Sensitivity and Impedance Measurements on UHF RFID Transponder Chips

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Abstract. We present a method to perform accurate measurements in the UHF (ultra high frequency) band on passive RFID (radio frequency identification) transponder chips. Our samples were extracted from commercially available RFID tag inlays. We determine the minimum operating power necessary to get a response from the transponder chip. Furthermore, we measure the chip input impedance in both, the reflecting and the absorbing state as a function of input power. We present measurement results of four transponder chips and find good agreement with values claimed in the manufacturer's data sheets. At the end of the paper we draw conclusions for the optimum antenna design and the link budget.

1 Motivation

The main tasks in designing passive RFID (radio frequency identification) transponders that operate in the UHF (ultra high frequency) band are

- the development of a transponder chip that uses a rectifier to turn an RF signal into the supply voltage for the built-in logic, and
- the design of an appropriate antenna that is matched to the chip and can cope with the environment that is given by the application.

The typical input impedance of passive state-of-the-art UHF transponder chips is highly reactive (e.g. $Z_{\mathrm{chip}} \approx (20 - 200j)\,\Omega$) which is a result from technological aspects and efficient RF-rectifier design. In a conventional impedance measurement, the chip is directly connected to the $50\,\Omega$ system of a VNA (vector network analyzer) [1]. As a result the VSWR (voltage standing wave ratio) at the chip input is by far larger than 10:1 which leads to inaccurate results for the input impedance.

Besides the input impedance, the power accepted by the transponder chip is of high interest, first and foremost to obtain the minimum operating power. In a conventional test setup, the accepted power could in principle be calculated from the VNA's source power and the reflection coefficient determined by the VNA.

But, foregoing measurements showed that, at high VSWR, any inaccuracy of the measured reflection coefficient has a particularly strong impact on the accepted power determined in this way.

It is common practice that modulated backscattering by the transponder chip is achieved by changing its input impedance. Depending on the modulation scheme and the data rate used in the transmission, a switching between two impedance states is done with a rate up to 640 kHz. This makes separate measurement of the corresponding input impedances particularly difficult.

Finally, causing the chip to respond requires a carrier that is modulated with a command sequence—a feature which, to the knowledge of the authors, is not provided by any VNA available on the market.

To attain accurate results for both power and impedance, that are useful for the antenna designer on the one hand, and for the chip designer on the other hand, we developed a new measurement method. In Section 2 we describe the pre-matched impedance test setup we use to improve accuracy of the input impedance and the power level measurement. Impedance tuners are used to connect a VNA with a test fixture that holds the transponder chip (Section 3). An external signal source provides a carrier modulated with a command sequence that causes the transponder chip to respond. The sequence which is compliant to the EPCglobal Gen2 UHF RFID Protocol Standard [2] is described in Section 4.

With an exemplary measurement presented in Section 5, it is shown how the input impedance of a transponder chip is obtained. This is done at a carrier frequency of 866 MHz which corresponds to the European ISM (industrial scientific and medical) band dedicated to RFID systems. Section 6 elaborates on the relation between input impedance and operating power. The delta gamma value, which is a very useful quantity to specify the strength of the signal returned by the transponder chip is introduced in Section 7, and results are discussed. At the end of the article, in Section 8, we present a short comparison of some transponder chips. In Section 9 we draw conclusions for the radio link budget [3] and for the optimum antenna design [4] which we consider useful for RFID system designers.

2 Chip test setup

This section describes the test setup and measurement procedure that was developed to characterize and compare the tag chips.

The measurement setup depicted in Figure 1 consists of the following components:

- The **tag chip** mounted in the test fixture (DUT).
- The **vector signal generator** (R&S SMU200A) that provides a signal at 866 MHz that is modulated with the wake-up sequence. Output power and timing parameters are controlled by the measurement computer.
- The **vector network analyzer** (R&S ZVA24) determines the impedance of the transponder chip. The wake-up sequence is provided by using the signal generator as an external source for the VNA. After the command, a series

