the read mode was found to be 12.5 μW and 35 μW during write mode. Using the previous equations when $m = 0.5$, the available power is 16.7 μW .

For the 2.45 GHz band, the minimum input RF power is 45 μW for the read mode and 126 μW for the write mode. Considering an 4 W ERP and the larger parasitic losses, the reading range is found to be 2.6 m and the write range 1.1 m.

CHAPTER 4. RFID DRONE RELAY

In this paper [3] the authors introduce a technique to extend the maximum range of an existing passive RFID system. To overcome the typical range of <10 m, the authors use an indoor drone to act as a relay in the communications: when the relay picks a message from the reader, it picks it up and forwards it to the tag, and does the same for the tag's response back to the reader.

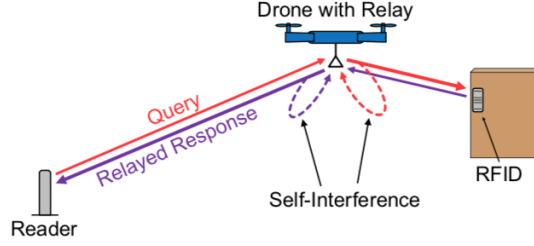


Figure 4.1: The system - RFLy - overview.

This system not only improves the range but also includes a localization algorithm to track the tags. The authors achieve a range of 55 m and a median accuracy of 19 cm.

To achieve these features, two main issues regarding self-interference and phase acquisition must be solved.

4.1. Self-interference

Self-interference is a main challenge in the system because the relay amplifies and forwards the signals without making any digital manipulation. If this interference dominates, the phase component is altered and the localization cannot take place.

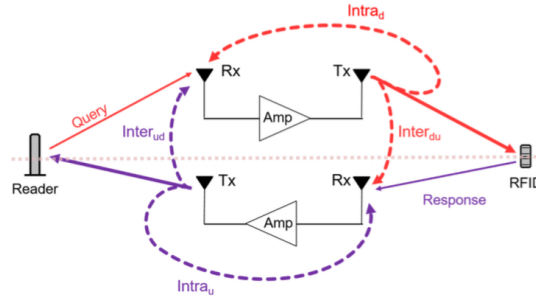


Figure 4.2: Mirror architecture and types of self-interference.

Therefore, the isolation of the relay (interference cancellation) affects directly its performance. To assure that the interference power is lower than the reader's signal, the following inequation must be satisfied:

$$I > L = 20 \log(4\pi R/\lambda) \quad (4.1)$$

Where I is the isolation, L is the path loss between the reader and the relay and R the distance between them.

4.1.1. Inter-link self-impedance

As the tag reflects the input power to answer to the reader, the uplink and downlink frequencies are the same. Therefore, interference between the channels may occur ($inter_{ud}$ and $inter_{du}$).

To solve this interference, the authors exploit the fact that although the query and response are around the same central frequency, they use different subbands.

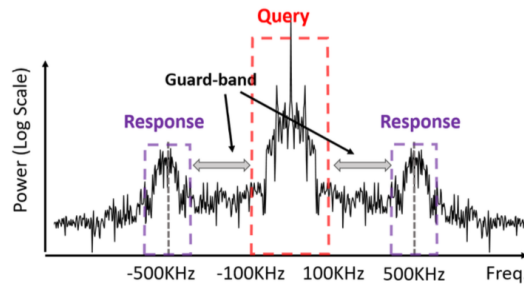


Figure 4.3: RFID frequency spectrum.

The downlink and uplink relays are designed with filters to attenuate the interference signal. Nevertheless, to implement these filters a prohibitive quality factor is required since the guard-band is kHz wide respect a central frequency of about 900 MHz.

Therefore, the strategy used is to downconvert the signal to baseband, filter and upconvert back. Specifically, in the downlink channel (query) the signal is low-pass filtered at baseband (100 kHz cutoff frequency) to avoid the $inter_{ud}$ interference. On the other hand, in the uplink channel the signal is band-pass filtered (500 kHz cutoff frequency) around the tag's response to avoid the $inter_{du}$ interference.

The key parameter of this approach is the central frequency of the signal. To detect it, the usual technique of performing a Fourier transform is not used, since it would require to digitalize the signal.

Instead, RFLy sweeps the center frequency for downconversion correlates with all possible central frequencies within the ISM band and chooses the most appropriate. This process lasts 20 ms and then the relay locks on the frequency found.

4.1.2. Intra-link self-interference

Part of the signal transmitted in one channel leaks into the receiver antenna of the same channel, this is represented by $intra_d$ and $intra_u$.

