Dynamic Performance Evaluation of Full Time Domain EMI Measurement Systems

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***Abstract*— This paper presents the evaluation of the performance of Full Time Domain Electromagnetic Interference measurement systems in terms of the noise figure, the linearity, the dynamic range, the voltage standing wave ratio and the crosstalk. The abovementioned parameters allow a broader characterization of the oscilloscope-based implementations of CISPR 16-1-1 measuring receivers, providing relevant specifications that are beyond the standardized baseline requirements. Such metrics are assessed using the actual settings and operating conditions required for compliant time-domain EMI measurements. For the specific oscilloscope used in the experiments, the noise figure is measured for all the different vertical ranges between 5 mV/div and 1 V/div. Likewise, the linearity and the dynamic range, in terms of the effective number of bits, was measured for sine wave input signals with an rms voltage swept between 20 mV and 1 V. This experiment was repeated for CISPR bands A, B and C/D using 10 kHz, 1 MHz, and 100 MHz sinusoids, respectively. The results allow a more comprehensive comparison between Full-TDEMI measurement systems and the more conventional superheterodyne architecture receivers that are completely specified in the frequency domain.**

Keywords*— *Dynamic range, electromagnetic interference, measuring receiver, noise figure, time-domain measurements

I. Introduction

The measuring receiver is the fundamental instrument for conducted and radiated electromagnetic emissions testing. According to the standard definition given by the CISPR 16-1-1:2015, it is an "instrument such as a tunable voltmeter, an electromagnetic interference receiver, a spectrum analyzer or a Fast Fourier Transform (FFT) based measuring instrument, with or without preselection, that meets the relevant parts of this standard" [1]. In this regard, the standard CISPR 16-1-1 does not provide a particular implementation of a measuring receiver but a number of requirements that manufacturers have to fulfill under a "black-box" approach.

However, in practice, there are two broad categories for classifying the measuring receivers. On the one hand, there are conventional swept receivers with super-heterodyne architecture that, fundamentally, measure the amplitude of the spectrum in the frequency domain [2]. On the other hand, there are the FFT-based measuring receivers that take advantage of time-domain measurements for speeding up emissions testing and for providing time-frequency analysis features which are useful for evaluating and mitigating the impact of transient and stochastic disturbances [3]–[5]. Currently, real-time analyzers [6], [7] and oscilloscope-based implementations are the two approaches for realizing FFT-based measuring receivers.

In recent years, the idea of using oscilloscopes for EMI measurements [8], beyond pre-certification purposes, has been brought back for discussion in academia [9], [10]. What has been called "Full Time Domain EMI measurement systems" is a software-defined implementation of a measuring receiver that allows for EMI testing using oscilloscopes while meeting all baseline requirements of CISPR 16-1-1 [10], [11]. In that sense, previous studies by the authors have reported that, provided a general-purpose oscilloscope with the appropriated technical specifications, Full-TDEMI measurement systems fulfill CISPR 16-1-1 baseline requirements for CISPR bands A to D. In particular, two different implementations of the Full-TDEMI measurement system were characterized with regards the sine-wave voltage accuracy (level error), the frequency selectivity, the pulse response (absolute and relative) and, the voltage standing wave ratio (VSWR) at the receiver's RF input port. The results of such characterization provided sufficient evidence to conclude CISPR 16-1-1 requirements were satisfied [10], [11].

Nonetheless, CISPR 16-1-1 requirements might be insufficient for providing a complete description of Full-TDEMI measuring systems. In fact, other parameters such as the noise figure, the displayed average noise level, the dynamic range, among others, are commonly used to benchmark spectrum analyzers and measuring receivers. Translating the dynamic performance metrics of oscilloscopes for delivering such complementary specifications regarding Full-TDEMI measurement systems is the objective of this paper. The paper is organized as follows. First, an outline of Full-TDEMI measurement systems is provided along with some summarized results that support their compliance with CISPR 16-1-1 requirements in CISPR bands A to D (9 kHz – 1 GHz). Then, section III defines the dynamic performance measures included in the scope of this paper and presents the mathematical relationship between them. Subsequently, the actual results of the evaluation of the noise figure, the linearity, the dynamic range, the VSWR and the crosstalk are given in section IV. Finally, the paper closes with the conclusions and a couple of remarks concerning the adequacy of the test setup used in the experiments.

