Radiofrequency remote powering of wireless sensors over a frequency range of 863/870 MHz

Relatori
Ch.mo Prof. Pasquale Daponte
Ch.mo Prof. Manuel Gasulla
Ch.mo Prof. Luca De Vito

Candidato
Marco Salvatore
Mat. 196/226

ANNO ACCADEMICO 2007 / 2008
**Presentazione del progetto**

Questa tesi di Ingegneria delle Telecomunicazioni dell’Università del Sannio, nasce grazie alla collaborazione internazionale con l’Escola Politecnica Superior de Castelldefels (EPSC), dipartimento appartenente alla Technical University of Catalunya. La sua implementazione è stata possibile grazie alla presenza del personale e all’utilizzo delle risorse di laboratorio concesse dal dipartimento di elettronica ISI Group (INSTRUMENTATION SENSORS AND INTERFACES GROUP) della EPSC. Nel presente lavoro si analizzerà una problematica piuttosto attuale e di notevole interesse, ovvero quella legata all’alimentazione remota degli elementi appartenenti ad una WSN (Wireless Sensor Network). L’obiettivo della tesi è quello di progettare, simulare e ottimizzare dal punto di vista energetico, un sistema di alimentazione remota per un sensore wireless, a bassa potenza, per brevi distanze, alimentato tramite l’energia trasportata da un segnale RF operante nelle frequenze UHF a 863/870 MHz e presente nell’ambiente circostante. Questo verrà effettuato tramite l’accoppiamento di due elementi cardine, ovvero un rettificatore e un antenna. Il successivo disegno e simulazione dell’elemento rettificatore ed il dimensionamento e la costruzione dell’antenna ricevente, verranno effettuate grazie all’ausilio del software commerciale ADS (Advanced Design System) 2008.
Chapter 1

Overview and general aspects

1.1 Principal goals

The objective of this thesis is to draw, simulate and optimize a remote alimentation device for a wireless sensor, low power, short range, powered by the energy transported over the RF signal. This signal working at UHF frequencies, in particular at 863/870 MHz. The combination of two key components, that is a rectifier circuit based on using Schottky diodes and a folded dipole antenna at $\frac{\lambda}{2}$, represents the main elements for a possible remote alimentation system. The connection of the previous elements forms the rectenna element. This conversion system allows finding a DC voltage, by the energy harvested from the ambient RF power. This direct voltage is destined to an energy storage block, presents on each sensor platform. So, it is necessary constantly provide, to the sensor platform, a voltage flow that is sufficient to keep the device operative, for every working mode. The aim is to maximize the power-conversion efficiency of the rectenna for input-power level. A comparison between the stored energy and consumed energy, is fundamental in order to achieve a system able to keep the battery charged, for a specific electric load. It will be employed a method of directly conjugate-matching between the rectifying circuit and the folded dipole antenna, so that this matching network, between the two elements, can improve the rectenna efficiency.
1.2 Implementation in the simulation environment

In order to design and simulation the rectifier device, as well as the dimensioning and the construction of the receiver antenna element, the commercial software ADS (Advanced Design System) 2008 update 1 of Agilent Technologies software, is utilized. This calculation and elaboration environment provides an advanced processing system for RF (Radio Frequency) applications and circuits. This software platform is specifically created for carefully drawing, analyzing and optimizing electric power devices, and complex devices working at a high frequency. Thanks to the software, many simulations have been made in order to measure the efficiency of the rectifier and antenna. A good choice of the electric components in the circuit, is necessary in order to start the simulation process. The study conducted during the thesis has been divided in the following 5 processes for project implementation, shown in Fig. 1.

![Fig. 1 - Working progress.](image-url)
The first step in the project is “analyzed problems linked to the remote sensors powering” in order to understand general aspects of related environment. The second step is “Analysis of the main technological solutions proposed in the literature”: is a significant observation of best technological solutions. The third step is “Detailed description of devices concerning the RF/DC conversion process”: is the heart of my project. The fourth step is the “Introduction and implementation of the simulation environment, ADS 2008”, in which an introduction of the software used in the thesis, are described. Finally, the fifth, called “Analysis of the results and comparison of the performance” that is the last step, it shows all the considerable data results, obtained from the simulation, followed by a general considerations about the performance comparison.
Chapter 2

Proposed Architecture

This chapter is an overview of a possible option for RF-power transmission system. Therefore the transmitter and receiver elements, will be explained. Subsequently, it will be briefly described the features and the components of a sensor platform.

2.1 Example of a wireless power transmission system

It is useful to quote as follows, the typical structure of a RF-power transmission system, where the transmitter antenna with gain $G_t$ irradiates a power $P_{\text{EIRP}}$ in the direction of receiver (battery-less device) composed by an antenna with a gain $G_r$, radiation resistance $R_S$ and effective area $A_e$, situated at a distance $d$. The Fig. 2 represents a classical wireless power transmission system bocks:

![Diagram of a wireless power transmission system](image)

Fig. 2 - Example of a wireless power transmission system.

Supposing that system of reception is located at a distance $d$ from the transmitter, the main problem is the evaluation of the received power of receiving antenna when is well-known

\[ P_{\text{EIRP}}(\text{Effective Isotropically Radiated Power}) \] is the power which would be radiated by an isotropic antenna in order to obtain the same field level generated by the antenna took into account.
the transmitting power. The solution is showed in the formula of connection described on end. Related to the Fig. 2, the power density that affects on the receiving antenna is so:

\[ S = P_{EIRP} \frac{G_T}{4\pi d^2} \]  

(1)

Fixed \( A_e \) as the effective area of receiving antenna, the transferred power (called available power) at an adapted load with polarization adaptation, results:

\[ P_{AV} = A_e \cdot S \]  

(2)

Where \( A_e \) is equivalent to:

\[ A_e = \frac{\lambda_{RF}^2}{4\pi} G_R \]  

(3)

So that:

\[ P_{AV} = S \frac{\lambda_{RF}^2}{4\pi} G_R = P_{EIRP} G_R G_t \frac{\lambda_{RF}^2}{(4\pi d)^2} \]  

(4)

Supposing that the connection is not in the free space, is introduced the attenuation factor fixed \( F \):

\[ P_{AV} = S \frac{\lambda_{RF}^2}{4\pi} G_R = P_{EIRP} G_R G_t \frac{\lambda_{RF}^2}{(4\pi d)^2} F^2 \]  

(5)

### 2.2 Friis free space propagation formula

The exact calculation of the matching between the two antennas show some difficulties. In the practice this calculation is carried out approximately through the Friis equation, well known as Friis free space propagation formula, which gives the relationship between received power and transmitted power. It will be considered two generic antennas in a free space, where the transmitting antenna allows a certain global power, directed gain and effective area, and it will be the same for the receiving antenna. Supposing that between
the receiving antenna and the transmitting element there is a distance \( d \), this condition assures to operate in the far-field region of antenna. The far-field region is the region in which plane-wave propagation takes place. The beginning of the far-field region occurs at a distance from the antenna roughly equal to one wavelength of the emitted signal. In this case, this condition has been obtained for a lower distance of 25 cm, as Fig. 3 shows. According to this information, relation (6) represent the available power density collected by the receiving antenna, and then, transferred to a load.

\[
P_{\text{RX}} = P_{\text{TX}} G_{\text{TX}} G_{\text{RX}} \frac{\lambda^2_{\text{RF}}}{(4\pi d)^2}
\]

(6)

In which there are are respectively:

- \( G_{\text{TX}} \) and \( G_{\text{RX}} \) are respectively the gain in dB of transmitting antenna and receiving antenna;
- \( P_{\text{TX}} \) is the power which the transmitting antenna irradiates in the direction of receiver;
- \( P_{\text{RX}} \) is the power obtained in reception of antenna and then it is transferred to the load, fixed in a simulation phase as available power (\( P_{\text{AV}} \));
- \( d \) represents the distance between the devices;
- \( \lambda \) is the wavelength of the signal;

The previous relation is an interesting and useful instrument, because it points out the importance of matching factor for the antenna, in order to obtain an excellent energy transfer to the load. From a second point of view, it is obtained a quadratic dependence relation for the received power, respect to the distance. In Fig. 3, the trend of the received power, according to the distance between the transmitter and receiver antenna, is shown. In order to design the antenna, it needs to take into consideration the following parameters:

- Frequency band at 868 MHz;
• Maximum transmission power equal to 0.5 W (limited by regulations from the Electronic Communication Committee);

• Gain obtained from receiving antenna and transmitting antenna equal to unit;

![Fig. 3 - Received power versus distance between receiver and transmitter.](image)

2.3 Transmitter

The transmission system is composed by an oscillator (radiofrequency generator) and an omni-directional antenna that irradiates an RF signal with a carrier of 868 MHz, in a multipath presence environment. This signal, composed of a sinewave with arbitrary amplitude, does not transport any information, and so, it can not transport any considerable data. As already mentioned, the aim of a WSN is the monitoring of a specific physical phenomenon throughout periodic surveys realized by each sensor node. The modulation mode is an Amplitude Modulation (AM) with peek amplitude of the sinewave (for example 1 V) always constant. The effective distance that is between the reception and transmission block, keeps the conditions of far field and it is above 20 cm. This is aimed to avoid phenomenon of capacitive and inductive matching. It is emphasized that the full charge of capacitor, depends on two main factors: firstly, the amplitude of maximum RF signal that affects on rectenna, and, secondly, the duration of radiation, in terms of time exposition. In order to assure the optimal working of system, it has to be
obtained energy issued by transmitter (or other source) as much as possible taken in an exterior environment and to extend the emission time. However this is not always possible because, as is previously showed, the regulation limits the exposition, both in power and in radiation time and utilization. In Table. 1 the characteristics and specifications related to the transmission system are reported:

<table>
<thead>
<tr>
<th>Transmission Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Frequency</td>
<td>868 MHz</td>
</tr>
<tr>
<td>Wavelength ((\lambda_{RF}))</td>
<td>0.345 m</td>
</tr>
<tr>
<td>Operating Distance (TX / RX)</td>
<td>(d \geq \frac{\lambda}{2} \iff d \geq 20\text{ cm})</td>
</tr>
<tr>
<td>Carrier Power ((P_{\text{max}} = P_{\text{TX}} G_{\text{TX}}))</td>
<td>(\leq 500\text{ mW})</td>
</tr>
<tr>
<td>Transmission Duty Cycle</td>
<td>10%</td>
</tr>
<tr>
<td>Network topology</td>
<td>Point to Point</td>
</tr>
<tr>
<td>Modulation</td>
<td>Amplitude (AM or ASK)</td>
</tr>
</tbody>
</table>

