Optimization of the law of variation of shunt regulator impedance for Proximity Contactless Smart Card Applications to reduce the loading effect.

Catherine Marechal, Dominique Paret.

Laboratoire LRIT – ESIGETEL
1, rue du Port de VALVINS - 77210 Avon, FRANCE
Email : catherine.marechal@esigetel.fr

Abstract. These paper deals with RFID system and in particular with the ”loading effect”. We often confuse the load-modulation with the loading effect. If the load modulation is well known, it is not the case of the loading effect. We focus in particular on the loading effect due to the shunt regulator in the tag. We search a law of these shunt regulator to improve and/or reduce the loading effect.

Introduction.

RFID (Radio Frequency Identification) systems are more and more present commercially. Contactless identification systems involve a base station / interrogator communicating with tags/ badges/ transponders/ smart cards/ via optical/Infra Red or radiofrequency (HF, UHF) links. This paper deals with inductive coupling RF link between base station and transponder. In this paper, as an example, we describe a proximity contactless smart card in accordance with the ISO 14 443 standard.

The **load modulation** and the loading effect have the same physical basis. The current in the antenna of the base station varies with the load of the tag. In the first case, with the load modulation, we want this variation to assure the communication between the tag and the base station thanks to the retromodulation of the load.

The **loading effect** is due to different factors:

- the nominal load : nominal consumption of the IC, communications rate
- variation of the dynamic applicative load : embedded crypto coprocessors consuming more energy during phases of activity, dynamic variation of the communication rate
- the environment : presence of copper, ferrite or a hand
- last but not least, a parallel shunt regulator acting as a function of the distance
  a) on one hand, as a voltage regulator to supply the smart card IC
  b) on the other hand as a power variation damper against incoming power from the base station.

This loading effect will be emphasized in the coming years because future applications will need:

- larger memories sizes,
- larger calculation facilities using higher calculation / clock speeds requiring higher consumption for a higher communication rate
- more sophisticated security (embedded crypto coprocessors) consuming more energy during phases of activity
- new electromagnetic environments due to the use of NFC (Near Field Communication) for Mobile Phone applications.

In the applications, sometimes, in specific cases, some base stations communicate correctly with a smart card at full range (12 – 15 cm), but not at short distance (0 to 3 – 4 cm), due to the « loading effect ». This results of a lack of transmitted power due to strong influence of the load of the card to the base station.

Paper [1] proposes an adaptive matching network at the base station in order to improve poor power transfer efficiency.

The goal of the paper is devoted to study an other way to reduce the loading effect that is to find a particular law of the shunt impedance as a function of the distance between the base station and the smart-card.

The paper summarizes the physical origins of the loading effects and shows, in a different way that in [1] [2] [6], the base station antenna current equation - including shunt regulator influence - as a function of the distance between the base station and a smart card. In fact the magnetic field H created by the base station is proportional to the current value flowing into the base station antenna. A modeling of the system (including magnetic coupling) of the base-station and smart card is used to calculate the loaded/unloaded (with or without card) base station antenna current ratio (I_1/I_{10}) as a function of the distance between the base station and the smart card.

The simulation shows that the current (I_{10}) flowing into the base station antenna and the related magnetic field created by the base station could be dramatically reduced when the smart card is very close to the base station. This explains why communication can cease due to a lack of energy transfer. For more precision, we simulate also the magnetic field at the smart card at a distance d of the base station. Results are discussed below.

Loaded/unloaded base station antenna current ratio.

Modeling of magnetic coupling between base station and contactless smart card

Fig. 1 shows the modeling of the magnetic coupling between base station and a contactless smart card [2].

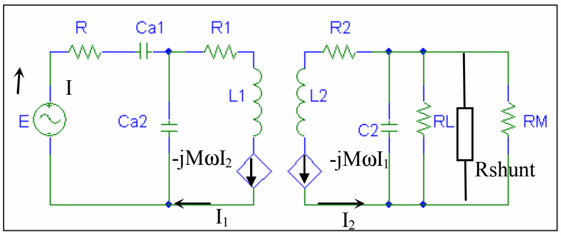

Fig. 1. Modeling of the coupling between base station and contactless smart card.

Where the components are described below with their value for the simulations.