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II. Full Time Domain EMI Measurement Systems

A. *Overview of Full-TDEMI measurement systems*

Full-TDEMI measurement systems are oscilloscope-based implementations of an EMI measuring receiver. In general terms, a Full-TDEMI measurement system is described by the block diagram shown in Fig. 1 [9], [11]. For the measurement of radiated EMI, a broadband antenna shall be used, while for the measurement of conducted EMI corresponds either a current clamp or a Line Impedance Stabilization Network (LISN). The measured signal could be amplified or filtered if this provides better sensitivity. In the analog-to-digital converter (ADC), the full spectrum signal is digitized in real-time and stored in as a time-discrete value-discrete signal.

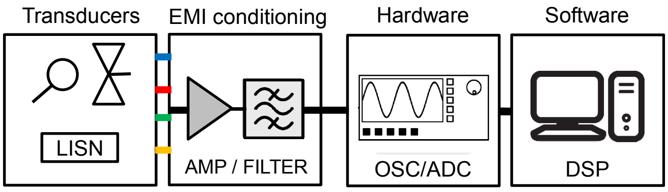

Fig. 1. Block diagram of a Full Time-Domain EMI measurement system.

The final measurement results are computed via the processing techniques implemented in a software layer that provides compliance with the relevant CISPR 16-1-1 requirements. After deep memory acquisitions, the software of the Full-TDEMI measurement system performs signal processing tasks including windowing, resolution enhancing, resampling, spectral estimation (using the Short-Time FFT and the Welch's method) and the detector emulation. Those mathematical transformations are responsible for delivering the measurement results in accordance with CISPR 16-1-1 requirements [11].

Full-TDEMI measurement systems capture the whole spectrum of the EMI with every acquisition enabling multi-domain analysis. Besides, the triggering and multichannel capabilities found in most oscilloscopes provide additional tools for testing multi-functional mode equipment and for emissions testing parallelization. On the other hand, much higher sampling rates and a deeper memory are required than with real-time analyzers. This imposes bandwidth and dwell time constraints based on the current oscilloscope technology.

B. *Summary of the oscilloscope's specifications*

The capability of a Full-TDEMI measurement system to comply with CISPR 16-1-1 baseline requirements depends not only on the application of the adequate processing techniques (software) but also on the adequacy of the oscilloscope in terms of resolution, an effective number of bits, sampling frequency, and bandwidth. That being said, Table I gives a summary of the key specifications of DPO5104B from Tektronix®.

Regarding the specifications shown in Table I, the oscilloscope has a 1 GHz bandwidth, a maximum sampling rate of 10 GS/s, 50 MS of memory depth, and its nominal input impedance can be set to 50 Ω. The preselection is not used by default and overload is prevented by adjusting dynamically the vertical scale while attempting to maximize the sensitivity.

TABLE I. Oscilloscopes specifications at the operating conditions configured in the Full TDEMI measurement system

Resolution [bits]	8
ENOB [bits]	6
Enhanced resolution [bits]	0.5 to 4
Max sampling frequency [GS/s]	10
Sampling freq. for Band A (typical) [MS/s]	50
Sampling freq. for Band B (typical) [MS/s]	500
Sampling freq. for Band C/D (typical) [GS/s]	5
Bandwidth (Bands A/B/C&D) [MHz]	20/500/1000
Input impedance	50Ω / 1 MΩ

C. *Compliance with CISPR 16-1-1 baseline requirements*

As has been extensively explained in [11], Full-TDEMI measurement systems based on the selected oscilloscope have demonstrated to be compliant with CISPR 16-1-1 requirements. Table II shows the summary results from the corresponding assessment of conformity.

TABLE II. Results from the assement of conformity performed on Full TDEMI measurement systems.

