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Jari-Pascal Curty, Michel Declercq
Catherine Dehollain, Norbert Joehl
École Polytechnique Fédérale de Lausanne, Switzerland

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Jari-Pascal Curty
Michel Declercq
Catherine Dehollain
Norbert Joehl
École Polytechnique Fédérale de Lausanne, Switzerland

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Preface

RADIO Frequency IDentification (RFID) is an automatic identification method, relying on storing and remotely retrieving data using devices called RFID tags or transponders. An RFID tag is a small object that can be attached to or incorporated into a product, animal or person. An RFID tag contains an antenna to enable it to receive and respond to Radio-Frequency (RF) queries from an RFID reader or interrogator. Passive tags require no internal power source, whereas active tags require a power source.

As of today (2006), the concepts of ubiquitous computing and ambient intelligence are becoming widespread. In order for these to become a reality, a number of key technologies are required. In brief, these technologies need to be sensitive, responsive, interconnected, contextualised, transparent and intelligent. RFID, and in particular passive RFID tags, are such a technology. In order to deliver the necessary characteristics that could lead to ambient intelligence, however, there are some challenges that need to be addressed.

Remote powering of the tags is probably the most important challenge. Issues concerning the antenna-tag interface and the rectifier design, that allow the RF signal to be converted to Direct Current (DC) are top priorities. Secondly, the communication link and the reader should be optimized. The RF signal that contains the tag data suffers from a power of four decay with the distance between tag and reader. As a result, both the reader sensitivity and the tag backscattered power efficiency have to be maximized. Long-range powering, as well as sufficient communication quality, are the guidelines of this work.

This work proposes a linear two-port model for an N-stage modified-Greinacher full wave rectifier. It predicts the overall conversion efficiency at low power levels where the diodes are operating near their threshold voltage. The output electrical behavior of the rectifier is calculated as a function of the received power and the antenna parameters. Moreover, the two-port parameter values are computed for particular input voltages and output currents for the complete N-stage rectifier circuit, using only the measured I-V and C-V characteristics of a single diode.

Also presented in this work is an experimental procedure to measure how the impedance modulation at the tag side affects the signal at the reader. The method allows the tag designer to efficiently predict the effect of a modulator design at the system level and gives a useful instrument to choose the most appropriate impedances.

Finally, the design of a fully-integrated, remotely powered and addressable RFID tag working at 2.45 GHz is described. The achieved operating range at a 4 W Effective Isotropically Radiated Power (EIRP) reader transmit power is at most 12 m. The Integrated Circuit (IC) is implemented in a 0.5 μm silicon-on-sapphire technology. A state-of-the-art rectifier design is embedded to supply energy to the transponder. Inductive matching and a folded-dipole antenna are key elements for achieving this performance.

1

Introduction

THE trend in the automated industry is to move towards fast and real-time identification, further improving the high level of accuracy needed to enable continuous identification and monitoring. Such a level of real-time knowledge is often called *ambient intelligence*. One of the technologies that made this concept viable is known as Radio Frequency IDentification or more simply RFID. Companies, individuals and states can benefit from such a technology. There are numerous applications including: logistics, access control, transportation, pet management, counterfeit struggle, e-documents (biometric passports), etc. As usual with new technologies, these benefits should be balanced with the impact on personal privacy. Like no other technology, RFID opens new application horizons but also introduces new topics of reflection for lawmakers.

Passive (without embedded electrical energy) RFID transponders are composed of an electronic Integrated Circuit (IC) that usually contains data and an antenna. The IC is powered by a reader that also communicates with the tag in order to get its data (usually on the order of a few hundreds bits). The general overview of such a system is shown in Fig. 1.1.

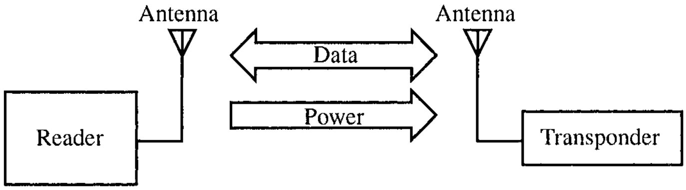

Fig. 1.1. RFID system overview.

