White Paper

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Time-Domain Scan Increases Speed of CISPR 16 Compliant EMI Measurements

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Even when using various time-saving procedures, EMI measurement times are still very long – for measurement of radiated emissions typically several hours. However, they can be significantly reduced (by a factor of up to almost 2000) using time-domain methods based on the Fast Fourier transform (FFT) technique to identify the disturbance spectrum. Nevertheless, when using a time-domain EMI receiver for analyzing a combination of unknown narrowband and broadband EMI signals, care must be taken when the EMI test receiver is supposed to carry out the tests in accordance with CISPR 16. This white paper describes the fundamentals of a time-domain EMI measurement system based on the R&S®ESU EMI test receiver (Fig. 1), identifies major challenges using the time-domain technique, and shows how to solve them without missing disturbance signals or degrading accuracy.

Figure 1: R&S®ESU EMI test receiver

MINIMUM MEASUREMENT TIMES

Every measurement of an unknown disturbance quantity in the frequency domain requires the test receiver or analyzer to be tuned through a frequency range, ideally in the shortest possible time. An optimum solution would be a refresh rate that produces a stationary spectrum display, which means each frequency sweep would not be longer than about 20 ms.

However, realistically the measurement must account for the settling time of the resolution bandwidth and the signal timing of the disturbance signals. These signals can appear as continuous and pulsed narrowband signals, or as continuous and intermittent broadband disturbances. For the intermittent disturbances, a proper measurement time adjustment is essential.

Annex B of CISPR 16-2-1 to 16-2-3 contains a table of the minimum sweep times (fastest scan rates), from which the minimum sweep times in Table 1 for each of the CISPR bands can be calculated:

Frequency band		Peak detection	Quasi-peak detection
A	9 kHz to 150 kHz	100 ms/kHz: 14.10 s	20 s/kHz: 2820 s = 47 min
B	0.15 MHz to 30 MHz	100 ms/kHz: 2985 s	200 s/MHz: 5970 s = 1 h 39 min
C/D	30 MHz to 1000 MHz	1 ms/MHz: 0.97 s	20 s/MHz: 19,400 s = 5 h 23 min

Table 1: Minimum sweep times in accordance with CISPR 16 for peak and quasi-peak detection

These are minimum sweep times, and depending on the type of disturbance they may have to be increased, even with the quasi-peak detector. Since nearly all commercial product standards use quasi-peak detection for compliance with a specific limit, EMI tests usually apply time-saving procedures, such as reducing the number of quasi-peak measurements to the minimum needed.

Also, MIL-STD-461 specifies minimum measurement times for analog measurement receivers and minimum dwell times for synthesized measurement receivers (Table 2). For equipment whose operation produces potential emissions at only infrequent intervals, times for frequency scanning must be increased as necessary to capture any emissions.

Frequency Range	6dB Bandwidth	Dell Time	Minimum Measurement Time Analog Measurement Receiver
30Hz - 1 kHz	10Hz	0.15 sec	0.015 sec/Hz
1 kHz - 10kHz	100Hz	0.15 sec	0.15 sec/kHz
10 kHz - 150kHz	1kHz	0.15 sec	0.015 sec/kHz
150kHz - 30MHz	10kHz	0.15 sec	1.5 sec/MHz
30MHz - 1 GHz	100kHz	0.15 sec	0.15 sec/MHz
Above 1 GHz	1MHz	0.15 sec	15 sec/GHz

Table 2: Bandwidth and measurement time requirements acc. to MIL-STD-461F

CONVENTIONAL PREVIEW MEASUREMENTS

Preview measurements to commercial or automotive standards use a “max. peak” detector to first identify all frequencies at which emissions approach the limit values. A significant reduction of the total measurement time is then obtained using quasi-peak detection for the final measurements on just the detected frequencies. However, preview measurements of radiated emissions alone can take hours, since they must be performed between 30 MHz and at least 1 GHz. To reliably detect a pulse-like disturbance, the observation time per frequency point must be at least as large as the reciprocal of its pulse rate. In addition, disturbance measurements must always be made at the maximum level (worst case emission), usually requiring positioning of the antenna and test device.

