IMPROVEMENTS IN THE FAST EMISSION MEASUREMENT IN TIME DOMAIN

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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 set-up 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 signals and on the measurement of broadband signal such as pulses. Furthermore, the noise level and signal-to-noise ratio is discussed.

I. INTRODUCTION

Emission measurements for the EMC check of a device must be carried out (according to the standard [4]) 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 (Fast Emission Measurement In Time Domain) is described.

I.1 Measurement set-up

When measuring in the frequency domain, the signal is directly recorded with the test receiver, which executes a frequency sweep. This measuring set-up in comparison to FEMIT is shown in Figure 1.

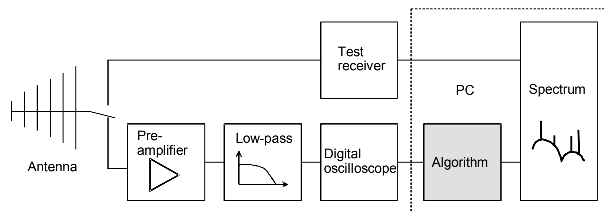

Figure 1 Measurement set-up

The central device for FEMIT is a digital oscilloscope. If the noise level has to be lower than approximately 10 dB below the limits (EN 55011, etc.), it is necessary to use a preamplifier. To make sure, that the sampling theorem is kept, an appropriate anti-aliasing low-pass should be connected in series to the oscilloscope.

I.2 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, low-pass, etc.) into account, so that narrowband signals are measured correctly. This basic algorithm was already described in detail [1].

I.3 Time consumption and accuracy

The time consumption of one FEMIT measurement is, depending on the parameters, 10 - 100 times lower than the one of a test receiver measurement; one measurement takes ≈ 5 – 15 s. The error is typically < 1 dB for narrowband signals and < 1 - 3 dB for broadband signals.

I.4 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 separately.

II. MEASUREMENT OF AM SIGNALS

The previously mentioned basic algorithm calculates correct results for narrowband signals with constant amplitude. If the amplitude is not constant, errors can occur. Therefore, this chapter is focused on the measurement of those signals that can be described by amplitude modulated (AM) signals.
AM signals can often be found: on the one hand AM signals themselves, on the other hand all kinds of instable signals, e.g. the influence of the 50 Hz power supply or a moving EUT.

II.1 Amplitude modulation (AM)

Generally, an AM signal can be described by the formula

$$u(t) = \hat{u}(t)\cos(2\pi f_0\, t). \tag{1}$$

Here, the amplitude *û(t)* of a alternating voltage is itself a function of the time. To get an simplified overview over the problem, in this chapter a normalized sinusoidal modulation function is regarded:

$$u(t) = (1 + m\cos(2\pi f_m t))\cos(2\pi f_0 t)\,. \tag{2}$$

In (2) the parameters are: m ... modulation factor (0 - 1),
f_m ... modulation frequency,
f_0 ... carrier frequency.
Measurements have shown that the so obtained results can be applied to most signals in reality.

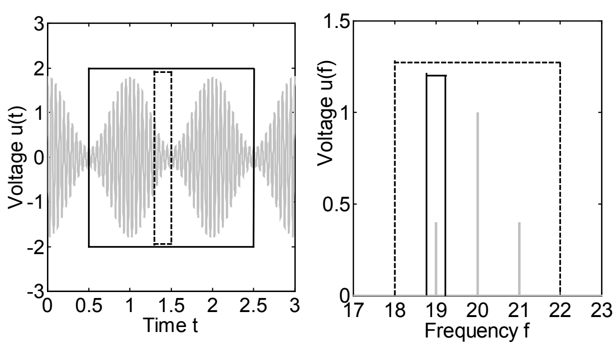

Figure 2. AM signal ($m = 0.8$) in time (left) and frequency (right) domain. Boxes refer to II.2, II.3

Figure 2 shows an AM signal with m = 0.8 (sinusoidal modulation) in the time and frequency domain. The spectrum of such an AM signal always consists of three narrowband signals: the carrier with the (normalized) amplitude "1" at $f = f_0$ and the two sideband peaks with the amplitude $m/2$ at the frequencies $f_0 + f_m$ and $f_0 - f_m$.

