Antennas for RFID tags

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Abstract

This communication covers the design and optimization of antennas for RFID tags at UHF and microwave frequencies. Such design will focus on the specific characteristics of RFID applications such as back-scattering mode, variability of substrates and low cost constraints. The introduction includes a short history of RFID development. The second part will address the main characteristics of RFID antennas. The third part introduces the material characterization. Current developments of RFID antennas that meet the objectives of low-cost and size reduction are presented in part four. Design of antennas on plastic substrate using conductive inks will be shown as an example of low-cost approach. Advanced design techniques for size reduction, such as fractal techniques will be introduced and some design examples will be discussed. The fifth part concerns antenna modeling from the system point of view and examples of system simulation of an RFID communication will be shown.

1. Introduction

The birth of the Radio Frequency IDentification (RFID) was in October 1948 after the paper of Harry Stockman entitled "Communications by Means of Reflected Power" [1]. The popular system "Identification of Friend of Foe" (IFF) for aircraft was one of the first applications of the RFID. R.F. Harrington developed the electromagnetic theory related to the RFID application [2,3] and the 1960s were the prelude to the RFID explosion [3]. Commercial activities exploiting the RFID began also during the 1960s and the Electronic Article Surveillance (EAS) application is one example. The EAS is a simple "1-bit" tag since only the presence or the absence of a tag can be detected [4]. Under the drastic development of microelectronic technology during the 1970s, companies, universities and government laboratories were actively engaged in the development of practical applications of RFID such as animal tracking, vehicle tracking and factory automation. The 1980s was the decade for mass deployment of RFID technology. The interest in the US was mainly for transportation and access control. In Europe the greatest interests were for animal tagging, industrial applications and toll roads. Since the 1990s many technological developments are dramatically expanding the functionality of the RFID. Advances in microelectronics, embedded software and microwave circuits integration are opening the door to new wireless system and expanding the application field of RFID.

2. Main characteristics of RFID antennas

Radio-Frequency IDentification (RFID) [5] wireless systems generally consist of three parts, from the simplest to the more complex:

- T*ag* : a small mobile communication circuit embedded on radiating element.
- B*ase-Station* (BS): a fixed or mobile transmitter/receiver.
- Data base system for the processing of collected information.

A schematic RFID system and associated communication protocol is shown on figure 1.

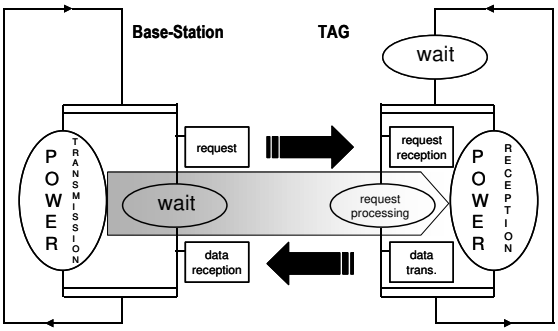

Fig. 1. Simplified BS-tag communication protocol.

RFID systems can be distinguished by their operating frequency ranges. There are four frequency bands :

- Frequency (LF) band corresponding to 125KHz and 134.2KHz.
- High Frequency (HF) band (13.56 MHz)
- The UHF band (869MHZ and 915 MHz and 950MHz)
- Microwave (2.45 GHz, 5.8GHz) band

Depending on applications and frequency, RFID tags can be active or passive. Passive tags operate without internal battery source but in practice they get their operating power from the signal coming from the BS.

The LF and HF are well developed and are currently used in several applications and domains such as : security, access control, animal identification, toll, transport and rail applications... From wireless point of view LF and HF operate under the near field regime of antenna elements and this will limit the communication distance to less than one meter. However, at these frequencies, many reliable and low cost electronic processing circuits are available and allow large diversity of applications. For larger communication distances UHF and microwave bands are more suitable since typical reading distance is larger than 3 meters (under 4 W emission permitted in US). Useful microwave Schottky diodes were fabricated on a regular CMOS integrated circuit. This development permitted the construction of microwave RFID tags that contained only a single integrated circuit, a capability previously limited to LF and HF systems [4].