As an example, scanning 30 MHz to 1 GHz with an IF bandwidth of 120 kHz and a step width of 40 kHz, to measure the entire spectrum without gaps and with sufficient measurement accuracy, produces 24,250 measurement points. If the dwell time is 10 ms per frequency point, total measurement time for a single preview scan is 4 min. However, this must be multiplied by a factor of 20 or more, to account for the time required for positioning the turntable and antenna height, and antenna polarization switching.

Using a spectrum analyzer instead of a test receiver does not overcome the problem, because the time of a single sweep must be long enough for at least one disturbance pulse event to fall into the instrument’s resolution bandwidth at each frequency. For repetitive sweeps and maximum hold for the trace display, observation time must continue until the spectrum becomes stable, and a continuous broadband signal will require many fast sweeps to show the envelope of the broadband spectrum.

Another inherent limitation of spectrum analyzers is their reduced number of sweep points compared with test receivers. Usually they do not provide sufficient frequency resolution for measurement of radiated emissions, and so make time-consuming partial sweeping necessary.

THE TIME-DOMAIN SYSTEM

Against this background, any technique that can reduce the time required for preview measurement is welcome as long as it does not degrade the accuracy and completeness of the final results – but how? Time-domain technique is the answer, and it has been seen as an effective method for many years. In conventional EMI measurement systems only the signal within the resolution bandwidth can be measured in a given measurement time, but FFT-based time-domain EMI measurement systems allow a much wider part of the observed spectrum to be simultaneously analyzed.

Here, the EMI test receiver samples successive sections of spectrum at the IF, not with a bandwidth of 120 kHz (as in the earlier example), but with a bandwidth of several megahertz. Each “subspectrum” is calculated simultaneously with the desired resolution using FFT.

Lined up next to each other, these subspectra yield the same picture as that provided by a classic receiver using the conventional stepped–frequency scan (Fig. 2).

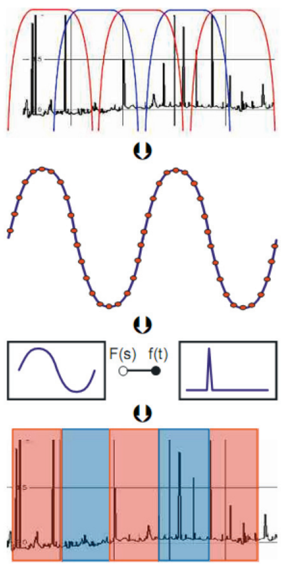

Figure 2: Principle of time-domain scan

Implications of FFT

Special measures must be taken when applying the time-domain technique, to ensure that all types of signals that can appear in a disturbance spectrum are detected correctly, and that even intermittent signals with a very low pulse repetition frequency are not missed. Otherwise the frequency spectra calculated by the FFT may be displayed incorrectly in terms of level and frequency.

Basically an infinite period of observation would be required for an exact calculation of the frequency spectrum of a time-domain signal. Another prerequisite is that the signal amplitude should be known at every point in time. It is obvious that these requirements cannot be fulfilled when implementing the Fourier transform with the aid of digital signal processing in practice.

Through analog-digital conversion the continuous input signal is converted into an amplitude- and time-discrete signal. Applying the fast Fourier transform limits observation of the signal to a finite interval. That means that only a certain number of the discrete signals in the time domain are used for calculation of the frequency spectra. This process is called windowing.

If the length of this window does not exactly correspond to an integer multiple of the periods of the frequencies contained in the input signal, there is a spreading or leakage of the spectral components away from the correct frequency, resulting in an undesirable modification of the total spectrum. The generation of spectral components not present in the original time-domain signal is known as "leakage effect," and is most severe when the simple rectangular window is used. The best way to reduce this effect is to choose a suitable window function that minimizes the spreading.