II.2 Fast AM

The result of a test receiver measurement of an AM signal depends on the modulation frequency f_m. If this frequency is greater than the bandwidth B of the test receiver band-pass ("fast AM")

$$f_m > B\,, \tag{3}$$

the distance between the three peaks is greater than the bandwidth (see Figure 2, solid line). Therefore, the three peaks are measured separately and correctly. As the step size of FEMIT (DFT step) corresponds to the step size of the test receiver ([1],[2]), FEMIT produces the same result. In the time domain this means that at least one period of the modulation function is inside the measurement window.

II.3 Slow AM

Different condition are met for slow AM signals, charcterized by

$$f_m < B\,. \tag{4}$$

In this case, all of the three peaks are located *inside* the pass-band of the test receiver band-pass. Here, the result of the test receiver depends on the detector. The peak and quasi-peak detectors measure the maximum of the envelope, that is 1+*m*. The average detector is not affected by the modulation and measures the average value "1".
In time domain formula (4) corresponds to a capture time shorter than one period of the modulating frequency (see Figure 2, dotted line). This means that the result of FEMIT depends on the phase angle of the modulating function. Therefore, the result can vary between 1+*m* and 1-*m*.

II.4 Measurement algorithm for AM signals

For the simulation of the *peak* and *quasi-peak* detector, the result is correct, if the measurement takes place when the signal reaches the maximum. As it is not possible to control this in the usual mixture of signals, the result is statistically distributed.
To get close to the result of the test receiver, several time domain measurements are recorded. After the DFT, at each frequency the *maximum* of the spectra is calculated (Figure 3). The more measurements are evaluated, the closer the result approaches the correct value.
For the *average* detector, the *average* value at each frequency has to be evaluated. The remaining error has

statistical character and depends on the number of measurements and on the modulation factor.

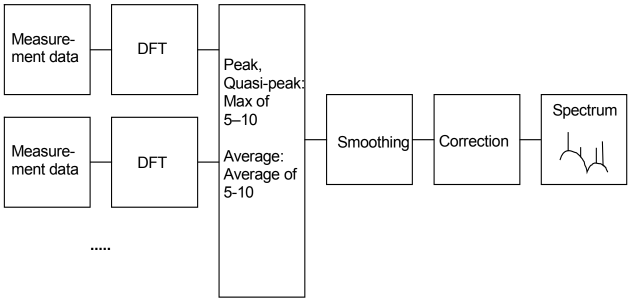

Figure 3 Measurement algorithm for AM signals

In the next chapters the number of measurements that is necessary to keep the remaining error lower than a defined limit is estimated by the example of the quasi-peak detector.

II.5 Error in slow AM measurements

The error δ_{dB} (in dB) for a amplitude a is given as

$$\delta_{\mathrm{dB}} = 20\,\log(\frac{1+m}{a}) \tag{5}$$

and the maximum error $\delta_{\mathrm{dB,max}}$ can be calculated as

$$\delta_{\mathrm{dB,max}} = 20\,\log(\frac{1+m}{1-m})\,. \tag{6}$$

Figure 4 shows this maximum error as a function of the modulation factor. For 5 % AM (m = 0.05) the error amounts to 1 dB, for 20 % AM to 3.5 dB and for 50 % to 10 dB.

