Gain and Input Impedance Measurement for UHF Transponder Antennas

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Abstract

It was shown by numerous authors that the characterization of RFID (radio-frequency identification) transponder antennas that are favored to be small, have low gain, and show a strongly reactive input impedance, is far from trivial. We propose a method that utilizes a small, highly-stable, battery-driven signal source to generate the transmit signal directly at the antenna. The signal source is equipped with a tunable matching network that allows to determine the antenna impedance by a source-pull measurement. Antenna gain can be measured by using the battery-powered oscillator as a calibrated transmitter.

1. Motivation

It has been published in numerous articles that the characterization of directional pattern and input impedance of small antennas is far from trivial [1], [2]. The main reason is that a measurement cable leading to the antenna-under-test has to be avoided because it carries common-mode currents that may cause radiation by far stronger than the original radiation of the antenna. The fact that in RFID (radio-frequency identification) technology, antennas are not only small but also lossy due to low-cost manufacturing processes, makes the characterization of such antennas particularly difficult.

In [3] a method specific for antennas used in mobile equipment is presented. A small, battery-powered VCO (voltage controlled oscillator) is used to generate a CW (continuous wave) signal directly at the antenna. Since antennas in mobile equipment are operated by an RF (radio-frequency) frontend typically presenting a $50\,\Omega$ impedance, matching issues are not considered in detail. Although maximum gain and efficiency of the antenna can be determined with the method in [3], the directional pattern is left unexplored.

A more advanced method that uses fiber optics instead of a measurement cable is presented in [4]. This is a very promising approach because it allows to determine gain, phase patterns, and even the input impedance. On the downside, the assembly needed at the antenna site is by far too large to apply this method to RFID antennas.

A very interesting approach to measure the input impedance of RFID tag antennas is given in [5]. The impedance is determined from measurement results obtained for antennas loaded with different calibration standards. But, to our understanding, the results depend on the accuracy of the chip impedance which has to be known or characterized separately.

Input impedance measurements are also shown in [6], where an on-wafer-prober is modified to characterize planar antennas. The authors put the antenna on a styrofoam spacer and use absorbing material to reduce the impact of the on-wafer-prober and the probe-head metal. Still, it is argued that the probe head influences the measurement results.

We propose to characterize gain and input impedance of RFID tag antennas by means of a small, battery-driven oscillator that is mounted directly on the antenna and generates a CW (continuous wave) transmission signal at 864 MHz. The oscillator is equipped with a tunable matching network that allows power matching with the antenna. The input impedance is determined by a source-pull method. For the directional pattern measurement, the autonomously operating oscillator supplies the tag antenna with RF power. The antenna can thus be freely rotated. The accuracy of the measurement mostly depends on the properties of the oscillator that has to provide

- sufficient output power to overcome noise at the receiver,
- stable frequency and power level, regardless of battery status and load situation,
- a matching network that is tunable to the complex conjugate of the antenna impedance,
- sufficient battery life to conduct the measurement procedure, and
- it has to be small enough to maintain the electrical properties of the antenna-under-test.

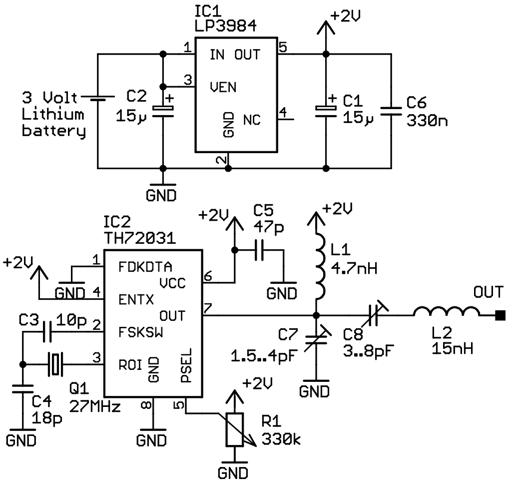

Figure 1: Oscillator schematic.

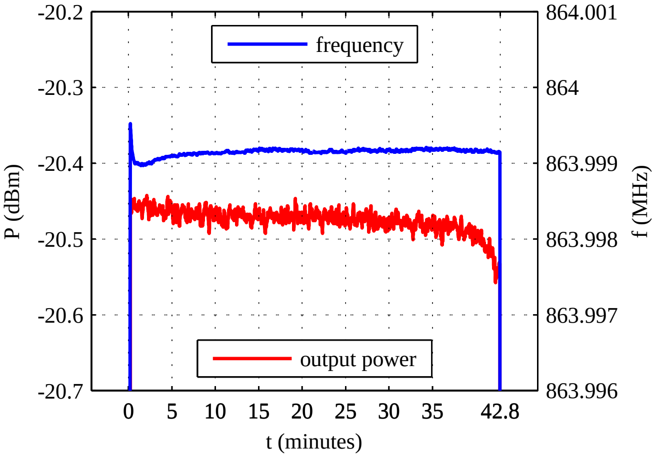

Figure 2: Oscillator output power and frequency.

