

Automatic Analysis of 13.56 MHz Reader Command modulation pulses

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Abstract—We present a method for automated analysis of Reader Command modulation pulses for the ISO/IEC 14443 Type A air interface. Interoperability, which can be assured by this method, is a necessary pre-condition for secure and efficient communication. To achieve an H-field strength in the specified range efficiently, a Reader antenna with a high Q-factor is required. This Q-factor can simply be determined from the antenna equivalent circuit. A high Q-factor, however, also means longer time constants and so takes influence on the modulation. We investigate pulse parameters as described in the standard for ideal conditions, present a method for automated measurement in detailed steps and verify this method with practical measurements for different Q-factors of the antenna specified in the ISO/IEC 10373-6 laboratory standard. Results and alternative options are discussed with regard to the specific requirements of the broadband RFID system.

I. INTRODUCTION

The product standard [1] for Contactless Proximity Transponder Systems specifies the properties for Reader and Transponder at the air interface. For example, H-field strength range and limits for the modulation of the commands can be found there, whereas implementation in electronics is not specified. An antenna arrangement and some measurement methods are specified in the laboratory standard [2]. This is probably a wise definition, as it leaves the manufacturers room for development, patents and improvement of their products but also leaves them the burden, to handle all effects due to the coupling of resonant circuits in the near field as the devices have to fulfil the requirements for the air interface, which will assure product interoperability. In detail, the measurement of field strength is comparatively simple, while the measurement of modulation characteristics is more demanding, and so far no other method but to read out a scope display using cursors for time and amplitude is defined. To reduce errors caused by human interpretation, and to develop and speed-up measurement methods, we discuss a method to calculate modulation parameters automatically from data acquisition of a modulation pulse.

II. EFFICIENT H-FIELD EMISSION

The H-field emission of a Reader loop antenna in the near field can be calculated by the Biot-Savart law, which has the general form given in (1). In this formula I_A is the current in the antenna conductor, $d\vec{s}$ is an element in the

way along the loop antenna conductor, and \vec{r} is the vector from antenna conductor to the receiving point in space.

$$\vec{H} = \frac{I_A}{4\pi} \oint_s \frac{d\vec{s} \times \vec{r}}{|\vec{r}|^3} \quad (1)$$

The H-field emission is depending on the antenna geometry and the distance to the Transponder antenna, and on the current. The current in the antenna conductor in fact is the source of the H-field, and it is directly related to the properties of the field, e.g. to the field strength and to the time constants for modulation. Any current produces an H-field, active as well as reactive current.

Power consumption is of importance to any device such as a Reader, but especially for battery-powered or mobile systems. In a typical *Near Field Communication (NFC)* Reader, more than 90 % of the supply power is consumed by the driver stage for the antenna, and this has significant impact on the operating time within one battery charge cycle. For a mobile phone, this is a critical parameter for sales. In general, low power design also is key for environmental protection. The driver power is given by

$$P_D \approx \frac{I_A^2 \cdot \omega \cdot L_A}{Q_A \cdot N_A^2} \quad (2)$$

where ω is the angular resonance frequency, L_A is the loop antenna inductance ($L_A \sim N_A^2$), Q_A is the antenna Q-factor and N_A is the number of antenna conductor turns. To keep the driver power low for a certain H-field strength, the main option is to increase the reactive current due to energy oscillating between inductance and capacitance along the antenna conductor. Fig. 1 shows this relation for the antenna specified in [2].

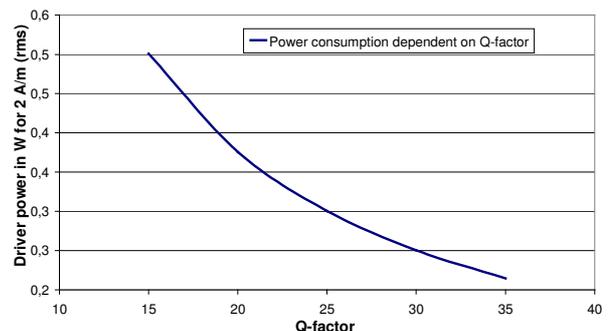


Figure 1. Driver output power dependent on antenna Q-factor.