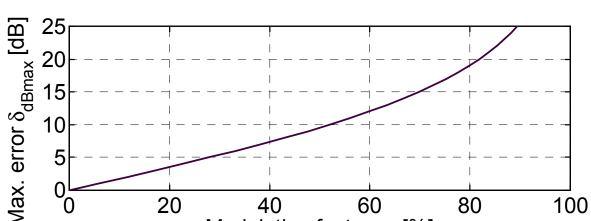

Figure 4 Max. error as a function of the mod. factor

II.6 Distribution curve

For the following considerations, the distribution curve $\Phi(y)$ of the envelope of the AM signal is needed. For this example, a sinusoidal modulation function like in Figure 2 is used. By regarding half a period of a cosine and exchanging abscissa and ordinate, $\Phi(y)$ can be obtained as

$$\begin{aligned} &\Phi(y) = \frac{1}{\pi}\arccos\left(\frac{1-y}{m}\right), \quad 1-m \le y \le 1+m \\ &\Phi(y) = 0, \quad y < 1-m \\ &\Phi(y) = 1, \quad y > 1+m \end{aligned} \tag{7}$$

$\Phi(y)$ represents the distribution of the random variable "amplitude of the envelope of the AM signal for a random measurement". In other words: the probability $P(y \le a)$ that the amplitude y in a random measurement is lower than a (and the corresponding error according to (5) is higher than δ_{dB}) is

$$P(y \le a) = \Phi(a)\,. \tag{8}$$

Figure 5 shows $\Phi(y)$ for m = 0.8 (80 % AM).

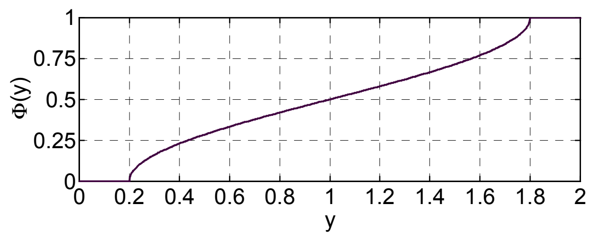

Figure 5 Distribution curve $\Phi(y)$ of an 80% AM signal

II.7 Necessary number of measurements

The probability p_1 that the maximum amplitude of *one measurement* is higher than a (and the corresponding error according to (5) is lower than δ_{dB}) is given as

$$P(y > a) = 1 - P(y \le a) = 1 - \Phi(a)\,. \tag{9}$$

Furthermore, the probability p_{n} that for *n measurements* at least one amplitude is higher than a can be calculated by "1 – the probability that no amplitude is higher than a". As the single measurements are independent of each other, the latter probability can be obtained as the product of the single probabilities according to (8):

$$p_{\mathrm{n}} = 1 - \Phi^{n}(a)\,. \tag{10}$$

Combining (7) and (10) and replacing a by δ_{dB} according to (5) the number of measurements n that are necessary to get an error lower than δ_{dB} at a probability p_{n} can be obtained as

$$n = \frac{\lg(1-p_{\mathrm{n}})}{\lg\left(\frac{1}{\pi}\arccos\left(\frac{1}{m}\left(1-\frac{1+m}{10^{\frac{\delta_{\mathrm{dB}}}{20}}}\right)\right)\right)}\,. \tag{11}$$

Figure 6 shows n as a function of m for parameterized δ_{dB} and the probability $p_n = 0.9$ (sinusoidal modulation).

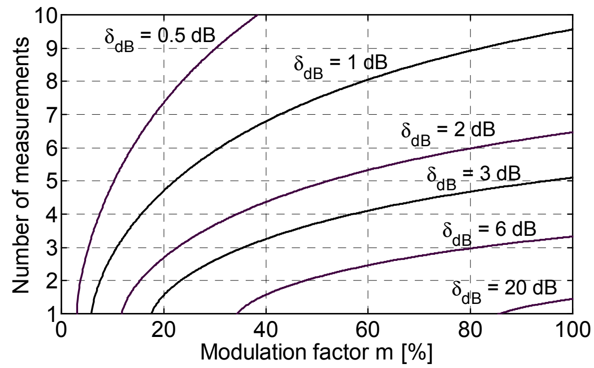

Figure 6 Number n of measurements as a function of the modulating factor that are necessary to get an error lower than δ_{dB} at a probability of 90 % (sinusoidal modulation)

Therefore, with a probability of 90 % the following statements can be made for sinusoidal modulation (comparing to peak and quasi-peak measurements):

- For one measurement the error of FEMIT is higher than 3 dB, if the modulation factor is 0.2 or higher.
- If the max. of 10 measurements is evaluated, even in the worst case ($m = 1$) the error is lower than 1 dB.
- A useful compromise between accuracy and time consumption are 5 measurements. Here, the error in the worst case is approximately 3 dB and for $m = 0.2$ the error is lower than 1 dB.