2. Small battery driven oscillator

The oscillator unit is built around a fully integrated PLL-stabilized oscillator (TH72031) by Melexis Microelectronic Integrated Systems. It consists of a crystal oscillator that operates with an external quartz, a PLL unit that transfers the crystal frequency to 864 MHz, and a power amplifier that allows to set the output power to four different levels between $-12\,\mathrm{dBm}$ and $9.5\,\mathrm{dBm}$. The schematic of the oscillator unit is depicted in Figure 1.

At the output, the oscillator is equipped with a matching network that transforms the output impedance of the chip ($Z_{\mathrm{osc\,pin7}} \approx (15 - j56)\,\Omega$) to an impedance available at the oscillator's output Z_{out}. The matching network consists of two inductors (L1 and L2) and two tunable capacitors (C7 and C8). By tuning the capacitors, the real and imaginary part of the output impedance of the oscillator can be adjusted. A miniature coaxial connector (W.FL series by Hirose Electric Co.,LTD.) allows to connect the oscillator to measurement equipment or to an antenna with a thin coaxial cable. This cable introduces an electrical delay which leads to a transformation of the antenna impedance. For best matching, the output impedance of the oscillator Z_{out} is therefore not the complex conjugate of the antenna impedance Z^{*}_{ant} but rather matched to the transformed version of the antenna impedance Z'_{ant}.

To further improve stability, a linear, low-dropout, low-noise, fixed voltage regulator (LP3984) was inserted to obtain a more stable 2V supply voltage from the 3V lithium button cell (CR1220, 25 mAh). The voltage regulator enables stable operation of the oscillator until the battery voltage drops below 2.0 V. Figure 2 depicts the oscillator's frequency f and output power P versus time. It is seen that during the first minute of operation the frequency varies slightly. This is due to thermal effects in the crystal oscillator and in the voltage regulator. Then, output power and frequency both remain sufficiently constant for approximately 40 minutes—long enough to conduct the antenna measurements. After 40 minutes of operation the voltage of the button cell drops below 2 V thus causing a marginal decay in output power until the oscillator switches off.

Figure 3 shows a photograph of the small, battery-driven oscillator mounted on a dipole antenna. The size of the oscillator is $18\,\mathrm{mm} \times 9\,\mathrm{mm} \times 3\,\mathrm{mm}$.

Figure 3: Half-wavelength reference dipole with the battery powered oscillator (drawn to scale).

3. Antenna impedance measurement

With the battery driven oscillator described in Section 2., the antenna impedance can be determined by the following four steps. Figure 4 illustrates the measurement procedure.

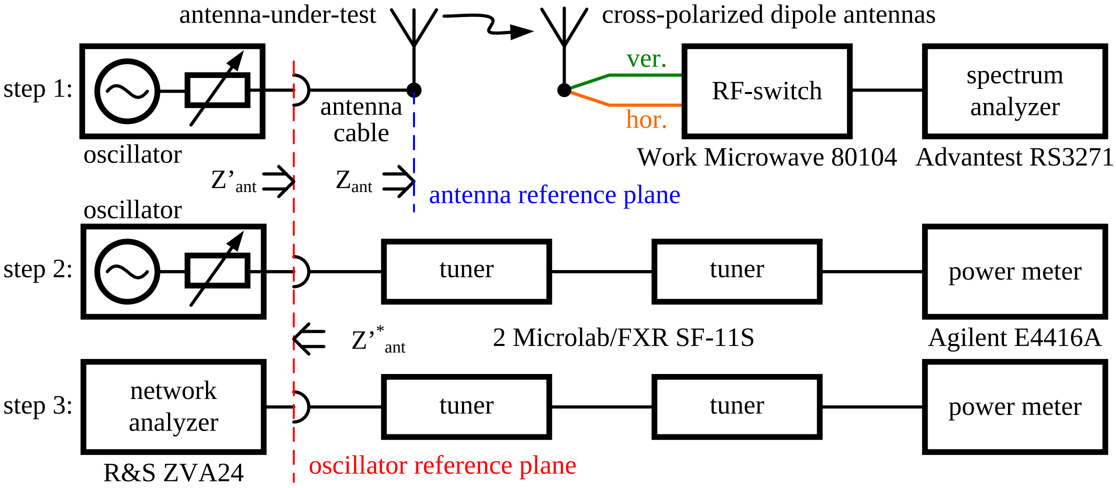

Figure 4: Block diagram of the impedance measurement procedure.

1. The antenna-under-test with the oscillator attached is mounted in front of two cross-polarized dipole antennas. With the RF-switch the dominant polarization is selected. The power received by the dipole antenna—which is in fact proportional to the power radiated by the device under test—is monitored with a spectrum analyzer. Next, the capacitors C7 and C8 are tuned to maximize the radiated power (source-pull measurement). This is done with a ceramic tuning tool. If the tuning range of the oscillator contains the complex conjugate of the transformed antenna impedance $Z'^{*}_{\rm ant}$, power matching is achieved between oscillator and tag antenna. This means that $Z^{*}_{\rm ant}$ is now provided at the end of the antenna cable or, equivalently speaking, the oscillator provides a source impedance of $Z'^{*}_{\rm ant}$.