- For the base-station

Capacitive coupling network antenna to the base station's output stage (Ca1 = 43pf, Ca2 = 233 pF); Base station antenna inductance and resistance (L1 = 500nH, R1 = 0.7 Ω); Output impedance of base station amplifier (R=30 Ω) ; Equivalent Thevenin voltage of the base station's amplifier

- For the smart card

Smart card antenna inductance and resistance (L2 = 4 µH, R2 = 10 Ω); Total smart card capacitor (IC equivalent input capacitor + antenna stray capacitor + packaging) (C2 = 24 pF); IC equivalent load resistance (this value depends on the IC operating conditions) (RL = 50 kΩ); IC modulation resistance for data communication. (average value RM = 5 kΩ); M : mutual inductance between antennae; Shunt resistance to avoid overvoltage, Rshunt.

The purpose of this paper is to define and optimize this shunt resistance law.

The direct resolution of the equations issued from the original diagram (Fig. 1) leads to a complicated equation. For this reason, this diagram is transformed into a new one presented in Fig. 2.

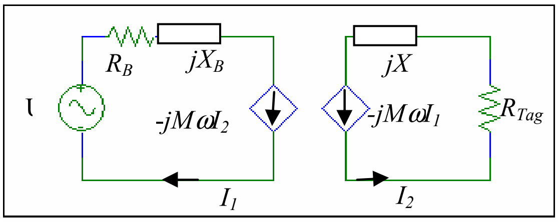

Fig. 2. Simplified diagram of the system base station / smart card

$$\text{with} \quad R_{BS} = R_{eq}+R_1 \tag{1}$$

$$jX_{BS} = \frac{1}{jC_{eq}\omega} + jL_1\omega \tag{2}$$

$$R_{tag} = R_2 + R_7 \tag{3}$$

$$jX_{Tag} = \frac{1}{jC_5\omega} + jL_2\omega \tag{4}$$

$$R_7 = \frac{R_6}{1 + Q_{c2}^2} \tag{5}$$

$$\text{where } \frac{1}{R_6} = \frac{1}{R_{shunt}} + \frac{1}{R_L} + \frac{1}{R_M} \tag{6}$$

$$Q_{c2} = R_6 C_2 \omega \tag{7}$$

$$\text{And with } {}^{1}\!/\!_{C_5\omega} = \frac{{}^{1}\!/\!_{C_2\omega}}{1 + {}^{1}\!/\!_{Q_{c2}^2}} \tag{8}$$

$$Z_{eq} = R_{eq} + jX_{eq} = \frac{\frac{1}{jC_{a2}\omega}\left(R + \frac{1}{jC_{a1}\omega}\right)}{R + \frac{1}{jC_{a1}\omega} + \frac{1}{jC_{a2}\omega}} \tag{9}$$

Now let's have a look on unloaded and loaded situations.

– ***unloaded*** - *Without smart card*

We note I_{10} , the unloaded base station antenna current.

$$I_{10} = \frac{U}{R_{BS} + jX_{BS}} \tag{10}$$

– ***loaded*** - *With a smart card in the communication range .*

$$U - jM\omega I_2 = \left(R_{BS} + jX_{BS}\right)I_1 \tag{11}$$

$$-jM\omega I_1 = (R_{Tag} + jX_{Tag})I_2 \tag{12}$$

From this equation we find the ***loaded (I_1) /unloaded(I_{10}) base station antenna current ratio :***

$$\frac{I_1}{I_{10}} = \frac{R_{BS} + jX_{BS}}{R_{BS} + R_{Tag}\frac{M^2\omega^2}{R_{Tag}^2 + X_{Tag}^2} + j\left(X_{BS} - X_{Tag}\frac{M^2\omega^2}{R_{Tag}^2 + X_{Tag}^2}\right)} \tag{13}$$

$$\text{with } M = k\sqrt{L_1 L_2} \tag{14}$$

$$\text{and } k = \mu_0 \frac{r^2}{2\left(r^2 + d^2\right)^{3/2}} n_1 n_2 s_2 \frac{1}{\sqrt{L_1 L_2}} \text{ [3, p32]} \tag{15}$$

where
$\mu_0 = 4\pi 10^{-7}$ H/m magnetic permeability,
r : base station antenna radius (0.03m).
n_1: base station antenna turn number (n1 =1)
n_2: smart card antenna turn number. We simulate with different values of n_2.
s_2: smart card antenna one turn area (0.004 m^2)
d : distance of the smart-card from the base station.