III. BROADBAND SIGNALS

The so far presented algorithm produces correct results when measuring narrowband signals like signals with discrete frequency and pulses with a repetition frequency f_{rep} higher than the bandwidth B of the test receiver. 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].

III.1 Measuring algorithm for broadband signals

Figure 7 shows the block diagram of the algorithm and Figure 8 illustrates 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 (curve "Trigger max" in Figure 8) and is corrected for all frequencies according to the correction value given by the correction curve (see III.2) at the repetition frequency of the broadband phenomenon ("-24dB", curve "corr" in Figure 8).

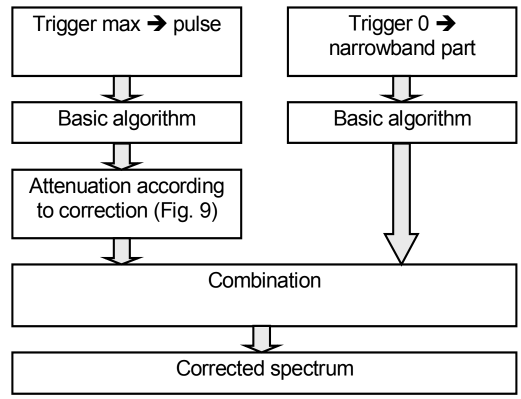

Figure 7 Measuring algorithm for broadband signals

For the correct measurement of narrowband peaks, a second measurement has to be recorded without a pulse (trigger level 0), because narrowband peaks cannot be located below the level of the broadband spectrum (e.g. at 95 MHz in Figure 8). The corresponding spectrum ("Trigger 0" in Figure 8) contains all the narrowband peaks with the correct level.

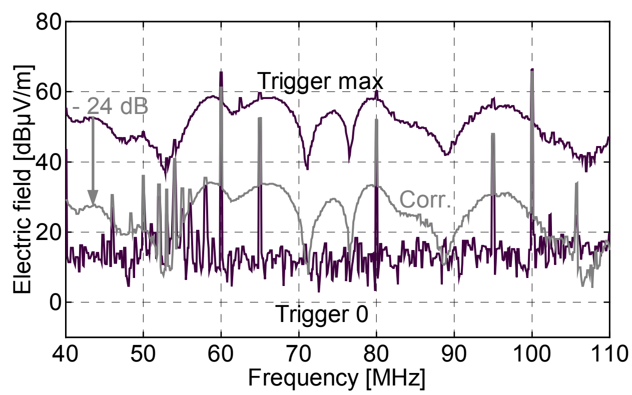

Figure 8 Example for broadband correction

In a last step the two spectra are combined: the broadband parts are taken from the first, attenuated measurement, the narrowband parts (peaks) from the second measurement.

III.2 Correction curve

The correction curve depends on the bandwidth and the detector of the test receiver as well as on the capture time. Figure 9 shows correction curves for the quasi-peak detector and the 120 kHz band-pass for parameterized capture time T. The correction curves are obtained by the comparison of the corresponding characteristics of the test receiver and the DFT [2].

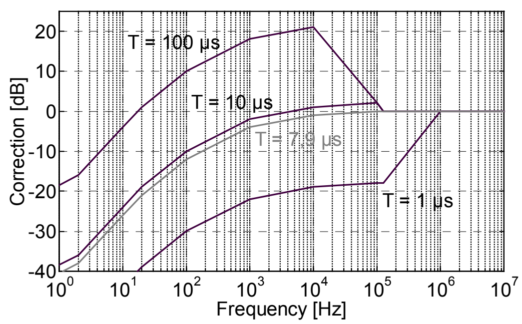

Figure 9 Correction for 120 kHz band-pass and quasi-peak detector. Parameter: capture time T

III.3 Choice of capture time T

Figure 9 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.