The spectrum calculated by the FFT is a discrete frequency spectrum consisting of individual frequency components at the so-called frequency bins. The frequency bins are determined by the FFT parameter. This means that the original spectral response can only be observed at the discrete frequency bins, and there may be higher amplitudes in the original signal spectrum at frequencies between two adjacent frequency bins. The amplitude error caused by this effect is known as the "picket fence effect" (Fig. 3). It also appears with the stepped-frequency scan, and with a conventional EMI test receiver it depends on the ratio of IF bandwidth and related step width.

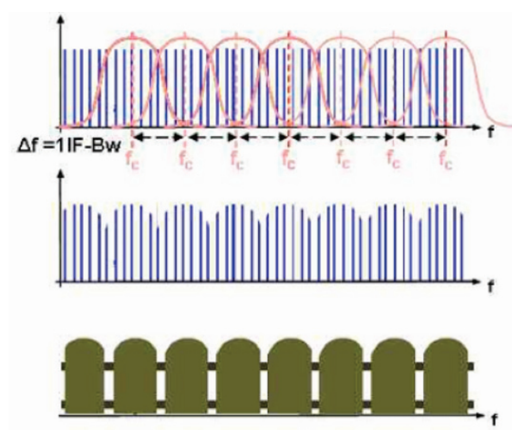

Figure 3: Description of picket fence effect

TECHNICAL IMPLEMENTATION

The measurement system used in this discussion (Fig. 4) is based on the R&S®ESU, a modern EMI test receiver that includes preselection.

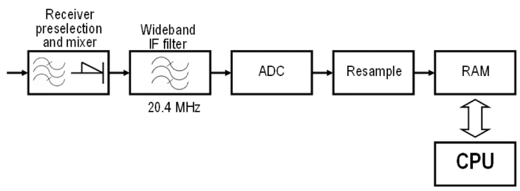

Figure 4

It combines both frequency and time-domain capabilities in a single instrument. A fast A/D converter with a sampling rate up to 81.6 MHz converts the IF signal (20.4 MHz) at up to 7 MHz at a time.

Unlike other FFT analyzers, the R&S®ESU EMI test receiver applies the FFT to the IF signal and not to the baseband signal. Thus, the performance of the receiver frontend determines the frequency range that can be used by the time-domain technique (20 Hz to 40 GHz for the R&S®ESU40).

The resolution of the A/D converter is 14 bit, which in combination with the preselector ensures greater dynamic range than FFT analyzers using 8-bit A/D converters. A resampler reduces the sampling rate to avoid unnecessary oversampling at narrower IF bandwidths, resulting in less processing time. To provide an overview of the emission spectrum over a wide frequency range, the R&S®ESU evaluates the total spectrum in consecutive steps. The maximum FFT span is 7 MHz. This is called time-domain scan (TD-SCAN), and it uses the stepped-frequency scan features of the measuring receiver along with data storage for later EMI analysis.

With 16 Mwords of RAM, the R&S®ESU ensures continuous data sampling with a dwell time of up to 100 s depending on the resolution bandwidth selected. The algorithm for the evaluation of the spectra is the Fast Fourier Transform (FFT) discussed above, which transforms a discrete time signal sequence into a discrete frequency spectral sequence.

The preview scan used to obtain a detailed overview of the emission spectrum (and which takes the greatest percentage of the EMI test time if the equipment must be manipulated) is then analyzed with the receiver functions of the R&S®ESU in the conventional way. In this way, the system combines the classical test receiver functions with new time-domain technique, ensuring a full CISPR 16 compliance of the measurement. As will be shown later, the time-domain scan of the R&S®ESU is designed so that the received frequency spectrum matches the spectrum detected with a conventional compliant EMI test receiver.

The IF bandwidth characteristics specified in the basic CISPR 16-1-1 standard as well as in MIL-STD-461 can best be implemented in the frequency domain with a Gaussian-type filter characteristic. Consequently, the R&S®ESU uses Gaussian-type windowing in the time domain when calculating the FFT, because the Fourier transform of a Gauss function in the time domain is again a Gauss function in the frequency domain. Thus, the IF bandwidth requirements in the frequency domain are ideally met. At the same time a gaussian-type windowing in the time domain minimizes the leakage effect to a negligible level.