**Table. 1- Basic parameters of transmitter.**

2.3.1 Regulations

The considerable problem related to the selection of the frequency band is related to the presence of accurate local specifications, required for the allocation of the frequency band, according to the country taken into consideration. The good choice of the transmissive band utilized, represent an important parameter. The bands so called ISM (Industrial, Scientific and Medical) represent one of the best realizable choices, because these bands are available in different countries without extreme differences. It has to be remembered that, for a development of a wireless sensors network, should be realized devices with costs and dimensions limited as much as possible. In the last years all studies related to bands have been concentrated in the frequency range around 2.4 GHz. On this
circumstances, the magnitude of incident FR signal would be so large, for guarantying the best functionality of the whole system. This may require the power sent by the base station to be near the maximum set by regulations. The devices working with radio frequency in the ISM band, in fact, are limited and regulated by normative by FCC (Federal Communications Commission) for USA and ECC (Electronic Communication Committee) for Europe. This recommendations govern the safety issues and describe the spectrum management requirements for the SRDs. These bulletins relate respectively, how to allocated frequency bands, channel spacing and duty cycle, and finally, how much power is allowable for a device that sends out a RF signal. In other words, the recommendations limit are the maximum levels for the transmitted power. In Table. 2 there are some contents about reference values for limits of emission in force nowadays. The normative includes information parameters recommended for various frequency bands mostly utilized for telemetry, radio control, alarm systems and data transmission.
<table>
<thead>
<tr>
<th>Frequency Band</th>
<th>Power / Magnetic Field</th>
<th>Duty cycle</th>
<th>Channel spacing</th>
<th>ECC/ERC Decision</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>a 685-695 kHz</td>
<td>42 dBuA/m at 10 m</td>
<td>No Restrictions</td>
<td>No sparring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b 13.55-13.95 MHz</td>
<td>42 dBuA/m at 10 m</td>
<td>No Restrictions</td>
<td>No sparring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c 26.67-27.28 MHz</td>
<td>42 dBuA/m at 10 m</td>
<td>No Restrictions</td>
<td>No sparring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d 30.00-30.70 MHz</td>
<td>20 mW r.s.p.</td>
<td>No Restrictions</td>
<td>No sparring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e 138.10-138.45 MHz</td>
<td>10 mW r.s.p.</td>
<td>1.0 %</td>
<td>No sparring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f 433.050-434.790 MHz (note 4)</td>
<td>10 mW r.s.p.</td>
<td>-10 %</td>
<td>No sparring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>g 343.050-344.790 MHz (note 4)</td>
<td>2 mW r.s.p.</td>
<td>up to 100 %</td>
<td>No sparring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>h 434.050-434.790 MHz (note 4)</td>
<td>10 mW r.s.p.</td>
<td>up to 100 %</td>
<td>No sparring</td>
<td>EEC/ERC(04/02)</td>
<td></td>
</tr>
<tr>
<td>i 863.870 MHz (note 3, 4 and 6)</td>
<td>≤ 25 mW r.s.p.</td>
<td>≤ 0.1 % or LBT (note 1, 2 and 5)</td>
<td>≤ 160 kHz for 47 or more channels (note 2)</td>
<td>FISSS modulation</td>
<td></td>
</tr>
<tr>
<td>j 863.870 MHz (note 3, 4 and 6)</td>
<td>≤ 25 mW r.s.p.</td>
<td>≤ 0.1 % or LBT (note 1, 2 and 5)</td>
<td>≤ 160 kHz for 1 or more channels (note 2)</td>
<td>No sparring</td>
<td></td>
</tr>
<tr>
<td>k 863.870 MHz (note 3, 4 and 6)</td>
<td>≤ 25 mW r.s.p.</td>
<td>≤ 0.1 % or LBT (note 1, 2 and 5)</td>
<td>No sparring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>l 863.870 MHz (note 3, 4 and 6)</td>
<td>≤ 25 mW r.s.p.</td>
<td>≤ 0.1 % or LBT (note 1, 2 and 5)</td>
<td>No sparring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>m 863.870 MHz (note 3, 4 and 6)</td>
<td>≤ 25 mW r.s.p.</td>
<td>≤ 0.1 % or LBT (note 1, 2 and 5)</td>
<td>No sparring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>n 863.870 MHz (note 3, 4 and 6)</td>
<td>≤ 25 mW r.s.p.</td>
<td>≤ 0.1 % or LBT (note 1, 2 and 5)</td>
<td>No sparring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>o 863.870 MHz (note 3, 4 and 6)</td>
<td>≤ 25 mW r.s.p.</td>
<td>≤ 0.1 % or LBT (note 1, 2 and 5)</td>
<td>No sparring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p 863.870 MHz (note 3, 4 and 6)</td>
<td>≤ 25 mW r.s.p.</td>
<td>≤ 0.1 % or LBT (note 1, 2 and 5)</td>
<td>No sparring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>q 863.870 MHz (note 3, 4 and 6)</td>
<td>≤ 25 mW r.s.p.</td>
<td>≤ 0.1 % or LBT (note 1, 2 and 5)</td>
<td>No sparging for 1 or more channels (note 2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>r 863.870 MHz (note 3, 4 and 6)</td>
<td>≤ 25 mW r.s.p.</td>
<td>≤ 0.1 % or LBT (note 1, 2 and 5)</td>
<td>No sparging for 1 or more channels (note 2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>s 863.870 MHz (note 3, 4 and 6)</td>
<td>≤ 25 mW r.s.p.</td>
<td>≤ 0.1 % or LBT (note 1, 2 and 5)</td>
<td>No sparging for 1 or more channels (note 2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t 863.870 MHz (note 3, 4 and 6)</td>
<td>≤ 25 mW r.s.p.</td>
<td>≤ 0.1 % or LBT (note 1, 2 and 5)</td>
<td>No sparging for 1 or more channels (note 2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>u 863.870 MHz (note 3, 4 and 6)</td>
<td>≤ 25 mW r.s.p.</td>
<td>≤ 0.1 % or LBT (note 1, 2 and 5)</td>
<td>No sparging for 1 or more channels (note 2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>v 863.870 MHz (note 3, 4 and 6)</td>
<td>≤ 25 mW r.s.p.</td>
<td>≤ 0.1 % or LBT (note 1, 2 and 5)</td>
<td>No sparging for 1 or more channels (note 2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>w 863.870 MHz (note 3, 4 and 6)</td>
<td>≤ 25 mW r.s.p.</td>
<td>≤ 0.1 % or LBT (note 1, 2 and 5)</td>
<td>No sparging for 1 or more channels (note 2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>x 863.870 MHz (note 3, 4 and 6)</td>
<td>≤ 25 mW r.s.p.</td>
<td>≤ 0.1 % or LBT (note 1, 2 and 5)</td>
<td>No sparging for 1 or more channels (note 2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>y 863.870 MHz (note 3, 4 and 6)</td>
<td>≤ 25 mW r.s.p.</td>
<td>≤ 0.1 % or LBT (note 1, 2 and 5)</td>
<td>No sparging for 1 or more channels (note 2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>z 863.870 MHz (note 3, 4 and 6)</td>
<td>≤ 25 mW r.s.p.</td>
<td>≤ 0.1 % or LBT (note 1, 2 and 5)</td>
<td>No sparging for 1 or more channels (note 2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AA 863.870 MHz (note 3, 4 and 6)</td>
<td>≤ 25 mW r.s.p.</td>
<td>≤ 0.1 % or LBT (note 1, 2 and 5)</td>
<td>No sparging for 1 or more channels (note 2)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 2: Regulations of FCC exposure limit for several frequency bands. Extracted from:**


Talking about the frequency range taken into consideration in this project, the regulation limits the transmitter with an emission power below 500 mW and with a duty cycle below 10%. This can mean a break from work of one hour, every six minutes of working, or it means 10 s every second of transmission. Since the maximum transmit power is limited, it is necessary increasing the efficiency of the RF/DC conversion. In Table 3, the values and limits given by the normative related to this project, are reported:
<table>
<thead>
<tr>
<th>Frequency Band [MHz]</th>
<th>Power / Magnetic Field</th>
<th>Duty cycle</th>
<th>Channel spacing</th>
<th>ECC/ERC Decision</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>g3</td>
<td>≤ 500 mW e.r.p.</td>
<td>≤ 10% or LBT. (note 1)</td>
<td>25 kHz (for 1 or more channels)</td>
<td>ERC/DEC/ (01)04</td>
<td>Narrow/wide-band modulation. The whole stated frequency band may be used as 1 channel for high speed data transmission</td>
</tr>
</tbody>
</table>

**Table. 3- Bound values for the transmitter.**

Extracted from the URL: [http://www.ero.dk/doc98/official/pdf/rec7003e.pdf](http://www.ero.dk/doc98/official/pdf/rec7003e.pdf)

### 2.4 Receiver

The first element of RF to DC conversion system is the antenna. The design, dimension and characteristics of this element are crucial as they are reflected on the efficiency and the total behaviour of the whole conversion system. It is important to point out that the rectifier DC power and efficiency is characterized as a function of DC load, circuit topology, RF frequency polarization and power density of the electromagnetic wave. In Fig. 4 the simplified blocks diagram of a RF/DC conversion system and the related load will be point out:

![Fig. 4 - Receiver block diagram.](image-url)
The characteristic building block of the system is composed by the rectifier block, the storage energy block, the DC/DC converter, in case a boost converter, and finally the logic circuitry. In theory, a system so structured is able to:

- Recycle and storage ambient energy power;
- Perform operations of collecting and processing ambient data and then storage information, thanks to the sensor;
- Re-sending processed data to the base station which compiles data gathered by individual sensor nodes;
- Avoid battery replacement operation;

### 2.4.1 Antenna frequency band and brief explanation of a folded dipole antenna

As already said, the energy conversion process from RF signal to DC voltage has been realized thanks to the rectifier circuit, united to the presence of the antenna. In order to realize that, is necessary the find of a special kind of antenna, able to work in a better way for the frequency range UHF (433, 868, 915, 2450 MHz). Among the different antennas which work in this frequency range, a folded dipole represents the best candidate. The structure is composed by a conventional dipole, but by adding a second parallel conductor, and connecting it to the extremities of the dipole. So, it consists of two $\lambda/2$ dipoles, connected to the extremities. A necessary condition is that the distance interposed between the two longitudinal conductors (called $d$), is much less than wave length, associated to work frequency band, as showed in Fig. 5:

![Folded dipole structure](image)

**Fig. 5 - Folded dipole structure.**
A folded dipole can be analyzed by use of the principle of superposition of effects, by decomposing the voltage applied in two parts, a differential mode (regarding the two conductors which receive an opposite voltages) and a common mode (regarding left and right segments) which receive the same voltage. The Fig. 6 shows it:

![Fig. 6 - Voltage decomposition.](image)

