A New Method of Emission Measurement

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Abstract
According to the standards, emission measurements are carried out in the frequency domain using a test receiver. In this paper the setup and algorithms of a measuring system in the time domain is presented. The advantage of this system is, that measurements can be done approximately 10 to 100 times faster. The emphasis in this paper is set on algorithms to increase the measurement accuracy of narrowband and broadband signals. Furthermore, the choice of the best capture time for the time domain measurement is described.

Keywords
Emission measurement, time domain, fourier transform, window function, pulse response curve

INTRODUCTION
Emission measurements for the EMC check of a device must be carried out (according to the standard [3]) in the frequency domain with e.g. a test receiver. It is necessary to execute a frequency sweep and to measure the emission at each frequency. This method has the disadvantage that the measurement lasts, depending on the selection of the parameters, for a quite a long time (typically 10 to 30 min). Since a long measurement always implies high costs, it is profitable to look up for possibilities to shorten the measurements without a loss of quality.

In particular, the measurement in the time domain provides a good possibility to save time. Instead of measuring in the frequency domain with a test receiver, several single shots are recorded with an oscilloscope. From these data a comparable spectrum can be calculated by using the Discrete Fourier Transform (DFT) and several correction algorithms. In this paper the time domain measuring system FEMIT (**F**ast **E**mission **M**easurement **I**n **T**ime Domain) is described.

MEASUREMENT SETUP
When measuring in the frequency domain, the signal is directly recorded with the test receiver, which executes a frequency sweep. This measuring setup in comparison to FEMIT is shown in Fig. 1.

The central device for FEMIT is a digital oscilloscope. Depending on the level of the signal, it is often necessary to use a preamplifier if the lowest measuring range of the oscilloscope is not sensitive enough. To make sure, that the sampling theorem is kept, an appropriate anti-aliasing lowpass should be connected in series to the oscilloscope.

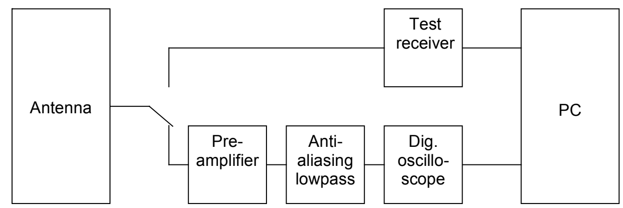

Figure 1. Measurement setup

BASIC ALGORITHM OF EVALUATION
The basic FEMIT algorithm consists of a DFT, a smoothing and a correction algorithm. The correction takes all frequency characteristics (antenna factor, lowpass, etc.) into account, so that narrowband signals are measured correctly. This basic algorithm was already described in detail [1].

Time consumption and limits
The time consumption of one FEMIT measurement is, depending on the parameters, *10 – 100 times lower* than the one of a test receiver measurement. The (in comparison to the test receiver lower) dynamic range of FEMIT is limited by the quantization of the oscilloscope. The theoretical maximum is approximately 50 dB (8 bit), a typical value is approximately 40 dB. However, this is no restriction for EMC measurements, because here mainly the levels around the limit line are interesting. The effect of a lower dynamic range is only a higher noise level.

Typical applications
Typical applications for FEMIT are quick previews, repeated emission checks and the measurement of short or rare phenomena (e.g. switching impulse, flashover). The height scan and the check of the direction of highest emission can be performed fast. Furthermore, the emission of different modes of operation of a device can be measured seperately.

NARROWBAND SIGNALS
The so far described basic algorithm shows correct results, when the frequency of a narrowband signal corresponds to a DFT frequency step and a measurement frequency of the test receiver. Here, the test receiver and FEMIT show the same results.

If a narrowband peak is located *between* two DFT steps the peak widens itself and the peak level is attenuated. This DFT effect is called the “scallop loss”. The test receiver shows a similar effect. When the frequency of a narrowband signal does not fit exactly on a measurement frequency (center of the bandpass), the peak is also attenuated according to the characteristic of the transfer function of the bandpass.

In this chapter, these effects are examined and an algorithm is presented to improve the accuracy of the FEMIT measurement.

Parameters of the DFT

The result of the DFT depends mainly on two parameters: the sampling frequency f_S and the capture time T.