III. ANTENNA Q-FACTOR

Antenna and matching circuit specified in [2] is similar to a Reader loop antenna. In principle, the main elements of the conductor equivalent circuit are the antenna inductance L_A and the resistance R_A , consisting of DC resistance and skin-effect at the operating frequency. The antenna is matched to a driver amplifier output, in this case to 50 Ohm impedance, by a matching network consisting of serial and parallel capacitor. The parasitic parallel antenna capacitance can be neglected or seen as part of C_P in this case. Fig. 2 shows the equivalent circuit in principle.

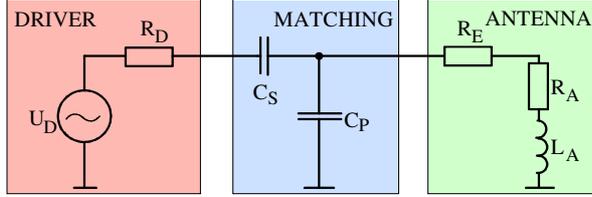


Figure 2. Equivalent circuit for transmit loop antenna.

With the matching network, the antenna is also tuned to a resonance frequency very close to the carrier frequency of 13.56 MHz. The Q-factor of the antenna can then be estimated by

$$Q \cong \frac{\omega L}{R_E + R_A} \quad (3)$$

In practical application, an external damping resistor R_E is added to the conductor resistance R_A , to reduce the Q-factor to a value which can support the required modulation bandwidth. A practical value range is discussed in detail in the following chapter.

IV. MODULATION PULSE PARAMETERS

The parameters of the modulation for the Reader commands are defined at the air interface by the product standard [1]. For an ideal scenario, not considering any loading effect, detuning or load mismatch, it is possible to use a simple parametric approach and to calculate all modulation parameters (time constants, modulation index, edge steepness) based on the Reader antenna Q-factor.

The amplitude envelope of a second-order resonant circuit like the Reader antenna in load matching according to fig. 2 can be described by an exponential function. For the falling edge, the envelope is described by (3), where τ is the time constant, after which the amplitude has decreased from 1 to $1/e$ or about 37 % of its initial value.

$$u_F(t) = e^{-t/\tau} = e^{-t \cdot \frac{2f_c \pi}{Q}} \quad (4)$$

Accordingly, the rising edge of the envelope is described by (4)

$$u_R(t) = 1 - e^{-t \cdot \frac{2f_c \pi}{Q}} \quad (5)$$

Using expression (4), the time constant can be expressed by the Q-factor and the resonance frequency (which in this case will also be the carrier frequency) f_c ,

and vice versa for this load-matched case Q can be determined from the time constant and the carrier frequency

$$\begin{aligned} u_F(\tau) &= e^{-\frac{2f_c \pi}{Q}} = e^{-1} \quad | \ln \\ -\tau \cdot \frac{2f_c \pi}{Q} &= -1 \quad | \cdot \frac{Q}{2f_c \pi} \\ \Rightarrow \tau &= \frac{Q}{2f_c \pi}, \quad Q = \tau \cdot 2f_c \pi \end{aligned} \quad (6)$$

In the product standard [1] the pulse parameters for Type A interface are specified as shown in fig. 2.