			Band C/D	
			Cal.	**Req.**
Level error [dB]			±1.5	± 2 dB
Selectivity [kHz]	1.5 dB		59±2	[40, 140]
	6 dB		119±2	120±20
	20 dB		210±2	[100, 280]
Response to pulses (absolute) error	PK [dB]		±0.1	± 1.5
	QP [dB]		±0.1	± 1.5
	AV [dB]		±0.1	± 1.5
Response to pulses (relative) error	PK/QP [dB]	100 Hz	11.9	12.0 ± 1.5
		1 kHz	-	-
		5 kHz	-	-
	QP/QP(ref) [dB]	100 Hz	0	0
		1 kHz	-8.0	-8.0±1.0
		5 kHz	-	-
	AV/QP [dB]	100 Hz	-	-
		1 kHz	38.4	38.1±1.5
		5 kHz	26.4	26.3±1.5
VSWR (0 dB att)			<1.4	2.0 to 1

Typical values for every channel of the corresponding Full TDEMI measurement system.
*Reference pulse repetition frequency.

With this oscilloscope, it is possible to declare compliance with sine wave accuracy (amplitude level error), absolute and relative response to pulses, frequency selectivity, and VSWR requirements.

Even if compliance with the CISPR 16-1-1 baseline requirements has been achieved using the previously specified oscilloscope, the reported results provide scarce information regarding the actual dynamic performance of the Full-TDEMI measurement system.

III. Dynamic Performance Measures

Considering oscilloscopes are used by the Full-TDEMI measuring receivers, their dynamic characterization should be performed at the operating conditions required for compliance with CISPR 16-1-1. In summary, from the oscilloscope's calibration methods it is well known the importance of quantifying the ADC noise, the gain and the linearity of the channels, and the input mismatch and crosstalk [12]–[14]. In the following subsections, such aspects will be investigated.

A. Noise Figure

The noise contribution from circuit elements is usually defined in terms of noise figure, and it accounts for the amount of noise that a circuit adds to the signal. In this regard, the noise figure of a circuit, *NF*, is defined as the signal-to-noise ratio (*SNR*) at the input divided by the *SNR* at the output expressed in decibels, that is,

$$NF = 10\log\left(\frac{SNR_{input}}{SNR_{output}}\right)\Bigg|_{B_{input}=B_{output}} > 1 \quad (1)$$

where B is the bandwidth. Equation (1) can be simplified for the case of a test receiver because the level of the signal is the same at the input and at the output (displayed measurement result). Assuming true noise at the input of the receiver when terminated in a 50 Ω, the former equation can be written as,

$$NF = N_{output}[\mathrm{dB}] - 10\log(kTB) \quad (2)$$

where k is the Boltzmann constant and T is the temperature in Kelvins.

Typically, *NF* is specified for a 1 Hz bandwidth and a room temperature of 21 ºC. Therefore, *NF* is given by

$$NF\big|_{B=1\,\mathrm{Hz}} = N_{output}[\mathrm{dBm}] - 10\log(\mathrm{RBW}) + 174\,\mathrm{dBm} \quad (3)$$

where RBW is the resolution bandwidth used for measuring the displayed noise level noise, N_{output}.

For oscilloscopes, the N_{output} depends on the vertical noise at the different volts-per-div sensitivities. Therefore, vertical noise must be measured for each vertical range setting with every oscilloscope channel terminated into 50 Ω and using the same sample rate and acquisition mode specified for EMI measurements [9]. Then, the recorded base-line noise floor waveform is transformed into the frequency domain according to the method described in [4], [15]. Finally, N_{output} is the average noise level measured with the rms detector for each CISPR band.

B. Linearity and Dynamic Range

A perfect linear oscilloscope would be able of registering the waveforms without distortion. However, the effect of quantization noise and other nonlinearities limit the dynamic performance of the ADC and, in consequence, the actual specifications of Full-TDEMI measurement systems.

The effective number of bits (*ENOB*) is a measure that summarizes information about the linearity and the dynamic range of the ADC. The equation of the *ENOB* is derived from the theoretical *SNR* of an ideal N-bit ADC, by replacing the *SNR* by the Signal-to-Noise-and-Distortion (SINAD), that is,

$$ENOB = \frac{SINAD - 1.76\,\mathrm{dB}}{6.02}. \quad (4)$$

Equation (4) assumes a full-scale input signal, but this is not recommended in order to avoid distortion due to signal clipping. If the signal level is reduced, the value of SINAD decreases and the *ENOB* decreases. Thus, a correction factor, that normalizes the *ENOB* value to a full-scale, $V_{\mathrm{full\ scale}}$, must be added for calculating it at reduced signal amplitudes, V_{input}, as shown in (5),

$$ENOB = \frac{SINAD[dB] - 1.76\,\mathrm{dB} + 20\log\left(\frac{V_{\mathrm{full\,scale}}}{V_{\mathrm{input}}}\right)}{6.02} \quad (5)$$