Sampling frequency

According to the sampling theorem the required sampling frequency equals twice the wanted maximum frequency (Nyquist frequency) of the calculated spectrum. To avoid aliasing errors it is recommended to set the sampling frequency 2 to 4 times higher.

Choice of capture time T *(part 1)*

The capture time T (duration of the time domain record of the oscilloscope) and the frequency resolution Δf_{DFT} (distance between two frequencies in the spectrum) are given as

$$T = \frac{1}{\Delta f_{\mathrm{DFT}}} \tag{1}$$

To compare the test receiver spectrum and the FEMIT spectrum, the frequency resolution should be similar:

$$\Delta f_{\mathrm{DFT}} \approx \Delta f_{\mathrm{recv}} \tag{2}$$

where Δf_{recv} is the distance between two measurement frequencies of the test receiver (step size). A much shorter time T is not allowed, because then the frequency steps increase in comparison to the test receiver and so the resolution decreases. A longer time implies (needless) higher computing time.

Approx. of the test receiver's transfer function

The transfer function of the bandpass of the test receiver can be approximated well by a Gaussian curve as shown in Figure 2.

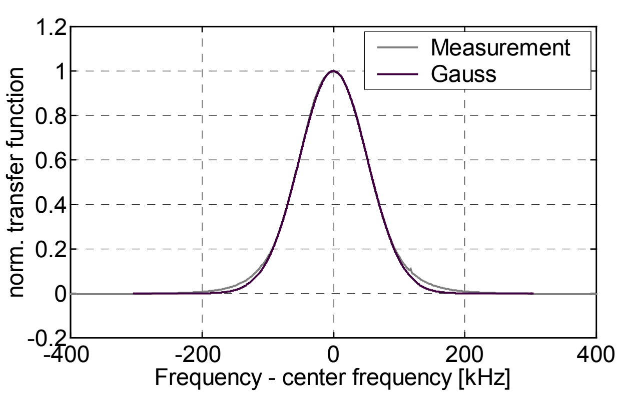

Figure 2. Transfer function of the test receiver and fitted Gaussian curve (120 kHz bandpass)

Therefore, in the following discussion a Gaussian curve with the same 6 dB-bandwidth B_6 is used.

Window functions

Window functions can be used to reduce the scallop loss and to affect the level of narrowband signals, that are located between frequency steps. The recorded time domain signal is multiplied by the window function before the DFT.

For the following discussion, it is necessary to understand the effect of a window function. Even if no window function is explicit used, the window effect can be observed in the spectrum. The reason therefore is that a recorded signal of limited length can be regarded as an infinite signal multiplied by a rectangular window.

A sinusodial signal can be defined as

$$u(t) = \cos\left(\omega_0\, t + \varphi\right). \tag{3}$$

Multiplied by the window function *w(t)* the windowed function *v(t)* is given as

$$v(t) = w(t) \cdot u(t). \tag{4}$$

Using properties of the Fourier Transform and regarding only the physical measurable part of the spectrum, the spectrum $V(\omega)$ of the windowed function results to

$$\left|V(\omega)\right| = \left|W(\omega - \omega_0)\right|, \tag{5}$$

where $W(\omega)$ is the spectrum of the window function itself [4]. Obviously, the spectrum of a windowed cosine equals the spectrum of the window function itself, shifted by the frequency ω_0.

Used window functions

In the algorithm, the rectangular and the Flat Top window is used in the algorithm. Figure 3 shows these window functions and (for comparison) the well-known Hamming window.

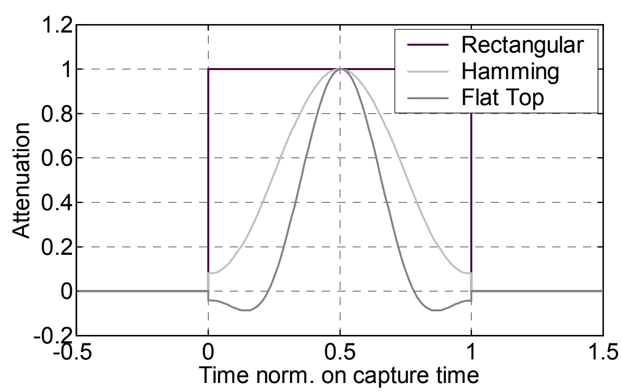

Figure 3. Window functions

With the exception of the rectangular window, all window functions attenuate the signal. In the frequency domain this results in an attenuation of the whole spectrum. This attenuation is called the coherent gain and has to be taken into consideration. In the following graphs the coherent gain is corrected.