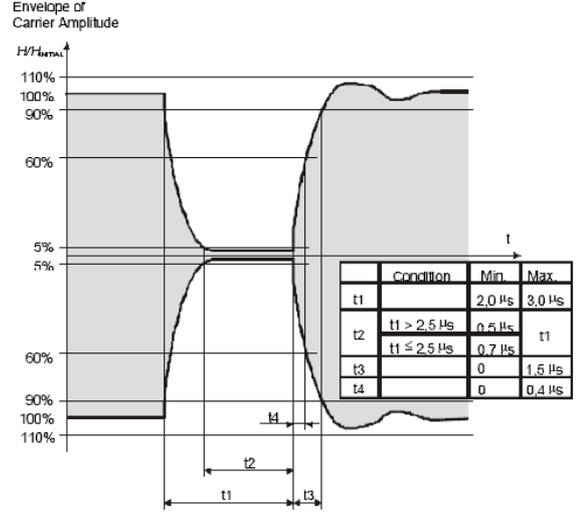


Figure 3. Modulation pulse parameter definition according to [1].

For the base data rate of 106 kbit/s time parameters $t_1 - t_4$ determine the falling and rising edge of modulation pulses and the residual carrier a specifies the required minimum envelope amplitude during the modulation pulse. In this ideal scenario, the parameters for Type A interface at the base data rate can be calculated from Q as given in (7) – (10).

$$(t_1 - t_2) = \frac{Q}{2\pi f_c} \cdot [\ln(0.9) - \ln(0.05)] \quad (7)$$

$$t_3 = \frac{Q}{2\pi f_c} \cdot [\ln(0.95) - \ln(0.1)] \quad (8)$$

$$t_4 = \frac{Q}{2\pi f_c} \cdot [\ln(0.95) - \ln(0.4)] \quad (9)$$

$$a = u_F(t_1) = e^{-t_1 \cdot \frac{2\pi f_c}{Q}} \quad (10)$$

This also gives an upper limit for the antenna Q-factor. To reach the required steepness of the edge, the parameter t_4 is most critical, specified smaller or equal than 400 ns. Note that this small value is necessary, because the anti-collision mechanism (specified in part 3 of the product standard) is based on accurate timing of the transponder response, over the full H-field range. So the upper limit for the Reader antenna Q-factor is given by

$$Q \leq t_{4,\max} \frac{2\pi f_c}{\ln(0.95) - \ln(0.4)} \cong 39.4 \quad (11)$$

Although the Q-factor is not specified in the product standard, the range for Q is limited by the definition for modulation parameters and efficiency in power consumption. Table I gives pulse parameter values for Q in a typical range of 10 ... 35.

TABLE I. MODULATION PULSE PARAMETER RANGE FOR TYPE A INTERFACE AT BASIC DATA RATE OF 106 KBIT/S

Type A	Time in μs		Time in carrier cycles	
	Q = 10	Q = 35	Q = 10	Q = 35
$t_1 - t_2$	0.339	1.187	4.6	16.1
t_3	0.264	0.925	3.6	12.5
t_4	0.102	0.355	1.4	4.8
a ($t_1 = 2 \mu\text{s}$)	0	0.008	0	0.008

For a typical communication system operating in the Far Field e.g. in the UHF frequency range, this section would give a sufficient description for the air interface. Modulation parameters depend on each other and all follow in a deterministic way the Q-factor. For an RFID system operating in the Near Field, the main challenges rather start at this point. In practice, several aspects have to be considered, which change the relations given for the ideal case. Two main points to consider are:

- The Reader driver output stage contains filters. As a minimum, there will be an EMC filter to prevent emissions outside the frequency mask in the 13.56 MHz ISM band. If a non-linear amplifier with a high power added efficiency is used, there will be additional resonant circuits in the collector branch. These will not only introduce additional time constants, but also introduce a conversion from a voltage source towards a current source. As a result, rising edges can be made steeper, but on the expense that overshoots are generated.
- A transponder circuit, but also conducting material in proximity to the Reader antenna will change the antenna impedance and detune the resonant frequency. This means for the practical case of operation, the Reader will change the modulation characteristics, depending on distance and properties of the transponder.