To solve this effect, RFLy separates in the frequency domain both links by using a different upconvert frequency than the downconvert one.

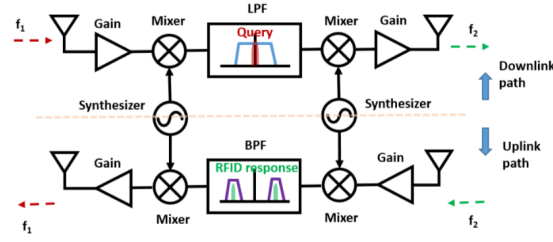


Figure 4.4: Detailed mirror architecture implemented in RFLy.

However, this frequency offset distorts the phase which is fundamental for the localization algorithm.

$$\phi'(t) = 2\pi(f - f')t + \phi_0 \quad (4.2)$$

To address this problem, and since the relay has control of both channels, the downconvert frequency used in the uplink channel is the one previously used to upconvert in the downlink channel. Therefore, it introduces a $-\phi'$ shift that cancels the phase offset.

4.2. Phase acquisition

RFLy's approach to take accurate phase samples is to capture signals from different positions and process them as an antenna array. Before that, two issues must be considered: each link is divided in two sublinks and multipath.

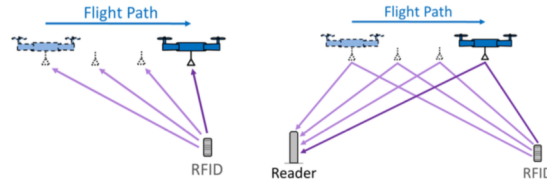


Figure 4.5: RFLy radio link is formed by two sublinks.

4.2.1. Disentangling the Phase Half-Links

Since is formed by two sublinks (reader-relay and relay-tag) the phase measurements from the reader do not allow to locate the RFID tag. To do so, the sublinks must be disentangled.

Mathematically, the channel seen by the reader can be expressed as:

$$h_{LOS} = e^{-j2\pi(f(2d_1/c) + f_2(2d_2/c))} \quad (4.3)$$

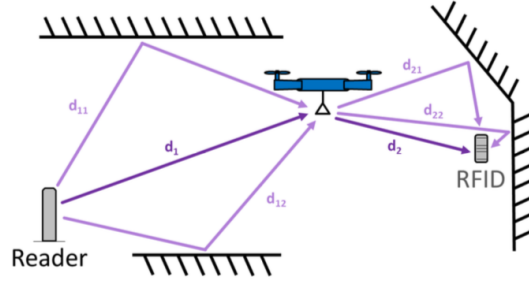


Figure 4.6: Multipath.

However, due to indoor multipath the different paths linearly combine at the receiver:

$$h = \sum_i e^{-j2\pi f(2d_{1i}/c)} \sum_j e^{-j2\pi f_2(2d_{2j}/c)} \quad (4.4)$$

Which shows that even if the drone position is known (d_1), the relay-tag sublink cannot be isolated because of the multipaths on the reader-relay link.

The solution that the authors use is to embed a tag into the relay itself. Then, the channel seen by the reader related to this embedded RFID is only the relay-reader sublink. Therefore, the relay-tag sublink can be obtained by dividing both signals.

$$h' = \frac{h}{h_b} = \sum_j e^{-j2\pi f_2(2d_{2j}/c)} \quad (4.5)$$

4.2.1.1. Drone localization

Since the channel of the embedded tag consists only in the sublink between the reader and the relay, it could be used to localize the drone itself. Nevertheless, this is not the scope of the paper and the authors use instead accurate vision-based systems.

In this other paper [4], the authors introduce a long-range communication system based on drones. Specifically, these drones are outdoor drones and use GPS autonomous position acquisition.

The system is based on a Ground Control Station, a leader UAV, and a set of secondary UAVs used to extend the radio range. When the leader drone crosses the radio range limit, the first secondary drone takes off to act as a relay between the leader and the GCS and allow the leader to fly further away.

When the first relay reaches the radio limit with the GCS, a second relay takes off to link them both. This process is iterated until the last secondary UAV is used.