Differential voltages propagate in the same manner, as what happens in a conductors pair, because the current on the left conductor is always the same (magnitude) and opposite in phase to the right one; the radiation given by the two currents is cancelled, so the voltage transmission line component does not show any radiation resistance. Because of the impedance of a dipole does not result susceptible to the cross section, the conductor pair can be seen as a classic dipole able to give a common mode current. Half of this current flows in the left conductor segment, while the other half in the right one. So, is obtained a quarter of the current which can be observed with a classic dipole, while the power transmission coefficient is better than a standard dipole, giving more voltage to the load. The consequence is that when the same electromagnetic field, and so with the same radiated power, the source current is half compared to the classic $\lambda/2$ dipole. It can be deduced that a folded dipole has got a radiation resistance which in resonance condition results four time bigger than the classic dipole, with a value around $260-280 \Omega$, described from the following relation:

$$R'_a \approx R'_i = \frac{P_i}{(I_a/2)^2} = 4R_i \approx 4R_i$$  \(7\)

In which:
• $R_a'$ is the resistance of folded dipole antenna, approximately the same as radiation resistance, in the condition of the losses are negligible;
• $R_{i}$ and $R_i'$ are radiation resistance respectively of the folded dipole antenna and the classic dipole;
• $P_i$ is the power radiated by the folded dipole, which equals to the half of source current by a classic dipole ($I_a$), which radiates the same power;

The folded dipole shows a resistance which equals to the characteristic impedance of a bifilar line (300 $\Omega$), and so it can be powered directly, without using coupling device. Furthermore, a folded dipole structure, for antenna design, has been employed also because it offers smaller dimensions, ease of manufacture and low associated costs. In spite of it, it has to be considered that the work frequency band decreases when impedance levels increase.

### 2.4.2 Load

A WSN is composed of many small self-contained elements, distributed in the space, and able to cooperate among them for monitoring a specific event, called nodes. The sensor node which will be used in this project, in general, can be part of a generic network of sensors and its characteristics will be reported in the next table. Every node can be seen as a elaboration device in miniature, typically constructed by the main following elements:

- A set of sensors in order to survey ambient data;
- Processing and control unit;
- Communication module (transceiver unit block + antenna);
- A powering source, also called power unit, for instance a battery;
- A memory unit;

Fig. 7 shows the generic draft of node architecture with a transducer connected to the A/D conversion block. The analog signals, which comes from the transducer, in fact, are converted into digital signals and sent as input to the process unit, which once again will
be connected to a transceiver. The transceiver is connected to the antenna so it can form the RX/TX communication module that can be considered a transmitting radio or a device for wireless data communication versus the base station or with other sensors that compose the network.

The power storage and management block controls the supplied power from the source of alimentation. This power is appointed to the sensor and for all electronic devices related. The unit of elaboration is called also Control and Processing Unit and it is composed by a CPU and a block of memory, generally of limited capacity. The small local memory allows the temporary storage of data obtained by the sensor and once again it can send to the conversion A/D block that is in charge to supplying the digital version of this data.

### 2.4.3 Power Management and Storage block

The voltage obtained as output of this block is sent in a power management block. In practice, the goal of this block is to guarantee to the load, that is the sensor and the its electronic devices, the amount of energy that it needs\(^2\). So, a necessary condition is that the amount of recharging energy has to be able to guarantee the minimum working for the electronic circuitry, that represents the load. Consequently, the stored energy in the power storing block, has to be always greater in reference to load requirements. There are,

---

\(^2\) In a sensor node, the maximum consumption mode is tested in the data transmission and communication time
generally, two options for storage energy, that include capacitors and micro-batteries. Capacitive storage energy is appropriate for applications where repeated functions of storing and utilizing small energy packets are performed, using on-chip capacitors. While, for prolonged operation or larger energy packet, energy densities can be achieved using micro-batteries. Therefore it optimizes, controls, manages the quantity of accumulated energy in the storage element. This energy is so utilized for the alimentation of all sensor platform, discharging the capacitor. In particular a mode selector decides when the system is in active, transmitting data or in a stand-by mode. The latter phase allows the capacitor to recharge. The internal draft of this element is showed in Fig. 8:

![Power Management Block](image)

**Fig. 8 - DC Power Management Block**

The DC Power Management block in addition to the Load and Storage Element block, it consists also both of a digital DC- DC converter, which raises the peak value of voltage signal (often referring to itself with the name of boost element), and low Power Controller which manages the operation of the DC-DC converter and the storage of energy. Anyway it has to be noticed that the DC supplied voltage stored on the capacitor by the rectifier cannot exceed the peak signal amplitude of the received RF signal. In the following Table 4 there are the main features and information of the sensor.
Table. 4 - Summary of device.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setup Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology RX</td>
<td>Discrete component</td>
</tr>
<tr>
<td>Load Range Supply [V]</td>
<td>$V_{cc} = 2.1 \sim 3.6$</td>
</tr>
<tr>
<td>Sensor Carrier Frequency</td>
<td>2.45 GHz</td>
</tr>
<tr>
<td>Frequency Range</td>
<td>2.40 \sim 2.48 GHz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sensor Power Consumption</th>
<th>STATE DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Transmit (Radio ON)</td>
</tr>
<tr>
<td></td>
<td>$I_{TX} = 36mA$</td>
</tr>
<tr>
<td>Sensor Duty Cycle</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Supercapacitor</td>
<td>100 nF – 1000 F</td>
</tr>
</tbody>
</table>

2.4.4 Sensor Platform

In this paper, the sensor platform represents one of the essential components for the entire project. It is the load for the conversion system. However, some specific functioning and characteristics will be left out, taking into consideration that the focus of the project is the system of conversion rather than the load. As already showed previously, the sensor platform consists of a wireless sensor, which can be imagined in a wider context like a single element of a network more or less large of wireless sensors. As the main function of a sensor platform is to communicate, then, the information to the control and elaboration center unit, it will be briefly describe the different working and, subsequently, it will be exposed a brief general view in the Chapter 4 for the protocol communication characteristic utilized, the ZigBee. The sensor node is able to work in different modes that are:
- reception and transmitting mode, called also transmit mode;
- idle mode, that is the inactivity or awaiting time;
- standby mode or called also sleep mode;

The first mode corresponds to the setting of active transmitter which the sensor platform is in a position of transmitting data from network to the processing base. The last phase, also called stand-by mode, is that with lower energetic consumption, where the node is incapable to receive data. The choice of transition from a mode to another, depending on energetic consumption, is not trivial, because the transition from a mode to another with a lower energetic consumption needs of time and, in particular, a waste of energy. This has brought to the born of a new approach with the aim of increasing the power efficiency called Sleep Management. This branch of research is concerned with the optimization of best temporal moments of turn on and switching off for the nodes in order to minimize the global power consumption of the network, without affecting the transmissive issues. Supposing that the nodes can operate in different operative modes, linked to different power consumptions and, supposing that, during the transition from a mode to another, there is a waste of energy and a time interval during that the node cannot make any operation, it is necessary to choose cleverly, when and in what phase it is better to locate every node in the entire network. Moreover, if the node could be in an operative mode with low power consumption, it could not be in a position of reply to the network demands in a predetermined time interval or, actually, could be totally isolated from the rest of the network, consequently it will be unable to receive messages. To enforce this technique, it is necessary to know a great number of working features and, in according to them, to decide, for every moment, what will be the optimum operative mode for every node.

2.5 RFID System

A technology from which is possible to inherit many circuital solutions useful for the purpose of this study, and linked to the problems of the WPT, is the RFID technology. The RFIDs make frequent use of rectifiers as energy sources, both at low frequencies and in the UHF band. An RFID system is composed of two main elements: a reader and a transponder. These are often installed in all kinds of objects and, for this reason, are commonly called tags. The reader is a receiver-transmitter device that has a double
function: it supplies energy with which the transponder is able to function and engages in
dialogue with the transponder, transmitting commands and collecting replies. Basically, a
transponder is a little chip linked with the antenna; when it is next to the an
electromagnetic field, generated by the reader, a current is induced in its antenna that
supplies the chip. The chip elaborates the received command, and retransmits the results
of its processing. Every tag has an individual identifier (ID), which distinguishes it from
the others. Various categories of tag exist, based on the presence or absence of an internal
source of power, the internal storage capacity, the type of identifying code adopted, the
working frequency band and finally, the standard used for the data transmission. Active
tags have a source of power and continuously transmit information; semi-passive tags
have a source of power and transmit information only when asked for it; finally, passive
tags do not have batteries or power sources and are, therefore, taken into greater
consideration in this study. As far as the working frequencies are concerned, tags can be
classified in 4 categories: Low Frequency tags (from 125 to 134 kHz), High Frequency
tags (13.56 MHz), microwave tags (2.45 GHz) and UHF tags (from 868 to 956 MHz),
which is the frequency band analysed in this project. Also in this case, for each frequency
band, there is a series of European and International specification, aimed at regulating the
use of this technology.
Chapter 3

Wireless Sensor Network

This chapter deals with a general description of features and functions of wireless sensor network. A batch of examples will enhance the introduction of this technology in ordinary life and its many applications.

3.1 Introduction and state of art

Latest progress made in the radio communication and micro-electronic systems, together with those made in the miniaturization, memorization and communication process, let the production of sensors able to observe the environment in which they are inserted, to process on board data, and to communicate with the rest of the network, through radio waves. Interesting examples of these peripheral, intelligent and pervading systems, are the WSN, which represent the instrument for collect, fusion and aggregation of the data flow, stored in any sensor node. The goal of a WSN is the optimization of the resources which result limited. In this case is clear how energy saving is very important in order to obtain a longer network lifetime. Anyway, every single element of a WSN has no unlimited energy sources. So, working time depends on the capacity of the alimentation supply source, generally made of batteries and super capacitors, which present a low leakage current and high charge capacity. Optimizing energy consumption of the nodes, in order to maximize the whole network lifetime, isn’t sufficient. For example for some application the lifetime needed corresponds to some years. The need to create a sensor node, with low power consumption which does not need the operation of battery replacement, able to recycling and collecting a source of alimentation from a generic energy source in the surrounding, where the node itself is put. Many techniques has been invested for searching new and potential energy sources (e.g. mechanics stress or solar energy) to exploit in conversion process. It allows a longer lifetime for the sensor platform and then a reduction
of the costs linked to device maintenance and network assistance, which can not always take place.