A tag is composed of a chip (RFID IC) and an antenna. The tag antenna has three major functions :

- Collect the power from the BS. The signal sent by the BS is an electromagnetic wave at a fixed frequency. This signal is used for biasing the RFID IC
- Collect the modulated signal delivered by the BS. This signal is a request which have to be processed by the Chip..

- Send the information requested by the BS. This is accomplished thanks to the backscattering technique.

The backscattering method is based on load modulation technique. Indeed, from the circuit point of view, any antenna is modeled by its impedance. On the other hand the RFID IC has an equivalent impedance. So, when illuminated with an electromagnetic signal, the antenna will absorb an amount of power and will generate a reflected signal. Under perfect impedance matching between the antenna and the RFID IC, the absorbed power (Pabs) and the reflected power (Pref) are equal. So, under perfect matching conditions we have

$$P_{abs} = P_{ref} = P_o = S_{in}.A_e = S_{in}.D.\lambda^2/(4.\pi) \quad (1)$$

Where **Sin** is the incident power density
Ae is the antenna effective aperture
D is the directivity of the antenna
λ is the operating wavelength.

It is important to remark that the previous antenna parameter are frequency dependant. The reflected power is depends on the impedance mismatch between the antenna and the RFID IC. A basic circuit calculation shows that the maximum (**4Po**) reflected power arises when the RFID IC impedance is zero and the reflected power will vanish for very high (open circuit condition) IC impedance.

The previous comments clearly show the drastic importance of the antenna parameter and the impedance of the RFID IC.

3. Material for antenna

Antenna performance at UHF and microwave frequencies are dependant on the substrate i.e. thickness and electromagnetic properties (conductivity, permittivity and permeability). It also depends on the conductive quality of electrodes. Low cost constraints and diversity of RFID applications lead to consider non standard materials to be used for both tag and antenna. Investigations are needed in order to characterize these materials.

3.1. Substrate characterization

These investigations concern low cost substrate material such as paper, plastic and polymers. The dielectric characteristics of these materials are usually non available at UHF and microwave bands. A possible determination of the dielectric permittivity could be obtained thanks to perturbation method applied to microwave cavity. Indeed by inserting a small piece of the considered materials into a cavity, the resonant frequency of the cavity will change. The measurement of the changes in the resonant frequency and the transmission coefficient will permit the determination of the relative permittivity and the losses factor[6]. Typical results for a group of usual plastics are given in table below.

Table 1: Permittivity and dissipation factor for 9 polymers at 2.45GHz.

material	ε' @ 2.45GHz	tanδ @ 2.45GHz *10^{-3}
1	2.16	1
2	2.1	1.7
3	2.64	1.8
4	2.53	2.1
5	2.47	2.4
6	2.88	2.5
7	2.81	2.9
8	2.82	3.5
9	2.38	6

3.2. Electrode characterization

The use of conductive inks is an alternative to usual electrodes made with standard conductors such as copper and aluminium. The performance of antenna made with conductive ink is limited by the conductivity and the thickness of the deposited ink. To avoid excess loss and get good directivity, the thickness of the ink must be larger than skin depth (which is dependant on the conductivityand the frequency). So, measurement of thickness and conductivity are needed. The 4 tips method can be used to measure these parameters. An example of experimental results are given on table 2.

Table 2: Conductivity, thickness, and skin depth of several sample of conductive ink deposited (by silk-screen printing) on plastic substrate.

Sample	1	2	3	4	5	6
h (μm)	15	14	14	18	16	16
σ x10^4 (S.cm^{-1})	2.17	5.42	0.20	1.69	2.81	3.19
δ(μm)	7.04	4.46	31.36	8.43	6.19	5.94

4. Antenna design

The tag antenna is generally omni directional in order to ensure the identification in all directions. The structure of the tag antenna should also be as small as possible in size. Because of its simplicity and omnidirectionality, the λ/2 dipole is one of the most preferred form. At UHF frequencies the typical size is 15cm, which is a big size. Usually the dipole is folded in order to reduce its size. This usually needs fullwave electromagnetic simulation in order to take into account the capacitive and inductive coupling introduced by the folded form. Some recent works are considering meander line antennas [7]. In such architecture the line is continuously folded in order to reduce the resonant length for a given frequency. An attractive approach of using text as a meander line for size reduction of dipole antennas for RFID can be found in [8].