Table I - Capture time *T*

Band	*Bandwidth*	T	$\Delta f = 1/T$
B	9 kHz	100 µs	10 kHz
C, D	120 kHz	10 µs	100 kHz

Here, the error is minimal, when a correction is not possible (e.g. superposition of several different pulses).
Adequate choices for T and the resulting DFT step sizes Δf are listed in Table I.

III.4 Example

Figure 10 shows a comparison of the spectra of the test receiver and FEMIT. The EUT, a burst-generator, emitted a pulse with f_{rep} = 100 Hz.

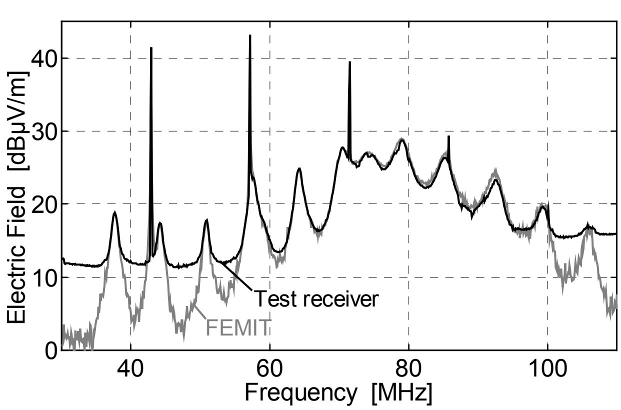

Figure 10 Comparison test receiver – FEMIT

Both narrowband and broadband parts of the spectrum show good agreement of the FEMIT and the test receiver spectrum (for differences in the noise level see IV.5).

IV. SIGNAL-TO-NOISE RATIO, NOISE LEVEL

An important aspect of the quality of a measurement system is the signal-to-noise ratio *SNR* and the absolute noise level. Especially EMC measurements require a high dynamic range of the system.

IV.1 Quantization noise

In this time domain measuring system, the generally limiting effect is the quantization noise of the oscilloscope. The *SNR* of a system with B bit can be described as [3]

$$SNR\big|_{\mathrm{dB}} = 6.02\,B + 1.76\,. \tag{12}$$

For a typical oscilloscope with 8 bit, the *SNR* is 49 dB.

IV.2 Increase of the SNR by Fourier transform

The *SNR* according to (12) refers to the *SNR* in the time domain. The Fourier transform shows a processing gain. The more points are used for the transform, the higher the *SNR* of the spectrum becomes. The increase of the *SNR* of a spectrum with N points compared to the *SNR* of a spectrum with N' points can be described as [3]

$$SNR_{\mathrm{N}}\big|_{\mathrm{dB}} = SNR_{\mathrm{N'}}\big|_{\mathrm{dB}} + 20\log\left(\sqrt{\frac{N}{N'}}\right)\,. \tag{13}$$

IV.3 Measurement of the SNR

The *SNR* of the FEMIT-system was measured by calculating the spectrum of the record of a full-range sinus (N = 20000). The *SNR* corresponds to the distance between the peak value of the sinus and the noise level. The measured *SNR* is in the range of *70 - 75 dB*.
It is evident that the *SNR* is often some dB lower than this value, because to avoid overdriving (signal clipping), it is not wise to use the full scale of the oscilloscope.

IV.4 Incoherent averaging

Another possibility to increase the *SNR* is the averaging of n spectra [3]. The best effect shows the *coherent* averaging. As the coherent averaging needs signals with identical time phase, this cannot be applied here.
However, the *incoherent* averaging can be used here. The incoherent averaging does not decrease the average noise power (unlike the coherent averaging), but reduces the variance of the noise. This results in an additional gain of

$$SNR_{\text{gain,incoh}}\big|_{\text{dB}} = 10\log(\sqrt{n})\,. \quad (14)$$

For the incoherent averaging, the average value of the absolute levels at each frequency is calculated. For $n = 10$ the additional SNR gain amounts to 5 dB.

