Quantitative Theory of Signal Inversion in RFID

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Abstract. Inversion is a phenomenon that affects the signal received by an RFID reader from a transponder in an unwanted way, as it creates zones of non-communication on the reader antenna. In a previous work we have shown how to locate and evaluate inversion with the aid of 2D maps produced with an automated scanner. The present paper supplements that work with a theory that clarifies the dependence of inversion on the parameters of the transponder circuit and on the magnetic coupling between antenna and transponder.

Keywords: RFID · Reader · Transponder · Signal inversion
Automated scanner

1 Introduction

A measure of the performance of Radio-Frequency Identification (RFID) systems is the quality of the signal received by the reader from the transponder (called tag in what follows). Clearly it depends on the position of the tag on the reader antenna and as such it should be tested at all positions to be expected in the targeted application. The main parameter varying with position is the magnetic coupling between reader antenna and tag coil. For a tuned tag the amplitude of the baseband signal demodulated by the reader varies monotonically with the absolute value of the coupling. However with detuned tags and with readers that do demodulation with an envelope detector a more intricate phenomenon may occur. There may be areas on the antenna for which the signal from a detuned tag placed there is the mirror image of the one normally expected; such a signal is called inverted. The areas with inverted and with normal signals are separated by zones of pure phase modulation where the output of an envelope detector has zero magnitude and no communication is possible. For this reason it is important for the developer to be able to locate those zones. The developers have been warned against this phenomenon in an NXP application note [1], where a graphical example is presented in the form of a 2D diagram that displays inversion in function of reader antenna and tag

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coil detuning, the position of the tag being fixed. The authors of the present paper have been interested in how and where inversion may occur when the tag is displaced over the reader antenna. In our previous work [3] we have described an automated scanner with the aid of which one can obtain 2D maps of inversion. It is the purpose of the present paper to supplement that work with a quantitative theory of inversion, under the assumption that the reader antenna is tuned but the tag coil may be detuned to various degrees. In Sect. 2 we recall some basic facts, namely the model of the RFID system used in the subsequent discussion and the definition of a numerical measure V_{12}, already discussed in [2, 3], whose sign is determinant for the occurrence of inversion. The computation of V_{12} in [2, 3] has been based on a first order Taylor development and did not realistically reflect the inversion second order dependence on the coupling. The theory of Sect. 3 starts from an algebraic approach that gives the exact sign of V_{12} and hence allows for a precise discussion of inversion in terms of the coupling and of the circuit parameters of the tag. Finally Sect. 4 presents some experimental illustrations of the theory obtained with the 2D scanner.

2 Models and Definitions

Figure 1 presents the model of a typical RFID system in which the reader is of current-driven type and employs an envelope detector as demodulator. The reader feeds the antenna with a current of constant amplitude I_A and frequency ω. Because of the mutual inductance M_{TA} between the tag coil and the reader antenna a voltage is induced in the tag coil, the rectified version of which being used by the tag for powering its internal circuits. The tag transmits data to the reader via the procedure of load modulation: switching between the two resistors R_1 (=R_T in Fig. 1) and R_2 (=$R_T \parallel R_{MOD}$) internal to the tag determines, because of the mutual inductance, a change in the effective impedance Z_A of the antenna circuit and hence a change in the antenna voltage sensed by the reader. When no tag is present on the antenna, Z_A is resistive and equals R_A as the antenna circuit is tuned to ω. When a tag is present with the switch positioned for R_i (i = 1, 2), the antenna impedance becomes $R_A + \Delta Z_i$.

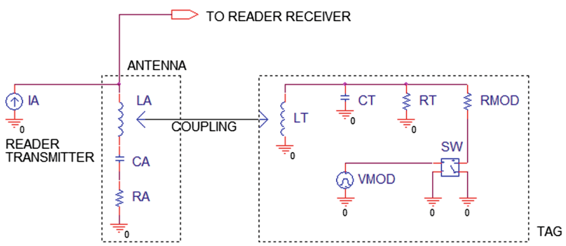

Fig. 1. Model of an RFID system.

The concept of ideal magnitude of the baseband signal extracted by the reader as defined in [2, 3] is fundamental for evaluating the quality of the received signal. Let V_1 be the amplitude of the antenna voltage when the tag switch is open and let V_2 be the amplitude of that voltage when the tag switch is closed. The ideal signal magnitude V_{12} is defined as the difference $V_1 - V_2$; it is ideal in the sense that its absolute value would be the amplitude of the baseband signal output by the envelope detector provided that the transients were short enough with respect to the duration of the bit interval. V_{12} is a signed quantity given by

$$V_{12} = I_A R_A \left(\left| 1 + \frac{\Delta Z_1}{R_A} \right| - \left| 1 + \frac{\Delta Z_2}{R_A} \right| \right). \tag{1}$$

Performance evaluation tests may use V_{12} as a measure of quality of the received signal, since the higher is the absolute value $|V_{12}|$ of V_{12} the lesser is the probability of bit decoding error. In general, the larger is the coupling $|M_{TA}|$, the higher is V_{12}; this is especially true for tuned tags, for which the resonant circuit composed of L_T and C_T in Fig. 1 is tuned to ω. For detuned tags the situation is complicated by the phenomenon of signal inversion: there may be areas on the reader antenna where $V_{12} > 0$ and areas of inversion where $V_{12} < 0$ separated by zones where V_{12} is nearly zero. In the zones where V_{12} is nearly zero the demodulated signal is mainly composed of transients, with the consequence that the bit decoding would most certainly fail.