The FFT algorithm includes the calculation of the different IF bandwidths in compliance with commercial and military standards, and a "virtual" step size. The step size, i.e. the spacing between two adjacent frequency bins, is exactly one quarter of the selected IF bandwidth, which is an optimum value in terms of the amount of sampled data and amplitude error due to the picket-fence effect. Compared to the conventional stepped scan, which usually uses a step width of one third of the selected IF bandwidth, the amplitude error is even lower.

MEASUREMENT UNCERTAINTY CONSIDERATIONS

The application of time-domain measurement techniques employing FFT on intermittent disturbance signals requires special consideration of certain system parameters, in order not to miss any disturbance signals or degrade measurement accuracy.

Windowing

When an impulse-type disturbance signal is captured by the Gaussian-type FFT window, the signal amplitude may be reduced at the window edges. To minimize this error and also to ensure that no impulse-type disturbance signal is missed, the R&S®ESU time-domain scan includes an overlap of the window function in the time domain.

The EMI test receiver offers two different settings for the step mode of the time-domain scan. In the "Auto CW" mode, the overlap in the time domain is about 20%, to allow narrowband signals to be analyzed in the shortest possible time. The "Auto Pulse" mode provides a degree of overlap of more than 90%. It is intended for broadband-impulsive and mixed signals, and ensures that even very short impulse signals at the edge of the Gaussian-type time-domain window are calculated without significant amplitude error. With this high degree of window overlap, only a small amount of ripple remains in the time domain that can cause a small measurement error. The worst-case amplitude error is 0.4 dB for the lowest point of the amplitude ripple referred to the maximum pulse amplitude. The resulting average error is 0.09 dB. This is a theoretical value for a minimal pulse width. The real error value depends on the pulse duration and is usually even lower.

When performing the time-domain scan with weighting detectors to CISPR (e.g. quasi-peak), for correct detection of single pulses the data rate for internal digital signal processing must be sufficiently with reference to the IF bandwidths used. An overlap of the FFT windows in the time domain of more than 90% – as provided by the R&S®ESU EMI test receiver – has been proven to be essential for a proper quasi-peak detection.

Analog Filtering

Analog filtering in the signal path has an influence on the frequency response of the time domain scan. In particular, non-ideal correction of the analog filters in the RF and IF signal path of the test receiver adds to overall measurement uncertainty.

The bandwidths of the preselection filters get smaller with lower RF frequency; e.g. 2 MHz bandwidth at 8 MHz RF frequency vs. 80 MHz bandwidth at 500 MHz RF frequency. To minimize the influence of the frequency response of the preselection filters, the R&S®ESU reduces the bandwidth for the time-domain scan accordingly, e.g. from 7 MHz down to 150 kHz depending on the scan range. Additionally, the receiver compensates the frequency response of the analog IF filters.

IF Selectivity

In frequency bands A to E, the basic CISPR16-1-1 standard specifies the bandwidths and tolerance masks for IF filters used in disturbance measurements to commercial standards. MIL-STD-461 defines 6-dB bandwidths in decimal steps that must be met with a 10% tolerance. Any deviations from the specified tolerances cause amplitude errors.

For verification of IF selectivity, a time-domain scan with max. peak detection was performed for sinusoidal test signals. A single measurement is insufficient for correct verification, because the spacing of adjacent frequency bins is set to one-quarter IF bandwidth (Fig. 5).

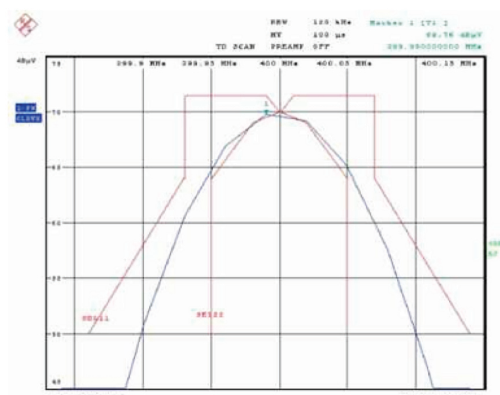

Figure 5: Display of IF selectivity using time-domain scan

The tests were repeatedly performed, increasing the start frequency of the time-domain scan step-by-step in small increments. All received frequency points were then merged into a single trace using MatLab (Fig. 6).

