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Study on non-linear effects of two coupled UHF-band RFID tags

Jari Holopainen*, Xinwei Gao, and Ville Viikari
Aalto University School of Electrical Engineering, Espoo, Finland, jari.holopainen@aalto.fi

Abstract

In this article, the combined effect of the mutual coupling of two closely located RFID tags and the inherent non-linearity of the impedance of the microchip of a tag is studied. The conclusion of the study is that these factors together might result in a counter-intuitive condition where some of the tags suddenly become inactive while the reader increases the transmit power.

1. Introduction

A passive UHF-band RFID system works in such a way that a reader transmits an RF signal to one or more RFID tags. The antenna and the rectifier of the tag transfer the power to the microchip which becomes activated if its absorbed power is larger than the chip-specific threshold power. Consequently, the activated chip creates an information-modulated RF response signal that is transmitted back to the reader by the antenna of the tag. Typically, the absorbed power of the chip increases monotonically as a function of the transmitted power of the reader. However, some lab experiments found a strange behavior of the tags when one reader is activating a number of identical closely spaced tags simultaneously. During the activating process, when the transmitted power of the reader is increased or the reader is brought closer, some tags first operate normally but suddenly stop responding above certain transmit power. This is very likely because the microchips of some tags fail to absorb the minimum threshold power to support the operation of the tag at that moment [1]. One possible explanation for this behavior is the combined effect of the mutual coupling between closely located antennas of the tags and the inherent nonlinear behavior of the microchip. The objective of this study was to test with EM and circuit simulations whether this hypothesis is correct. According to authors' knowledge, this behavior has not been explained earlier in literature.

This article is based on the Master's thesis work of Mr. Xinwei Gao in Aalto University School of Electrical Engineering [2].

2. Problem description and research methods

Several previous experiments show that the impedance of an RFID microchip is inherently non-linear as a function of its absorbed power. Typically, for maximizing the reading distance, the impedance of the tag antenna is designed for the maximized power transfer using the complex conjugate matching to the impedance of the chip at the threshold level. However, when the absorbed power of the chip increases above the threshold power, the impedance of the chip will change causing a larger mismatching between the antenna and the chip. As a result, a larger part of the power is reflected and reradiated by the antenna.

According to authors' knowledge, only a few papers have discussed the effects of the inherent non-linear behavior of the chip impedance. However, some papers present the study of the non-linear properties of the chip impedance. For instance, Pavel Nikitin et al. presented such a study in [3]. Of the two measured chips in [3], the chip "NXP UCODE G2XM" is selected to be used in this work. Some values of its impedance behavior are reported in Table 1. The threshold power of the chip is -12.6 dBm. The impedance of a passive RFID chip is inherently highly capacitive at used frequencies because it has typically a rectification Schottky diode with a junction capacitance.

Table 1. Approximated values of the impedance of the NXP chip at 900 MHz at its different absorbed power levels [3].

Absorbed power (dBm)	-18	-14	-12.6	-8	-2	2
Impedance (Ω)	15 -j·155	22 -j·152	26 -j·150	42 -j·138	56 -j·90	50 -j·80

As given in Table 1, the selected RFID chip has the impedance of 26-j·150 Ω at 900 MHz at the threshold power level -12.6 dBm. Hence, the impedance of the tag antenna is assumed to be close to 26+j·150 Ω at 900 MHz for ensuring maximum power transfer to the chip at the threshold power level. Such an inductive impedance can be implemented, for example, with a loop and dipole arms with end capacitors. The used tag antenna is designed in CST MWS electromagnetic simulator and it is presented in [2]. The size of the tag antenna is 52 mm x 52 mm [length x width] and its maximum directivity is about 2 dBi. The used reader antenna is a circularly-polarized patch antenna (size: 150 mm x 150 mm x 30 mm [length x width x height]) and the realized gain in the main lobe is 8 dBi [2].

Figure 1 shows the placement of the reader antenna and the two identical coupled tags modelled in CST MWS simulator from which the simulated S-parameters of the antennas are exported. All the antennas were placed into each other's main lobes. The separation of the two identical tag antennas in the *z*-direction is marked as *z* and in the *y*-direction as *y*. Several cases were studied in [2] with different variables of z and y, and two of them is shown in the next chapter.

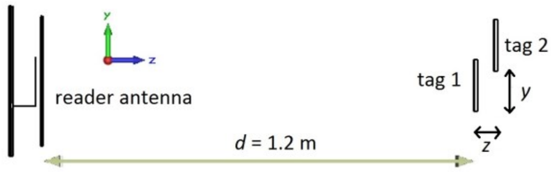

Figure 1. Placement of the antennas of the reader and the two identical coupled tags in CST MWS electromagnetic simulator.