On the other hand, SINAD expressed in decibels, is given by (6),

$$SINAD = 20\log\left(\frac{S}{N+D}\right) = -10\log\left[10^{-\frac{SNR}{10}} + 10^{-\frac{THD}{10}}\right] \quad (6)$$

where *SNR* and *THD* are the signal-to-noise ratio and the total harmonic distortion, respectively. Then, the *SNR* and the *THD* must be measured for the all vertical ranges of the oscilloscope and for every measurable CISPR band.

The *SNR* is measured using a well-known sinusoidal input signal. The level of the reference signal is taken directly form the final measurements displayed in the frequency domain using the standard detectors and resolution bandwidths. It is important to notice that cable attenuation must be corrected in the signal level measurement. The (output) noise level, for each vertical scale and corresponding RBW, is obtained from the previously characterized noise figure (3).

Moreover, *SNR* could be theoretically estimated using the following expression,

$$SNR = 6.02(N + N_E) + 1.76\,\mathrm{dB} + G_P + G_{Window} + G_{Welch} \quad (7)$$

where N is the number of physical bits of the ADC, N_E is the increase in the number of bits due to the smoothing filter applied by the oscilloscope in high resolution algorithm, G_P is the FFT processing gain, G_{Window} is the processing gain from using a non-rectangular windowing function, G_{Welch} is the reduction of the white noise variance when estimating the spectrum using the Welch's method.

For instance, Tektronix oscilloscopes can reduce the waveform noise HiRes by applying a smoothing digital boxcar filter on the decimated acquisition. The filter 3 dB bandwidth is approximately 0.44 of the sample rate. In the same vein, N_E is given by

$$N_E = \frac{1}{2}\log_2(D) = \frac{1}{2}\log_2\left(\frac{F_{\max}}{F_s}\right), \quad (8)$$

where D is the decimation factor that is calculated as the ratio between the maximum non-interleaved sampling frequency of the scope, F_{max}, and the actual sampling frequency set for the output waveform [9].

The FFT processing gain, G_P, is obtained by means of oversampling the time-domain waveforms. Such reduction in the noise floor is explained by the spectral spreading of the quantization noise power as the sampling frequency increases [8]. G_P is given by (9),

$$G_P = 10\log\left(\frac{F_s}{2B}\right), \quad (9)$$

Likewise, the G_{Window} is the reduction of the noise due to the filtering effect of the bell-shaped windowing function applied to the time-domain signal. It is measured as the ratio between the RBW and the Equivalent Noise Bandwidth, ENBW, expressed in decibels, that is,

$$G_{Window} = 10\log\left(\frac{\text{RBW}}{\text{ENBW}}\right). \quad (10)$$

Additionally, time-domain EMI measurements typically use the Welch's method for estimating the spectrum of the measured signals over the set of highly overlapped windows that segments the whole waveform acquisition. Consequently, when estimating the noise spectrum, there is a reduction of its amplitude variance due to the combination of spectrum calculated for all the overlapped windows according to the standard weighting detectors, in comparison with the spectrum that would have been obtained using the regular periodogram, that is, with neither windowing nor overlapping applied.

In that sense, such reduction is given by

$$G_{Welch} = 10\log\left(\frac{\text{Var}\{\text{P}_\text{X}\}}{\text{Var}\{\text{P}_\text{W}\}}\right), \quad (11)$$

where $\text{Var}\{\text{P}_\text{X}\}$ is the variance of noise spectrum estimated using a regular periodogram while the $\text{Var}\{\text{P}_\text{W}\}$ is the variance of noise spectrum estimated using the Welch's periodogram for a given window function, resolution bandwidth, and overlapping factor. Both variances can be numerically calculated using the Monte Carlo approach.

Consequently, the theoretical model for the SNR of Full-TDEMI measurement systems can be used for calculating a maximum *SNR* under the assumption the ADC is ideal. The results are shown in Table III.