### 3.2 From cable networks to wireless network

Sensors network in the beginning, have been produced with cable communication structures, but this produce some disadvantages and obstacles: firstly, difficulties of installation in inhospitable places to man. Secondly there is a problem of costs, because the installation of each device needs work and materials for cabling operations. Furthermore, a cable structure is mainly stiff, that is it is difficult to add nodes to the network or to modify the position of the pre-existent sensors without reconsidering the whole structure of the network. It can be illustrated by means of an example to a simple applications for home heating monitoring and lighting system in a house. The wireless solution shows with no doubt an advantageous choice for many applications. Fig. 9 shows the main features:

![Fig. 9 - The main advantages of WSN.](image)

- **Networking**
  - Self-configuration
  - Scalable
  - Flexibility
  - Hybrid Networks
  - AdHoc
  - Redundant

- **Wireless**
  - Auto-configuration
  - Energy efficiency
  - Very low duty cycle

- **Circuits**
  - Limited in power
  - Low cost
  - Low troubleshooting
  - Self powered
  - Fault tolerance
It has to be considered that the just listed advantages in many applications are not sufficient to provide a total substitution of cable networks. It can be considered for example a problems linked to the propagation of the signal, interferences, required power, security, legislative rules. It leads to consider the possibility to make hybrid network made of both a cable part and a wireless one, able to cooperate and interact easily for the final user. In this context wireless technologies add specific value to the application.

### 3.2.1 Application examples based on WSN

WSN basic sensors are interconnected with low cost, low power, low maintenance and troubleshooting, so that many of them can be distributed in the environment to capture data, check cargo movement, and make a new and advanced way of interaction with the surrounding. The developed network can be enforced by using a wide range of sensors like those: seismic, magnetic, infrared, acoustic, radar and temperature sensors, Global Positioning System, able to supervise a wide range of parameters and events. In Fig. 10 are shows a set of parameters end events detected by a WSN:

![Parameters and Events](image)

**Fig. 10 - Most important parameters and event detected by a WSN.**

Therefore, in reference to the parameter or event to measure, from the simplest to the most difficult, there is a specific technology of WSN with suitable features in the environment taken into account. Some of the main application of the WSN can be classified in seven macro-groups, as showed in Fig. 11:
In Table 5 some of the main and interesting utilizations fields and applications sets, based on the WSN and used in the everyday life, are shown:

<table>
<thead>
<tr>
<th>Interaction verification and checking</th>
<th>Object inspection</th>
<th>Environmental monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production cycle flow control</td>
<td>Building structure test</td>
<td>Ambient and natural habitat checking</td>
</tr>
<tr>
<td>Interaction between persons, objects and ambient</td>
<td>Ecophysiology$^3$</td>
<td>Precision-agriculture</td>
</tr>
<tr>
<td>Urban traffic control</td>
<td>Management and control of motors and equipments</td>
<td>Air-conditioning unit control</td>
</tr>
<tr>
<td>Examination of wild habitat</td>
<td>Laboratory diagnostic</td>
<td>Weather and geo geophysical research</td>
</tr>
<tr>
<td>Disaster and catastrophe testing</td>
<td>Landscape and territory mapping</td>
<td>Pollution control</td>
</tr>
<tr>
<td>Emergency intervention</td>
<td>Asset tracking$^4$</td>
<td>Surveillance management</td>
</tr>
</tbody>
</table>

Table 5 - Fields and practical setting based on WSN.

$^3$ The sensors are utilized in order to monitoring the tolerable values of the ambient parameters

$^4$ Containers localization and position finding of luxury goods
Chapter 4

Analysis of conversion system

In this chapter the elements that are the basis of this project and that make up the RF/DC conversion system will be described.

4.1 Rectenna

The name derives from the coupling of a rectifier and an antenna. This particular circuit, under suitable conditions, is able to convert the energy associated with the RF signal into a flow of continuous DC electrical energy. From the simple connection of a diode at the mid point of a dipole antenna, it is already possible to obtain a type, even though the simplest, of rectenna, as seen in Fig. 13:

![Fig. 12 - Basic rectenna example.](image)

The presence of diodes implies the need to reach a voltage at the ends that is higher than, or approximately equal, to the threshold voltage, so as to permit the transfer of energy and direct the diodes into the conduction mode. It is important to underline that, in low power applications, like in the case of ambient energy recycling, the power levels present are not usually sufficient to allow the diode to work in the high-efficiency mode. The antenna design is strongly influenced by the choice of the diode, and generally, it is used both p-n diodes and transistors, working at low frequency (kHz to low MHz), in the rectifier
process. In the case, Schottky diodes with short transit times, and low turn on voltage, are required in order to obtain a high conversion efficiency.

4.2 Equivalent model of antenna and matching condition

The antenna represents the second principal block of a rectenna, and its features modify the global efficiency of the system. Fig. 14 is an example of an equivalent circuit for a generic antenna:

Fig. 13 - Antenna equivalent circuit with matching condition.

The primary role of the system, in this context, is to collect the maximum energy in order to send it to the load, which is represented by the rectifier circuit. The energy transfer in a basic electric circuit, with an electric load, is linked to the matching conditions. To analyze this, it is useful to make a reference to the circuit showed in Fig. 14, and structurally identical to that of the antenna of Fig. 13:
Since every real circuit presents voltage or current sources with an limited electrical power, for a case of an antenna, this restriction is synthesised by the presence of the source impedance ($R_S$). When this impedance is purely resistive, it is clear that the maximum energy transfer to the load resistor ($R_L$) takes place when the two impedance show the same value. By the Ohm law, the current results as:

$$I = \frac{V}{R_S + R_L}$$

Consequently the dissipated energy for each resistor will be:

$$P_S = \frac{V_S^2}{2R_S}$$

$$P_L = \frac{V_L^2}{2R_L}$$

Given the fact that each voltage on the resistor is equal to $RI$, with the same current, the previous relations can be expressed as follows:

$$P_S = \frac{I^2 R_S}{2R_S}$$

$$P_L = \frac{I^2 R_L}{2R_L}$$
Substituting the current in the expression of the energy, it is obtained:

\[ P_L = \frac{R_L V^2}{2 (R_S + R_L)} = \frac{1}{R_S} \frac{\left( \frac{R_L}{R_S} \right) V^2}{2 \left[ 1 + \left( \frac{R_L}{R_S} \right) \right]^2} \]  

(13)

It follows that, the energy sent to the load, for a given value of \( R_S \), is maximised when the source resistance and the load resistance are equal, and this happens only in conditions of load coupling. Generalising the case in which the source and the load also contain the reactive parts, the expression of the current remains unvaried but with the addition of the complex parts as shown below:

\[ I = \frac{V}{(R_S + jX_S) + (R_L + jX_L)} \]  

(14)

Given that the energy is a function of the module of the respective complex quantities and is independent of the phases, the energy transferred to the load can be expressed as:

\[ P_L = \frac{|I|^2 R_L}{2} = \frac{V^2 R_L}{2 \left| (R_S + jX_S) + (R_L + jX_L) \right|^2} = \frac{V^2 R_L}{2 \left| Z_S + Z_L \right|^2} \]  

(15)

It is clear that with a low denominator in the equation (15), it is possible to obtain the maximum energy transfer to the load. Therefore, with constant values of load and source resistance, minimising the denominator means cancelling the imaginary part, composed of the source reactance and of the load reactance. In this case, the load reactance, being negative, results as being pure capacitive, given the connection to the rectifier device. The cancellation of this complex component is possible by supplying a reactance with the opposite sign to the circuit, which means with positive sign and equal magnitude. When the real parts of the impedance result the same, and the complex parts results with the same magnitude but with opposite phase, the two impedances result as complex conjugates, thus reaching the condition of maximum energy transfer, also known as conjugate matching. Returning to the antenna, it can be considered as a voltage supply, with open circuit voltage for example equal to \( V_S \). This source will be connected to the load via an electrical impedance, with real part called \( R_{\text{rad}} \), and imaginary part (inductive
or capacitive), defined as $X_{\text{ant}}$. Similarly, the load (that is represented by rectifier circuit) can be synthesized and simplified through an electrical impedance. It is to be noted that this condition is, nevertheless, a theoretical approximation, because the diodes, at the base of the component, are actually non-linear. It is verified that the condition of maximum energy transfer is obtained when the source and load reactance are complex conjugates, so as to cancel each other. The resulting diagram is shown in Fig. 15:

This condition is normally assumed for the calculation of gain and in the use of the Friis equation. Thus the energy received in these conditions of matching results as being:

$$P_{AV} = \frac{I_{\text{ant}}^2 R_{\text{load}}}{2} = \frac{V_S^2}{8 R_{\text{rad}}}$$  \hspace{1cm} (16)

Naturally, in non perfect matching conditions, the energy transferred to the rectifier is lower than that described in the equation 12. Thus the problem of designing an interface between antenna and rectifier is that of guaranteeing the best matching condition. Considering a source impedance linked to the antenna, with the null imaginary part, ($X_{\text{ant}} = 0$), the capacitive behaviour of the rectifier still has to be compensated. It is represented as the parallel between a resistor and a capacitor, or rather, an RC circuit. This is showed in Fig. 16:
As it will be shown later on, an inductive matching consists of the dimensioning of the inductance value. Thanks to the software and the simulation tools, it can possible to find the best value of this inductance, as will be showed in the Chapter 5.

4.3 Rectifier models

The principal subject of this section proposes a linear two-port model for a N-stage modified-Greinacher full-wave rectifier. At the present, a modified-Greinacher rectifier results as being an excellent candidate for the supplying of low consumption, short range devices. The wireless sensors networks can, therefore, to take advantage from this technology.

4.3.1 Rectifier building blocks

The rectifier circuit is composed of two basic electrical circuits, that permit the conversion from low-voltage AC to high-voltage DC supply, described in the follow section:

---

5 The term Short Range Device (SRD) is intended a system able to cover the radio transmitters which provide either unidirectional or bi-directional communication and which have low capability of causing interference to other radio equipment.
**Clamping circuit**

The clamping circuit, also defined as DC restored, has the aim of establishing a DC reference for the output voltage, thanks to the use of the diode. The Fig. 17 shows the electric circuit and its waveform of this component:

![Diode clamp circuit and its output waveform.](image)

In the case the voltage at the output terminals of the capacitor results negative, this circuit accumulates an average charge at the terminals, that is sufficient to prevent the output, from ever going negative. Whilst the positive charge on these terminals is effectively stored. In an ideal case, the residual negative voltage $\Delta v_f$ would result null while the output voltage would be:

$$v_{out} = v_{in}^* + v_{in}$$

(17)

with $v_{in}^*$ peek amplitude of $v_{in}$.

**Envelope detector circuit**

This second block, also called peek detector shows a behaviour which is substantially different, in comparison with the Clamping Circuit, even though it has the same components. In fact, applying a voltage at the input of the circuit, the capacitor will be in its recharging cycle, until the voltage $V_C$ reaches the maximum value of $v_{in}$. As shown in Fig. 18, if no resistor is connected in parallel to the capacitor, the voltage $v_{out}$ does not tend to diminish.
In practice, the leakage currents of the capacitor, lead to an output voltage drop $^6$. If the voltage $v_{in}$ results a sinewave signal, the capacitor will change every time its voltage level is close to its peek value. As a consequence, the average output voltage $v_{out}$ is slightly smaller than the peek value $v_{in}$. In all cases, the threshold voltage of the diodes is not taken into consideration, despite its importance in the design stage, since it reduces the amplitude of the output voltage.