The rapid evolution of the Radio Frequency Identification market at UHF bands requires the development of low cost & small tags operating within different networks. Fractal antenna structures based on the use of self-similar, iteratively reducing shapes, are now being designed for use within RFID systems to satisfy such requirements.

We present new antennas based on fractal shapes according to two new approaches. First we use a fractal pattern to shape a traditional patch antenna in order to reduce its size. Performances of both antennas are compared. A modified Sierpinski Gasket antenna optimized for a dual-band at the ISM 2.45 GHz and 5.8 GHz bands is then reported. Figure 2 shows the realized antennas on a glass-epoxy substrate.

4.1. Von Koch-bounded microstrip patch antenna for a compact antenna operating at 2.45 GHz.

The antenna is based upon the fractal curve `Von Koch', a self-similar, iteratively reducing shape with an indentation angle $\theta = 80°$ (cf Figure 3(a)). This fractal pattern applied on one dimension of an euclidean-shaped antenna like a microstrip rectangular patch antenna reduces the antenna size of about 30%. For a fixed frequency, increasing the fractal iteration increases the path of current resulting in a reduction of the antenna electrical size. The antenna operating at 2.45

GHz has a smaller length *L = 22.4mm* than a traditional rectangular antenna with *L = 30.4mm*.

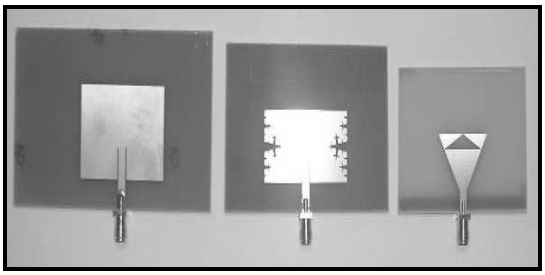

Figure 2: *Left to right: (a) 2.45 GHz rectangular patch antenna (b) 2.45 GHz Von Koch-bounded patch antenna (c) Dual-band microstrip-fed printed antenna based on Sierpinski Gasket.*

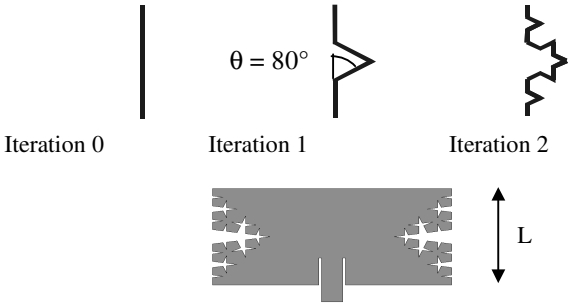

Figure 3: (a) Generation Process of a `Von Koch curve' with an indentation angle θ = 80° (b) An iteration 3 Von Koch-bounded patch antenna operating at 2.45 GHz

4.2. Microstrip-fed Sierpinski Gasket printed antenna optimized for a dual-band operation at the ISM 2.45 GHz and 5.8 GHz bands.

Figure 4(a) describes the generation process of the perturbed `Sierpinski Gasket' fractal pattern including a reduction of the triangular form by a scale factor $\delta = 0.2$ and then 3 recopies. A microstrip line feeds the fractal metallization and the ground plane under the radiating element is removed (see Figure 4(b)). This configuration allows a good compromise between compactness and adaptation for the fundamental frequency [9].

The antenna has a base of *L = 24mm*. The ground plane length $L_{GND} = 4.5mm$ fixes the fundamental mode at 2.45GHz and the reduction factor size $\delta = 0.2$ determines the second resonant frequency at 5.8 GHz. The return loss of the antenna are presented Figure 5. A very good agreement is found between experimental results and calculations with CST Microwave Studio, a 3D electromagnetic solver.