Shunt resistance R_{Shunt} already introduced into calculation by the way of R_{tag} and X_{tag}, gives a very complex formulation of equation (13). R_{Shunt} is very difficult to be isolated from this equation in order to define and optimize its literal law of variation. So, to find the shunt resistance variations as a function of distance in order to obtain a current ratio as high as possible, we simulate the current ratio I_1/I_{10} as a function of both a) the distance between smart card and base station, and b) shunt resistance value.

Simulations

We already introduced the values used for simulations.

Simulation with different values of n_2.

We simulate the current ratio with several number of turns of the smart-card antenna, (n_2 = 1, 4, 8), distance between base station and smart card from 0m to 0.1m (10 cm) and shunt resistor from 30 Ω to 100 kΩ. (fig 3 to 5).

Theses figures show that when the smart card is far from the base station (10 cm), the card has no effect on the current flowing into the base station' antenna (loaded/unloaded base station antenna current ratio equals 1). For very short distance (below 2cm), the current ratio drops. The higher the turn numbers of smart-card antenna, the more important is this drop so the more important is the loading effect.

Figures show also the benefice of having a shunt resistor to minimize the global loading effect. For short distance, the current ratio value is higher with the presence of a shunt resistor of small value.

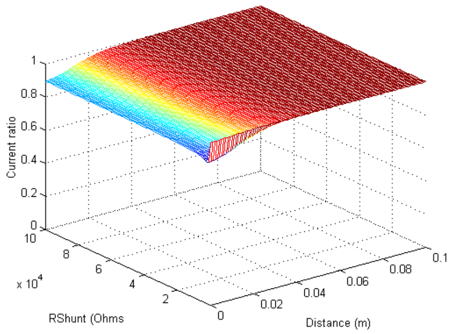

Fig. 3. : Current ratio as a function of the distance and the shunt resistor for n2 = 1 turn number of the smart-card antenna.

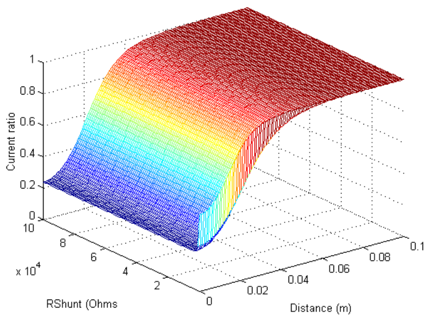

Fig. 4. Current ratio as a function of the distance and the shunt resistor for n2 = 4 turn number of the smart-card antenna.

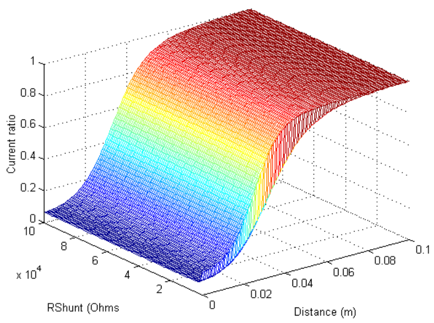

Fig. 5. Current ratio as a function of the distance and the shunt resistor for n2 = 8 turn number of the smart-card antenna.

Simulation of the magnetic field ratio at the smart card.

To complete this study, we simulate the magnetic field H located at a distance d from the base station without and with a smart-card.

The magnetic induction B without a card is given in [3, p12].

$$B(d)\big|_{\text{Without a card}} = \mu_0 \frac{r^2}{2\left(r^2 + d^2\right)^{3/2}} n_1 I_{10} \qquad \textbf{(16)}$$

Note : without card I_{10} is a constant.

So at the base station, the magnetic induction is

$$B(0) = \frac{\mu_0 n_1 I_{10}}{2r} \qquad \textbf{(17)}$$

We simulate the ratio $\left|\frac{B(d)}{B(0)}\bigg|_{\text{Without card}}\right| = \frac{r^3}{\left(r^2 + d^2\right)^{3/2}}$ **(18)**

as a function of the distance (Fig.6).