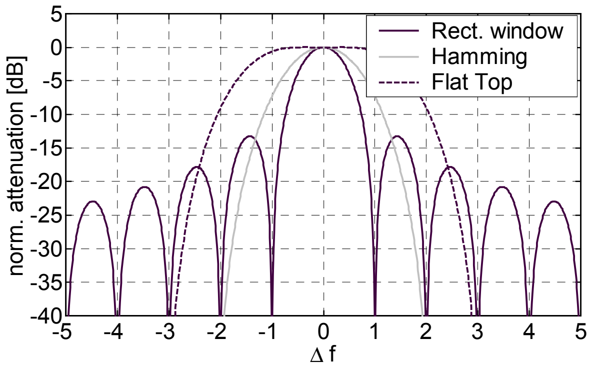

Figure 4. Spectra of window functions

Figure 4 shows the spectra of the mentioned window functions. The difference between the spectrum of the rectangular and the Flat Top window is obvious: the latter has a lower scallop loss (flatter peak of the main lobe), a broader main lobe and lower side lobes (not visible in Fig. 4).

Sampling effect

These spectrums of the window functions give the theoretically exact result, but the DFT samples the exact spectrum at the discrete frequencies. The sampling effect can be explained by the example of the rectangular window.

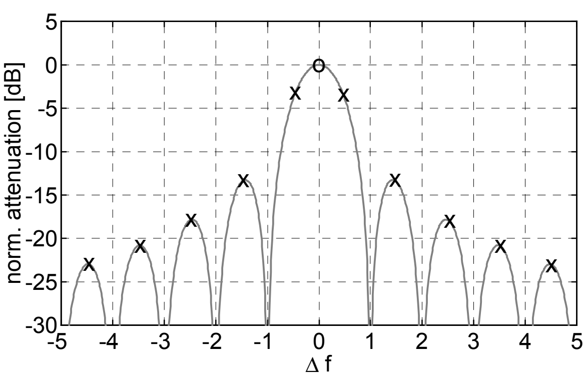

Figure 5. Spectrum of the rectangular window

Figure 5 shows the spectrum of a rectangular window. The x-axis is normalized on Δf_{DFT}. If a narrowband signal is located in the center of the main lobe, the surrounding frequency points are located on the zeros of the spectrum ("**o**" in Fig. 5). Therefore, the DFT result contains only the correct value.

On the contrary, the surrounding points of a narrowband signal between two Δf_{DFT} meet the maxima of the side lobes spectrum ("**x**" in Fig. 5) and result in a broadened spectrum with a damped maximum value.

120 kHz bandpass (band C,D), Δf_{DFT} = 100 kHz

Figure 6 shows the spectrum of the rectangular window, the normalized Gaussian curve of the bandpass and the normalized limits (according to the standard [3]) by the example of the 120 kHz bandpass and T=10µs=1/100 kHz. The x-axis is normalized on the frequency resolution Δf = 100 kHz.

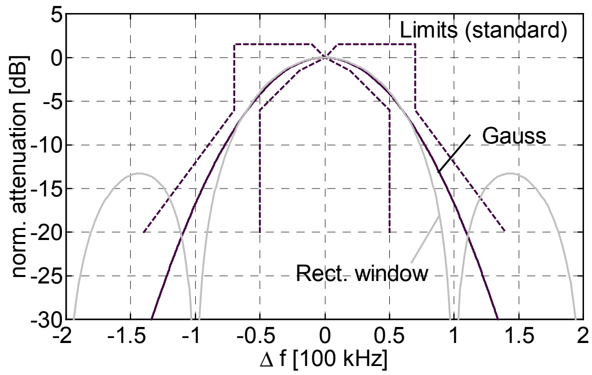

Figure 6. 120 kHz bandpass, limits (standard), rectangular window spectrum

The figure shows, that a good agreement between the spectrum of the rectangular window and the selection curve of the 120 kHz bandpass can be found. The only problem is the widening of the peaks due to the high side lobes. However, this effect is hardly noticeable as it is only visible, when a peak stands off the surrounding noise more than about 15-20 dB.