1.1 Objective of this work

The goal of this work is to bring to light the trade-offs that occur in the optimization of passive Radio Frequency Identification systems operating at UHF and microwave frequencies. At these frequencies[1] (VHF: 433 MHz, UHF: 900 MHz or 2.45 GHz[2]), the identification transponder (called tag or transponder hereafter) is operating in the *far-field region* of an 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. At low frequencies (LF: 135 kHz and HF: 13.56 MHz or 27.12 MHz) where we find 95 % of the RFID market (2004 values [1]), the tag lies in the *near-field region* in which the inductive coupling phenomenon is used. LF and HF tags thus inherently reach a smaller operating range than their VHF, UHF and microwave counterparts. In this work, we consider only UHF and microwave systems. LF and HF systems are treated extensively in [2] and [3].

1.2 Organization of this book

There are three key issues in the development of a UHF or microwave system. First, we find the Wireless Power Transmission (WPT) issue. As will be presented in **chapter 2** and **chapter 3**, the choices of the *rectifier architecture*, the *antenna design* and the *integrated circuit process technology* are of central importance. These chapters are a developed version of [4].

Tag-to-reader communication is the second issue and will be addressed in **chapter 4 and chapter 5** where a complete study of the possible signal modulations will be proposed. **Chapter 6** presents an experimental method to quantify the backscattered power in phase and amplitude of any antenna. In **chapter 7**, we take advantage of the previous chapters to design a full integrated passive transponder operating from 900 MHz up to 5 GHz depending on the antenna size and achieving 12 m of reading range at 2.45 GHz. This chapter is an extended version of [5].

The third issue that limits the performance of an RFID system is the reader design. This aspect will be described in **chapter 8** where an architecture of both the RF and baseband system is proposed.

Finally, **chapter 9** concludes this work with the obtained results as well as new research ideas.

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[1]LF: Low Frequency
HF: High Frequency
VHF: Very high frequency
UHF: Ultra-High Frequency

[2]Although the 2.45 GHz Industrial Scientific and Medical (ISM) band is part of the UHF spectrum according to the DIN40015 standard, it will be named "microwave" in this work.

2

Wireless Power Transmission

This chapter presents the history of Wireless Power Transmission (WPT) from Tesla to the rectenna. The basic rectifier, its building blocks and the full-wave modified Greinacher rectifier are then described [4]. The antenna and its issues for WPT illustrate the basic trade-offs that occur. Finally, a numerical example of WPT concludes this chapter.

2.1 History of Wireless Power Transmission

THE idea of Wireless Power Transmission (WPT) was first conceived and explored in 1899 by Nikola Tesla. During a conference, he announced that his personal dream of WPT was realized. He attempted to distribute ten thousand horse-power under a voltage of one hundred million volts. As said in his words: "This energy will be collected all over the globe preferably in small amounts, ranging from a fraction of one horse-power to a few horse-power. One of its chief uses will be the illumination of isolated homes."

Tesla conducted his experiments in Colorado Springs, Colorado, in 1899 (Fig. 2.1). Under a $30,000 (value in 1900!) grant from Colonel John Jacob Astor, owner of the Waldorf-Astoria Hotel in New York City, Tesla built a gigantic coil in a large square building over which rose a 60 m mast with a 1 m diameter copper ball positioned at the top. The coil was resonated at a frequency of 150 kHz and was fed with 300 kW of low-frequency power obtained from the Colorado Springs Electric Company. When the RF output was fed to the mast, an RF potential was produced on the sphere that approached 100, 000, 000 V, according to Tesla [6]. Some of his experiments were related by the journalists of his time. According to them, he succeeded in lighting two hundred 50 W incandescent lamps 42 km away from the base station.

Tesla not only thought that the globe was a good conductor but that the moderate altitude atmospheric layers were excellent conductors. Therefore, he wanted to prove it was possible to use these layers in order to transmit large amounts of electrical