The (quasi-static) reduction of H-field strength (amplitude) due to close coupling to a Transponder can be expressed as a reduction of the current in the Reader antenna conductor. A practical formula as given in [5] is

$$\left(\frac{I}{I_0}\right)_{PCD} \cong \frac{1}{1 + k^2 \cdot Q_{PCD} \cdot \left(\frac{L}{\mu_0 (NA)^2}\right)_{PICC} \cdot \frac{|Md|_{PICC}}{H_{PCD}}} \quad (12)$$

where I is the reduced current relative to I_0 , the current without "Card Loading", k is the coupling factor, Md is the magnetic momentum produced by the Transponder. In

general, index *PCD* stands for the Reader (*Proximity Coupling Device*) and index *PICC* stands for the Transponder (*Proximity Integrated Circuit Card*).

As a practical example, fig. 4 shows the impedance mismatch for PCD antennas of two different Q-factors caused by close coupling to a second PCD antenna in short-circuit for coupling distances of 10 – 120 mm. The measurement was performed with a Network Analyzer.

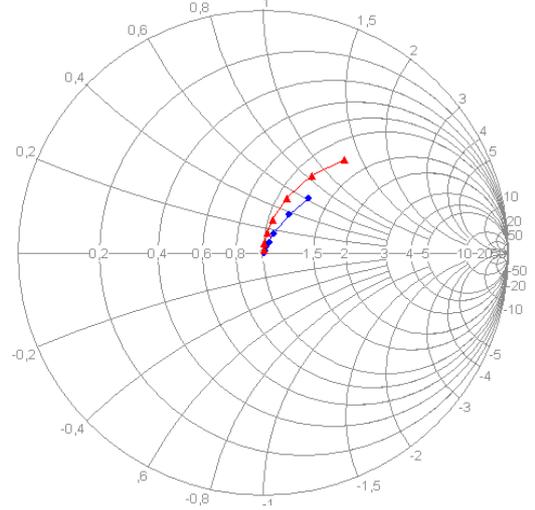


Figure 4. Antenna mismatch caused by close coupling.

As the relations for changes of time constants and modulation characteristics are even more complex, it makes sense to measure the modulation characteristics in the H-field, to assure inter-operability between different Readers and Transponders and standard conformance. Also, as the signal is rather broad band (frequency components for the specified modulation format for up to 848 kbit/s are high compared to the carrier frequency of 13.56 MHz), the method to determine the envelope of the modulated carrier is important. Different methods exist – and may lead to different measurement results for the modulation parameters. Fig. 5 shows a distorted pulse as measured under loaded conditions on a real Reader. One can observe ringing and beat frequency effects, and overshoots for the rising edge.

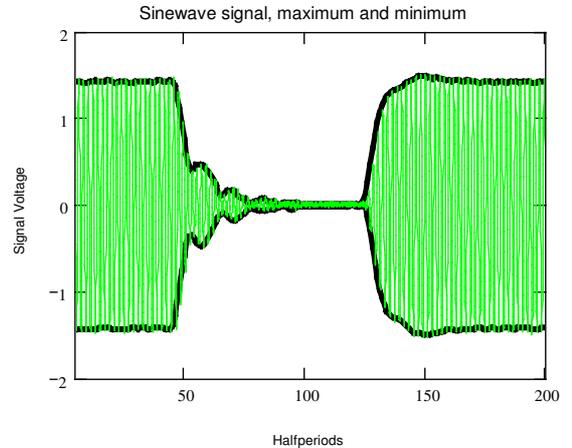


Figure 5. Realistic Reader modulation pulse under load.

In the next section, we present a simple but effective method to determine the signal envelope and calculate the modulation parameters.

V. METHOD FOR AUTOMATIC MEASUREMENT OF READER MODULATION PULSE PARAMETERS

The following steps of a pseudo-code can be implemented in any mathematical software, e.g. MathCad or Matlab. Measurement data typically from a digital sampling scope (at sampling rates in the range of 500 MS/s) can either be imported to a computer for evaluation, or the program can be implemented on the scope and export only the resulting parameters.