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5. System Simulation Results

System level modeling and simulation is a major step in the SoC design flow. But there still is a lack of behavioral models of RF components and antennas in particular. These models must be written with standardized Hardware Description Languages (HDLs) as the VHDL-AMS. The use of such a language permits TOP-DOWN design of complex hybrid systems and also the reuse of the behavioral models as IPs (Intellectual Properties) in other systems. In this context, we realized a VHDL-AMS model of an RFID system that includes an RF link IP.

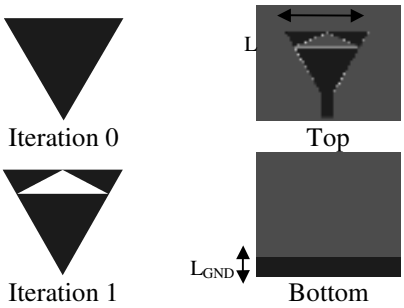

Figure 4: (a) Generation process of a perturbed Sierpinski Gasket with a scale factor δ = 0.2 (b) Configuration of the dual-band microstrip-fed printed antenna based on Sierpinski Gasket.

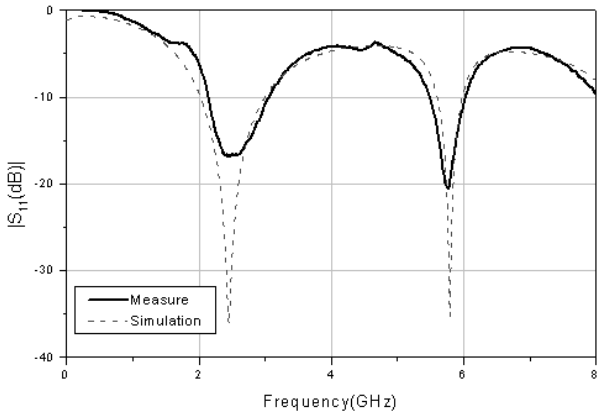

Figure 5: Calculated and measured return loss of the antenna on Figure 4.

5.1. Behaviora l antenna models

Analog HDLs as VHDL-AMS can't handle Partial Differential Equations (PDE) as usual RF simulation tools do. However, such a full-wave model would take too much simulation time and so, it would not be adapted for complete system simulation[10].

Behavioral modeling permits a good compromise between description accuracy and simulation speed. In fact, the simulation time of a behavioral model should be as short as it is for a functional model and its description should include the two major antenna behaviors which are its complex impedance and its radiation diagram. Actually, the VHDL-AMS language permits such a mixed description: the antenna complex impedance behavior, is modeled by its complex equivalent circuit and the radiation diagram is modeled by an equation extracted from the Friis Formula [11].

5.2. RFID system modeling case study

In order to demonstrate the interest of this approach, we included our far field antenna models in a 2.45 GHz passive RFID system behavioral model (as IPs our models of the RF link can be used within different wireless systems and at different frequencies). In fact, such systems are complex hybrid integrated systems, which makes essential the system-level simulation. The modeled RFID system consists of a base-station (BS) and a tag with no internal power: our models take

into consideration the wireless power collecting issue. System-level simulation of our RFID model makes possible, early in the design flow, the evaluation of the system's architecture which means evaluating the system's functionality and the essential system performances:

- Optimizing the TAG antenna matching in order to obtain the best power collection configuration.
- Comparing the power levels collected with different types of antennas and different radiation diagrams.
- Optimizing the backscattering technique depending on the working distance and the TAG's antenna matching.
- Checking the adequacy of the system with the RFID standard requirements (Power levels, spectrum forms, Radar Cross Section evaluation, response time…)

5.3. System simulation results

The use of a behavioral system model allows designers to perform functional design validation earlier in the microelectronic design flow. This validation step permits not only to check the system's functionality, but also to evaluate several system performances. We used Advance MS (ADMS) from Mentor GraphiCs to simulate our RFID system. This tool is a multilingual mixed-signal mixed-mode simulator.

