Power and Phase Variation of Backscattered RFID Signal with Respect to the Incident Power at the Tag

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***Abstract*—In this paper, we investigate how the incident power at the tag affects the backscattered signal that reaches the reader. It is shown experimentally and theoretically that the backscattered complex signal, i.e. magnitude and phase, changes significantly with respect to the incident power at the tag's antenna. This effect is neglected in prior art and is due to the change of the input impedance of the tag's front end, due to the presence of non-linear components, like the rectifier's diodes. Measured deviation of 14dBs and phase shift of 100 degrees is reported herein. These variations might lead to large localization errors, depending on the method and the measured quantity, unless the localization algorithm accounts for the expected variability.**

***Index Terms*—Passive RFID, RFID tag, Modulation Factor, RSSI, Phase**

I. Introduction

The majority of localization techniques exploits either the measured power or phase of the tag backscattered signal. In such methods, a constant "reflection" coefficient is assumed for the tag-backscattering model. This term is usually referred to as the "modulation factor" and is introduced in the round-trip path loss equation.

In this paper, we explain theoretically and demonstrate experimentally that this "factor" is not constant. In fact, the backscattered signal strongly varies in magnitude and phase with respect to the incident power at the tag's Integrated Circuit (IC), because of the non-linearity of the tag's front-end.

We find that this factor depends on the matching of the tag-antenna to the IC; therefore it is different for each tag. Hence, each tag should be characterized separately along its destined operational frequency band. This effect is expected to have a significant impact on the localization accuracy, depending on the deployed method.

In this work, we measure 6 different tags and 4 different IC's in the anechoic chamber, showing how the power of the incident signal on the tag, affects the power and phase of signal measured at the reader. Experimental results, demonstrated herein show 14dB variability in the backscattered power, due to change of the incident power at the tag and phase-shifts greater than 100°. To the best of our knowledge, this is the first time that this effect is investigated.

II. Theoretical Model

Fig.1 shows an overview of a passive RFID system which involves a reader and an RFID tag. A passive RFID tag consists of an antenna and an integrated circuit (IC) chip. The reader transmits a continuous wave (CW) towards the tag which is received by the tag's antenna. A portion of the received wave powers up the IC through a charge-pump. As a consequence, in one modulation-state the tag's antenna is designed to be conjugate-matched to the tag's IC; the reflection coefficient $\Gamma_0 = 0$. In the other state, the "load" connected to the antenna is such, that the reflection coefficient is maximized; thus enhancing the detection of the modulated backscattered signal at the reader.

Therefore, the two modulation-states (high or low) arise from two different reflection coefficient at the tag antenna. Let Γ_i be the reflection coefficient for state $i = \{0, 1\}$. [1]–[5] define Γ as:

$$\Gamma_i = \frac{Z_l^i - Z_a^*}{Z_l^i + Z_a}, \tag{1}$$

where Z_a denotes the input impedance of the tag antenna and Z_l^i the input impedance of the chip; the latter depends on the state of the chip as shown in Fig. 1. Γ_i in (1) is a complex number, resulting to both power and phase changes on the backscattered signal.

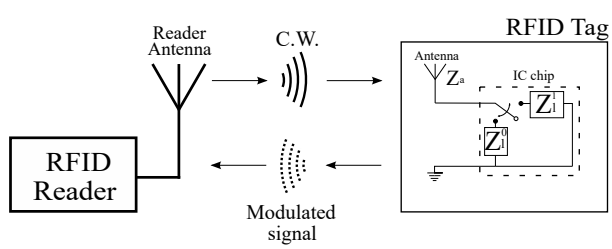


Fig. 1: Representation of an RFID System.