1. Read in the measurement signal data as amplitude vector over time.
2. Optional: Noise filtering and re-sampling at a multiple of the carrier frequency.
3. Look for the first positive half wave. Data processing starts with the first amplitude point after crossing zero (defined starting point).
4. The complete amplitude vector is split up into segments, each containing 1 period of the (known) carrier frequency.
5. For each period, the maximum signal amplitude is calculated and exported to a new vector containing the maximum amplitudes over the period number, and the minimum is calculated and exported to a new vector containing the minimum amplitudes.
6. The two vectors are re-sampled to have one point per half-period. From the vector of the maximum values, the first (measured) value is cut away, so that the vector starts with an interpolated point for the second half period.
7. The difference between a point of the maximum amplitude vector and a point of the minimum amplitude vector is calculated over all half-waves in the measured data. This is considered as the envelope vector, containing one value per half-period.

This data vector is then actually used to calculate the 14443-2 specified parameters.

Then, the parameters specified for the modulation can be calculated from this envelope vector over time. Before doing so, the data is prepared in the following steps:

1. To increase resolution, the vector is re-sampled by a factor of 100.
2. An envelope of 100 % is calculated as average of the first 3 carrier signal periods of the Envelope vector.
3. For the calculation of the times, the envelope vector is split up to one vector containing values from start to the minimum amplitude (falling edge), and from minimum amplitude to end of the envelope vector (rising edge). Note: The vector of the rising edge is used in a reversed index way, so that calculations are done from right to left.
4. The time points for a certain amplitude (e.g. 90% of the envelope value for the falling edge) are calculated as specified in the standard.

The actual time parameters can then be easily calculated from these envelope values of measurement time, and the residual carrier a is calculated as the minimum envelope (relative to the initial absolute value) over 3 carrier cycles.

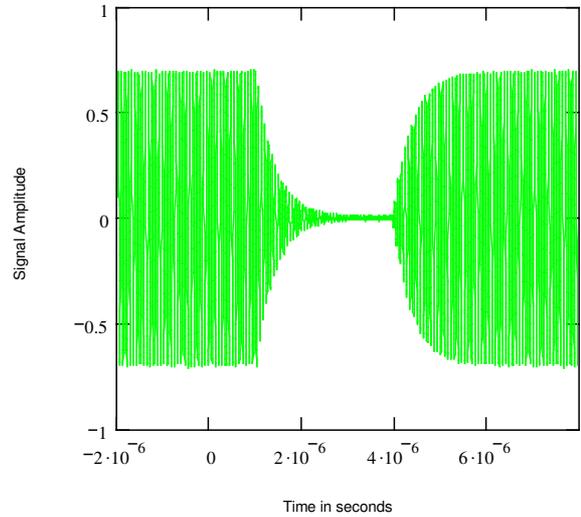


Figure 6. Data of modulation pulse shape as used for evaluation.

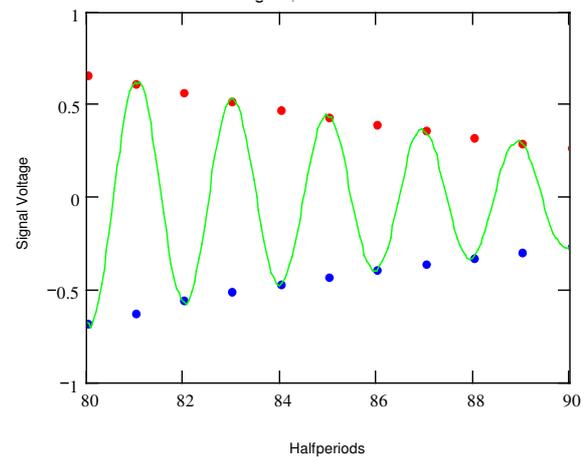


Figure 7. Sine wave signal, calculated (and interpolated) points for minima and maxima for the falling edge.