2. Measurement of the oscillator source impedance can now be done by a load-pull measurement. Therefore, two double slug tuners (SF-11S by Microlab/FXR) and a power meter (Agilent E4416A) are connected to the oscillator. The tuners are then set to deliver the maximum power to the power meter. With this, the impedance at the tuner input is equivalent to the transformed antenna impedance $Z'_{\rm ant}$. Also, the power produced by the oscillator $P_{\rm out,oscillator}$ can be determined by considering the losses in the tuners and the cables. This is the power that is delivered to the antenna during the measurement. Later, it is very important for calculating the antenna's efficiency and gain.

3. The input impedance of the tuner $Z'_{\rm ant}$ can now be measured with a vector network analyzer. This load-pull measurement is very accurate because the network analyzer characterizes a passive load. Experiments have shown that direct measurements at the running oscillator by means of a vector network analyzer are inaccurate because the results strongly depend on the test port power.

4. Finally, the antenna cable has to be deembedded to determine the antenna impedance $Z_{\rm ant}$ from the measured impedance $Z'_{\rm ant}$. This is done with

$$\rho'_{\rm ant} = \frac{Z'_{\rm ant} - Z_0}{Z'_{\rm ant} + Z_0}, \qquad \rho_{\rm ant} = \rho'_{\rm ant} \cdot \mathrm{e}^{2\gamma l}\text{ , and} \qquad Z_{\rm ant} = Z_0 \cdot \frac{1+\rho_{\rm ant}}{1-\rho_{\rm ant}}$$

   where $\rho_{\rm ant}$ and $\rho'_{\rm ant}$ denote the reflection coefficients corresponding to the impedances $Z_{\rm ant}$ and $Z'_{\rm ant}$, l is the cable length and γ is the complex propagation constant of the antenna cable that includes losses and the velocity factor. For the antenna cable a propagation constant of $\gamma = (0.33 + j26)\frac{1}{\rm m}$ was determined by measurement. The reference impedance Z_0 is $50\,\Omega$.

For testing, the input impedance of a half-wavelength dipole (see Section 4.) was measured. The result of $Z_{\rm dipole} = (77 - j15)\,\Omega$ agrees well with the simulated result of $Z_{\rm dipole,\,sim} = (55 - j18)\,\Omega$. Furthermore the method was successfully used to determine the impedance of the RFID tag antenna presented in [7].

4. Gain measurement

A gain measurement of RFID tag antennas is unconventional, not only because the feeding cable has to be avoided, but also because the input impedance of tag antennas are far from $50\,\Omega$. Since the oscillator described in Section 2. can be perfectly matched to the antenna, is small, and has a highly stable output power and frequency, it is appropriate for a gain measurement. Here, it is essential that the oscillator is placed at the tag antenna in a way that the interaction with the antenna is minimized. We suggest placing the oscillator on the biggest metal area of the antenna. The thin coaxial cable ($\varnothing = 0.7\,\mathrm{mm}$) can then be routed to the feedpoint of the antenna along the antenna metal. Depending on the length of the cable, the antenna impedance Z_{ant} is transformed into Z'_{ant}. The oscillator then has to provide an output impedance of Z'^{*}_{ant}.

For calibration of the gain measurement setup, a dipole antenna that was characterized in an earlier measurement, and can be considered as an ideal half-wavelength dipole with a gain of $2.15\,\mathrm{dBi}$ was used as a reference antenna (thickness $d = 6\,\mathrm{mm}$, length $l = 156\,\mathrm{mm}$, input impedance $Z_{\mathrm{IN}} \simeq (77 - j15)\,\Omega$, center frequency $f_c = 864\,\mathrm{MHz}$). A dedicated battery powered oscillator similar to the one described in Section 2. is permanently attached to the dipole. This unit (Figure 3) provides a highly stable reference and allows reproducible measurements on tag antenna prototypes. The calibration of the measurement setup is done by characterizing the reference dipole unit and extracting the parameters of the setup from the results.

To distinguish between horizontal and vertical polarization two cross-polarized dipole antennas were used as pickup antennas. The spectrum analyzer is connected to the pickup antennas' outputs by means of an RF-switch that selects either the horizontal or the vertical polarization. A detailed description of the gain measurement procedure that uses a two-axis rotation apparatus made from styrofoam can be found in [2]. Gain measurement results obtained for an RFID antenna are presented in [7].

5. Summary

A method was presented that allows the characterization of input impedance and gain of small antennas. We find that the use of the tunable matching network in the oscillator is a good way to determine the antenna input impedance. However, the accuracy of the measurement result mainly depends on the miniaturization and placement of the oscillator on the antenna. For antennas that consist of very thin, wire-like conducting structures only, this oscillator might still be too big and intrusive. Further miniaturization has to be done to extend the measurement method to higher frequency bands.

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