Let S_{rx}^i be the modulated backscattered signal that reaches the reader from the tag at state i; S_{rx}^i being proportional to Γ_i:

$$S_{rx}^i \propto |\Gamma_i| \cos(\omega_c t + \phi_{channel} + \phi_{\Gamma_i}), \tag{2}$$

where $\phi_{channel}$ represents the phase shift due to the distance traveled by the wave (i.e. $\frac{4\pi d}{\lambda}$) plus phase shifts due to multipath and ϕ_{Γ_i} is the phase shift at state i due to the

reflection coefficient of (1). The received signal is then I/Q demodulated and low-pass filtered:

$$\begin{aligned} I_i &\propto |\Gamma_i| \cos(\phi_{channel} + \phi_{\Gamma_i}) \\ Q_i &\propto |\Gamma_i| \sin(\phi_{channel} + \phi_{\Gamma_i}). \end{aligned} \tag{3}$$

The reader reports the phase of the vector at the two modulation states; i.e. $\arctan \frac{\Delta Q_i}{\Delta I_i}$, [6], which depends on the reflection coefficients Γ_i, as shown in (3).

The power reported by the reader, commonly known as RSSI (Received Signal Strength Information), is proportional to the difference of the magnitude of the reflection coefficient of the 2 modulation states [5], [7]:

$$RSSI \propto |\vec{\Gamma_1} - \vec{\Gamma_2}|^2 \tag{4}$$

Therefore:

- the measured phase depends on Γ_i,
- and the measured power depends on Γ_i.

Notice from (1) that Γ_i depends on the tag's load at state i. However, the front-end of the tag comprises diodes, in order to rectify the incident wave. Due to the non-linearity of the front-end, the equivalent impedance of the tag depends on the incident power at the tag. Consequently, the terms of interest, i.e. Γ_i, ϕ_i and P_i, depend on the incident power at the tag's antenna P_{inc} and should be changed to $\Gamma_i(P_{inc})$, $\phi_i(P_{inc})$ and $P_i(P_{inc})$ respectively.

In this paper, we measure the variation of these parameters in several tags with respect to the incident power and discuss on the implications of this variability on the accuracy of different localization methods. In an effort to simplify the notation, we treat separately the variation of the amplitude and the phase of the backscattered RFID signal. We use the typical notation of M for the backscattered power, but introduce the dependence on the incident power at the tag P_{inc}. Hence, the received power at a monostatic reader is:

$$\begin{aligned} P_i(P_{inc}) &= \frac{P_{tx} G_r^2 G_{tag}^2 \lambda^4 M(P_{inc})}{L_{sys} d^4 (4\pi)^4} \\ \Rightarrow P_i(P_{inc}) &= \xi_{link} M(P_{inc}), \end{aligned} \tag{5}$$

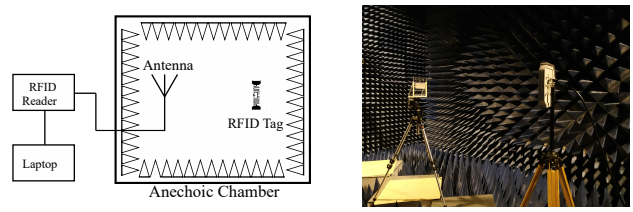
where P_{tx}, G_r, G_{tag} are the reader's Tx power, the reader's antenna gain and the tag antenna gain respectively, d is the tag to reader-antenna distance and L_{sys} represents the system losses in the reader. The phase variability with respect to the incident power is defined as:

$$\phi_i(P_{inc}) = \phi_i(P_{ref}) + \phi(P_{inc}) \tag{6}$$

where $\phi_i(ref)$ is the phase for a reference incident power level denoted as P_{ref}; thus, if $P_{inc} = P_{ref}$, $\phi(P_{ref}) = 0$. The tag designers typically design the antenna, in order to conjugate match the tag's impedance at the minimum operational power level of the tag; i.e. the tag's sensitivity. In the above notation, this value will be used as the reference power value P_{ref}, in order to calculate the reference phase shift $\phi_i(P_{ref})$. By using the notation of (5), (6), we expect to measure the variability of the received power and phase from a given reference marginal value: the tag's performance at minimum reception.