The non-linear part of the study was carried out in the AWR circuit simulator, see Figure 2. The three port in the middle is the imported S-parameters of the CST-simulated reader antenna and the two coupled tag antennas (Figure 1). The sub-circuits for the tags 1 and 2 include the non-linear, power-dependent impedance (Table 1) that is modelled as a parallel circuit of a variable resistor R and a variable capacitor C. The feed port (marked PORT) models the feed power of the reader antenna. The probes measure the absorbed power of each tag.

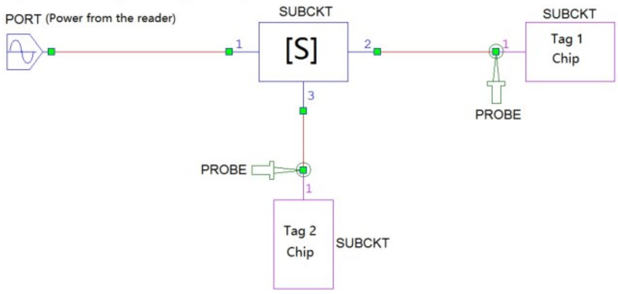

Figure 2. Circuit schematic of the reader and two identical coupled tags in the AWR circuit simulator.

3. Results of the case studies

Before studying the operation of two coupled tags, it is useful to perform a reference study with one single tag. This way it is possible to see the effect of the non-linear impedance. The single tag reference case is identical to the case shown in Figures 1 and 2, but so that tag 2 is removed. Figure 3 shows the absorbed power of tag 1 as a function of the transmitted power of the reader antenna at 900 MHz.

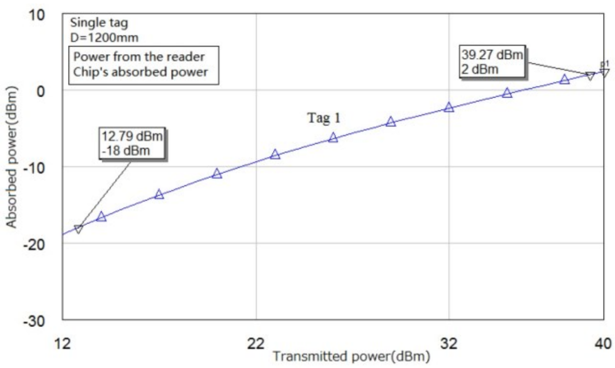

Figure 3. The absorbed power (dBm) of the chip as a function of the transmitted power of the reader antenna (dBm) at 900 MHz for the reference case with one single tag.

Figure 3 shows that the absorbed power of the chip does not increase linearly with the transmitted power. The system of three coupled antennas is perfectly linear, the only non-linear part being the impedance of the RFID chips. Therefore the obvious reason for the simulated non-linear relation between the transmit power and absorbed power is that the impedance of the microchip changes as its absorbed power is increasing, and that results in a larger mismatching and less-effective power transfer between the antenna and the chip. It is also worth mentioning that it was confirmed that the curve remained linear in the simulation when the impedance of the microchip was set constant (e.g., 26-j·150 Ω) at 900 MHz.

In this work, several cases with two coupled tags were studied [2]. The results of two cases are shown next. Tag 1 remains in the same location as in the reference case. Tag 2 is located the following way. In case 1: z = 5 mm and y = 0 mm and in case 2: z = 5 mm and y = 39 mm, see Figure 1. The absorbed powers of tags 1 and 2 as a function of the transmitted power of the reader antenna at 900 MHz for cases 1 and 2 are shown in Figures 4 and 5.

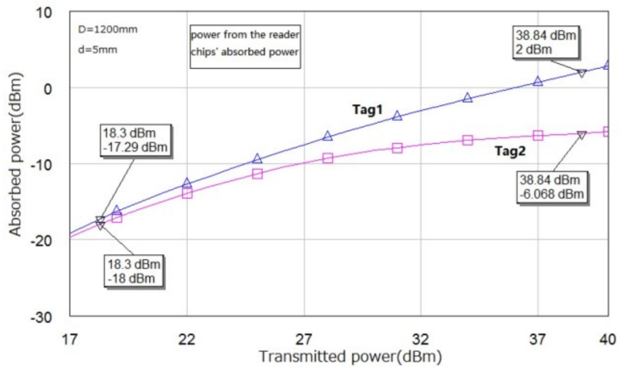

Figure 4. The absorbed power (dBm) of the chip of tags 1 and 2 as a function of the transmitted power (dBm) of the reader antenna at 900 MHz for the case 1 (z = 5 mm and y = 0 mm).