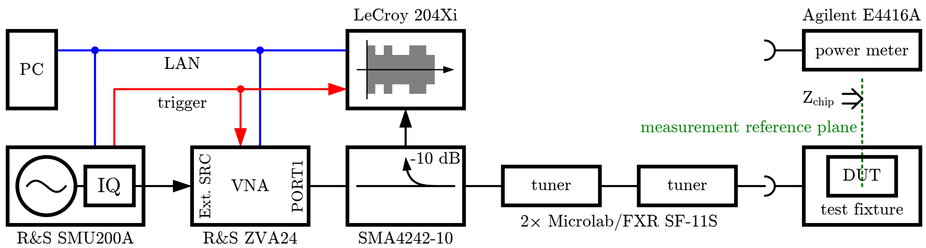

Fig. 1. Block diagram of the measurement setup used to characterize the transponder chips.

of impedance measurements is triggered to measure the chip impedance in both, the absorbing and the reflecting state. The real and the imaginary part of the impedance can be shown versus time.

- Two **impedance tuners** (Microlab/FXR SF-11S) provide static pre-matching [5] between the 50 Ω output of the VNA and the tag chip. This means that if the chip is in absorbing mode (equivalently speaking: if the chip does not try to reflect power) all available power is provided to the rectifier and no power is returned[1]. Firstly, this allows direct adjustment of the power accepted by the chip, and secondly, the pre-matching transforms the transponder chip impedance into the 50 Ω system impedance. This enables a more accurate impedance measurement due to lower VSWR at the VNA input. Moreover—since the tuners provide the complex conjugate chip impedance Z^*_{chip1} which is in fact the optimum antenna impedance—the measurement is equivalent to one with an antenna that is perfectly matched to the chip. The calibration of the VNA is done after pre-matching with the impedance tuners. Pre-matching is adjusted at the minimum operating power.
- The **directional coupler** (Narda SMA4242-10) separates the power returned by the tag chip from the source power. Firstly, this is necessary to find the optimum setting of the impedance tuners by minimizing the returned power. Secondly, the returned signal can be displayed on the
- **oscilloscope** (LeCroy Waverunner 204Xi) which is connected to the output of the directional coupler. A backscattered signal from the tag chip can thus be clearly identified.
- A **computer** is used to interface the oscilloscope, the VNA and the vector signal generator. This allows to control the experiments by the use of Matlab scripts and helps to find and compare characteristics of the transponder chips, to perform parameter sweeps, and to visualize results.
- The **power meter** (Agilent E4416A) to calibrate the available power at the chip input. This is done by replacing the DUT with the probe, adjusting the

[1] Strictly speaking this only holds for the fundamental frequency. Due to the fact that the chip rectifier is a nonlinear load, some power will be returned at harmonic frequencies.

impedance tuners to match, and read the power $P_{\text{Available}}$. Since the tuner's insertion loss is practically independent on the tuner's setting, $P_{\text{Available}}$ is equivalent to the available power at the chip input in a subsequent chip measurement.

3 Chip test fixture

For characterization, a test fixture was designed that allows precisely reproducible measurements of input impedance and backscattering behavior. For calibration of the VNA, three dedicated test fixtures were used as calibration standards. The match- and short-standards were equipped with a $49.9\,\Omega \pm 1\,\%$ and a $0\,\Omega$ resistor, respectively, while the open-standard was left empty. The parameters of the calibration standards were determined by measurement and used during the calibration process [6, 7]. Due to the relatively low frequency of 866 MHz and the small dimensions of the calibration standards, the parameters of the kit emerged very closely to the expected values in terms of impedance and electrical offset due to mechanical length.

For characterization, the chip with a small rest of its connection to the antenna was cut out of the RFID transponder inlay. The antenna connections were exposed, cleaned, and then glued to the test fixture with electrically conducting adhesive (Loctite 3880). A photograph of the calibration kit and of a test fixture holding a transponder chip that was extracted from a UHF tag is shown in Figure 2.