III. Measurements

The experimental setup is shown in Fig. 2. Each tag was placed inside an anechoic chamber with an 8.5dBic RH circularly polarized antenna, manufactured by Kathrein, connected to the "Speedway R420" monostatic RFID reader. The reader collected RSSI and phase measurements. For each measurement, the tag was fixed to a specific distance and the reader reduced the transmitted power level within 20dB at steps of 1dB. Given the fixed setup, if we hadn't accounted for the variability of the tag's load with respect to the incident power, we should have measured a constant phase throughout the experiment, and constant M. The measurements were repeated at three different distances, at 1.00m, 1.30m and 2.60m, to ensure a larger range of incident powers and better characterization of each tag. Finally, the results are combined in unified plots per tag, where we have accounted for the distance factor in the incident power.



(a) Sketch of the Setup (b) Photo of the Setup

Fig. 2: The Experimental Setup of the Measurements in the Anechoic Chamber.

Three tags with different ICs and three with same IC were measured, namely: 1) Confidex "Survivor" with "NXP UCODE G2iM+" IC (- 17.5dBm sensitivity), 2) Confidex "Carrier Pro" with "Impinj Monza 4QT" IC (-19.5dBm sensitivity), 3) Tageos "EOS-400" with "Monza R6-P" (-22.1dBm sensitivity) and 4) Alien ALN-9740 "Squiggle" , 5) Alien ALN-9730 "Squiglette", 6) Alien ALN 9741 "Doc", all three with "Higgs – 4" IC (- 19 dBm sensitivity). Measurements were collected at 4 different channels in the European operation band of UHF-RFID. Still, we present results only in the frequency of 865.7MHz, as the variance between measurements was minor due to the narrow nature of the band.

Assuming, free space conditions, the power reaching the tag's antenna at distance d is:

$$P_{inc} = \frac{P_{tx} G_r G_{tag} \lambda^2}{(4\pi d)^2}. \tag{7}$$

Solving for $M(P_{inc})$ eq. (5) and substituting (7), one calculates the modulation factor $M(P_{inc})$:

$$M(P_{inc}) = \frac{P_i(P_{inc}) L_{sys} d^2 (4\pi)^2}{P_{inc} G_{tag} G_r \lambda^2}. \tag{8}$$

During the measurements, P_{inc} is calculated by (7), $P_i(P_{inc})$ is measured by the reader (the RSSI value), and $L_{sys} = -1.5$dB. The results of $M(P_{inc})$ are shown in Fig. 3.