**The voltage doubler**

The voltage doubler, showed in Fig. 19, is obtained via the cascade connection of the two previous blocks.

$^6$ Fall of voltage, that is the measurement after the passage of a component or a conductor via the current flow, that crosses the resistance or the impedance of the component itself
This system is able to supply, in the ideal case, continuous DC voltage, with a double amplitude with respect to the AC input component.

4.3.2 Full-wave rectifier

The present analysis is based on the study of an ideal full-wave rectifier. Following, the characteristics and the conditions that have been taken into consideration for the simulation will be described. For the ideal condition of the components it will be consider the follow conditions:

- The rectifier operates in the steady-state mode;
- All elements are lossless;
- The ideal capacitors present respective null leakage currents, threshold voltage equal to zero (0 V), an absence of inverse current for every single diode and infinite conductance in forward mode;
- All the diodes are identical;

The actual behaviour of the components obviously has an effect on the multiplicative factor between the voltage amplitude of the input and output signals, and then, indirectly on the conversion efficiency. An example of a circuit of the 1 stage rectifier and its output waveform in showed in the Fig. 20:

![Fig. 20 - Full wave rectifier 1 stage and output voltage.](image)

32
Usually, to obtain improvements and higher amplitude levels of the output signal, a second circuit is inserted in cascade, obtaining a full-wave rectifier, called cascade Greinacher rectifier. The Fig. 21 shows the circuit scheme:

![Directed cascade version circuit](image1)

**Fig. 21 - Directed cascade version.**

Starting from the model of rectifier, showed in Fig. 21, a modified version is obtained. Instead of the Direct Cascaded Version, a Capacitors Path Modified Version has been used, in which the connection of two diodes is bypassed, as shown in Fig. 22:

![Capacitors path modified version circuit](image2)

**Fig. 22 - Capacitors path modified version circuit.**

Thanks to its symmetry, the capacitors are connected such that every diode works with the same input signal amplitude, in the rectification action. An advantage of this structure is
tied to the low capacitive losses during the passage of the RF signal to the diodes. The capacitors act indeed as voltage dividers. The output voltage is equal to $4N v_{in}^*$ with N number of stages. As it will be shown later on, the use of a rectifier, with low energy levels, is difficult in cases where both the energy and the working range are considered to be important parameters. The electrical output characteristic of the rectifier is calculated as a function of the received energy and the parameters of the antenna. It follows that inductive coupling techniques and the use of a folded dipole antenna will be extremely useful.

4.3.3 Antenna-Rectifier interface

In this section, it will be examined several points linked to the problems concerning the performance of a full-wave Greinacher rectifier in the modified version. The antenna has the obvious task of collecting as much energy as possible from the RF wave, and is connected to the integrated circuit of the rectifier. It has the task of transforming the RF signal into DC voltage output for the powering of a generic device, low side connected. Because the rectifier is made up of diodes, it is necessary that the voltage applied to the diodes be greater than (or approximately) their threshold voltage. Then, the rectifier circuit, directly connected to the antenna, is modelled as a resistive load $R_{in}$, as in Fig. 24:

![Fig. 23 - Antenna connected to a resistive load.](image)
In which:

- $V_S$ is the voltage source amplitude;
- $R_{\text{ant}}$ is the radiation resistance;
- $R_{\text{in}}$ is the resistive load;
- $V_{\text{in}}$ is the input voltage;

So $V_{\text{in}}$ is obtained at the input terminals of the rectifier

$$V_{\text{in}} = V_S \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{ant}}}$$  \hspace{1cm} (18)

The actual goal, is to maximise the powering range, therefore, it is clear that, in the ideal case, the maximum energy transfer destined to the rectifier input circuit is found. This condition is strictly tied to the level of matching between antenna and rectifier, which in the ideal case results as:

$$R_{\text{in}} = R_{\text{ant}} \iff Z_{\text{in}} = Z_{\text{ant}}^*$$  \hspace{1cm} (19)

Under the previous conditions, the following equation is reached:

$$V_{\text{in}}_{\text{max}} = V_S \frac{R_{\text{in}}}{2R_{\text{in}}} = \frac{V_S}{2}$$  \hspace{1cm} (20)

getting the available power with matching conditions, that is:

$$P_{AV_{\text{max}}} = \frac{V_{\text{in}}^2}{2R_{\text{in}}} = \frac{V_{\text{in}}^2}{8R_{\text{in}}}.$$  \hspace{1cm} (21)
The available power at the output, is proportional to the input voltage. Furthermore, $V_{in}$ results function of the values of the two resistances, for the voltage divider. With the matching condition, it therefore results as:

$$V_s = 2\sqrt{2} \frac{P_{AV} R_{ant}}{R_{in}}$$

Substituting, it is obtained:

$$V_{in} = 2\sqrt{2} P_{AV} \frac{R_{in}}{R_{ant}} \frac{R_{in}}{R_{in} + R_{ant}}$$

This result is important for WPT issues because it shows that for an optimum project of the system, it need both a good level of power-matching (keep $R_{in}$ equal to $R_{ant}$), and a high value of the radiation resistance of the antenna (called $R_{ant}$), in order to increase the powering range. Furthermore, $R_{in}$ is proportional the current consumption of the WPT device, which has to be minimized as much as possible.

### 4.3.4 Equivalent circuit

In Fig 24 an equivalent circuit of the rectifier is represented:

![Equivalent circuit for the Rectifier.](image)

This four ports circuit is studied as a steady-state model and includes the following:
✓ A controlled input impedance, that is $R_{in}$ and $C_{in}$, function both of the input voltage amplitude and of the output current;
✓ A controlled output resistance $R_{out}$, function both of the input voltage amplitude and of the output current;
✓ Controlled voltage source $V_0$, which depends only on $V_{in}$;

The circuit in Fig. 24, shows substantially a shared circuit, separated by two matching points, necessary for a correct connection between the external circuits that are the antenna and the load respectively. The input equivalent circuit has been modelled as a simple resistor $R_{in}$, depending on the energy transfer to the rectifier. This allow the setting of conversion and global efficiency parameters of the system. To reach a good degree of matching it is, therefore, necessary to choose in an appropriate manner, the input resistance $R_{in}$. The maximum output current, instead, can be considered as the minimum difference between the ideal case and the actual case. As there is no pre-established model that is sufficiently accurate and suitable for any context, it is necessary to take many measurements and conduct many simulations aimed at researching the best features able to guarantee good behaviour by the rectifier measurements, even in those cases where the energy input levels are extremely low. Furthermore, in the cascade connection in several stages, it is to be noted that each diode, belonging to the rectifier, must integrate a quantity of energy equal to $I_{out}T^7$. Since the quantity of load is limited by the energy received from the rectenna, the number of stages is limited. Thus, the optimum number of stages could be in function of the energy received. As already mentioned, the equivalent input resistance $R_{in}$ is inversely proportional to the output current $I_{out}$, and the parallelism of the structure. It is also inversely proportional to the number of stages $N$, that is an important parameter for the whole project.

4.3.5 Rectifier efficiency

Differently from the previous case, the energy of the rectifier $P_{in}$ is calculated indirectly, using the knowledge of the input resistance of the rectifier itself. In this case, there is not a

---

7 In this section $T$ stands for the time
maximum energy transfer condition linked to the matching issue. From the voltage divider formula, the following equation can be obtain:

\[ v_{\text{in}} = V_S \frac{R_{\text{in}}}{(R_{\text{in}} + R_S)} \]  \quad (24)

from which, knowing all the quantities involved, \( R_{\text{in}} \) is obtained:

\[ R_{\text{in}} = \frac{V_{\text{in}}}{V_S} (R_{\text{in}} + R_S) \quad \Rightarrow \quad R_{\text{in}} = \frac{\frac{R_S}{V_S}}{-1} \]  \quad (25)

The input power results as being the following:

\[ P_{\text{in}} = \frac{v_{\text{in}}^2}{2R_{\text{in}}} \]  \quad (26)

in which the calculation of \( v_{\text{in}} \) will, therefore, be made using the software processing. The result of the previous equation is useful to discover which is the parameter that best can characterize and synthesize the quality of the rectifier, or rather the efficiency, defined in general terms as:

\[ \eta_c = \frac{\text{DC Output Power}}{\text{Incident RF Power} - \text{Reflected RF Power}} \]  \quad (27)

From the previous formulas, the equation to describe the efficiency of the component is obtained:

\[ \eta_{\text{rectifier}} = \frac{P_{\text{DC}}}{P_{\text{in}}} \quad \text{with} \quad P_{\text{DC}} = V_{\text{out}} I_{\text{out}} \]  \quad (28)
4.3.6 Rectenna Efficiency

A knowledge of the available power is necessary to obtain the efficiency of the rectenna as well as that of the rectifier which is defined as follows:

\[ \eta_{\text{rectenna}} = \frac{P_{\text{DC}}}{P_{\text{AV}}} \]  

(29)

Often the direct energy, or rather \( P_{\text{DC}} \), can also be called \( P_{\text{OUT}} \) that is the circuit output power. The denominator is the available energy present, which results as being

\[ P_{\text{AV}} = \frac{V_s^2}{8 R_s} . \]  

(30)

As a consequence, it is to be noted that an increase of the radiation resistance, leads to a decrease of the available power and, therefore, an increase of the efficiency. The continuous energy, as it will be shown later on, is obtained from the simulation stage.
Chapter 5

Simulation of the rectifier circuit

In this chapter the steps made during the building up of the rectifier and the analysis of performances will be described. At the end of this chapter, the results obtained by simulations will be presented and proposed. Generally, the Chapter 6 describes the following contents:

- Simulation set-up and description of basic building blocks;
- Matching issue;
- Simulation practice;
- Final simulation results;

5.1 Simulation set-up

Simulations were carried out in order to estimate the DC output voltage and then, the DC output power. At the same time, it is kept the ripple level, placed over the output signal, within tolerable limits, looking for a good compromise that limits, as much as possible, the electric transient of device. In this stage, the project design of two versions of the full-wave rectifier (1 and 2 stage), are analyzed. In Fig. 25 and Fig. 26, the schematics used for both rectifier version are shown

---

8 Defined as the alternating component (current or voltage) present over a DC power supply, due to an incomplete filtering consequently a rectification action
The choice for the size and the interconnection of all the components, is the basis for the circuit construction. The whole scheme of the circuit is composed by both the rectifier...
block and the components used for the simulations, which are considered external to the rectifier circuit. The basic elements which compose the rectifier are basically diodes and capacitors. The Agilent Technologies Diodes include various components in its library. The naming convention for the component utilized in order to build up the rectifier, is from the family HSMS. In Table 6, there is a detailed information of the component chosen as diode, from the ADS Schematic library:

<table>
<thead>
<tr>
<th>Description</th>
<th>HSMS2822:SOT23 Package 3 terminal HSMS-282x series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lib-Name</td>
<td>Hf-Diode Library</td>
</tr>
<tr>
<td>Placement Status</td>
<td>Layout</td>
</tr>
<tr>
<td>Availability&lt;sup&gt;9&lt;/sup&gt;</td>
<td>Available</td>
</tr>
<tr>
<td>Licence</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 6 - Description and information of the diode.