Conversely, total harmonic distortion is defined as the ratio of the total rms voltage of the harmonics to that of the fundamental component. In decibels, it is calculated as,

$$THD = 10\log\left(\sum_{i=2}^{N_h} V_i^2\right) - 20\log(V_1), \quad (12)$$

where V_1 is the rms voltage of the fundamental frequency, V_i is the rms voltage of the i-th harmonic and N_h is the highest order of the harmonic that is measured above the instrument noise floor.

TABLE III. THEORETICAL SIGNAL OT NOISE RATIO FOR FULL-TDEMI MEASUREMENT SYSTEMS FOR CISPR BANDS A TO D

Oscilloscope Specs	**CISPR Bands**		
	A	B	C/D
N [bits]	8		
$F_{\max}$ [GS/s]	10		
F_s [MS/s]	50	500	5000
N_E [bits]	3.8	2.2	0.5
B [Hz]	150×10^3	30×10^6	1×10^9
G_P [dB]	22.2	9.2	4.0
RBW [kHz]	0.2	9	120
ENBW	0.15	6.78	90.42
G_{Window} [dB]	1,23		
Dwell time *(ms)*	100	10	10
Window type	Kaiser-Bessel (β=16.7)		
Overlapping	80%		
G_{Welch}	12,7	19,6	31,0
SNR **[dB]**	**109**	**93**	**89**

C. *VSWR and Crosstalk*

The evaluation of the *VSWR* is intended to measure the impedance matching of the oscilloscope to the 50 Ω characteristic impedance required for the entire EMI measurement system. It is measured directly using a Vector Network Analyzer, for all the possible vertical range settings of the oscilloscope and covering the complete bandwidth.

On the other hand, the crosstalk evaluation is intended to quantify the coupling between the oscilloscopes channels by means of two-port S-parameters measurements. Crosstalk must be taken into account when performing multichannel EMI measurements according to the test setups suggested in [12].

IV. RESULTS

This section comprises the measurement results for the dynamic performance evaluation carried out to a Full-TDEMI measurement system implemented with the oscilloscope. Whenever applicable, the reference signal generator used was the 81160A Pulse Function Arbitrary Generator from Keysight technologies.

A. *Noise Figure*

Fig. 2 shows the measured noise figure referenced to a resolution bandwidth of 1 Hz for the Full-TDEMI measurement system under evaluation. There is a clear linear increase in the noise figure as the vertical range of the oscilloscope is set for measuring signals with a larger peak-to-peak voltage. This means a loss in sensitivity of the measurement system that should be considered when measuring simultaneously broadband impulsive noise and narrowband interferences.

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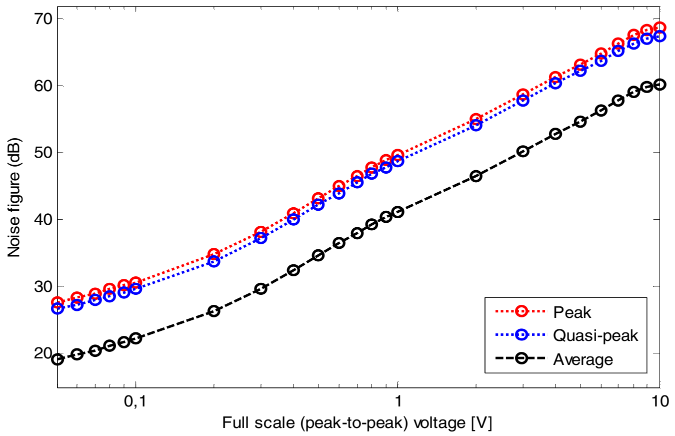

Fig. 2. Noise figure referenced to a RBW of 1 Hz for a Full-TDEMI measurement system based on the oscilloscope Tek DPO5104B configured for having 1 GHz of bandwidth and a sampling rate of 5 GS/s.

Fig. 2 can also be used for determining if, for a given signal amplitude, there will be enough margin with respect a certain emission limit. For example, for a noise figure of 30 dB and a resolution bandwidth 120 kHz, the displayed average noise level would be -94 dBm or 14 dBμV, approximate. Likewise, it is important to notice that for the maximum sensitivity and with the average detector, the results suggest the Full-TDEMI measurement system have a displayed average noise level (*RBW*=1 Hz) of approximately -155 dBm, which is in line with many commercial test receivers.