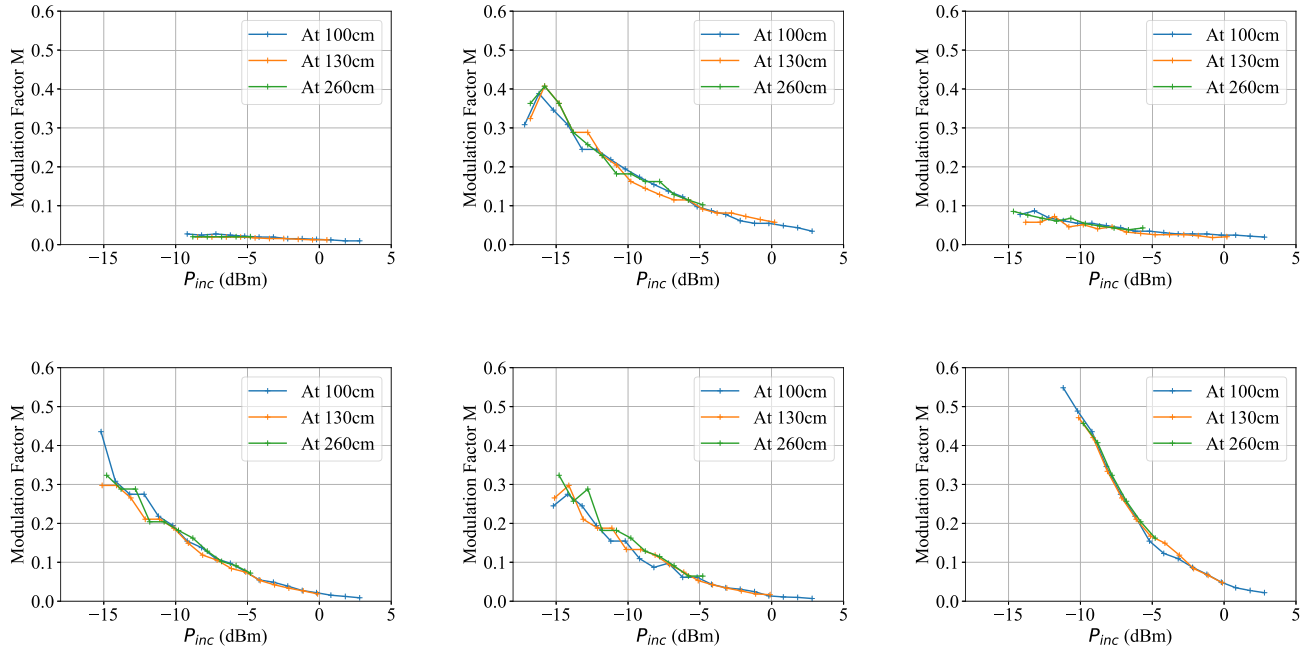


Fig. 3: Modulation Factor M vs Incident Power on Tag's Antenna.

A. Variation of M vs. Incident Power

Figs. 3a-d demonstrate the variation of M for tags connected to 4 different ICs, while Figs. 3d-f demonstrate the variation of M for 3 tags connected to the same chip; different antennas. In the case of Fig. 3a, the tag is destined to operate on top of metal, which was not used in the measurements. As a consequence, the antenna is not tuned and M is small and "stable" for all incident-powers, as the antenna mistuning dominates the reflection coefficient Γ_i. In all other cases, which are more representative for the effects of the incident power on the tag's performance, we identify the following key-remarks:

- M drops with respect to the power that reaches the tag; so it's not constant as typically assumed in prior-art.
- The best M is recorded for the minimum reception power, as expected, since the designer aims to "conjugate-match" the tag's antenna for the "worst" reception condition, thus maximizing the reader-to-tag range.
- The maximum variation of M is not the same for different combinations of antennas and ICs.
- The maximum variation of M ranges from 6.3dB in Fig. 3c (Tageos "EOS-400") to 14.3dB in Fig. 3f for Alien ALN 9741 "Doc". Bare in mind that in RSSI-based localization, M is assumed constant.

B. Variation of Phase vs. Incident Power

Figs. 4a-f demonstrate the corresponding variability of the measured phase at the reader. In agreement with (6), we have considered as P_{ref} the minimum recorded incident power level per tag and we have set $\phi_i(P_{ref}) = 0$ rad in all experiments, since we are not interested on the absolute value of the phase (which is affected by the path and is wrapped), but on its variation with respect to the incident power. In addition, since the reader reports the negative phase of the backscattered signal, in the results of Fig. 4 we show the inverse of the measured phase.

- the phase changes with respect to the power that reaches the tag; so it's not constant as typically assumed in prior-art.
- The maximum variation of the phase is not the same for different combinations of antennas and ICs. For example, notice that the phase of Alien ALN 9741 "Doc", shown in Fig. 4f changes by 1.8rad (103°) for 14dB variation of the incident power, but the phase of Alien ALN 9740, shown in Fig. 4d changes by 0.7rad, even though both tags are attached to the same chip; due to the different antenna-impedance.

IV. Effects on Localization - Discussion

In this paper, we have shown theoretically and experimentally that the backscattered power and phase from a tag at a given position changes with respect to the power that reaches the tag's IC. This change is not generally known and differs per combination of tag-antenna with chip. In the majority of localization models, either the power or the phase information is used to estimate the position of the tag. In prior art, the dependence of these metrics on power is not considered; M and phase ϕ are considered constants with respect to the incident power.