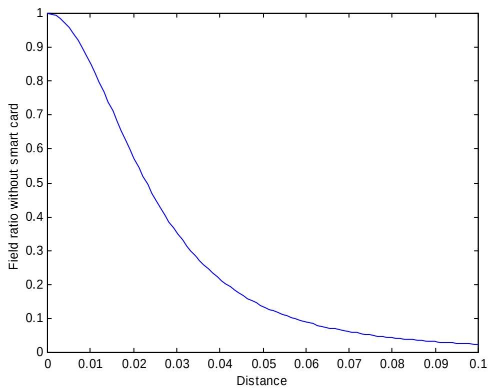

Fig. 6. Magnetic field ratio as a function of the distance without smart-card.

The magnetic induction with a card is:

$$B(d)\big|_{\text{With a card}} = \mu \frac{r^2}{2\left(r^2 + d^2\right)^{3/2}} n_1 I_1 \qquad \textbf{(19)}$$

Where I_1 is the current in the antenna of the base station with a card at a distance d. I_1 is acting as a function of d.

We simulate the ratio

$$\left|\frac{\left.B(d)\right|_{\text{With a card}}}{\left.B(0)\right|_{\text{Without a card}}}\right| = \frac{r^3}{\left(r^2+d^2\right)^{3/2}}\left|\frac{I_1}{I_{10}}\right| \qquad \textbf{(20)}$$

The current ratio $\frac{I_1}{I_{10}}$ is given in equation (13)

Fig. 7 shows the results for n_2=1. The loading effect is small and the system will probably work near the base station. In many cases, with same s_2, in order to increase the magnetic flux, the antenna tag turn number is larger than 1.

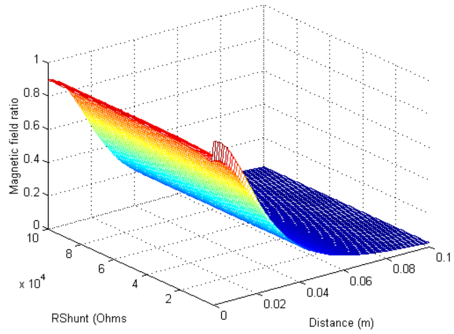

Fig. 7. Magnetic field ratio as a function of the distance and the shunt resistor for n2 = 1 turn number of the smart-card antenna.

Fig. 8 shows the magnetic field ratio with a turn number of the tag's antenna of 4. The magnetic field is very small and we can wonder how the system base station/tag work.

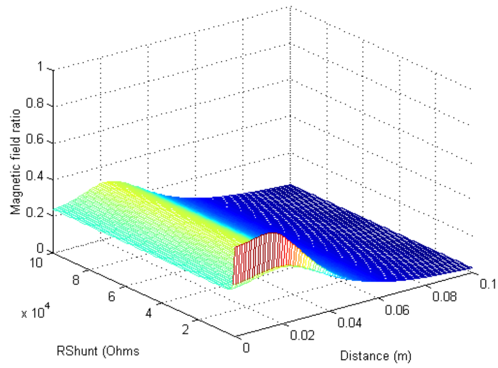

Fig. 8. Magnetic field ratio as a function of the distance and the shunt resistor for n2 = 4 turn number of the smart-card antenna.

In fact, for a same magnetic induction, same elementary surface, the induced voltage in the tag is greater as the turn number of the antenna is greater (equation 21).

$$e = -\frac{dBS_2}{dt} = -n_2 \frac{dBs_2}{dt} \tag{21}$$

Where e is the induced voltage in the tag
B the magnetic induction
n_2 the number of turn of the antenna of the tag
$\boldsymbol{s_2}$ the surface of one turn of the antenna of the tag

To take into account the increase of induced voltage with the number of the turn of the antenna of the tag we multiplied the magnetic induction / magnetic field ratio with a card by the number of the turn n_2 (Fig. 9). With $n_2 = 4$, the induced voltage is above the induced voltage without a card. If the tag is well designed the system should work at any distance in its operating range and this one will be greater than if the tag would have only one turn (see fig. 7).

