Behavioral Modeling and Simulation of Antennas : Radio-Frequency Identification case study

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Abstract

Efficient simulation of wireless systems requires the development of antenna models compatible with microelectronic tools. This article describes a first behavioral antenna model using the VHDL-AMS language. Moreover, we present a complete behavioral RFID system model using this antenna model. Finally, several system simulation results demonstrate the interest of this approach.

Introduction

For many years, microelectronic market has been a constant growing market. Predicted averaged growth rate keeps on high. This market is also a very competitive one. Thus, to conquer new application fields, designers must reduce the *time-to-market*. This implies generating a *first-time right design*. Moreover, to reduce costs and optimize performances (size, power…), systems reach very high level integration. Success of *System-on-Chip* (SoC) or *System-in-Package* (SiP), which are embedding on the same chip or package several different digital and analog cores - microprocessors, memories, filters, amplifiers - confirms this major trend. Furthermore, progress of microelectronic processes allows the integration of new hybrid components. Hybrid meaning that these components deal with non-electrical signals : for example, *Micro-Electro-Mechanical Systems* (MEMS) or RF components. Obviously, the integration of these new hybrid components increases designs complexity. Designers need new models compatible with classical microelectronic tools and adapted to microelectronic design flow.

In this context of hybrid system integration, top level design verification of complete integrated Radio-Frequency (RF) wireless communication systems, involving analog and digital parts, is a major task. A hot topic concerns simulation tools for these RF systems. In fact, the coexistence of a low baseband signal and a high carrier frequency involves high simulation time. This problem is clearly addressed by RF simulation engines (Eldo-RF, Spectre-RF) specialized in non-linear system simulations involving for example mixers or switches [1]. Due to this new class of tools, efficient simulation of a complete integrated communication system is possible [2] [3] [4].
Nevertheless, there still is a lack of RF component models : few works concern RF signal propagation modeling or electromagnetic effects modeling [5]. Moreover, this deficiency particularly concerns RF antennas modeling. Of course, without antenna models, complete functional validation of wireless communication systems is made impossible. Considering this problem, this paper presents a first behavioral antenna model using VHDL-AMS, the mixed-signal IEEE 1076.1 standard modeling language [6].

In the following part, a behavioral antenna model is described. Then, in the third part, to validate this model and to demonstrate its interest, we propose a complete behavioral model of a *Radio-Frequency Identification* (RFID) system. A RFID system is described and major RFID design issues are discussed. In the last part, several simulation results concerning these RFID issues are briefly analyzed.

Behavioral modeling of an antenna

A. Transmitting mode

An antenna is "a means for radiating and receiving radio waves". According to [7], in the transmitting mode, an antenna system can be represented by a Thevenin circuit equivalent as shown in Fig. 1.
In this figure, the antenna is represented by an impedance Z_A given by :

$$Z_A = R_L + R_r + j\,X_A \qquad (1)$$

Radiating element is symbolized by a radiation resistance Rr and an imaginary part X_A. R_L represents both the conduction and the dielectric losses of the antenna. The source to which the antenna is connected is represented by an ideal generator Vg having its own internal complex impedance. The radiation power delivered by the antenna is the power collected by resistance Rr and it is given by :

$$P_r = \frac{1}{2}\left|I_g\right|^2 R_r \qquad (2)$$

Where Ig is the current through Rr.

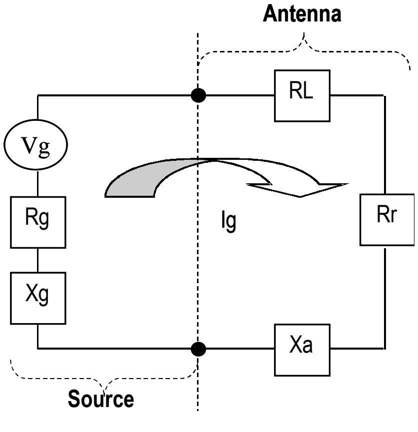

Fig. 1 : Thevenin circuit equivalent of a transmitting antenna.