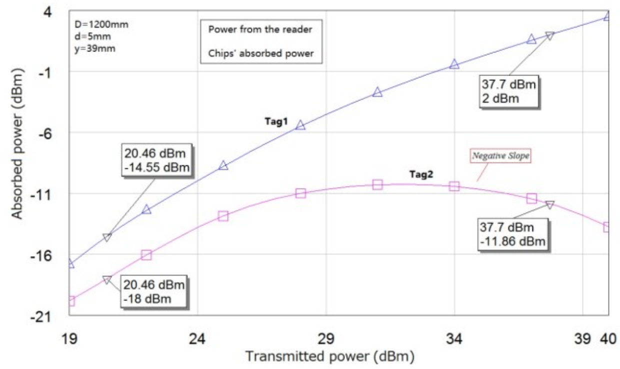

Figure 5. The absorbed power (dBm) of the chip of tags 1 and 2 as a function of the transmitted power (dBm) of the reader antenna at 900 MHz for the case 2 (z = 5 mm and y = 39 mm).

The results of case 1 show that the tags operate intuitively: when the threshold (-12.6 dBm) power of the chips is exceeded, both the tags remain activated. Whilst tag 1 needs a transmit power of 22 dBm to get activated, tag 2 needs 2 dB more. The obvious reason for this difference is that tag 1 causes some shadowing effect for tag 2.

Case 2 in Figure 5 presents the most interesting result of this work. As in the case 1, tag 1 becomes active when the transmit power exceeds about 22 dBm. Tag 2 becomes active when the transmit power exceeds about 26 dBm. However, after about 32 dBm, the absorbed power of the chip turns down. Consequently, tag 2 becomes inactivated when the transmit power exceeds about 39 dBm. This result demonstrates that it is possible – under certain conditions – that the combined effect of inherent non-linearity of the impedance of the chip and the coupling between closely spaced antennas of the tags can cause a sudden loss of operation of some of the tags when the transmit power of the reader is increased.

4. Discussion

Typically, the reading distance of UHF-band RFID tags is limited by the reader-to-tag (forward) link. The reason for this is that the threshold power (sensitivity) of the microchip of the tag is much worse than that of the reader (e.g., -10 vs. -80 dBm). Hence, for maximized reading distance, it is wise to match the tag antenna to the impedance of the chip at the threshold power level. [1]

The change of the impedance of the microchip (because of the inherent non-linearity) causes a larger mismatching between the antenna and the chip, and results in a larger reflection when the transmit power of the reader is increased or the reader is brought closer. Despite ever increasing reflected power, the absorbed power of the chip also keeps typically increasing.

However, the actual problem arises only just when the increasing reflected signal of one tag couples to another tag. In that case, this coupled signal (and its multiple reflections) and a direct signal from the reader superimpose and might have a destructive interference, which furthermore can result in a decrease in the absorbed power in one tag as demonstrated in this paper. Consequently, the absorbed power might drop below the threshold and this “unlucky” tag becomes inactive. Depending on the phase of the mutual coupling (which furthermore depends on the relative position and orientation of the tags and is hence often a random variable), a constructive interference might also take place. At the lower transmit power levels of the reader this phenomenon does not occur because the amplitude of the reflected signal is too weak.

A trivial way to overcome the problem would be to reduce the mutual coupling. This could be done by placing the tags far enough from each other. In that case the distance should be in the order of $\lambda/2\pi$ which would be a few centimeters at 900 MHz frequency. Because of the small electrical size of the tag antennas, it might be also challenging to reduce the coupling between the tags with the antenna design methods.

One of the research questions that arises from this article is that is it possible to design the impedance of the tag antenna such that the operation of closely located tags in large population would be more robust – i.e., is it somehow possible to increase the robustness of the whole system at the expense of the reading distance. On the other hand, one possible question is, whether some RFID microchips have a “better” impedance behavior, or is it actually possible to optimize the impedance behavior already in the IC design process. The study should also be continued by performing laboratory experiments.

5. References

1. P. V. Nikitin, and K. V. S. Rao, “Performance Limitations of Passive UHF RFID Systems,” *IEEE Antennas and Propagation Society International Symposium*, 2006, pp. 1011–1014.

2. X. Gao, *Population analysis of RFID tags*, Master’s Thesis, Aalto University, School of Electrical Engineering, Espoo, April 2015, 48 p.

2. P. V. Nikitin, K. V. S. Rao, R. Martinez, and S. F. Lam, “Sensitivity and impedance measurements of UHF RFID chips,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. **57**, No. 5, 2009.