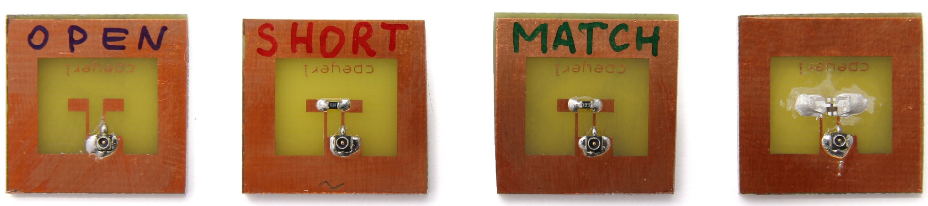

Fig. 2. Photograph of the calibration kit and the test fixture used for the measurement of chips extracted from RFID tags. The measurement cable is connected via a small surface mounted coaxial connector.

4 Wake-up sequence

Waking up the transponder chips—according to the EPCglobal Gen2 Standard—was done using an inventory command. The inventory command sequence was generated in Matlab and sent to a vector signal generator (R&S SMU200A) as IQ baseband samples. This allows to change the sequence quickly and to perform parametric sweeps.

The envelope of the wake-up signal is shown in Figure 3, a list of the parameters with their meaning, standard compliant value, and chosen value is given in Table 1. The inventory command (0x200010) sent to the chip requests an answer using the FM0 modulation scheme which provides the highest possible data rate.

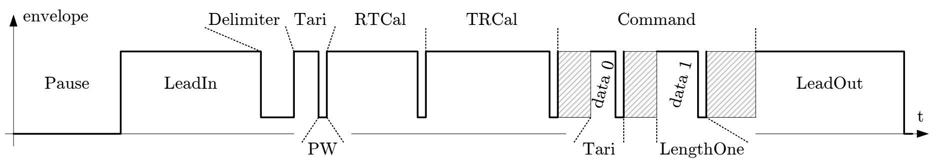

Fig. 3. Envelope of the wake-up sequence used to cause the transponder chip to respond.

Table 1. Parameters of the wake-up sequence.

parameter	meaning	range in standard	value used
Pause	power switched off	-	4 ms
LeadIn	power on before command	≤2 ms	2 ms
Delimiter	start of frame	12.5 μs ± 5%	12.5 μs
Tari	duration of a data 0 symbol	6.25 μs .. 25 μs	25 μs
PW	pulse width	(0.265 .. 0.525) Tari	0.265 Tari
RTCal	R⇒T calibration	(2.5 .. 3) Tari	2.75 Tari
TRCal	T⇒R calibration	(1.1 .. 3) RTCal	2 RTCal
LengthOne	duration of a data 1 symbol	(1.5 .. 2) Tari	1.75 Tari
Command	binary command code	dep. on modulation	0x200010
LeadOut	power on after command	-	1 ms
ModDepth	modulation depth	90 %	90 %

5 Impedance measurement results

In this section we present measurement results for one out of four different transponder chips. The four chips we characterized are denoted by the letters A to D. Figure 4 shows the results for chip A that was hit with the wake-up sequence at a peak envelope power of −6 dBm. In the top graph, the end of the inventory command can be seen. At $t = 0$, the inventory command ends and the chip starts processing the received data. Since the modulator in the chip is off, the input impedance of the rectifier loaded with the chips logic can be measured. We will refer to this impedance as the absorbing impedance Z_{chip1}. While in this state, no power is reflected at the chip input. The reason for this is that the tuners were set to provide the complex conjugate chip input impedance. In fact, the tuner's output can be seen as the output of a perfectly matched antenna.