Then, I_g magnitude is given by :

$$\left|I_g\right| = \frac{\left|V_g\right|}{\sqrt{\left(R_r+R_L+R_g\right)^2+\left(X_A+X_g\right)^2}} \quad (3)$$

Maximum power is delivered to the antenna under conjugate matching, which means when :

$$\begin{cases} R_r + R_L = R_g \\ X_a = -X_g \end{cases} \quad (4)$$

If we consider a loss less antenna ($R_L=0$), the ideal amount of power collected by Rr is given by:

$$P_r = \frac{\left|V_g\right|^2}{8\,R_r} \quad (5)$$

For a directive antenna, the radiated power per unit solid angle, also called radiation intensity, is given by:

$$I_r = \frac{P_r\,D_t}{4\pi} \quad (6)$$

Where D_t is the directivity of the transmitting antenna and 4π describes a full surface solid angle.

Let us now consider a receiving antenna at a distance r from the transmitting antenna. The usually used parameter to describe the power capturing characteristics of this receiving antenna is the effective area A_e given by :

$$A_e = \frac{\lambda^2 D_r}{4\pi} \quad (7)$$

Where D_r is the directivity of the receiving antenna and λ its operating wave length.

The power collected by the receiving antenna (under far field condition) is given by :

$$P_{received} = \frac{P_r\,D_t\,A_e}{4\pi\,r^2} \quad (8)$$

B. Receiving mode

Power collected induces a voltage Vt on the receiving antenna, which is analogous to Vg of the transmitting antenna model. The Thevenin equivalent circuit of the receiving antenna and its load is shown in Fig. 2. The load to which the receiving antenna is connected is represented by a complex impedance. As we did for the transmitting model, we extracted the functional equations from this receiving antenna model.

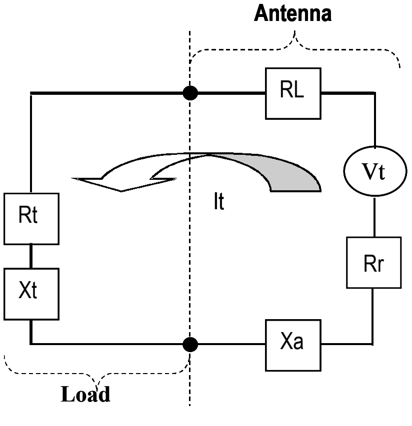

Fig. 2 : Thevenin circuit equivalent of a receiving antenna.

The equations extracted from both the receiving and transmitting antenna models allow us to describe the behavior of a single bi-directional antenna.

This model permits to describe a transmission between two antennas using the VHDL-AMS language. This simplified model assumes no losses and no antenna mismatches.

In order to show up the interest of this first behavioral model, this antenna model has been included in a complete behavioral model of a RFID system. The next part describes the major characteristics of this system.

RFID system modeling

A. RFID overview

Radio-Frequency IDentification (RFID) concerns technologies for tracking and access control applications [8]. RFID wireless systems allow non contact reading and are particularly effective in environment where bar code labels could not survive. Market for these applications has been regularly growing since 1980. Theses systems generally consist of two parts :

- a *base-station* (BS) : a fixed transmitter and receiver.
- a tag : a small mobile communication circuit stuck on tracked “products”.

The BS contains an antenna for RF signal transmission and reception, and an electronic part consisting of an analog *front-end* and a digital *back-end*.

The tag, which is sometimes called “smart label”, consists of an antenna and an electronic part.

RFID tags can be categorized as either active or passive. Active tags are powered by an internal battery. Passive tags operate without internal power source and get their operating power from the BS. These tags are consequently much lighter than active tags. The trade-off is that they have shorter reading ranges than active tags. In our case study, we chose to model a passive tag in order to deal with its design complexity.