3 Theory of Inversion

In [2] the following approximate expression for V_{12} has been given under the assumption that $\Delta Z_i / R_A$ are small quantities,

$$V_{12} \approx k^2 I_A R_A Q_A \frac{(Q_1 - Q_2)(1 - Q_1 Q_2 \Delta_T^2)}{(Q_1^2 \Delta_T^2 + 1)(Q_2^2 \Delta_T^2 + 1)}, \tag{2}$$

where $k^2 = M_{TA}^2 / L_T L_A$ denotes the square of the magnetic coupling between the reader antenna and the tag coil, Δ_T represents the detuning $1 - L_T C_T \omega^2$, $Q_A = L_T \omega / R_A$ is the quality factor of the reader antenna and $Q_i = R_i / L_T \omega$ are the quality factors of the tag corresponding to the open ($i = 1$) and closed ($i = 2$) positions of the switch. The approximation consisted in using in (1) the Taylor development up to first order

$$|1 + Z| = 1 + \mathrm{Re} Z + \ldots \tag{3}$$

for a small complex number Z. Since k^2 is the only quantity in (2) that varies with the position of the tag on the reader antenna and it is always positive, the approach based on (2) may leave the impression that the occurrence of inversion is dependent only on the detuning Δ_T and is independent of the tag position. However such dependence exists as a second order effect. For analyzing it we start from the identity

$$|1 + Z_1| - |1 + Z_2| = \frac{|1 + Z_1|^2 - |1 + Z_2|^2}{|1 + Z_1| + |1 + Z_2|}. \tag{4}$$

Further, the numerator of (4) may be computed by using

$$|1 + Z|^2 = 1 + 2\mathrm{Re}Z + |Z|^2 \tag{5}$$

which finally gives the new approximative formula that we shall use, obtained by neglecting the small complex numbers Z_1 and Z_2 in the denominator of (4):

$$|1 + Z_1| - |1 + Z_2| \approx_S \mathrm{Re}Z_1 - \mathrm{Re}Z_2 + \frac{|Z_1|^2 - |Z_2|^2}{2}. \tag{6}$$

In (6) the sign $\approx_S$ means that the right term is an approximation of the left term with the additional quality that the signs of the two terms coincide, without any approximation. When using (6) in (1) we find the approximation of V_{12}:

$$V_{12} \approx_S I_A\left(\mathrm{Re}\Delta Z_1 - \mathrm{Re}\Delta Z_2 + \frac{|\Delta Z_1|^2 - |\Delta Z_2|^2}{2R_A}\right). \tag{7}$$

In terms of our model of Fig. 1 we have

$$\Delta Z_i = k^2 L_A L_T \omega^2 \frac{1 + jR_i C_T \omega}{R_i \Delta_T + jL_T \omega}. \tag{8}$$

By substituting (8) in (7) and performing the algebra we arrive at the approximate formula for the analysis of inversion, exact as far as sign is concerned:

$$V_{12} \approx_S k^2 I_A R_A Q_A \frac{(Q_1 - Q_2)\left(1 - Q_1 Q_2 \Delta_T^2 + k^2 Q_A (Q_1 + Q_2)(\frac{1}{2} - \Delta_T)\right)}{(Q_1^2 \Delta_T^2 + 1)(Q_2^2 \Delta_T^2 + 1)}. \tag{9}$$

Since we always have $Q_1 > Q_2$ and the denominator in (9) is positive we finally obtain the formula for the sign of V_{12} to be used in the analysis of inversion, in which sgn(x) stands for the sign of x:

$$\mathrm{sgn}(V_{12}) = \mathrm{sgn}\left(1 - Q_1 Q_2 \Delta_T^2 + k^2 Q_A (Q_1 + Q_2)(\frac{1}{2} - \Delta_T)\right). \tag{10}$$

The discussion of inversion comprises several cases.

(A) $\Delta_T < 1/2$ and $Q_1 Q_2 \Delta_T^2 \leq 1$. The right term in (10) is positive and inversion does not occur. In particular this covers the case $\Delta_T = 0$ of tuned tags.