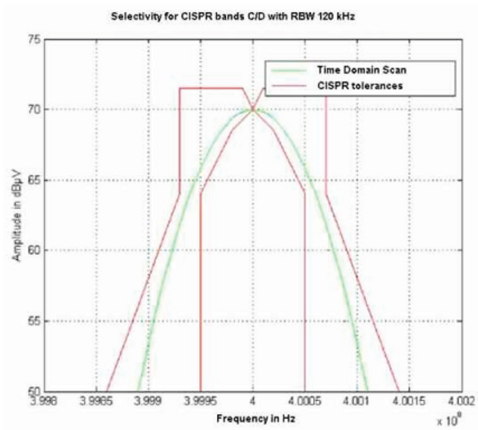

Figure 6: Measured IF selectivity for CISPR bands C/D (120 kHz)

Dynamic Range

At lower levels the inherent noise of the receiver limits the dynamic range, and is specified as displayed average noise level (DANL). At higher levels the nonlinearity of mixers and amplifiers limit the measurement range, and it is characterized by 1-dB compression point or third-order intercept point. Sensitivity figures of 1 dB and 3 dB are analogous to these. That is the point at which signal-to-noise ratio is high enough that measurement error caused by noise is not more than 1 or 3 dB. Dynamic range usually specifies the usable level range between 1-dB sensitivity and 1-dB compression point. The dynamic range of the R&S®ESU for the CISPR bandwidths 200 Hz, 9 kHz and 120 kHz is shown in Figure 7.

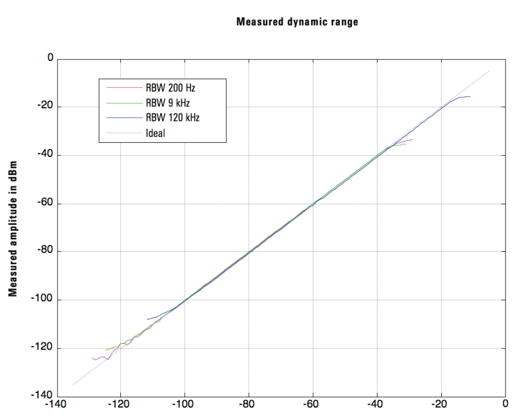

Figure 7: Measurement of dynamic range for time-domain scan for CISPR bandwidths 200 Hz, 9 kHz and 120 kHz

TIME-DOMAIN SCAN VS STEPPED-FREQUENCY SCAN

The best way to verify the accuracy of the time-domain scan is to compare it with the conventional stepped-frequency scan of the R&S®ESU. The stepped scan is a proven method that has low measurement uncertainty. The R&S®ESU provides both scan methods using the same hardware and firmware.

Frequency Response

An overview measurement using a pulse generator for CISPR bands C and D compares the frequency responses of the stepped-frequency scan and the time-domain scan (Fig. 8).

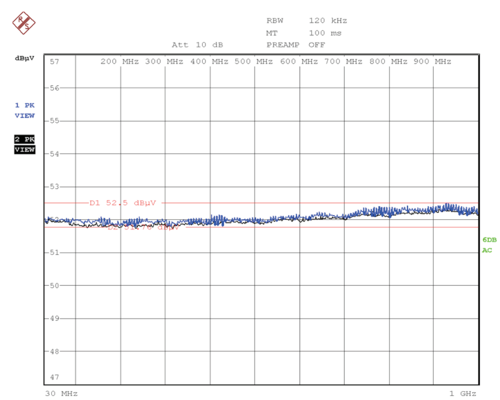

Figure 8: Overall frequency response of R&S®ESU EMI test receiver (max. peak detector; lin. scaling; 30 MHz to 1 GHz) for time-domain scan (trace 1: blue) and stepped frequency scan (trace 2: black). Frequency response of the CISPR pulse generator is included

Although an exact evaluation of the receiver measurement uncertainty is not possible with this measurement, and errors caused by the characteristic of the cable and the pulse generator itself (e.g. frequency response, matching, and long-term stability) are not considered, it clearly shows that the differences between the two scan modes are negligible.