Furthermore, RFID systems can be distinguished by their operating frequency ranges. Low-frequency systems have short reading ranges and low system costs. In these systems, transmission only relies on the induction principle. High-frequency systems offer high reading speeds, long range transmission, and small antenna dimensions. For these frequencies, transmission relies on RF signal propagation. Compared to low-frequency systems, performances of high-frequency RFID systems imply higher costs and more complex design tasks. Thus, in the following case study related to new tools for design flow optimization, we chose to model a High-frequency RF system. More accurately we chose a system operating within the 2.4GHz ISM (Industrial, scientific, and Medical) frequency band. The major advantage of this band is to be available throughout most parts of the world.

In the following, we first present the communication protocol which has been described in our RFID system model. Then, we detail the front-end circuit for both BS and tag.

B. RFID simplified communication protocol

Since our goal is to show the feasibility and the interest of our antenna model for wireless system design, we have just implanted a simplified communication protocol. Nevertheless, this protocol is functional, even if it has been reduced comparing to *ISO/IEC 18000-4* RFID standard requirements. This communication protocol, based on power activation and two basic communication stages, is presented in Fig. 3.

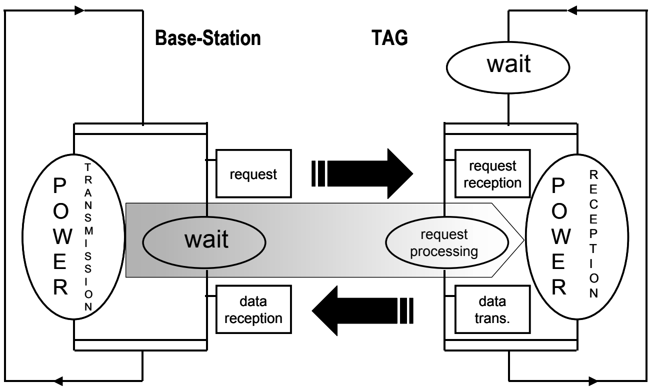

Fig.3 : Simplified BS - tag communication protocol.

During the *power up stage,* the antenna of the BS (left part) transmits a RF signal to activate the tag (right part). Obviously, tag activation is possible only when tag passes through the BS electromagnetic zone of influence. In this system, BS antenna / medium / tag antenna are the conduits between the tag and the BS.

Then, BS controls the system communication as illustrated in Fig. 3. Firstly, tag detects the reader's request signal : it corresponds to *the request and request reception stage*. In the tag and in the BS, this communication protocol is implemented in a *finite state machine* included in the digital electronic back-end.

Secondly, tag transmits a response, in our case its identification number, to the BS : it is the *data transmission / reception stage*.

Finally, the BS decodes these data previously encoded in the tag's integrated circuit and passes it to a host computer for processing.

C. Base-Station and tag font-end

The BS radio front-end consists of two signal processing chains : one for signal transmission and an other one for signal reception. A coupler, placed before the antenna, allows to drive the transmitted signal toward the antenna and the received signal coming from tag toward the reception chain. Fig. 4 presents a schematic view of these two chains. Components involved in this BS radio front-end are filters (low-pass and band-pass), mixer, amplifiers (PA : Power Amplifier and LNA : Low Noise Amplifier)… In conformity to standard requirements, these components realize an ASK modulation of a Manchester coded digital stream.

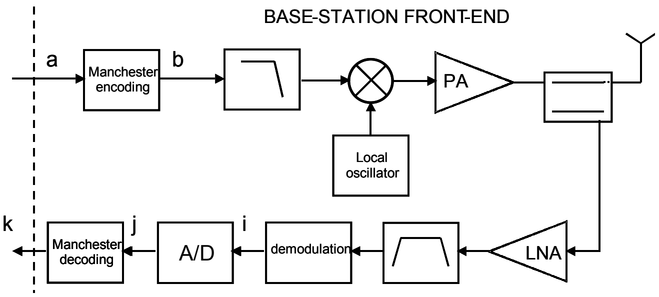

Fig.4 : Base-Station front-end.

In the transmission chain, the baseband digital signal is firstly Manchester coded, then filtered with a low-pass filter. After that, an ASK modulation is realized with a mixer working at the local oscillator frequency fixed at 2.45GHz. Next, a RF power amplifier adapted to the antenna is used to amplify the power of the signal before its transmission.