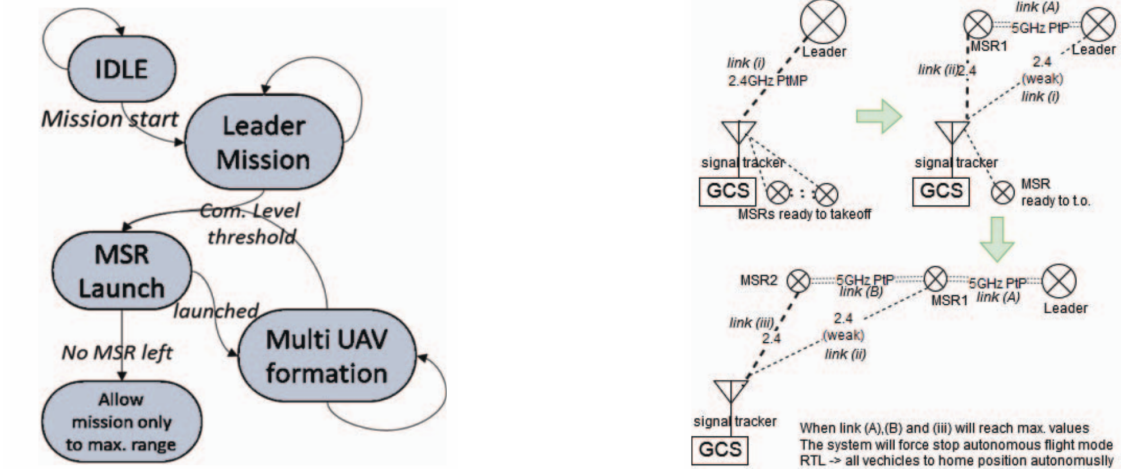


Figure 4.7: System's state diagram and example of operation.

4.2.2. Localization algorithm

The localization algorithm is based on that every point in 2D (tag's location) can be described as a set of distances from different positions (drone's trajectory) by using antenna array equations.

The tag position is estimated as follows:

$$(\hat{x}, \hat{y}) = \arg \max_{(x,y)} P(x,y) \quad (4.6)$$

Where

$$P(x,y) = \left| \sum_{l=1}^K h'_l e^{j2\pi f_c t} 2\sqrt{(x-x_l)^2 + (y-y_l)^2} \right| \quad (4.7)$$

Where K is the number of different drone's position, (x_l, y_l) its coordinates and h'_l the isolated channel for a given RFID.

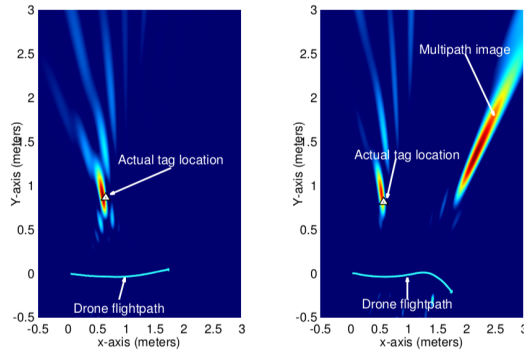


Figure 4.8: Tag localization heat map without and with strong multipath.

The system can estimate the tag's location by picking the peak value when the multipath is not severe. Nevertheless, under strong multipath, which is the case in indoor warehouses,

RFly picks the nearest peak to its trajectory instead of the biggest one because the indirect reflections always arrive along a longer path than the direct one.

The reliability of the algorithm grows when it is integrated over longer distances. However, since the limited coverage range between the relay and the tag, the integration is made in 3 to 5 meters.

4.3. Implementation

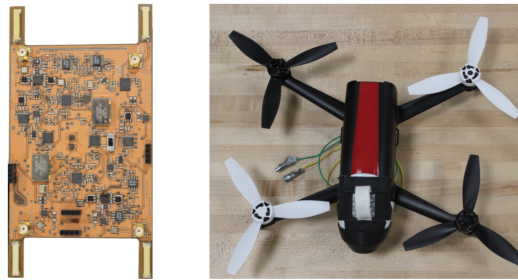


Figure 4.9: PCB board and indoor drone used.

All the circuitry of the relay has been designed on a 10 x 7.5 cm PCB and weights 35 g and has been attached to the drone that measures 32 x 38 cm.

The relay is powered up by the drone's 12 V battery with an intermediate DC-DC downconverter to 5.5 V. It consumes 5.8 W and requires 0.49 A which is about 3% of the drone's battery.

After testing, the authors show the following results:

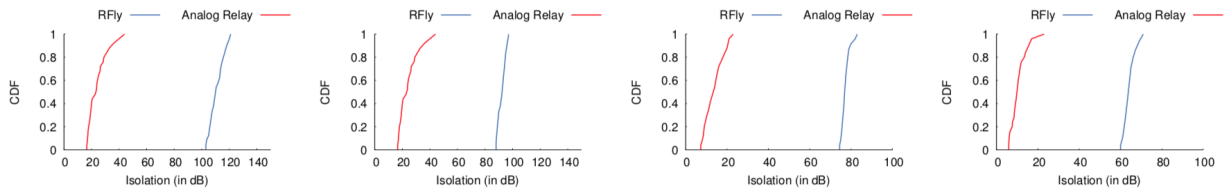


Figure 4.10: Self-interference results.