Correct measurement of peaks

Fig 6 shows, that both the test receiver and FEMIT *underestimate* a peak, when a peak is not located on a measurement frequency. In the worst case (peak between two measurement frequencies), this unwanted attenuation amounts e.g. for the 120 kHz bandpass to 3.9 dB (step size Δf_{recv} = 100 kHz) or to 1 dB (Δf_{recv} = 50 kHz). This chapter describes an algorithm for FEMIT that allows a correct measurement of peaks.

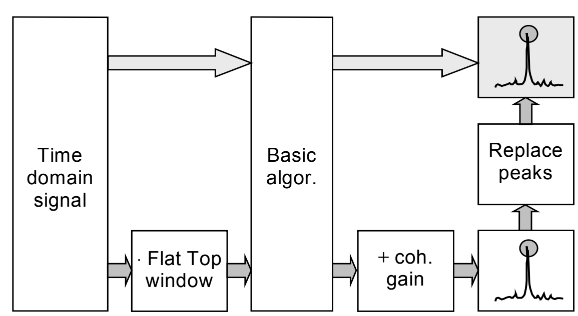

Figure 7. Algorithm for correction of peak-level

The perfect window spectrum has a rectangular shape with 0 dB in the range ± 0.5 Δf_{DFT}. The effect of this window is, that a peak is plotted at the next DFT frequency without attenuation and without widening due to side lobes. As it is not possible to use the corresponding window function si(x), the wanted effect has to be created by the combination of two windows.

Fig. 4 shows that the main lobe of the Flat Top spectrum is extremely flat. The disadvantage of this window is, that peaks are widened strongly (≈ 3 Δf_{DFT}). An algorithm that uses the Flat Top window, but avoids the widening is presented in Fig. 7. First, the time domain signal is transformed into the frequency domain directly (”using” the rectangular window). Then, the signal is multiplied with the Flat Top window. After the DFT the coherent gain is added. Now, the peak levels of the peaks in the first spectrum are replaced by the corresponding levels of the second spectrum.

The result is that the peaks have the *exact* level but not the extreme widening of the Flat Top spectrum. The important point is, that these levels often give a better representation of the real levels than the results of the test receiver!

BROADBAND SIGNALS

The so far presented algorithms produce correct results when measuring narrowband signals like signals with discrete frequency and pulses with a repetition frequency higher than the bandwidth of the test receiver bandpass (Fig. 8).

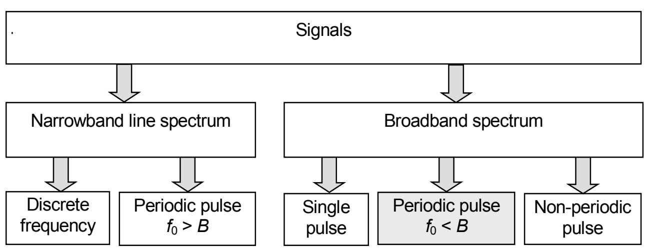

Figure 8. Narrowband and broadband signals

However, broadband signals (typically pulses with lower repetition frequency) are not measured correctly due to the influence of the detector of the test receiver. Here, the measured level depends *non-linear* on the repetition frequency. When using the quasi-peak detector the basic algorithm overestimates the signal up to 40 dB! Therefore, an algorithm was developed in order to correct this effect [2].

The following subchapters explain some aspects of the system theory of the test receiver that are necessary to understand the correction algorithm.

System theory of pulses

In the frequency domain, a pulse is represented by a line spectrum. The envelope of the line spectrum depends only on the shape of the pulse. The repetition frequency of the pulse determines the distance between the lines in the spectrum.

Ideal bandpass and pulses

The response of a ideal rectangular bandpass to a pulse depends on the repetiton frequency of the pulse. If the repetition frequency f_0 of the pulse is lower than the bandwidth B_r of the ideal rectangular bandpass, the pulses can still be recognized in the response signal. In the frequency domain, this means that more than one line is inside the filter pass band. If f_0 is higher than B_r, the response signal of the bandpass is a sinusoidal cw-signal. In the frequency domain, this means that at most one line is located inside the filter pass band.