The same value for all the capacitors of the device, has been chosen equal to 12 pF. The size of the capacitors for the rectifier, will have a slight impact on the efficiency of the rectifier, and the chosen value performs well for all input powers. The components defined as external are introduced in order to carry out the simulation process, and they are a virtualization of the actual component, associated to the rectifier itself. One of these, is the antenna circuit, connected in front of the rectifier, showed in Fig. 27:

<sup>9</sup>The word Availability in this case defines if this component is actually available or obsolete
The antenna is simulated using its Thevenin equivalent circuit. The input voltage value determines the power that arrives to the antenna ($V_S$ in equation (12)). The equivalent resistance stands for the radiation resistance of the antenna. In order to simplify the simulation, a purely resistive antenna is considered despite an actual antenna will have some imaginary component. In this project, two values were considered for the radiation resistance: 50 $\Omega$ (typical antenna radiation resistance) and 300 $\Omega$ (typical folded dipole radiation resistance). The load represents the electronic device component connected to the previous rectifier block, represented through a resistor. The output current of the rectifier still has an AC component that has to be removed with a low pass filter. The output capacitor serves for this purpose. Then, output voltage ripple and stabilization time are directly related. When low ripple is desired, a bigger output capacitor is needed (lower cut frequency) and then, the output stabilization time is larger resulting in very long and time consuming simulations. So, a thorough trade-off between these two parameters will save a lot of simulation time. Fig. 30 shows a zoom of the circuit called post-rectifier that is the load:
The rectifier project design is composed of a trade-off between the analysis, balancing and comparing of more main factors. So, the parameters involved in simulation are:

- Input voltage;
- Radiation resistance;
- Number of stages of the rectifier;
- Output capacitor value ($C_{load}$, it was varied in order to have an accurate output with a reasonable simulation time);
- Load resistance;

5.1.1 Looking for a good matching level

To solve problems linked to the coupling of antenna and rectifier circuit, it is used a technique called inductive matching, which consists of an inductance interposed between the two circuits, as showed in Fig. 30:

![Fig. 29 - Matching inductance between antenna and rectifier circuit.](image)
In this way there is a compensation in the capacitive part linked to the rectifier input circuit, allowing the maximum energy transfer to the load, and a consequent improvement of the global efficiency. At this stage, it is necessary to search for the best value of inductance, in order to find the highest level of output voltage and current signal. Obviously, the operation has to be carried out for the rectifier with both one stage and two stages, and for two different antenna radiation resistance values ($Rs = 300$ Ω, $Rs = 50$ Ω). The values of every other circuit component, will be kept constant, modifying and varying just the value of inductance, in a range starting from few nH, and increasing progressively. The best value is found when the output voltage reaches its maximum level. It has to be explained that the output voltage and current, will always be the differential ones, that is $V_{out} = V_1 - V_2$, and not those compared to the ground. In Fig.32 and Fig. 33 the screenshots of the rectifier circuits in which the positions of $V_1$ and $V_2$ voltage are highlighted with a red line, are shown:

![Diagram of the rectifier circuit](image)

**Fig. 30** - Screenshot of the 1 stage rectifier circuit, with differential voltages called $V_1$ and $V_2$. 


Fig. 31 - Screenshot of the 2 stage rectifier circuit with differential voltages called $V_1$ and $V_2$.

The Table. 7 shows the final result obtained after searching for matching inductance with other circuit information:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setup value</th>
<th>Parameter</th>
<th>Setup value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectifier Stage</td>
<td>1</td>
<td>Rectifier Stage</td>
<td>2</td>
</tr>
<tr>
<td>Source Voltage [V]</td>
<td>1</td>
<td>Source Voltage [V]</td>
<td>1</td>
</tr>
<tr>
<td>Load Capacitance [pF]</td>
<td>100</td>
<td>Load Capacitance [pF]</td>
<td>100</td>
</tr>
<tr>
<td>Load Resistance [kΩ]</td>
<td>10</td>
<td>Load Resistance [kΩ]</td>
<td>10</td>
</tr>
<tr>
<td>Radiation Resistance [Ω]</td>
<td>50 ; 300</td>
<td>Radiation Resistance [Ω]</td>
<td>50 ; 300</td>
</tr>
<tr>
<td>Best matching Inductance value [nH]</td>
<td>15</td>
<td>Best matching Inductance value [nH]</td>
<td>7</td>
</tr>
</tbody>
</table>

Table. 7 - Summary of the main values during simulation stage in order to search the matching inductance of the rectifier
As shown in the previous table, the best matching is not susceptible to the variation of $R_s$. Furthermore, the matching grade obtained with these values is still valid for little load variations used for the simulation.

### 5.2 Simulation practice

In this step a full simulation is carried out, with the more important and interesting results. Any important steps, which have been used for all the versions of the rectifier, will be described. Firstly, once the circuit construction has been completed, the simulation starts changing the load resistor in the range $[1 - 20] \text{ k}\Omega$ (in some case it is utilized a load of $500 \text{ } \Omega$ too). This takes place because the actual load is changeable like a resistor belonging to these values, besides the fact that the best performances can be found in this spread of values. In Table. 8, the parameters and the range of value, useful in the simulation stage, are shown:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setup value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage range ($V_{in}$) [V]</td>
<td>$[0.7 \sim 2.0]$</td>
</tr>
<tr>
<td>Load Resistance range ($R_L$) [kΩ]</td>
<td>$[0.5 \sim 20]$</td>
</tr>
<tr>
<td>Simulation Time range [μs]</td>
<td>$[10 \sim 20]$</td>
</tr>
<tr>
<td>Circuit Stages</td>
<td>$[1-2]$</td>
</tr>
<tr>
<td>Radiation Resistance $R_s$ [Ω]</td>
<td>$50 / 300$</td>
</tr>
<tr>
<td>Range of allowed Ripple threshold</td>
<td>$ [&lt; 0.1 \sim 1]$</td>
</tr>
<tr>
<td>placed over output current and</td>
<td></td>
</tr>
<tr>
<td>voltage signal [%]</td>
<td></td>
</tr>
</tbody>
</table>

*Table. 8 - Summary of values used for the simulation stage.*
5.2.1 Measurement and evaluation

Since the Greinacher rectifier is a non-linear device, due to the presence of diodes, it is difficult to analyze this element in the time domain, and during its working cycle. Once the transients have been completed, the rectifier reaches the steady-state mode, in which the circuit works in a symmetric mode. In this case the rectifier diodes absorb the same charge during a whole cycle of the input signal. Then, in every simulation, it will be tried to reduce, as much as possible, the signal transient time, in order to reach the steady-state mode in which the rectifier provides constant output current and voltage, called $I_{\text{out}}$ and $V_{\text{out}}$ respectively. In order to stabilize the circuit, the value of $C_{\text{load}}$ has been accurately decreased. It has to be decreased until the peak-to-peak amplitude value, of the ripple, taken on the voltage and current output waveforms, appears negligible if compared to the maximum value of these signals. With the term negligible, it is meant a ripple spread, from about 0.1% till a limit approximately of 1%, compared with the output signal. This needs to be carried out, for every single value both of the input voltage $V_{\text{in}}$ and the load resistance $R_{\text{load}}$.

5.2.2 Transient simulation time setup parameters

ADS provides access to Transient simulation parameters, enabling to define aspects of the simulation set up. In Fig. 33 is shown a screenshot for the Transient Time component, used in ADS:

![Fig. 32 - Transient Time Screenshot.](image)

In the Time Setup there are fundamentally, the following parameters:
- Start Time, that is the time at which the simulator begins outputting time-point results. This enables control over large amounts of output data.
- Stop Time, that is the time at which the simulator stops outputting time-point results. It must be long enough if steady-state is needed.
- Max Time Step, that is the largest time step to be taken in the simulation.

At the beginning, the Start Time has been set to zero value, and the Stop Time to 20 µs, aware that if the signal reaches the steady-state mode in a shorter time, than the previous spread, it will be decreased. Anyway, the simulation time set up, allows to choose the interval time which the simulation can be displayed.

### 5.2.3 Determination of the ripple for a full-wave rectifier

An analysis to quantify the ripple in the proposed system is provided. In this stage it has to be considered that a decrease of $R_{\text{load}}$, involves an increment of $C_{\text{load}}$. Furthermore, the dimensioning of this capacitor, takes a deep effect on the time needed by the curve to reach the steady-state mode, in other words, the transient time. Consequently, when the value of $C_{\text{load}}$ increases, better, and therefore lower, ripple levels are obtained. The effect of $C_{\text{load}}$ on the trend of the output waveform can be noted a kind of rectifier with the following features is taken into consideration:

- 2 stages;
- Radiation resistance of 300 Ω;
- Source Voltage $V_s = 1$ V;
- $L_{\text{matching}} = 7$ nH;
- Load Resistance of 20 kΩ;

By setting a value of $C_{\text{load}} = 250$ pF, it can be noticed that it is too high, leading to a transient time too long with reference to the maximum visualization time, that is 20 µs. The trend of the voltage signal is shown in Fig. 33, together with a zoom of the ripple level. In this case, with the value of $C_{\text{load}} = 250$ pF of capacity, the ripple level will result very low.
Fig 33 - Graphical plot of the transient phenomenon on the output voltage signal waveform with a long transient time and a good ripple level.

It is clear the need to decrease $C_{load}$ value. After many simulations, the conclusion is that with a 10 pF value, there is a better behaviour. Then, it is possible to reduce simulation time up to 5 µs, because of the reduced transient. The new graphical plot of the output voltage waveform, with a short transient time, is shown in Fig. 34, in which there is an acceptable ripple level:
An inevitable consequence, is the increase of the ripple level, which presents a peak variation between the markers m2 – m3 of 40 mV. However it is insignificant if compared to the output voltage level, that is 1.6 V. A better response is noticed on the input signal too, as Fig. 35 shows:

**Fig. 34** - Graphical plot of the transient phenomenon for the output voltage waveform.

**Fig. 35** - Input voltage waveform vs time, with peak marker.
5.3 Comparison: considerable results

After an accurate analysis, it has been possible to build the data tables in order to memorize, store and calculate all the parameters involved in every simulation. Thanks to these tables, graphical representations can be made in order to explain more clearly and synthetically the variation of results, and their comparison. First, the global results have to be summarized, and secondly the most interesting parameters have to be collected, in order to make a good comparison for all the results. For example, one of these, is the efficiency, which will be put in relation with every main parameter of the testing.