The effect of the variability on the localization accuracy depends on the method and its sensitivity on those parameters. For example, in phase-based localization methods, the

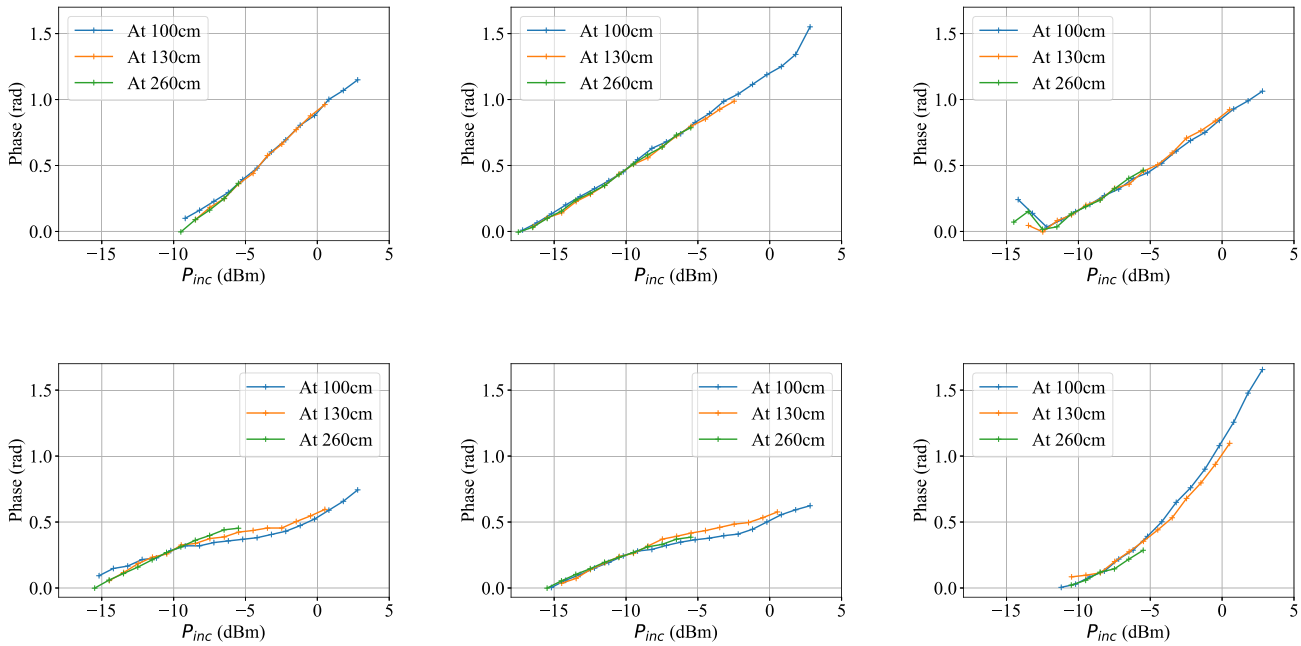


Fig. 4: Phase vs Incident Power on Tag's Antenna.

inaccuracy is expected to be greater for methods depending on measuring phase differences between different antennas [6]; in such cases the entire search-space is mapped in measurements within [0,2π], so a measurement phase error would result in large space-deviations (in the order of m). On the other hand, in Synthetic-Aperture-Radar localization techniques [8], [9], the effect is expected to be smaller, since the inclination of the measured phase will change but not the critical points, like the change of inclinations; the error is expected to be in the order of cm. In the case of RSSI based localization [10], [11], the errors are expected to be large, since M was measured to change significantly with respect to the incident power. Therefore, any method assuming a round-trip of the signal with fixed M is vulnerable to large errors.

We aim to further investigate the effect of the reported variability of the backscattered power and phase with respect to the power that reaches the tag on different localization methods and provide ways to correct the expected effects.

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