Theoretically a (repeating) pulse is always a narrowband signal. But due to the limited system bandwidth, for $f_0 < B_r$, the measured spectrum is a broadband spectrum and for $f_0 > B_r$ a narrowband spectrum.

Therefore, the boundary between broadband and narrowband spectrum is $f_0 = B_r$.

Equivalent bandwidth

In reality, the bandpass of the test receiver is not ideal. It can be described by a bell-shaped (gaussian) curve (see Fig. 2). To describe the relation between these bandpasses, the equivalent bandwidth has to be determined. Two conditions have to be met: for narrowband signals the maximum of the transfer characteristic has to be equal. For broadband signals, the impulse bandwidth has to equal, that is, the envelopes of the pulse responses must have the same maximum. By comparing the fourier transforms of the responses, the following relation between the bandwidth B_r of the ideal bandpass and the 6 dB bandwidth B_6 of the gaussian curve can be obtained:

$$B_r = \frac{1}{2}\sqrt{\frac{\pi}{\ln 2}}\, B_6 , \qquad \frac{1}{2}\sqrt{\frac{\pi}{\ln 2}} \approx 1.06 \tag{6}$$

In the standard [3], a factor of 1.05 is given.

Pulse response curve of the test receiver

The pulse response characteristic shows the attenuation as a function of the repetition frequency. These characteristics depend on the bandwidth and the detector. For frequencies lower than the bandwidth, the characteristics are listed in the standard [3]. For higher frequencies, the response is a sinusoidal signal, that is, we have linearity.

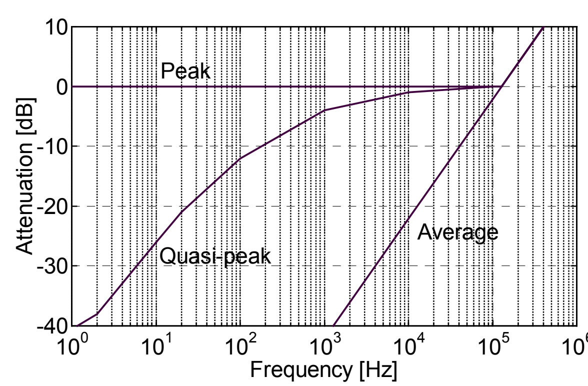

Figure 9. Pulse response curve of the test receiver (B_6 = 120 kHz, peak, quasi-peak and average detector)

Therefore, the characteristic rises with a gradient of 20 dB/dek. The knee of the curve is located at the transition form broadband to narrowband spectrum, at the frequency $f = B_r = 1.06\ B_6$ (=127 kHz for 120 kHz bandpass).

Pulse response curve of FEMIT

In the time domain, only a finite capture time T can be recorded. When measuring pulses with a period $T_0 < T$, several pulses are located within the recorded window (Fig. 10). In the frequency domain, this corresponds to a narrowband line spectrum. Therefore, for $f > f_0 = 1/T_0$ the characteristic rises again with a gradient of 20 dB/dek (linearity).

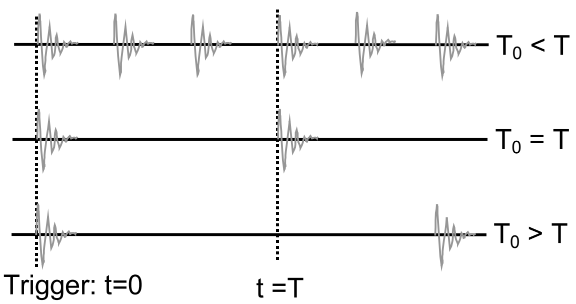

Figure 10. Pulses and capture time

On the contrary, for pulses with $T_0 > T$ only *one* pulse (the trigger event) can be found in the window. In the frequency domain this results in a broadband spectrum, that is independent of the repetition frequency. Therefore, the pulse characteristic is a constant line. The knee is located at the repetition frequency $f = f_0 = 1/T_0$. Fig. 11 shows the resulting characteristic for several capture times. Comparing Fig. 9 and 11 shows, that FEMIT (or the DFT generally) has the same principal pulse response curve as the peak detector of the test receiver.