B. Linearity and Dynamic Range

Fig. 3 shows the correspondence of the voltage level measurements performed with Full-TDEMI system and the input voltage applied to the reference signal generator. The measurement was repeated at three different frequencies using the specific settings required for CISPR bands A to D. Results show that for sine wave having amplitudes swept over the oscilloscope vertical ranges, the level error is linear and remains below ±0.15 dB which is significantly less than the CISPR 16-1-1 requirement of ±2 dB.

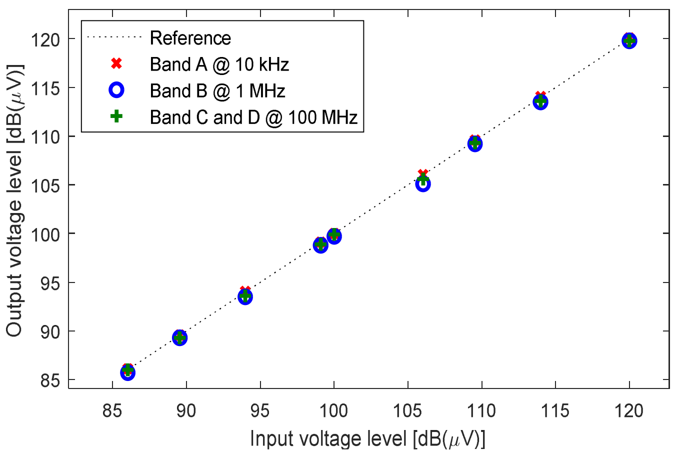

Fig. 3. Linear amplitude voltage swept and error level measurements.

Fig. 4 shows the measured *SNR*. The measured *SNR* ratio is closer to the theoretical value provided in Table IV as the full scale voltage level increases. As expected, the *SNR* is higher the lower the frequency of the CISPR band under assessment is. This is because the usage of a narrower *RBW* and also due to the noise reduction achieved by the combination of signal oversampling and high resolution waveform smoothing.

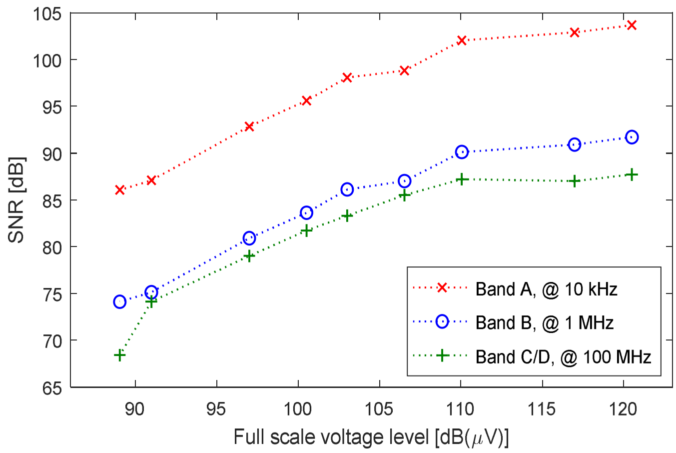

Fig. 4. Signal to noise ratio of a Full-TDEMI measurement system.

Regarding the *ENOB*, Fig. 5 shows a linear tendency in the increase of the *ENOB* as the full scale voltage level growths. Moreover, *ENOB* is less sensitive to the vertical range setting when performing measurements in CISPR bands A and B in comparison with the measurements in bands C and D. This is explained by the combination of a lower *SNR* and higher *THD* that characterizes the oscilloscope dynamic performance at frequencies in the range of bands C/D versus the higher *SNR* and lower *THD* observed in bands A/B.