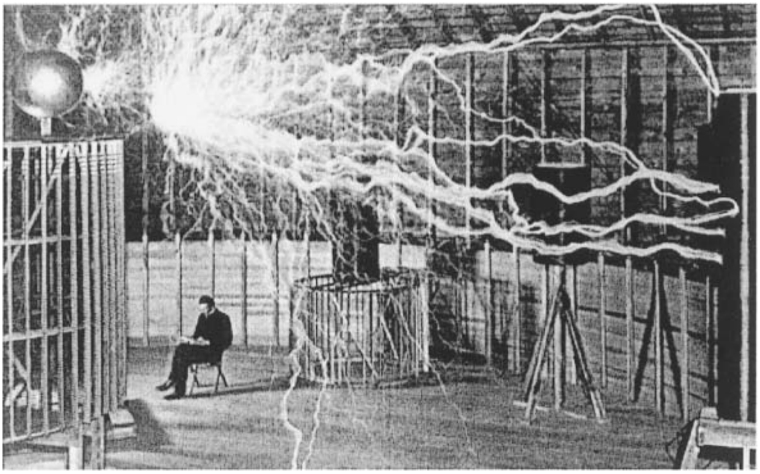

Fig. 2.1. Tesla in his Colorado Spring laboratory

energy over any distance. He proposed the idea (Fig. 2.2) but his sponsor, Morgan, retorted, "If everyone is able to draw energy from there, where would the electricity meter be?"

The work of Tesla was based on very long wavelengths and thus, the concept of radio wave focusing couldn't be used. The work of Heinrich Hertz demonstrated electromagnetic wave propagation in free space and its possible detection. Although theoretically possible, electromagnetic wave focusing was not feasible in practice, due to the lack of short wavelength generators. The klystron tube and the microwave cavity magnetron arrived in the late 30's [7]. Real interest in WPT began in the 50's and triggered the modern history of free-space power transmission. For an extensive historical presentation, the interested reader is referred to [6].

Since Tesla's experiments on WPT, there has been more than one century of research, with most progress made after 1958, on the topic of high-power beaming. Applications concerning high power transmission, like solar-powered satellite-to-ground systems (SPS) [6] and helicopter powering, have been developed. Typical efficiency of those systems is about 85% at lower microwave frequencies and less than this higher in the spectrum. The common point of these system is the *rectenna.*

2.2 The rectenna

In the work of Tesla, there was a need for an energy transducer. It was needed to convert one type of energy to another. For the WPT in this present work, the energy conversion from RF to DC is realized based on a *rectenna* circuit.

A rectenna is a rectifying antenna, a special type of antenna that is used to directly convert microwave energy into DC electricity. By connecting a Schottky diode to the access of a dipole antenna, we obtain a simple rectenna. The use of a Schottky diode is

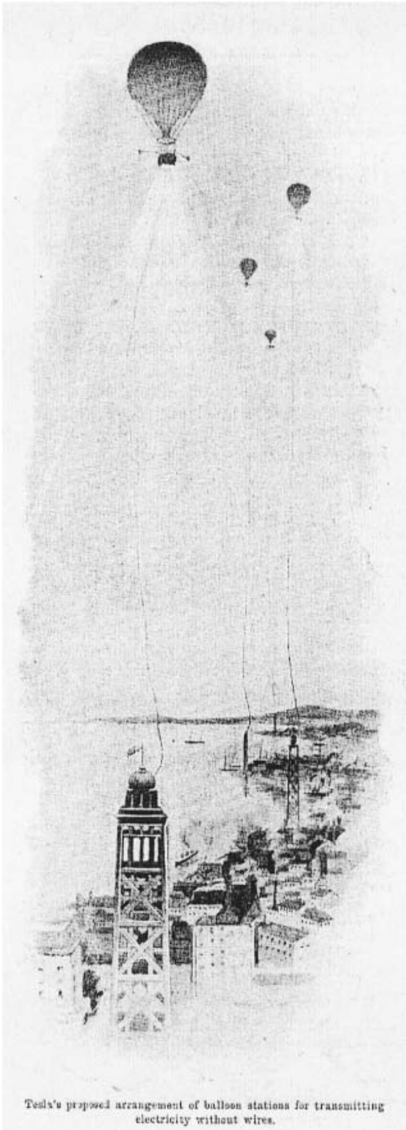

Fig. 2.2. Tesla's idea to transmit electrical energy from the atmosphere down to the earth. The use of a fire balloon would allow the electricity to flow along a conducting wire down to a base station. The city could then be "easily" energized.

necessary to achieve a high efficiency in the overall conversion process. A schematic of a typical rectenna circuit is shown in Fig. 2.3. The antenna captures the power from its surroundings (represented by the power density S) and generates a voltage at the diode D access. The latter rectifies the voltage to a DC current that charges the capacitor C at the rate RC.