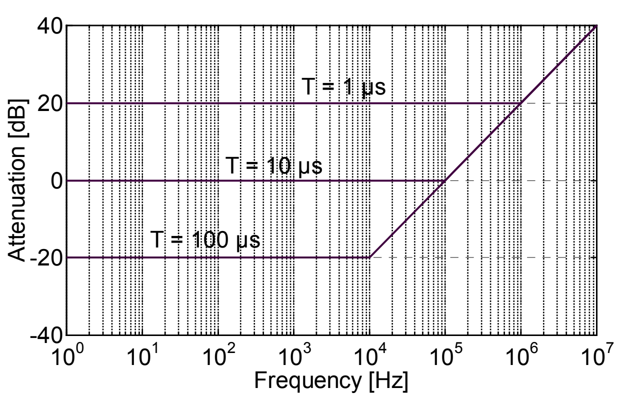

Figure 11. Pulse response curve of FEMIT

Comparision of pulse response curves and correction

To compare the characteristics of the test receiver and FEMIT, a relationship has to be found. The common part is the 20 dB/dek rise. At these frequencies, both the test receiver and FEMIT produce a line spectrum. In the time domain, these are sinusoidal, narrowband signals. As these signals are measured correctly with both systems, the characteristics have to be shifted vertically over each other, so that the 20 dB/dek part is equal.

For the correction of the spectrum a correction curve is defined as the difference between the test receiver and the FEMIT puls response curve.

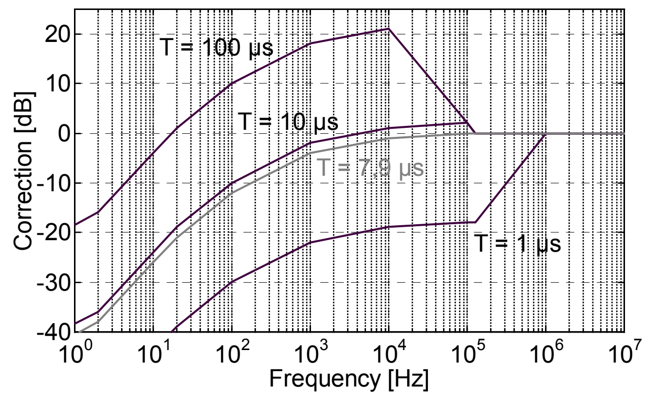

Figure 12. Correction for 120 kHz bandpass, quasi-peak detector. Parameter: capture time *T*

This curve depends on the bandwidth and the detector of the test receiver as well as on the capture time. Fig. 12 shows correction curves for the quasi-peak detector and the 120 kHz bandpass for parameterized capture time T.

Choice of capture time *T* (part 2)

Fig. 12 shows, that the shape of the correction curve depends on the capture time T. Generally, for every T the spectrum can be corrected. But it is better to choose a correction characteristic as close to 0 dB as possible. Here, the error is minimal, when a correction is not possible (e.g. superposition of several different pulses). Therefore, the optimal value for Δf_{DFT} regarding the correction of broadband signals is the equivalent impulse bandwidth of a rectangular bandpass (curve for T = 7.9 µs in Fig. 12):

$$\Delta f_{\mathrm{DFT,opt}} = 1.06\ B_6 \tag{7}$$

Table 1 shows the resulting values by the example of band B (9 kHz) and band C,D (120 kHz).

It is obvious that the theoretical best Δf_{DFT} is not a useful value. An adequate choice for Δf_{DFT} and T is listed in Table 1.

Table 1. Capture time *T*

Band	B_6	$\Delta f_{\mathrm{DFT,opt}} = 1.06\ B_6$	Chosen Δf_{DFT}	$T = 1/\Delta f_{\mathrm{DFT}}$
B	9 kHz	9.54 kHz	10 kHz	100 µs
C, D	120 kHz	127 kHz	100 kHz	10 µs

Measuring algorithm for broadband signals

Fig. 13 shows the block diagram of the algorithm and Fig. 14 shows an example. First, the trigger of the oscilloscope is set to a relatively high level in order to record a pulse. The spectrum is calculated by applying the basic algorithm ("Trigger max" in Fig. 14) and is corrected for all frequencies according to the correction value given by the correction curve at the repetition frequency of the broadband phenomenon ("-24dB", "corr" in Fig. 14).