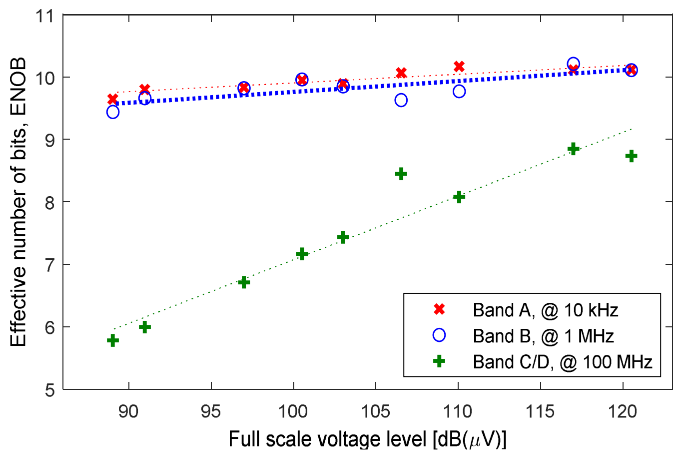

Fig. 5. An effective number of bits of a Full-TDEMI measurement system.

C. VSWR and Crosstalk

Fig. 6 presents the measurement results for the maximum *VSWR* (red axis on the left hand side) taken from all oscilloscope channels and among all the different vertical ranges. Likewise, Fig. 6 shows the mean and the min-max range of the oscilloscope input impedance. The evidence supports that the oscilloscope fulfills the requirements of CISPR 16-1-1 in terms of the maximum *VSWR* without an attenuator.

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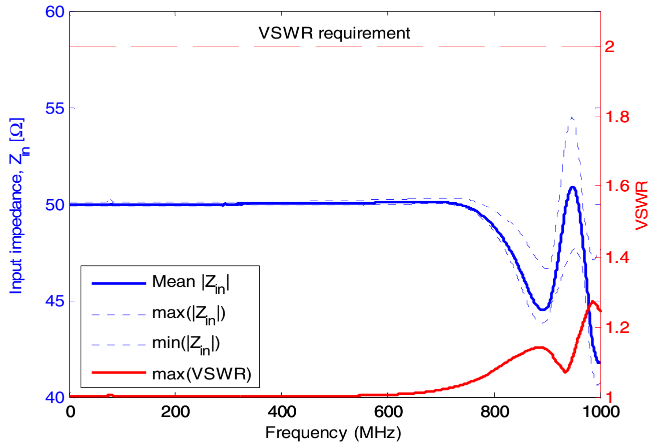

Fig. 6. Z_{in} and VSWR evaluation of a Full-TDEMI measurement system.

Furthermore, crosstalk was found to be higher between pairs of adjacent channels. In the worst case, approximately 60 dB of isolation was exhibited between pairs of adjacent channels, while for rest of pairs more than 75 dB of isolation is guaranteed. For frequencies below 600 MHz, all the pairs of channels experience similar crosstalk, however, above 600 MHz crosstalk is significantly larger among pairs of adjacent channels (S_{21}, S_{32}, S_{43}) than with the rest of pairs.

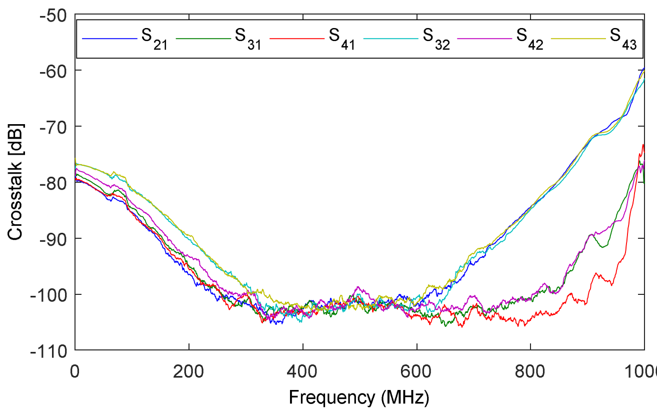

Fig. 7. Crosstalk evaluation of a Full TDEMI measurement system.

V. Conclusion

The dynamic performance of a Full-TDEMI measurement system based on the general-purpose oscilloscope Tektronix DPO 5104B has been presented. The influence of the configured vertical scale, sampling rate and acquisition modes were observed in the noise figure, the signal-to-noise ratio and in the effective number of bits. Using oscilloscopes for EMI measurements involves making compromises between the dynamic range and the sensitivity that are relevant, therefore, they must be characterized. However, currently such evaluation is beyond the scope of CISPR 16-1-1 baseline requirements.

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