5.3.1 Efficiency with reference to available power

The efficiency of the simulated rectenna of the rectifier across several load resistance values, as function of Available Power, are shown in Fig. 36 and Fig. 37:

![Fig. 36 - Trend of rectenna efficiency compared with the available power.](image)
The 300 Ω version, shows better performances better at lower input powers thanks to a better match between the antenna and the rectifier circuit. This is due to the growth of the rectifier input impedance at low input powers (below the mW). So, for larger powering ranges, a high radiation resistance is necessary. Ideally, radiation resistance has to change accordingly with the rectifier input impedance, so that a perfect matching is always achieved.

5.3.2 Efficiency with reference to RX-TX Distance

In Fig. 38 and Fig. 39 the trends of every rectifier version, grouped, together in the same graph, are shown in order to compare the efficiency with the transmitter distance. At every graphic curve is associated a different value of load resistance. This values of $R_{\text{load}}$, fixed with every curve, are those which showed the best performance and results from simulation, in terms of efficiency.
Thanks to the Friis relation, it has been shown that the distance result an inverse function of the available power, consequently, when distance increases, the available power decreases, together with the system efficiency. So, the conclusions are very similar to those of the previous section. The distance range in both cases is slightly more that 20 cm till a maximum of 1.4 m. For greater distances there are levels too low to be analyzed.
5.3.3 Simulation results for a 2 stage, 300 Ω rectifier

Particular attention is paid to the 2 stage rectifier, with a radiation resistance of 300 Ω, because it has been seen as the version with the greatest productivity during the simulation. In the graphical curves of Fig. 40 and Fig. 41, the efficiencies compared to the load resistance are analyzed. The obtained graphs are used to set the optimum value of $R_{load}$.

![Graph 40](image1)

**Fig. 40 - Trend of rectifier efficiency with reference to the load resistance.**

![Graph 41](image2)

**Fig. 41 - Trend of rectenna efficiency with reference to the load resistance.**
The values of the resistor, between 1 and 20 kΩ, have been reported, based on different values of equivalent source voltage $V_s$. Anyway, there is a different trend of the graphic, for the highest voltages, with $V_s$ between 1.5 and 2 V. In this range, after an almost increasing trend, for higher levels of the load resistor, the curves find a balance with small efficiency improvements. The graphs of Fig. 42 and Fig. 43, show the rectifier and the rectenna efficiency levels, compared to different values of available power. It has to be remembered that the available power depends on the voltage $V_s$. In the following, the values are collected and reported for different values of $R_{\text{load}}$:

**Fig. 42** - Trend of rectenna efficiency versus the available power with increasing load resistance.

**Fig. 43** - Trend of rectifier efficiency versus the available power with increasing load resistance.
Chapter 6

Dimension and analysis of the antenna

In this chapter the design of a folded dipole antenna, with high rectification efficiency at the frequency band of 868 MHz, is studied. This model of antenna will be utilized as a receiver element, in order to collect the RF energy assigned to the rectifier. Furthermore, a good antenna design helps to obtain higher DC combining efficiency. The simulation is based on the Method of Moments (MoM) in the ADS 2008. The topic treated in this chapter are the following:

- Design methodology
- Simulation and performance measurement
- Implementation of results.

6.1 Momentum Basics

Momentum is an electromagnetic simulator based on the finite element method that computes S-parameters for general planar circuits called Momentum. It gives a complete tool set to predict the performances of high-frequency circuit boards, antennas, and integrated circuits (ICs). It will be used the microwave mode of Momentum, suitable for the designs that require the full-wave electromagnetic simulations, and that include the microwave radiation effects. The main objective of this section, is to design a folded dipole antenna with a sharp return loss curve with high gain over the range of frequency from ambient RF energy. A folded dipole antenna structure has been selected because of its small dimensions, manufacturing easiness and low costs. In order to design the antenna the Layout mode of ADS has been used.
6.1.1 Substrates in Momentum

A substrate is the media upon which the circuit exist. A complete substrate definition is made up of a substrate layers and a metallization layers, and it is required in order to simulate a design. Momentum defines a *metallization layers* as the conductive layers between the substrate layers. They are used in conjunction with the layout layers. Furthermore, a substrate definition enables to specify properties such as the number of layers in the substrate, the dielectric constant, and the height of each layer for the circuit and, then, the composition of each layer. This is also where the layers of physical design have been positioned. To define a substrate for an antenna that radiates into air, it can be defined the following substrate definition

- Free_Space, defined for the top plane;
- Free_Space1, defined for the bottom plane;

Momentum considers, as a substrate layer, also the air portion above and below the antenna structure. Furthermore, Both layers are defined as open boundaries. This option, represents a layer of infinite thickness. In order to define the characteristics of the air, also called free space, from the Permittivity and permeability (Er) listbox, it can be selected respectively the values of the real and the imaginary portion. In this case, for the free space both the Permittivity and the Permeability have the real portion equal to 1 and imaginary equal to zero, as the Fig 44 shows:

![Fig. 44 – Set up of the free space Substrate layer](image)

- **Relative permittivity**, defined of the all dielectrics, it is assumed to be complex. In this case, for the permittivity of the free space (air), it is chosen the real portion equal to one;
- *Dielectric loss tangent*, associated with the material. It is a function of the frequency and it is linked to complex portion of the permittivity. With the free space it will be chosen a loss tangent equal to zero;

The antenna design is positioned on the metallization layer between the two layers of air. Interface layers have finite thickness, and they can be characterized using relative permittivity and permeability values. From the Permittivity ($\varepsilon_r$) and Permeability ($\mu_r$) listbox, a format for the relative permittivity and permeability of any layers has been selected, as Fig. 45 shows:

![Fig. 45 - Substrate layers for the dielectric.](image)

In this stage of design, thanks to the EMDS simulator, it is possible to invoke the 3D previewer, in order to validate that the proper mappings have been set up and that they have the correct height. In Fig. 46 a zoom of the region on the end section of the antenna is shown. The red area represents the area of interest, in which both the dielectric bricks and the substrate outline are shown with more details.
A variety of predefined substrates are included in ADS, which can be used. To edit an interface layer FR4 as layer name has been inserted, which is a kind of dielectric chosen from ADS library, and which offers many features useful to the development of this model. The layer thickness value in the range \([1.2 \sim 1.6]\) mm has been chosen.

### 6.1.2 Mapping a Layout Layer

In the Substrate Layer section name and characteristics of the following items have been defined:

- the dielectric substrates;
- the two layer of air defined free space;
- the two metallization;

Layout layers that contain any components, which are part of the circuit, must be mapped to metallization layers. A Strip is used to define the objects on the layout layer, as a conductor. Then, it has to be define the conductivity of metallization, in order to select the conductor type as Sheet Conductor from Type list. The Thickness has been set to 18 µm and the conductivity definition as Perfect Conductor has been set in the Material field.
This means that the strip is a lossless perfect conductor. It is necessary to repeat these steps for the remaining mapped layout layers. In Fig. 47 a screenshot of every substrate and layout Layer is shown:

![Layer Mapping](image)

**Fig. 47 - Layer mapping.**

### 6.2 Adding a port and assigning properties

Ports enable energy to flow into and out of a circuit. Energy is applied to a circuit as part of the simulation process. Firstly, the ports are added to the circuit in the drawing set up. Generally the port type, has to be selected. Therefore, two ports, called Differential Ports, with opposite polarity, will be inserted. Differential ports have the feature that each of the two ports is excited with the same absolute potential, but with the opposite polarity, so the voltages results opposite (180 degrees out of phase). This type of ports is used in situations where an electric field, that builds up between the two ports, will have an effect on the circuit that should be taken into account during the simulation. Moreover, differential ports should be used when they are connected to objects located on strip metallization layers. The currents are equal but opposite in direction when the ports are on two symmetrical lines. After inserting the two ports, respectively in the middle point of the two vertical strips on the folded dipole antenna, a port reference plane is showed in Fig. 48:
Once the substrate and dielectric layers have been defined, the port Editor, in the Momentum menu, can help to change the specific characteristics of the ports, so they can be configured properly, as shown in Fig. 49:

Among setting 300 Ω has been chosen as the real part of the impedance field and zero has been left for the imaginary part. For the associate condition of the ports it has to be put Normal and Reversed mode in the Polarity field, in order to produce an input and output energy flow, useful to the simulation stage.
6.3 Set up and generate the mesh to the circuit

Defining a good mesh value is essential for antenna simulation. First, a mesh is defined as a grid-like pattern of triangles and rectangles, that is applied to a design, in order to discretize the circuit into more and more small cells. The mesh is then applied to the circuit in order to compute the current within each cell, and identify any coupling effects in the circuit, during its simulation. Since a mesh is required in order to begin the simulation, in the following, it is described how to define the mesh parameters and calculate them for this project. This computation method is known as finite element analysis, and it enables to control the number of cells that are used to create the mesh. Two mesh parameters, Mesh Frequency and cell/wavelength, are used in combination in order to determine the mesh density, as Fig. 50 shows:

![Mesh Frequency and Density values](image)

The Mesh Density is kept between 100 and 400 cells/wavelength. After precomputing the substrate and apply ports to the circuit, a pattern of rectangles and triangles is computed and applied to the circuit. In Fig. 51 a layout of the circuit, after this operation, is shown:

![Display after mesh](image)
During a simulation, the surface current in each cell is calculated, and this information is then used to solve the S-parameters for the structure.

### 6.3.1 Mesh parameters

The mesh generator is relatively fast, even for complex meshes. However a complex mesh can have a significant effect on the simulation time. In particular, the number of cell in the mesh and the number of unknown currents, can affect the simulation time. Fig. 52 shows the consequence of a complex mesh:

![Diagram of mesh parameters](image)

**Fig. 52** – *Comparison of parameters implicated in the mesh operation.*

Simulation times will be faster when the mesh consists mostly of rectangular cells. A simple mesh is a mesh consisting of a few similar rectangles, so the size of matrix to be resolved during simulation will be small. Since the time required solving this matrix is proportional to the size of the cell, reducing the complexity of a mesh means reduce the matrix size, in turn the amount of time required to simulate.
6.4 Simulation set up and layout of results

In the simulation set up, the parameters of a frequency plan, such as the frequency range of the simulation and the sweep type, are specified. The Green function is used in the simulation process, in order to compute the mesh pattern for the substrate. So the currents are calculated in the design. The S-parameters are then computed basing on the currents. The Momentum solver uses information from the substrate database and the mesh generator to perform the circuit simulation. So, the next step is to set up the frequency plan, with the following parameters:

- **Sweep type**: Logarithmic, selecting the frequency points to be simulated in logarithmic increments.
- **Start / Stop frequency**: is the frequency range adapted for the project. It used a frequency range from 500 MHz to 1.2 GHz for a complete simulation of the system.
- **Points / Decade**: this parameter is able to beat the consecutive points which build the trend of the curve for the $S_{11}$ parameter. So, a relatively low value is set up. Then, for a better resolution of the results, this value will be increased progressively.