In the reception chain, a low-noise amplifier is used before the band-pass filtering for noise rejection. Then, a non coherent demodulation is realized to detect the signal. Finally, this signal is decoded and ready for use by BS back-end.

Tag front-end consists of a receiving chain equivalent to the previous BS one and a "reflection chain" based on the backscattering principle. In fact, backscattering is particularly well adapted due to low-power requirements for tag operations. Moreover, this communication technique permits tag design simplification. Modulating the load impedance of the tag antenna in synchronization with a bit stream permits to reflect or not the incident wave. Thus, this reflected signal is equivalent to a modulated signal coming from the tag.

The front-end tag schematic is given in Fig. 5. All functional blocks including antennas in both Fig. 4 and Fig. 5 have been described using VHDL-AMS language. For the moment, only high-level descriptions of these functions have been written. The following part presents several simulation results obtained with these descriptions and discusses their interest.

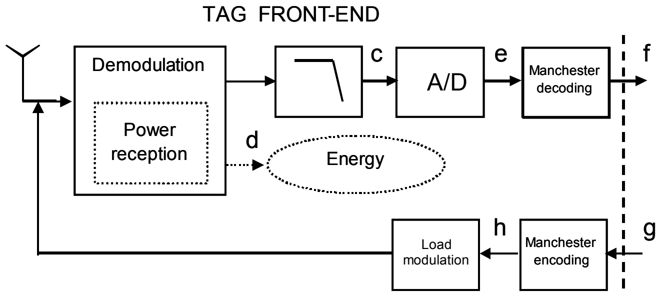

Fig.5 : Tag front-end.

Experimental 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 to verify equivalence between original specifications and design. The first simulation presented bellow checks the system's functionality, including several states of the communication protocol.

Furthermore, many evaluations of system performances using our behavioral system model are possible. For example, the evaluation of the *Signal to Noise Ratio* (SNR) in different points of the transmission chain can inform us about the communication quality. Thus, in the second simulation, we propose to analyze the SNR of the signal received by the tag and the SNR of the signal received by the Base Station.

A. Functional validation

We used *Advance MS* (ADMS) [9] from *Mentor GraphiCs* to simulate our RFID system. This tool is a multilingual mixed-signal mixed-mode simulator. The first work consists in verifying our system architecture equivalence with the previously described communication protocol. This simulation considers a fixed distance between the BS and the tag and a low-noise air medium.

Several signals obtained during the BS to tag transmission are presented in Fig. 6. Then, signals for the tag to BS transmission, corresponding to backscattered signal, are given in Fig. 7.

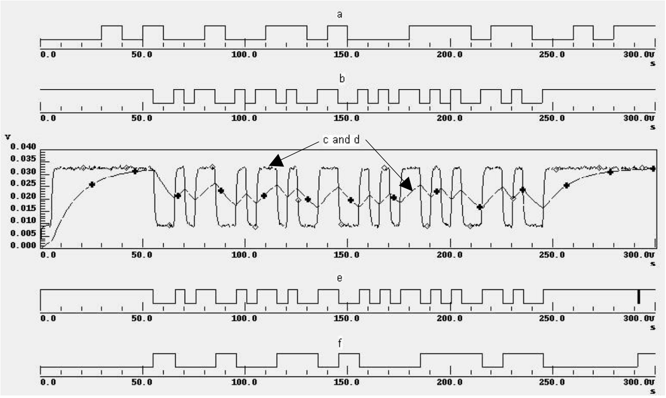

Fig.6 : Base-Station to tag transmission.

In Fig. 6, the transmitted bit stream consists of the first two stages previously presented in the communication protocol :

- a power up stage at the beginning and the end of BS's communication.
- a request transmission during 200µs.

In this figure, signal *a* contains the binary request (from 50µs to 250µs). This request is then Manchester coded into signal *b* between two constant high level signals; constant signals corresponding to power up stages. Next, signal *c* is a continuous quantity representing the demodulated and filtered signal received by the tag. A white Gaussian noise has been added to this signal during its propagation in the medium ; *d* signal is the power level of the tag ; *e* is the result of the analog to digital conversion of c *; f* is the decoded e signal, in which we can recognize the original request.