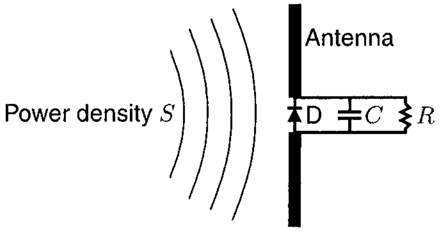

Fig. 2.3. A typical rectenna schematic.

William C. Brown was the first to succeed in demonstrating a microwave powered helicopter in 1964 using the rectenna [6]. The rectenna was thoroughly studied starting from the second half of the twentieth century resulting in high overall efficiency systems. With the advent of integrated circuits and low power technologies, new applications were made possible. In the mid 1980's [8], Radio Frequency IDentification Systems (RFID) appeared in which an inductive or electromagnetic coupling antenna was used for both power transmission and as a communication link. Other applications of WPT include biomedical implants with passive telemetry as a communication link [9]. More recently, the recycling issue of the ambient microwave energy was addressed [10]. The vast majority of these applications make use of a *rectifier* building block, similar to the basic rectenna of Fig. 2.3, to draw their energy.

2.3 Rectifier building blocks

The use of low threshold diodes (e.g. Schottky) and good quality capacitors allow a continuous voltage to be drawn out of a small amplitude pulsed signal (typically sinusoidal). The rectifier circuit is built out of two basic electrical circuits, the *clamping circuit* and the *envelope detector circuit.*

2.3.1 Clamping circuit

The goal of this circuit is to establish a DC reference for the output voltage by using a diode clamp as shown in Fig. 2.4.

By conducting whenever the voltage at the output terminal of the capacitor v_{out} goes negative, this circuit builds up an average charge on the terminal that is sufficient to prevent the output from ever going negative. Positive charge on this terminal is effectively trapped. If all elements are ideal, the residual negative voltage Δv_{r} is null and v_{out} is exactly equal to $\widehat{v_{\mathrm{in}}} + v_{\mathrm{in}}$ where $\widehat{v_{\mathrm{in}}}$ is the peak amplitude of v_{in}.

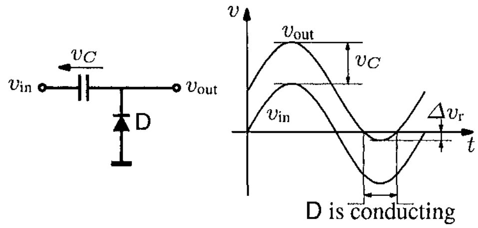

Fig. 2.4. Diode clamp circuit and its output waveform.

2.3.2 Rectifier circuit

When a voltage v_{in} is applied on the input of the circuit of Fig. 2.5, the capacitor charges until its voltage v_C is equal to the maximum of v_{in}. If no resistor is connected

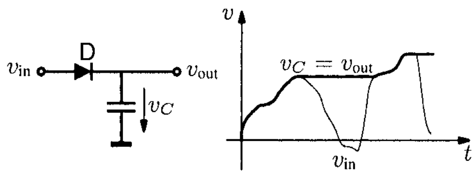

Fig. 2.5. Basic rectifier circuit and its output waveform.

in parallel with the output capacitor, the voltage v_{out} never reduces.

In practice, the leakage current of the capacitor induces an output voltage drop. If v_{in} is a sinusoidal signal, the capacitor will charge every time its voltage is near its peak value. Consequently, the mean output voltage $\overline{v_{out}}$ is slightly smaller than the peak amplitude of v_{in}.

In both cases, the threshold voltages of the diodes are not taken into account. But it should be mentioned that they further reduce the output voltage amplitude. All these effects are addressed later in this chapter.

2.3.3 The voltage doubler

The voltage doubler is obtained by cascading the blocks from sections 2.3.1 and 2.3.2. The result is shown in Fig. 2.6

As can be seen in Fig. 2.6, and from 2.3.1 and 2.3.2, the voltage doubler outputs a DC voltage. In the ideal case, v_{out} is twice the amplitude of v_{in}. This circuit is actually a half wave voltage doubler since only the positive peaks of the input signal are rectified. To take advantage of both positive and negative peaks, one must use the full-wave rectifier.