The relay achieves median isolations of 110, 92, 77 and 64 dB in inter-downlink, inter-uplink, intra-downlink and intra-uplink, respectively. This consists on an improvement of at least 50 dB respect traditional relays, according to the authors.

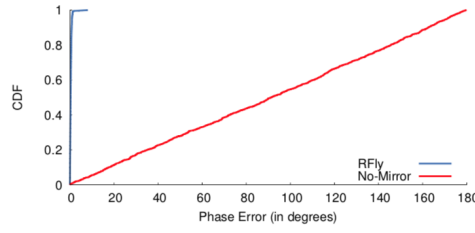


Figure 4.11: Phase error results.

RFly can accurately localize RFID tags. Results show that the median phase error is of 0.34° , and the 99^{th} percentile error is 1.20° . This is achieved by the mirror configuration (downconverting and upconverting) implemented by the relay.

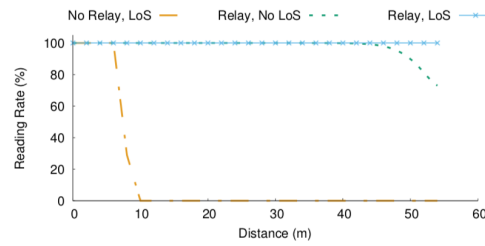


Figure 4.12: Range results.

In comparison with the 10 meters maximum range of traditional RFID systems, RFly provides a 100% accuracy at 50 meters with line of sight, and 75% accuracy without at 55 meters. This range is possible thanks to the achieved high self-interference isolation.

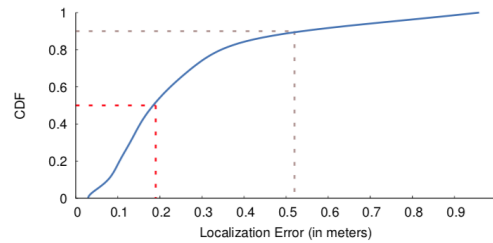


Figure 4.13: Accuracy results.

Median accuracy is of 19 cm and 90^{th} percentile of 53 cm. In contrast with other RFID proposals, RFly can keep the accuracy at 10x the range due to the phase-preserving relay and the localization algorithm.

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APPENDICES

APPENDIX A. SIMULATION OF A VOLTAGE MULTIPLIER WITH ADS

A simulation of the power harvesting block was simulated in ADS to check its behaviour with the theory explained in chapter 2. Impedance matching with the power supply (antenna) is assumed and the components used are ideal capacitors and Schottky diodes.

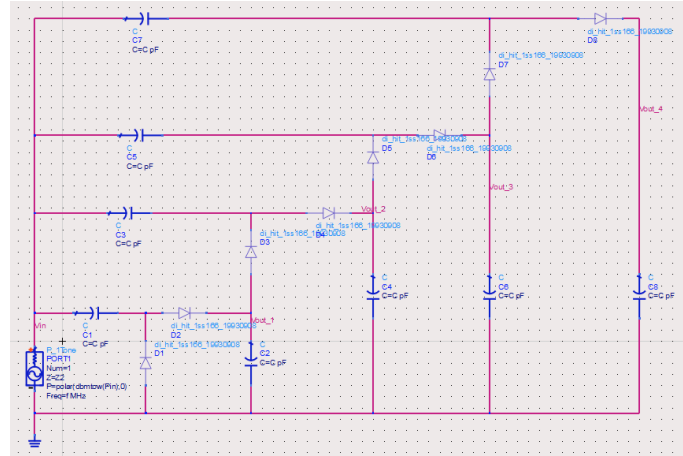


Figure A.1: Circuit simulated in ADS.

The figure above shows the simulated circuit which aims to get a multiplication factor of 4 by using 4 stages.