(B) $\Delta_T < 1/2$ and $Q_1 Q_2 \Delta_T^2 > 1$. Inversion occurs as soon as k verifies

$$k^2 < \frac{Q_1 Q_2 \Delta_T^2 - 1}{Q_A (Q_1 + Q_2)(\frac{1}{2} - \Delta_T)}. \tag{11}$$

Since the coupling may be made as small as wished by placing the tag farther from the antenna, it follows that inversion can occur in principle for the considered case. Of course in reality the communication might stop before reaching the needed distance.

(C) $\Delta_T = 1/2$ and $Q_1Q_2 \leq 4$. Inversion does not occur.
(D) $\Delta_T = 1/2$ and $Q_1Q_2 > 4$. Inversion occurs irrespective of the magnitude of k.
(E) $\Delta_T > 1/2$ and $Q_1Q_2\Delta_T^2 \geq 1$. Inversion occurs irrespective of the magnitude of k.
(F) $\Delta_T > 1/2$ and $Q_1Q_2\Delta_T^2 < 1$. Inversion occurs as soon as k verifies

$$k^2 > \frac{1 - Q_1Q_2\Delta_T^2}{Q_A(Q_1 + Q_2)(\Delta_T - \frac{1}{2})}. \tag{12}$$

However, being a magnetic coupling, k must also verify $k^2 \leq 1$. Therefore inversion may occur only if

$$\frac{1 - Q_1Q_2\Delta_T^2}{Q_A(Q_1 + Q_2)(\Delta_T - \frac{1}{2})} < 1. \tag{13}$$

4 Experimental Results

The automated scanner described in [3] works by displacing the tag over the reader antenna through a systematic 2D movement while the system computes V_{12} for each tag position. Figure 2 shows the changes in the demodulated signal as the tag passes successively over the non-inverted area, the boundary zone and the inverted area. The signal in Fig. 2B consists mainly of transients and cannot be decoded; the arrows point at those parts of the signal where one clearly observes that V_{12} vanishes.

The colors used in the 2D maps of V_{12} obtained with the scanner are red for non-inverted areas and blue for inverted areas; for the reader not disposing of the color figures graphs of the middle vertical sections through the maps have been included. The black and white maps show in black the positions at which the decoding of some data bit failed; the arrows on those maps point at the no-communication zones that separate the inverted and the non-inverted areas. Figure 3A shows the case of a tuned tag for which inversion does not occur. Figure 3B illustrates case B of the discussion in Sect. 3; one observes that indeed inversion occurs in the areas of lower coupling near the edges of the antenna. Figure 3F illustrates case F which is the most tricky to achieve since besides condition (12) on the coupling it needs condition (13) on the circuit parameters which might not be true for the tags available to the developer. For

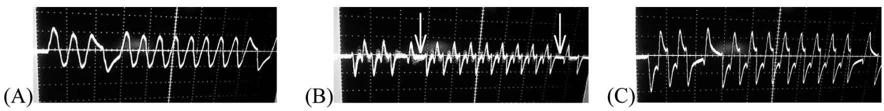

Fig. 2. (A) Not inverted signal; (B) signal at the boundary between non-inverted and inverted areas; (C) inverted signal.

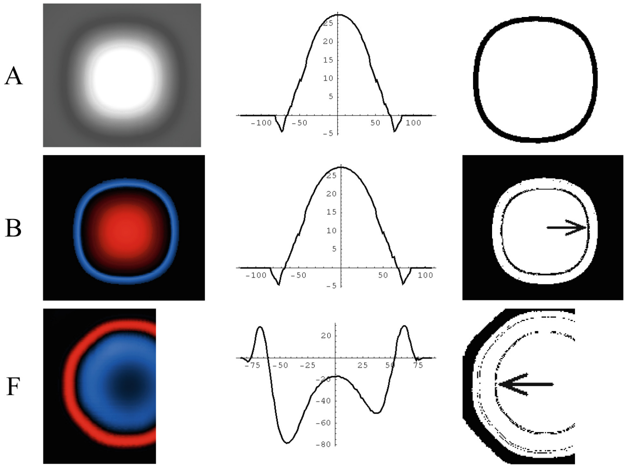

Fig. 3. Color map of V_{12}, graph of section and map of incorrect bit decoding for no inversion (A), inversion case B and inversion case F. (Color figure online)

this reason the map for this example has been obtained with a tag simulator with components carefully adjusted to satisfy (13); details about tag simulators are given in [4]. As predicted by (12) inversion occurs in the central area where coupling is higher.

5 Conclusions

We have exposed an exact theory, as far as the sign is concerned, of the dependence of inversion on the parameters of the tag circuit and on the magnetic coupling between reader antenna and tag. We have shown that inversion is associated with lower coupling in case of slightly detuned tags and possibly with higher coupling in case of heavily detuned tags, the latter case occurring only if the parameters of the tag circuit allow it. Each of the main cases of inversion has been illustrated with a map obtained with the 2D scanner. Together, the theory and the scanner provide useful insights into a phenomenon the RFID system developer should be aware of.

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