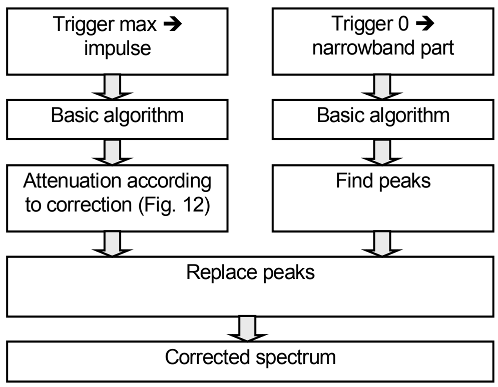

Figure 13. Measuring algorithm for broadband signals

The broadband part of the spectrum is correct now. Only the narrowband peaks are faulty. First, because the level of the peaks must not be attenuated and second, because peaks below the broadband spectrum are not measured at all (e.g. at 95 MHz in Fig. 14). Therefore, a second measurement is recorded *without a pulse* (trigger level 0). The corresponding spectrum ("Trigger 0" in Fig. 14) contains all the narrowband peaks with the correct level. In a last step the peak levels of the first (broadband) spectrum are replaced by the peak levels of the latter spectrum.

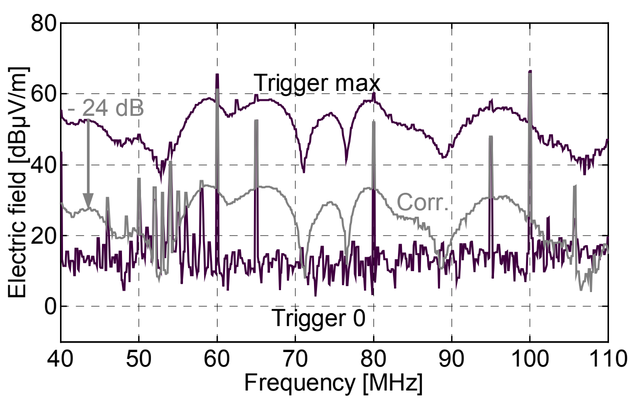

Figure 14. Example for broadband correction

Limits and error

The described algorithm can only be applied if the repetition frequency of the pulse is known and if *one* pulse dominates the spectrum. The typical difference between the test receiver and FEMIT spectrum at the broadband parts is in the range 0 to 3 dB.

Example

Figure 15 shows a comparison of the spectra of the test receiver and FEMIT.

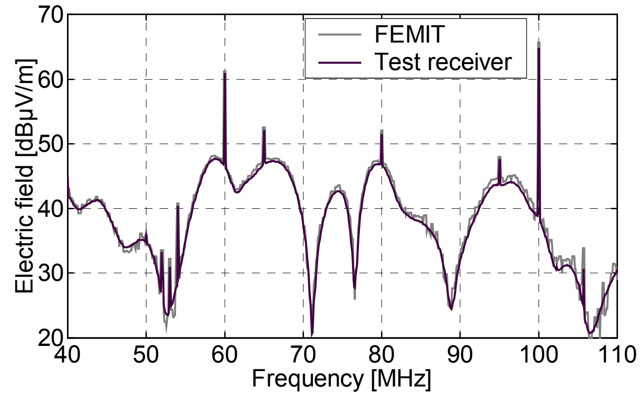

Figure 15. Comparison test receiver - FEMIT

The test signal consisted of a 100 Hz pulse and a quartz oscillator. Both narrowband and broadband parts of the spectrum show good agreement of the FEMIT and the test receiver spectrum.

CONCLUSIONS

The time domain measurement system FEMIT executes emission measurements approximately 10 - 100 times faster than a test receiver. The correct choice of the capture time and algorithms to correct the peaks of narrowband and broadband signals were presented. Often, the result of FEMIT is more correct than the one of the test receiver due to the bandpass characteristic.

FEMIT is an adequate measuring system especially for quick previews, repeated checks of the emission of an EUT and short phenomena.

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