(a)

(b)

(c)

(d)

(e)

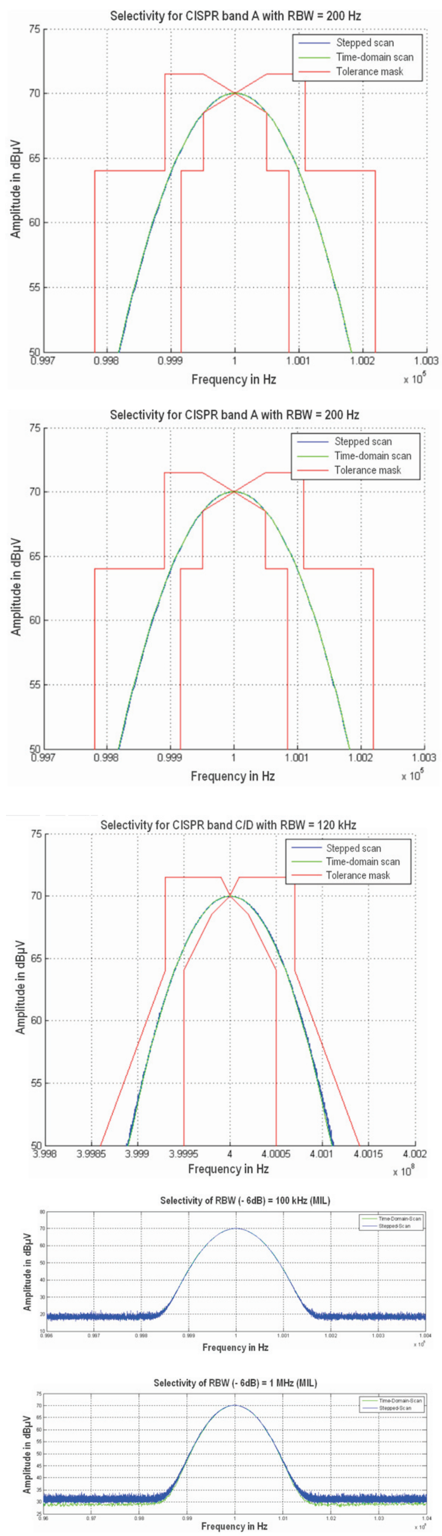

Figure 9a to 9e: Comparison of resolution bandwidths with stepped scan (blue trace) and time-domain scan (green trace) for commercial standards (CISPR) and MIL standards

IF Selectivity and Dynamic Range

Figures 9a to 9e show the measured frequency response of the CISPR bandwidths of 200 Hz, 9 kHz and 120 kHz and the MIL-STD IF bandwidths 100 kHz and 1 MHz for the time-domain scan and the stepped-frequency scan. Both traces match very well and are compliant with the requirements of the mentioned standards.

Table 3 shows that the time-domain scan offers a higher dynamic range than the stepped-frequency scan, almost without regard to the IF bandwidth employed.