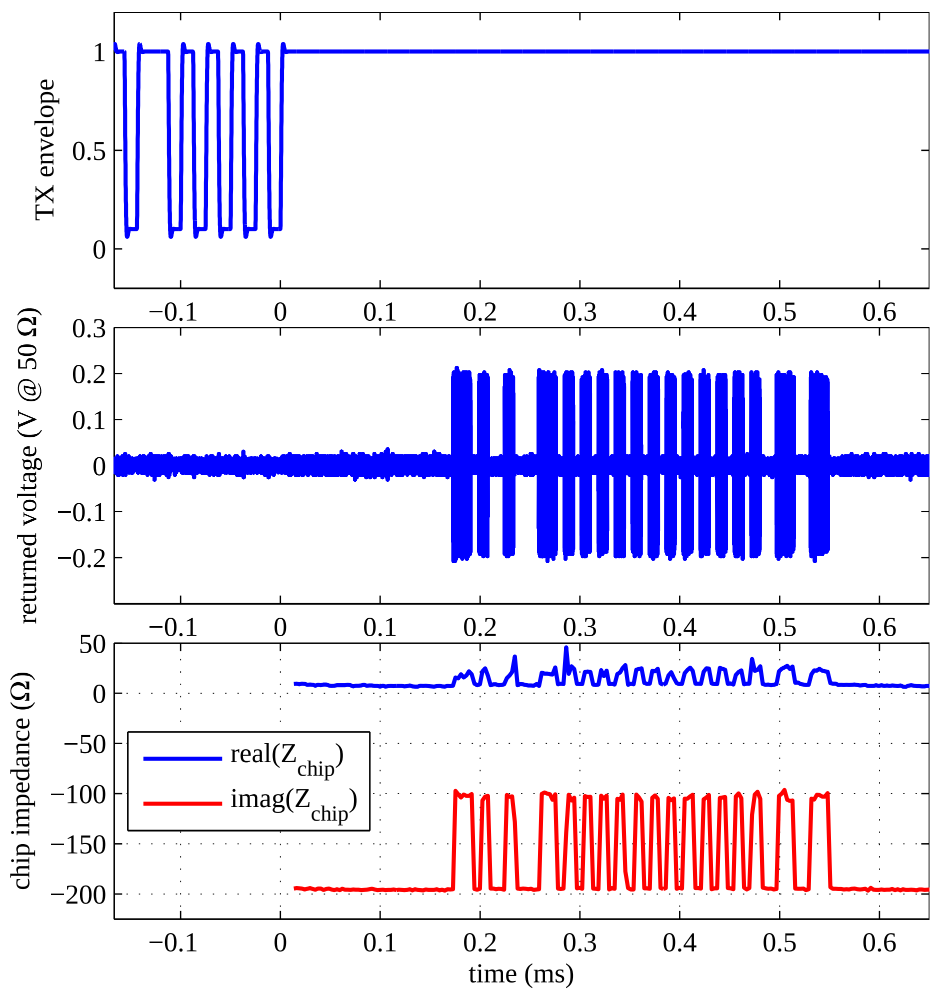

Fig. 4. Signals during measurement of chip A operated at minimum operating power level (−6 dBm).
Top: Envelope of the signal sent to the transponder chip. The end of the inventory command can be seen on the left at $t = 0$.
Middle: Returned voltage at the transponder chip. The mismatch caused by modulation of the chip's input impedance causes a reflected signal.
Bottom: Chip input impedance. During response, the impedance of the chip is switched between the two states Z_{chip1} and Z_{chip2}.

In the center graph of Figure 4, the reflected wave is plotted. While the chip is still processing the data—thus presenting Z_{chip1}, the reflected signal is close to zero. When the chip responds to the inventory command, it changes it's input behavior by—for example—switching on a shunt transistor. This destroys the matching condition and causes a strong reflected signal. The presence of this signal is controlled by the internal logic of the transponder chip.

From $t = 0$ on, the VNA takes a series of measurements to determine the chip impedance. It can be seen in the bottom drawing of Figure 4 that, during the chip's response, the input impedance switches to a new value at approximately $t = 0.17\,\text{ms}$. We will refer to this impedance as the reflecting impedance Z_{chip2}. From the measured values $Z_{\text{chip1}} = (8.3 - 159.2\,j)\,\Omega$ and $Z_{\text{chip2}} = (22.3 - 103.8\,j)\,\Omega$, it can be seen that a shunt transistor that is in parallel to a capacitor is switched on and off during modulation.

6 Power sweep

A power sweep has been performed to determine the operating power range of the transponder chip. Therefore, for every power step where a response was detected, the input impedances Z_{chip1} and Z_{chip2} were measured.