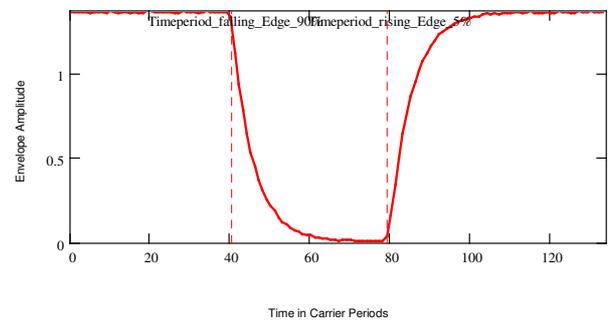


Figure 8. Calculated envelope (t_l parameter range indicated), derived from the difference vector.

The modulation pulse shown in fig. 6 – 8 was produced by the transmit antenna of [2]. The antenna was fed with a 13.56 MHz carrier signal, which was then switched off for 39 carrier cycles. As a practical example, the measured pulse parameters for this condition are given in tab. II.

TABLE II. MEASURED PULSE PARAMETERS

t_1	2.864 μs	38.84 cycles
t_2	1.672 μs	22.67 cycles
t_3	0.951 μs	12.90 cycles
t_4	0.383 μs	5.19 cycles
a	0.006	0.597 %

To further proof the method and to see the parameter dependency, the antenna Q-factor was modified and pulse parameters were measured for several Q-factors. Every antenna was well matched to 50 Ohm impedance and the measurement was done without any loading, under nearly ideal conditions. Measurement result compared to calculated time parameters (dashed lines) are shown in fig. 9.

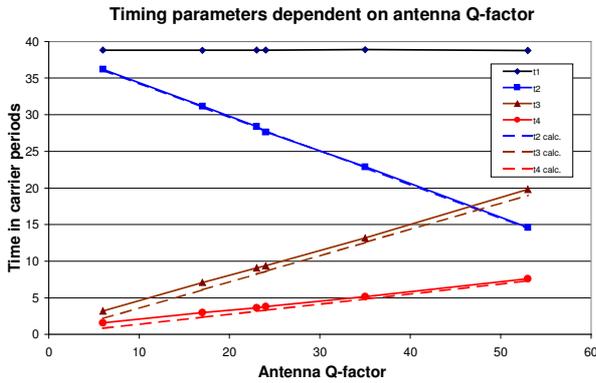


Figure 9. Time parameters depending on antenna Q-factor.

VI. AUTOMATIC ANALYSIS OF ANTENNA Q-FACTOR

The described method for automated pulse parameter determination can also be used for an approximative determination of the antenna Q-factor out of the pulse edges steepness. For simplicity reasons, we will directly use Type A pulse parameters. Re-arranging (7) and (8) results in solutions for the Q-factor, Q_F for the falling edge, and Q_R for the rising edge. One can take the average of the two measured values for Q.

$$Q_F = 2\pi f_C \cdot \frac{t_1 - t_2}{\ln(0.9) - \ln(0.05)} \quad (13)$$

$$Q_R = 2\pi f_C \cdot \frac{t_3}{\ln(0.95) - \ln(0.1)} \quad (14)$$

As a practical example for nearly ideal conditions, we will calculate the antenna Q factor for the pulse shown in fig. 3 – 5 and take the values from table 2. The calculation results in

$$Q_A \approx \frac{Q_F + Q_R}{2} = \frac{35.14 + 36.03}{2} = 35.57$$

which comes quite close to the nominal value for this antenna of $Q \sim 35$.

VII. INTERPRETATION AND ALTERNATIVE METHODS

There are also alternative methods, which should be mentioned in this context as they could also be used for an automated measurement. As the signal is a modulation of the carrier amplitude, several ways for amplitude demodulation in principle could be used. However, even if these methods may be state of the art for measurement instruments or other communication systems, they all have some critical aspects for RFID, which should be briefly mentioned.