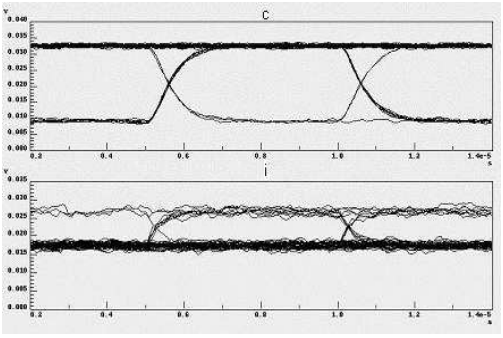

Figure 6: Eye diagrams of the signals received by the tag (c) and by the BS (i).

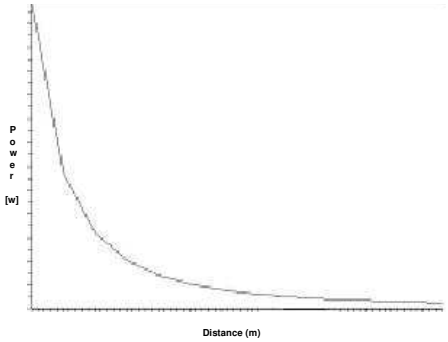

Figure 7: Amount of power collected by the tag to the distance between the base station and the tag.

The first eye diagram of Fig. 6 is the signal received by the TAG. The second eye diagram of this same Fig. 6 is the signal received by the BS after being backscattered. The shape of the eye shows the effect of the base band filtering on the transmitted symbols. The eye opening (aperture) shows how much the received signal is perturbed by noise effects: the more the eye is open, better is the transmission.
We can see on Fig. 6 that this aperture is much larger for the first transmission than it is for the second one. This means that the SNR is much lower for the tag to BS transmission than for the BS to tag transmission. This is because of the double propagation of the signal in the noisy medium.

The second simulation of this section focuses on the amount of power collected by the tag to the distance between the base station and the tag. Figure 7 shows a decreasing curve that describes the far field propagation power loss between the base station and the tag. We used two λ/2 resonant dipole antenna models working at 2.45 GHz.

6. Conclusion

More than 50 years after its invention, the RFID is becoming more and more considered in many domains and applications. UHF and Microwave bands allow RFID to increase the communication distances and data rate. At these bands, the antennas are operating under far field regime and accurate electromagnetic modeling is needed. To meet the low cost constraints for tags, non standard materials such as plastic and conductive ink are considered. On the other hand, size reduction of antennas and tags are of great interest for many applications. All these aspects are pushing strong activities on antennas for RFID tags..

7. Acknowledgments

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8. References

[1] H. Stockman "*Communication by Means of Reflected Power"* Proceedings of the IRE, pp 1196-1204, October 1948

[2] R.F.Harrington "Field measurements using scatterers" 1963-1964

[3] R.F.Harrington "Theory of loaded scatterers" 1963-1964

[4] J. Landt "*Shrouds of Time, The history of RFID" An Aim Publication, 2001, www.aimglobal.org*

[5] K.Finkenzeller "Fundamentals and Applica-tions in Contactless Smart Cards and Identifi-cation" 2nd ed., Wiley & Sons LTD April 2003.

[6] D.Bechevet, T.P.Vuong S.Tedjini *"Design and Measurements of Antennas for RFID, Made by Conductive Ink on Plastic*" IEEE-APS, Washington, july 2005

[7] G. Marrocco, "*Gain-optimized self-resonan tmeander line antennas for RFID application* ", IEEE AWP Lett., vol. 2, pp. 302–305, 2003..

[8] M. Keskilammi, M. Kivikoski "*Using Text as a Meander Line for RFID Transponder Antennas*", IEEE A W P. Lett., vol. 3, pp. 372–375, 2004..

[9] C. Gaubert, T.P.Vuong S.Tedjini, *« Quasi fractal antennas for RFID systemsoperating at 2.45GHz and 5.8GHz »* JINA, Nice 2004

[10] K. Kundert "*Simulation Methods for RF Integrated Circuits*", San Jose, California, Processdings of ICCAD'97 Nov. 9-13, 1997

[11] R. Khouri, V. Beroulle, T. Vuong, S. Tedjini, "*Wireless System Validation using VHDL-AMS Behavioral Antenna Models: Radio-Frequency Identification case study* ", ECWT 2004, EUMW 2004, Amsterdam, 11-15 October 2004.