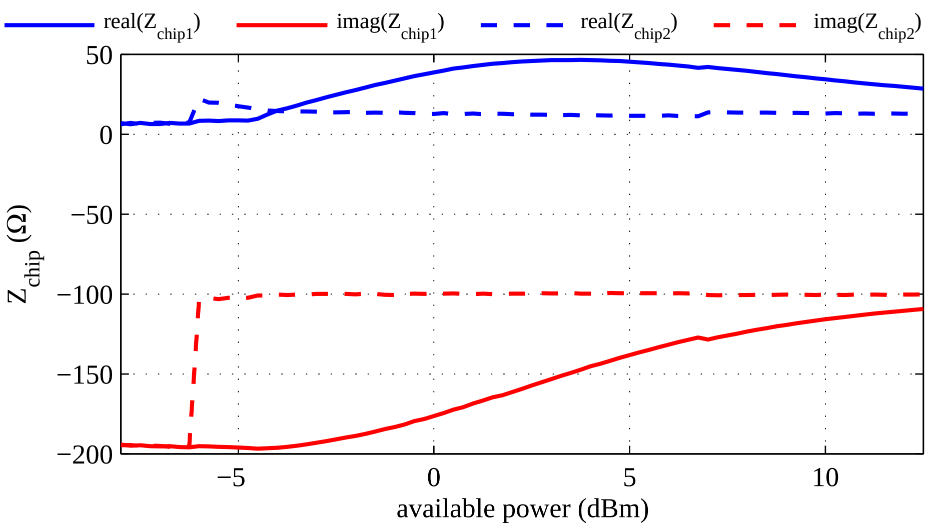

Fig. 5. Absorbing impedance Z_{chip1} and reflecting impedance Z_{chip2} of chip A versus power.

Figure 5 shows the result of such a sweep. The minimum operating power—or equivalently speaking the sensitivity—of this particular chip was $P_{\text{min}} = -6\,\text{dBm}$. The impedance Z_{chip1} measured at P_{min} can be considered the optimum antenna impedance. With increasing power the input impedances change quite significantly. This is first—at low power—because of the nonlinear characteristic of the rectifier and second—at higher power levels—due to the shunt control that regulates the internal supply voltage of the chip's logic part. With increasing power the absorbing impedance Z_{chip1} converges to the reflecting impedance Z_{chip2}. This is because at high power the internal shunt transistor is turned on even in absorbing mode. Please note that the setting of the tuners remains unchanged during the power sweep. This is very realistic because an antenna connected to the transponder chip will also provide a constant impedance regardless of the available power.

7 Efficiency of backscattering

The efficiency of backscattering is determined by how strong antenna and chip are mismatched when the chip switches to reflecting mode. Thus, a good transponder chip has a reflecting impedance Z_{chip2} that is far-off the absorbing impedance Z_{chip1} or equivalently far-off the complex conjugate of the antenna impedance Z^*_{ant}. A measure for this distance is the delta gamma value which is defined by $|\Delta\Gamma| = |\Gamma_{\mathrm{chip1}} - \Gamma_{\mathrm{chip2}}|$ where Γ_{chip1} and Γ_{chip2} denote the complex reflection coefficients corresponding to Z_{chip1} and Z_{chip2}, respectively. High delta gamma values result in strong reflected signals that are more easy to detect by an RFID system.

As a consequence from the characteristics of Z_{chip1} and Z_{chip2}, the delta gamma values converge to zero for high power levels. Figure 6 shows the characteristics of the delta gamma values of chip A to chip D versus power. It is interesting to note that for chip A, at low power the delta gamma value starts from $|\Delta\Gamma_{\mathrm{min}}| = 0.36$ and peaks at $|\Delta\Gamma_{\mathrm{max}}| = 0.39$ at a power level of $-4\,\mathrm{dBm}$. Similar behavior can also be seen for chip B. We suppose that this is due to the internal supply voltage which is not sufficient to exceed the threshold voltage of the shunt transistor at low power levels. The slight decrease in the real part of the reflecting impedance real(Z_{chip2}) at low power seen in Figure 5 is likely caused by an increasingly conducting shunt transistor and confirms this assumption.

The delta gamma plot is a powerful tool to determine the performance of a transponder chip. It shows the minimum operating power level and gives information about the strength of the reflected signals.