- Hilbert Transformation

Without going into details, for communication theory this function allows to calculate an imaginary part to real part functions. This allows to calculate a complete analytic signal (which has no negative frequency components) from only the real part signal. This is what is required for amplitude modulation, when the base band signal without negative frequency component is modulated on a carrier, producing a spectrum of upper and lower side band. The Hilbert transformation Hf is given by (15)

$$(Hf)(t) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{f(x)}{t-x} dx \quad (15)$$

Accordingly as one application, the Hilbert Transform can be used as a software AM demodulator, as shown in [6]. Given the signal $z(t) = A(t)\cos(\omega t)$, where the amplitude $A(t)$ is slowly varying, the Hilbert Transform is very close to $y(t) \approx A(t)\sin(\omega t)$. This allows to construct the analytical signal $z(t) \approx A(t)e^{j\omega t}$. Amplitude demodulation can now be simply performed by taking the absolute value $A(t) \approx |z(t)|$. This method would be exact, if $A(t)$ would be constant, so it is quite good for narrow-band envelope detection e.g. on a UHF carrier. However, for the ISO/IEC 14443 standard, the signal rather is broadband, considering high modulation signal frequency components compared to only 13.56 MHz carrier frequency. So in practice this principle introduces errors, in detail additional frequency components, which make the automatic determination of time parameters ambiguous.

- Hardware AM demodulator using rectifier

A simple alternative method is an envelope detector using diode demodulation and filters. This works and is a practical method to find modulation signals on the scope, and to be able to use smaller sample rate allowing to record longer signal sequences in limited scope memory. However, again the broad band characteristics of the signal is problematic, as the filters will introduce time constants and remaining RF carrier components will introduce ambiguities in envelope amplitude.

- Synchronous demodulator

Implemented either in hardware or software, the synchronous demodulator can avoid most of the problems with additional time constants in the case of ideal

synchronization. It is in a way actually very similar to the software implementation presented in this paper. The critical point is the tracking for the reference frequency, how changes in carrier frequency are handled, for example at the part of the falling envelope when the carrier signal is already switched off and the antenna rings at the resonance frequency, which may be slightly different. The synchronous demodulator will provide an error, if the sampling phase will shift in this portion of the signal. For comparison, our presented method will always find the extremum within a carrier frequency half-period, so there is no fixed sampling frequency (and the deviation between carrier and resonance frequency can be considered small enough not to exceed half a carrier period for the duration of a pulse).

- Spectrum Analyzer in zero span (time domain) mode

Quality state of the art Spectrum Analyzers are able to set signal filters and to allow the observation of signal power in time domain in a defined frequency band. This feature can also be used comfortable for envelope detection and pulse parameter determination. One point of course is the choice of filters and related time constants, but in practice for most instruments also the sampling rate in time domain at IF level is not very high, compared to a scope (typically 50 MS/s compared to 500 MS/s and beyond). If a broad band signal is sampled only at a few points per period, again this will introduce deviations to the original signal and result in slightly different measured pulse parameters. For this reason it may be questioned, if a high quality Spectrum Analyzer is the best option for this specific test case in time domain.

So, as a conclusion of the contribution we can say the method we have presented allows to calculate modulation pulse parameters in a definite, unambiguous way. Further, as statistical evaluation (not presented in this paper) has shown, the results for similar pulses are reproducible and very equal for the individual parameters.

For the nearly ideal conditions in the laboratory test set up for transponders, the analytical model for pulse shapes and the practical measurement depending on antenna Q-factor show a good coincidence, as can be seen in fig. 9. This should proof valid the formulas presented and give confidence in the evaluation method principle. One part of the remaining differences will originate from the antenna Q-factor determination (3), which rather gives an estimation than an exact value. Also, it has been observed, that due to temporary overload, the external resistors may slightly change their value over time, resulting in a gradual Q-factor change. Especially for the parameters on the rising edge, the amplifier time constant will add on the theoretical value, resulting in longer times for t_3 and t_4 , as it can actually be seen.

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