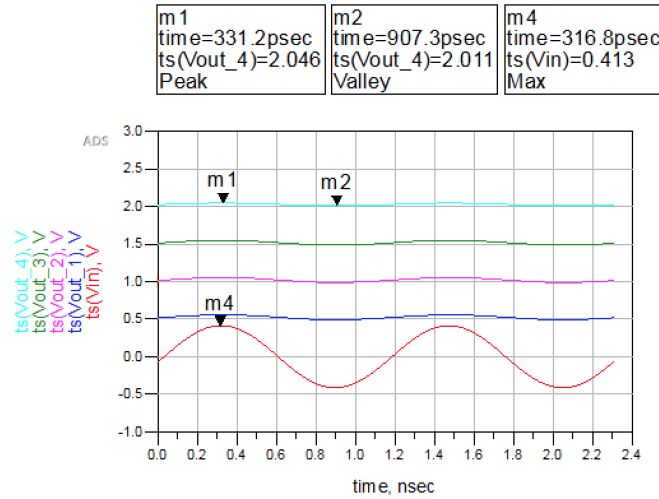


Figure A.2: Output signal results.

The main objective is to find the minimum input power that provides about 2 V at the output (typical μC working point). By tuning the capacitors, the best value was found to be 14 pF allowing a $P_{in}^{min} = -11.5 \text{ dBm}$.

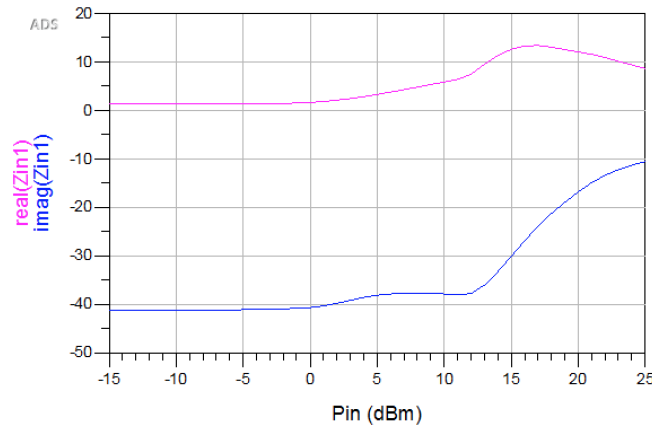


Figure A.3: Input impedance results.

Another parameter to analyze is the non-linear behaviour of the system due to the use of diodes. This affects the input impedance as it can be modified by different input power levels even at the same frequency.

It has been found that for input levels up to 0 dBm, the impedance remains stable at $Z \approx 1 - j41\Omega$, clearly showing a capacitive behaviour. For higher input levels, which are unlikely to be received, the impedance suffers an abrupt change which would mismatch the system and therefore produce power losses.

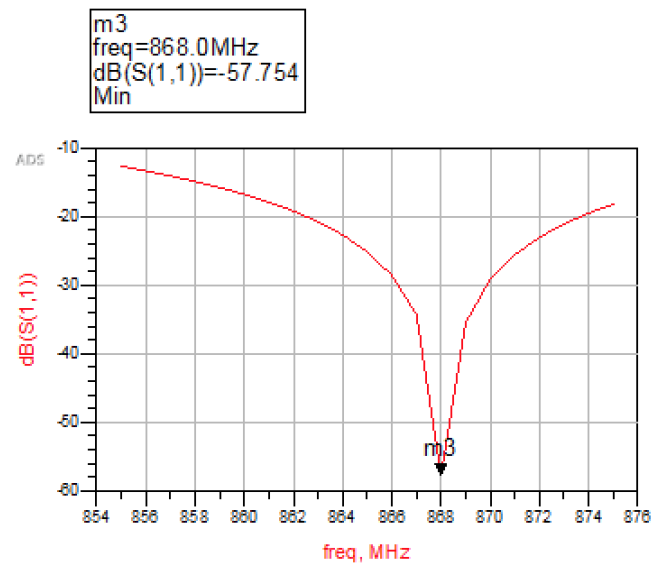


Figure A.4: Adaptation results.

| Properties | |
|-------------------|---------------|
| Frequency | 868 MHz band |
| Return loss | > 50 dB |
| Sensitivity | -11.5 dBm |
| Output voltage | 2 V |
| Multiplier factor | ≈ 4.4 |

Table A.1: Summarized results.

The results have shown that the multiplier can energize the μC if it receives at least 70.80 μW (-11.5 dBm) at the input. The main three simplifications used in the simulation are the following:

Firstly, the capacitors used are ideal with no parasitic losses. More accurate models should be used since in low power devices like this, it might have a considerable effect.

Secondly, transmission lines must be used on high frequency circuits to avoid losses. The connection of the different devices by means of junctions has to use this technology.

Finally, the multiplier has been tested alone, without the influence of the modulator, demodulator and without a proper simulation of the μC consume.

In addition to these, the need of very reduced capacitors (14 pF) which might not be available in the market, and the allegedly similar specs with the consumption optimized tag designed in Chapter 3, lead to take this simulation as an academic introduction and not a final design.