IV.5 Absolute noise level

Beside the SNR, the absolute noise level is an interesting value of the system. Figure 11 shows this level by the example of a radiated emission measurement with a biconical antenna in comparison to the test receiver noise level and the limits of the standard EN 55011 (CISPR 11) Group 1, Class B (domestic establishments, 3 m distance, quasi-peak detector).

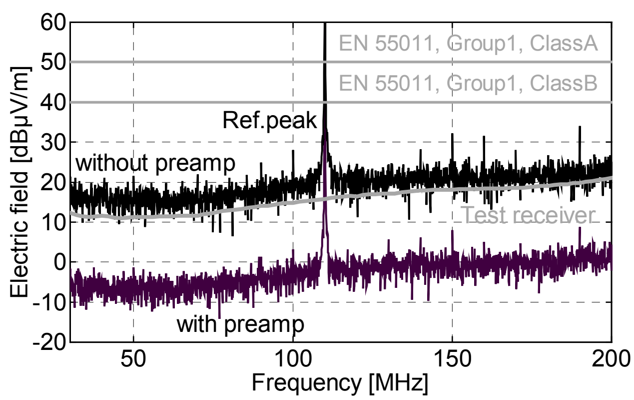

Figure 11 Noise level for a biconical antenna with and without a preamplifier (incoherent averaging of five spectra) in comparison to the limits and the test receiver

The upper FEMIT curve shows the noise level without a preamplifier and the lower one with a 20 dB preamplifier. The noise level of the test receiver (quasi-peak detector) is located between these two curves.
In Table II the distance of the lower limit (Class B, domestic establishments) to the lowest possible noise level is listed for important measurement ranges.

Table II – Distance of the noise level to the limit

Band	*Frequency range*	*Distance to limit (CISPR 11, Gr. 1, Cl. B)*
B	0.15 – 30 MHz	> 35 dB
C, D	30 -1000 MHz	Without Preamp. 10...20 dB
C, D	30 -1000 MHz	With Preamp. 30...40 dB

Even without a preamplifier, the noise level is at least 10 dB below the limit – a sufficient distance. For more sensitive measurements, the noise level can be significantly decreased by using a 20 dB preamplifier.

IV.6 Broadband signals and noise

When measuring broadband signals according to the described algorithm (chapter III), the noise level can increase by combining the narrowband and attenuated broadband part of the spectrum (Figure 7). This depends on the repetition frequency f_{rep} and the measurement ranges.
The lower the repetition frequency is, the more the broadband part of the spectrum is attenuated. This results in a *decreasing* noise level (e.g. f_{rep} = 100 Hz → - 10 dB). However, the measurement of the pulses usually requires a greater measurement range, resulting in an *increasing* noise level (e.g. narrowband: 10 mV/div, broadband: 50 mV/div → +14 dB).
If the increasing part due to the measurement range is greater than the decreasing part due to the attenuation, the resulting noise level increases (this example: + 4 dB). However, even in very unfavorable cases, the resulting noise level is located below the limits.

V. CONCLUSIONS

In this paper, the time domain emission measurement system FEMIT was described. The central results of the here investigated aspects are:

- Errors due to amplitude modulation can be reduced by evaluating several spectra.
- A statistical analysis shows, that 5 measurements are a good compromise between accuracy and time consumption.
- An advanced algorithm allows the correct measurement of broadband signals such as pulses.
- The SNR and noise level are sufficient for EMC emission measurements.

VI. REFERENCES

[1] C. Keller, K. Feser, "Fast Emission Measurement In Time Domain", *EMC 2001*, Zurich, Switzerland

[2] C. Keller, K. Feser, "A New Method of Emission Measurement". *2002 IEEE International Symposium On EMC,* Aug 19-23, Minneapolis, USA

[3] Richard G. Lyons, *"Understanding Digital Signal Processing"*, Addison-Wesley

[4] International Electrotechnical Commission IEC, CISPR 16: *"Specifications for radio disturbance and immunity measuring apparatus and methods"*