Fig. 53 presents a screenshot of the frequency plan used in this simulation:

![Fig. 53 - Frequency plan screenshot.](image)

Once the currents of the circuit have been known, the electromagnetic fields can be computed and the results can be displayed as $S_{11}$-parameter. Precisely, in Fig. 54 the magnitude in dB of the $S_{11}$-parameter is shown versus a long frequency range:
Information from Date Markers over $S_{11}$ parameter show a structure matched in the frequency band of approximately 90 MHz:

- m1 in the frequency of 868.7 MHz; $\text{dB}(m1) = -21.074$;
- m2 in the frequency of 823 MHz; $\text{dB}(m2) = -10.099$;
- m3 in the frequency of 914 MHz; $\text{dB}(m3) = -10.082$;

The used frequency plane, presents a wide range for the visualization of the results. The study is mostly concentrated near to the resonance frequency of the rectenna, that is 868 MHz. So, attention is paid to a smaller bandwidth, with a Return Loss Curve below the -10 dB value. Once a good dimensioning of the entire antenna structure has been made, the frequency simulation range can be reduced, for a better visualization, as shown in Fig. 56:
Fig. 56 - Return Loss Curve for Antenna ($S_{11}$ parameter magnitude) for a shorter frequency range.

Fig. 57 shows the structure of the folded dipole antenna with the dimensions of each segment.

![Dimensions of each segment of the geometric structure in a 2D view.](image)

Fig. 57 - Dimensions of each segment of the geometric structure in a 2D view.

Then, in order to display 2D and 3D representations and to animate current flows in conductors and slots, the Momentum Visualization option has been used. This gives a 3-dimensional perspective of the simulation results, as shows Fig. 58:
The colours in the folded dipole layout, in the previous Fig. 59, show the current density of the antenna. As expected (Section 2.4.1), the current distribution is more or less the same, in both arms of the folded dipole (green in the middle turning, blue towards the edges) allowing the antenna to behave as a quarter wavelength dipole, in terms of radiation, but with four times more radiation resistance.
6.4.1 Plotting S-parameter by Smith Chart

The Smith Chart is among the most used diagrams to solve problems referring to transmission lines, thanks to its easiness of use. Below, the trend of the antenna in the frequency range, which goes from 500 MHz to 1.2 GHz, is shown in the Fig. 59:

![Smith Chart for the antenna.](image)

The loop near the middle point of the Smith Chart, is a clear indicator of the fact that the antenna is resonating over these frequencies with a better $S_{11}$-parameter.

6.5 Radiation pattern and far field plot

Radiation of antenna properties are summed up in the radiation patterns, seen as the mathematical expression, or the graphical representation, which allows to describe the way in which the radiation properties change, on the base of the directions of the chosen reference system. When a problem contains far field data, a window of Momentum Visualization is used to display the far field plots in 3D. The kind of the obtained radiation diagram, is better defined as rotation solid, as shown in Fig. 60:
By default, the window is initialized by displaying the electric field pattern of the E-plane as shown in Fig. 61 and Fig. 62. For a linearly polarized antenna, the E-plane results the section of the radiation diagram containing the electric field and its maximum radiation direction.
The radiation pattern plotted in Fig. 62 and Fig 63 is very similar to that of the quarter wavelength dipole. Emission is maximal in the plane orthogonal to the dipole and zero in the direction of the wires. As said before, the folded dipole behaves similarly to the dipole in terms of radiation pattern, so this validates the design.

### 6.6 Antenna features

This section provides general information about the antenna features, that can be generated from the radiation fields calculated by Momentum simulation. For each graphic trend, a brief description of the equation which it represent will be shown. Following, a description of some variables and parameters used in the equations, are described, in order to understand the antenna features:

- $\Omega_A = \frac{P_{\text{rad}}}{U_{\text{max}}}$, is the solid angle through which all power emanated from the antenna would flow if the maximum radiation intensity is constant for all angles over the beam area. It is measured in steradians;

- $P_{\text{inj}}$, is the actual power, in watts, injected into the circuit;
\( \theta \), is the swept parameter of a planar cut. When THETA is swept, PHI is at a fixed angle specified in the Cut Angle field and is not returned to the dataset;

\( \phi \), is the swept parameter of a conical cut. When PHI is swept, THETA is at a fixed angle specified in the Cut Angle field and is not returned to the dataset;

\( U(\theta, \phi) \), is the radiation intensity in a certain direction, in watts per steradian;

\( U_{\text{max}} = \max_{\theta, \phi}(U(\theta, \phi)) \), for a certain direction, is the radiation intensity will be maximal, and the maximum value will be called \( U_{\text{max}} \);

\( P_{\text{rad}} \), is the total power radiated by the antenna, in Watts;

**Effective Area**

The power density is usually given in power per area (W/m\(^2\)), so the effective area indicates how much power can be collected by the antenna. The interest is maximizing this parameter in order to collect as much power as possible for the same distance from the transmitter. The effective area of the antenna is given by the expression (31) and its plot is shown in Fig. 63:

\[
A_{\text{eff}}(\theta, \phi) = \frac{\lambda^2}{4\pi} G(\theta, \phi)
\]

(31)

![Fig. 63 - Effective area plot of antenna.](image)
Directivity and Gain in dB

Directivity is dimensionless, and it is represented by the relation between the antenna radiation intensity in a specific direction, and the average radiation intensity among all directions. It can be also defined as the relation between the antenna radiation intensity and the isotropic antenna radiation intensity:

\[ D(\theta, \varphi) = 4\pi \frac{U(\theta, \varphi)}{P_{rad}} \tag{32} \]

The maximum directivity is given by:

\[ D = 4\pi \frac{U_{max}}{P_{rad}} = \frac{4\pi}{\Omega_A} \tag{33} \]

The gain of the antenna in the direction of maximum radiation, is described with a similar equation, that is the fraction between the isotropic radiated power and the real radiated power of the antenna taken into account, in order to achieve the same intensity of field, with a fixed distance, and in the maximum radiation direction. The gain and the directivity of the folded dipole, are shown in Fig 64:

\[ G(\theta, \varphi) = 4\pi \frac{U(\theta, \varphi)}{P_{inj}} \tag{34} \]

The maximum gain is given by the expression:

\[ G = 4\pi \frac{U_{max}}{P_{inj}} \tag{35} \]
The gain shows the directivity of antenna, that is its ability to irradiate energy by concentrating it in the desired direction. The definition of gain is based on the shape of radiation diagram. The graphic in Fig 64, has shown a gain and directivity plots, placed over each other, with the same trend. It happens when the studied antenna has an efficiency which equals to 100%, that is, when radiated power is perfectly the same as the source power. Actually the gain is always inferior to directivity.

**Efficiency**

The efficiency is given by the relation between the gain and the directivity. A plot of the efficiency for the antenna simulation, is shown in Fig. 65:

$$\eta = \frac{P_{\text{rad}}}{P_{inj}} = \frac{G}{D}$$

(37)
Fig. 65 - Efficiency plot of antenna.

To summarize, ADS allows to display a table where all the information useful to comprehension of simulation results is groped, and shown in Fig 66.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power radiated (Watts)</td>
<td>0.000374116</td>
</tr>
<tr>
<td>Effective angle (Steradians)</td>
<td>7.3597</td>
</tr>
<tr>
<td>Directivity (dB)</td>
<td>2.3235</td>
</tr>
<tr>
<td>Gain (dB)</td>
<td>1.88977</td>
</tr>
<tr>
<td>Maximum intensity (Watts/Steradian)</td>
<td>5.08331e-05</td>
</tr>
<tr>
<td>Angle of U Max (theta, phi)</td>
<td>131</td>
</tr>
<tr>
<td>E(theta) max (mag,phase)</td>
<td>0</td>
</tr>
<tr>
<td>E(phi) max (mag,phase)</td>
<td>0.195706</td>
</tr>
<tr>
<td>E(x) max (mag,phase)</td>
<td>0.195706</td>
</tr>
<tr>
<td>E(y) max (mag,phase)</td>
<td>3.59506e-17</td>
</tr>
<tr>
<td>E(z) max (mag,phase)</td>
<td>0</td>
</tr>
</tbody>
</table>

Fig. 66 - Electromagnetic parameters of antenna from Momentum Visualization.
Conclusions

The system achieved is able to convert energy efficiently by the receiving and rectifying a previously transmitted RF signal, over the range of 868 MHz. In fact, rectifier theory, and its applications, are able to provide a DC power supply for electronics systems. The result of my project of thesis shows that has been possible to achieve a folded dipole antenna with a bandwidth of 90 MHz and a return loss curve of -21 dB, with a radiation diagram like a classic dipole. Even though it has been taken into consideration many factors in the design step of antenna, but as often happens in a project development, there are some factors that is difficult to characterize completely, for example the parasite effects. Since only the fundamental factors are analyzed in this simulation, it could be useful a feed-back in the set-up stage, in order to minimize the possible imperfections in the layout of the antenna, in order to limit the parasite phenomena. Concerning the rectifier, the best obtained results are different according both to the used version of the rectifier and to the size of the electronics elements, linked to the rectifier device. The 1 stage 50 Ω rectifier, shows a good trend for a low level of the available power, while the 2 stage 300 Ω rectifier is a good choice when the transmission distance is higher. Generally, the optimal results are obtained, however, for high load resistance values. Anyway, the simulation stage and the following analysis of data and results, can be considered a beginning development of a wider working process, in order to realize a future possible energy supply system. A further step is to complete the simulation and then try to choose the best solution obtained, in order to realize the actual device, in other words the rectenna. Summarizing, the rectifier is a key block in every remotely powered system. So, this technology has been used successfully throughout the world. Traditionally, limitations in power ratings, lead to use a few numbers of specific devices working with low power level. The development of power semiconductor technology, over the last years, has led to a gradual improvement of rectifier design, with respect to the previous versions. This optimisation has led to the rectifier design both a practical and economic option, compared to the traditional powering source.
References


[9] MONGIARDO M., et al., Analisi di antenne a dipolo ripiegato a 2.5 GHz per applicazioni RFID. Dipartimento di Ingegneria Elettronica e dell'Informazione, Università di Perugia