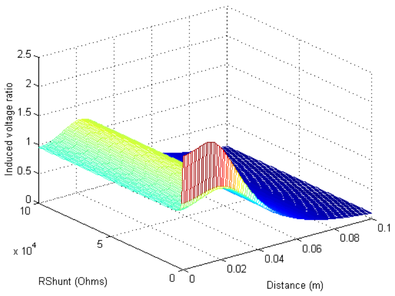

Fig. 9. Magnetic field ratio*n2 as a function of the distance and the shunt resistor for n2 = 4 turn number of the smart-card antenna.

If we increase the number of turns n2 of the antenna of the smart-card, we can see that the system may work between 6 and 8 cm, but not below 4 cm (Fig. 10). The same result can be find in [1].

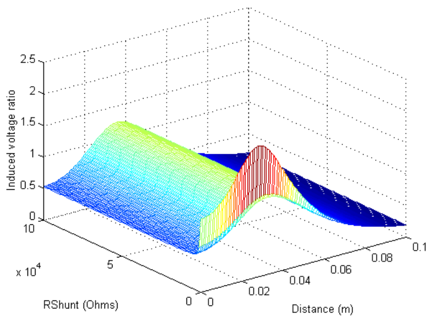

Fig. 10. Magnetic field ratio*n2 as a function of the distance and the shunt resistor for n2 = 8 turn number of the smart-card antenna.

Optimization of shunt resistance variations

To optimize the law of the variation of the shunt, we use the graph that gives the induced voltage ratio (Fig. 9 and 10) For a given distance between the base station and the tag, we take the value of the shunt regulator that gives the ratio of the induced voltage the nearest of 1. If there is the same induced voltage for a given distance, we take the higher value of the shunt resistor to avoid high consumption.

The projection of all these points on the plan R_{shunt}, d (see figure 11) gives an example of the graph of the optimized law of R_{shunt} as a function of the distance d between smart card and base station

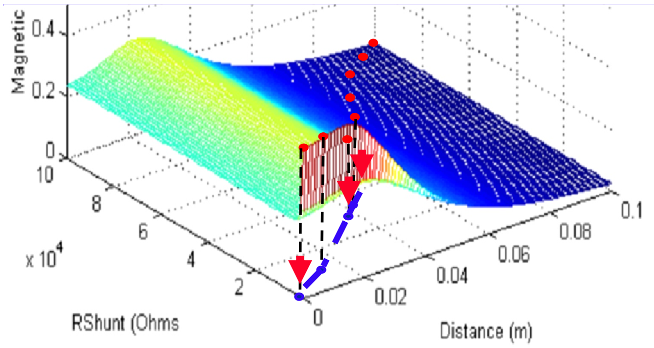

Fig. 11. Example of optimum law of the variation of internal shunt impedance of the smart card versus distance.

Conclusion

This paper deals with the loading effect that will be emphasized in the coming years. Taking into account the shunt resistance influence we modelized the coupling between base station and smart card at 13.56 MHz. This modeling leads to the simulation of the loaded/unloaded base station current ratio as a function of various parameters (shunt resistance, n_2, and distance). We show the drop of the current in the antenna of the base station (so the drop of the magnetic field radiated at the base station) for short distance between the reader and the tag

At this level, first results seem to show that it is not desirable to increase the antennae' turn number of the tag. The more important is this turn-number, the more important is the drop of the current in the base station. In addition, taking into account the number of turns in order to obtain a sufficient induced voltage "e" across the coil of the tag IC, we simulate the magnetic field at a distance d with a smart-card and we showed that a turn number of 4 for the smart-card's antenna gives good results, that is the induced voltage is more important than with only one turn. The communication range is increased. A too important number of the smart-card's antenna may lead to behavior of the system which may work for long distances but not for short ones.

To conclude, in despite of pure mathematical resolutions, using tri-dimensional simulated curves “induced voltage, e = f(d, shunt resistance)” presented in this paper, it is easy to define graphically the optimum shunt resistance law variations versus operational distance in order to minimize loading effects for Proximity Contactless Smart Card Applications. For a given distance between the base station and the tag, we take the value of the shunt regulator that gives the less drop of the induced voltage. If there is the same induced voltage for a given distance, we take the higher value of the shunt resistor to avoid high consumption.

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