8 Comparison of transponder chips

In this section a comparison of four different commercial transponder chips that were available to the authors is given. Only one chip of each kind was characterized. The results are thus influenced by production tolerances. Table 2 summarizes minimum operating power, input impedances, and delta gamma values. The results for the input impedance Z_{chip1} of chip B and chip C agree well with

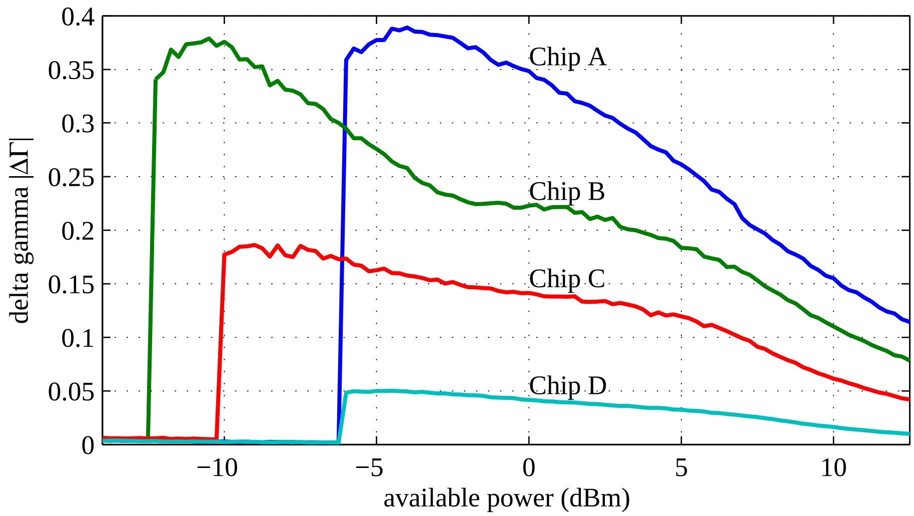

Fig. 6. Delta gamma $|\Delta\Gamma|$ versus power.

the values claimed in the manufacturers data sheet. For chip A and chip D no data sheets were available.

Table 2. Comparison of the transponder chips. The index *min* relates to operation at minimum power (a response from the chip is detected). *DS* denotes the claimed value in the data sheet. $|\Delta\Gamma|_{\max}$ relates to the maximum delta gamma value measured.

chip	$P_{\min}$	$P_{\min,\mathrm{DS}}$	$Z_{\mathrm{chip1,min}}$	$Z_{\mathrm{chip1,min,DS}}$	$\Delta\Gamma_{\min}$	$\Delta\Gamma_{\max}$
A	-6.00 dBm	-	$(8-195\,j)\,\Omega$	-	0.36	0.39
B	-12.25 dBm	-14.00 dBm	$(28-181\,j)\,\Omega$	$(26-204\,j)\,\Omega$	0.34	0.38
C	-10.00 dBm	-9.00 dBm	$(28-177\,j)\,\Omega$	$(23-161\,j)\,\Omega$	0.18	0.19
D	-6.00 dBm	-	$(25-432\,j)\,\Omega$	-	0.05	0.05

9 Conclusion

A measurement method was developed that allows to accurately determine minimum operating power and input impedance of transponder chips. For testing, we characterized and compared some chips that were extracted from commercially available tag inlays and found good agreement with the manufacturers data sheets.

From the results, it is seen that there are quite big differences between the transponder chips. Minimum operating power on the one hand ranges between

−6 dBm and −12.25 dBm. Maximum delta gamma values on the other hand range from 0.05 to 0.39, which makes an offset of approximately 18 dB in a link budget. Today, the read range of RFID tags holding chips that provide high delta gamma values is determined by the minimum operating power of the chip, the performance of the reader and the tag antenna, and the permitted transmit power of the RFID reader. In this case—because of the strong signal returned from the tag—the requirements on the dynamic range and the sensitivity of the RFID reader are fairly relaxed. Conversely, low delta gamma values cause a weaker response of the tag which requires a much higher sensitivity and dynamic range of the RFID reader. In this case, the read range can be extended by putting more effort into the reader design.

Furthermore, the transponder chips show quite different input impedance values and definitely require separate antenna design. We suppose that the differences between the tag chips are mostly due to technological advances in chip design over the last years.

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