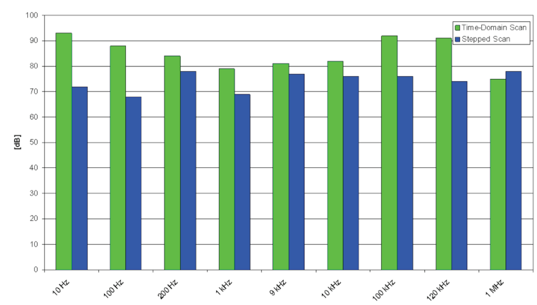

Table 3: Comparison of dynamic ranges of stepped frequency scan vs time-domain scan for EMI bandwidths (-6 dB) to commercial and military standards

Comparison of Measurement Times

Evaluation of measurement times (Table 4) of R&S®ESU was based on the frequency bands for EMI measurement to commercial and military standards, including measurements to CISPR 25 (EN 55025) for automotive products. CISPR 16-2-1 requires the measurements to be long enough so that at least one signal from the disturbance source is detected. For the comparison, the dwell time per frequency step for the commercial standards was set to 10 ms or 20 ms, to correctly detect impulsive disturbances down to a pulse repetition rate of 100 Hz or 50 Hz respectively. For measurements to MIL-STD-461 the measurement time was set according to Table 2. The figures in Table 4 show that the time-domain technique reduces the time required to perform a frequency scan by a large amount, even when using quasi-peak weighting and a dwell time of 1 s, with the exact reduction dependent on the IF bandwidth.

Standard	Frequency band	IF bandwidth (RBW)	Detector	Measurement time per frequency step	Step width		Total scan time in s			Measurement time reduction of time-domain scan by factor	
					Stepped Scan	TD Scan	Stepped Scan	TD Scan Auto CW	TD Scan Auto Pulse	Auto CW	Auto Pulse
CISPR	9 kHz to 150 kHz	200 Hz	Max. peak	20 ms	80 Hz	50 Hz	74	0.038	0.04	1947	1850
CISPR	150 kHz to 30 MHz	9 kHz	Max. peak	20 ms	4 kHz	2.25 kHz	155	3.0	3.1	51.6	50
CISPR	30 MHz to 1 GHz	120 kHz	Max. peak	10 ms	40 kHz	30 kHz	247	6.0	12.9	41	19
CISPR	1 GHz to 18 GHz	1 MHz	Max. peak	10 ms	400 kHz	250 kHz	428	101	250	4.2	1.7
EN 55025	30 MHz to 1 GHz	9 kHz	Max. peak	10 ms	4 kHz	2.25 kHz	2573	5.9	20	436	128
MIL-STD-461	30 Hz to 1 kHz	10 Hz	Max. peak	150 ms	4 Hz	2.25 Hz	142	0.34	0.34	418	418
MIL-STD-461	1 kHz to 10 kHz	100 Hz	Max. peak	15 ms	40 Hz	25 Hz	14	0.038	0.039	368	359
MIL-STD-461	10 kHz to 150 kHz	1 kHz	Max. peak	15 ms	400 Hz	250 Hz	6.8	0.024	0.027	283	252
MIL-STD-461	150 kHz to 30 MHz	10 kHz	Max. peak	15 ms	4 kHz	2.5 kHz	117	2.3	2.4	51	49
MIL-STD-461	30 MHz to 1 GHz	100 kHz	Max. peak	15 ms	40 kHz	25 kHz	367	10.5	27	35	13.6
MIL-STD-461	1 GHz to 18 GHz	1 MHz	Max. peak	15 ms	400 kHz	250 kHz	641	147	375	4.4	1.7
CISPR	150 kHz to 30 MHz	9 kHz	Quasi-peak	1 s	4 kHz	2.25 kHz	16 044	–	399	–	40

Table 4: Typical measurement times of stepped frequency scan vs. time-domain scan for commercial and military EMI standards

CONCLUSION

The Rohde & Schwarz R&S®ESU EMI test receiver shows that with FFT-based time-domain scan for preview measurements, EMI testing of an electrical device can be performed not only in accordance with CISPR 16, but with significantly reduced overall test time. Measurement time for time-domain scans is up to almost 2000 times faster compared to stepped-frequency scans, depending on the selected IF bandwidth. Since the measurement uncertainty of the time-domain scan is equivalent to the uncertainty of the stepped-frequency scan, and product development times and cost constraints place increasing burdens on test and design engineers, there is much to be said for combining both the frequency and time-domain techniques of the R&S®ESU for the complete design and certification process.

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