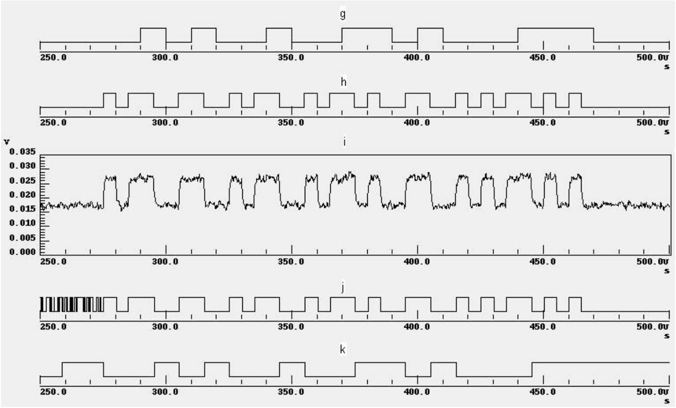

Fig.7 : Tag to Base-Station transmission.

In Fig. 7, the transmitted bit stream consists of two stages extracted from the communication protocol:

- a power up stage.
- a data transmission / reception stage.

These stages are activated after the request reception stage. *g* contains the binary identifier of the tag ; *h* is the Manchester coded signal. Then, *i* represents the received signal after demodulation and filtering. Finally, *j* and *k* are respectively the digitalized received and decoded signals. Obviously, *k* contains the binary identifier of the tag.

Signal analysis shows that our system architecture responds to specification requirements. Despite of perturbations, request and identifier are correctly transmitted through the medium. In the following, we analyze the performance of our architecture.

B. System performance evaluation

SNR is the usually used metric to evaluate a transmission quality. In order to visualize the SNR, we chose to analyze the eye diagram of the two received signals. ADMS provides a special built-in function to automatically realize these diagrams. Those eye diagrams are showed in Fig. 8.

The first eye diagram of Fig. 8 is related to signal *c* received by the TAG. The second eye diagram of this same Fig. 8 is related to signal *i* received by the BS after being backscattered. The shape of the eye shows the effect of the baseband 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. 8 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.

In the case of a passive tag, the level of the received power becomes crucial. Thus, another interesting experiment would consist in evaluating the overall transmitted power from BS to tag depending on distance between them. This experiment would permit to evaluate the maximum electromagnetic distance of influence of the BS.

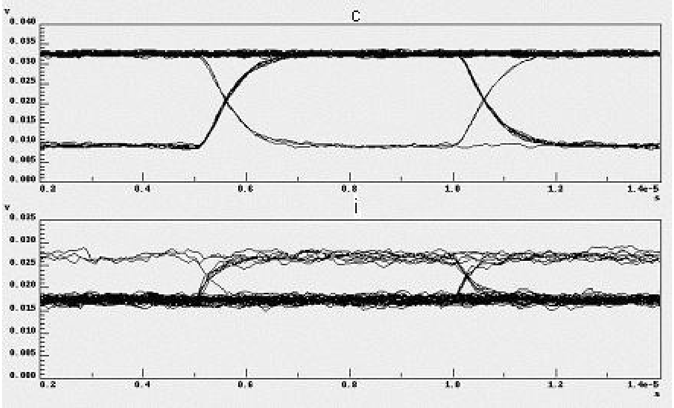

Fig.8 : Eye diagrams of the signals received by the tag (c) and by the BS (i).

Conclusion

We presented a simplified behavioral model of an antenna. Then, we included this model in a complete RFID 2.45 GHz system behavioral model and we showed what this model consists of. We also presented some of our simulation results in which the functional verification and the influence of noise on the quality of the communication. We showed how useful is the behavioral modeling of RF components, antennas in particular, to mixed-signal integrated circuit designers, in order to validate their design's functionality.
We are currently working on a lower level of an antenna model in order to provide designers with more accurate models. This antenna model will take into consideration geometrical and technological parameters.

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