System Strategies for Time-Domain Emission Measurements above 1 GHz

Christian Hoffmann¹ · Hassan Hani Slim¹ · Peter Russer²

Abstract

The application of time-domain methods in emission measurement instruments allows for a reduction in scan time by several orders of magnitude and for new evaluation methods to be realized such as the real-time spectrogram to characterize transient emissions. In this paper two novel systems for time-domain EMI measurements above 1 GHz are presented. The first system combines ultra-fast analog-to-digital-conversion and real-time digital signal processing on a field-programmable-gate-array (FPGA) with ultra-broadband multi-stage down-conversion to enable measurements in the range from 10 Hz to 26 GHz with high sensitivity and full-compliance with the requirements of CISPR 16-1-1. The required IF bandwidths were added to allow for measurements according to MIL-461F and DO-160F. The second system realizes a system of time-interleaved analog-to-digital converters (ADCs) and has an upper bandwidth limit of 4 GHz. With the implementation of an automatic mismatch calibration, the system fulfills CISPR 16-1-1 dynamic range requirements. Measurements of the radiated emissions of electronic consumer devices and household appliances like the non-stationary emissions of a microwave oven are presented. A measurement of a personal computer's conducted emissions on a power supply line according to DO-160F is given.

Key words : Electromagnetic Compatibility, Electromagnetic Interference, Time-Domain Measurements.

1. Introduction

Since the advent of electronic systems and radio transmission at the beginning of the 20th century, electromagnetic compatibility (EMC) and the measurement of electromagnetic emissions (EMI) have gained ever increasing importance. In order to protect those systems and services, organizations like the Comité International Spécial des Perturbations Radioélectriques (CISPR) or the Federal Communications Commission (FCC) propose standards that define limit lines for conducted and radiated electromagnetic emissions and determine the requirements for the needed measurement systems. As an example, among the over 30 standards published by CISPR, CISPR 11 defines limit lines and measurement methods for testing industrial, scientific and medical (ISM) equipment, while CISPR 14 proposes EMC-requirements for household appliances and electric tools. The requirements for radio disturbance and immunity measuring apparatus and methods are defined in CISPR 16.

Traditionally, heterodyne receivers have been the predominant instruments to measure EMI [1]. With low-noise preamplifiers and complex preselection filter assemblies, they offer the sensitivity and dynamic range that are needed to measure low-level and broadband transient

emission signals. The major drawback of those systems are the long scan times, as sequential measurements have to be done at all frequencies of interest. This can easily yield scan times on the order of hours or even days.

By the application of time-domain methods, scan times can be significantly reduced in comparison with traditional heterodyne receiver technology. Such systems have been realized using sampling oscilloscopes [2], [3]. A time-domain EMI measurement system that enables full-compliance measurements according to CISPR 16-1-1 was presented in [4]. With an implementation of the digital signal processing on field-programmable-gate-arrays (FPGAs), the system is capable of calculating a real-time spectrogram with a real-time bandwidth of 162.5 MHz and exhibits a bandwidth from 9 kHz to 1 GHz. A reduction of scan time by factors of up to around 4000 could be achieved in comparison to heterodyne receivers depending on the used IF-bandwidth.

Modern electronic consumer devices, communication systems and even household appliances operate in frequency bands well above 1 GHz. To protect those systems and services, EMC and EMI standards have to be met in the frequency range above 1 GHz. Because of the limited sampling frequencies of current analog-to-

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¹GAUSS INSTRUMENTS GmbH, Munich, Germany.

²Institute for Nanoelectronics, Technische Universität München, Munich, Germany.

Corresponding Author: Christian Hoffmann (e-mail : choffmann@tdemi.com)

digital converter (ADC) technology, system strategies have to be found in order to allow for time-domain measurements above the Nyquist-frequency of contemporary ADCs.

In [5] a time-domain system with a bandwidth of 9 kHz to 18 GHz is described. It combines ultra-fast analog-to-digital-conversion and real-time digital signal processing on field-programmable-gate-arrays with ultra-broadband multi-stage down-conversion. The presented time-domain EMI measurement system in this paper is based on this system and exhibits an increased bandwidth of 10 Hz to 26 GHz while adding the IF-filters required by the military and aviation EMC standards MIL-STD-461F [6] and DO-160F [7]. A measurement of a personal computer's power supply according to DO-160F is presented. With integrated preamplifiers and wideband preselection filters, the system allows for full-compliance measurements with high sensitivity according to CISPR 16-1-1 [8].

The second system presented in this paper employs a time-interleaved ADC architecture to sample signals above the Nyquist frequency of the used ADCs [9]. By the use of 3 parallel ADCs with phase-shifted sampling frequencies at around 2.7 GHz, signals with frequencies up to 4 GHz can be sampled without aliasing effects. With the implementation of an automatic calibration routine for the gain, phase and offset mismatches between the ADCs, the system fulfills the CISPR 16-1-1 requirements regarding the spurious-free dynamic range.

II. Time-Domain Measurement System

The system concept of the time-domain EMI measurement system based on the system described in [5] can be seen in the block diagram in Fig. 1. The EMI-signal is received by a broadband antenna for radiated emissions or a line impedance stabilization network (LISN) for conducted emissions. For measurements from 10 Hz to 1.1 GHz, the input signal is filtered by a low-pass filter to prevent spectral overlap due to a violation of Shannon's theorem.

The filtered signal is sampled by the floating-point analog-to-digital converter [4] with a sampling rate of

Fig. 1. Time-domain EMI measurement system.

around 2.6 GS/s. An FPGA computes the signal spectrum via the Fast-Fourier-Transform (FFT) and weights the spectrum by digital detectors. The amplitude spectrum is displayed.

In order to decrease the computational requirements for the signal processor and to enable real-time processing of the signal, the frequency range from DC to 1.3 GHz is subdivided into eight subbands with a bandwidth of 162.5 MHz each. For the in-phase and quadrature channel, a polyphase decimation filter reduces the sampling frequency in order to fulfill the Nyquist criterion. Every subband is digitally down-converted to the baseband and the subbands are processed sequentially. The output sampling frequency is 325 MHz, while the bandwidth is 162.5 MHz.

For non-stationary signals, a spectrogram is calculated via the short-time-fast-Fourier-transform (STFFT). A Gaussian window function ω_n is applied, corresponding to the IF-filter of a conventional measurement receiver. During the selected dwell-time, the window is shifted in time with a discrete time-coordinate τ . For every value of τ , the momentary spectrum is calculated via FFT. The calculated spectra over time describe a spectrogram. It depends on the discrete time coordinate τ of the window and the discrete frequency k . The short-term spectrum $X[\tau, k]$ is calculated by [10].

$$X[\tau, k] = \sum_{n=0}^{N-1} x[n + \tau] \omega[n] e^{-\frac{j2\pi kn}{N}}. \quad (1)$$

III. Multi-Stage Broadband Down-Converter

To enable measurements above 1 GHz, a multi-stage broadband down-converter is sequentially down-converting the bands above 1.1 GHz into the range below 1.1 GHz, so they can be sampled by the ADCs. This is achieved by the 1.1~6 GHz down-converter and the 6~26 GHz down-converter respectively.

As shown in Fig. 2, in the 1.1~6 GHz down-converter, a single fixed preselection bandpass filter suppresses the image frequency band and acts as a pre-selection filter, increasing the dynamic range for broadband, noise-like and narrowband out-of-band input sig-

Fig. 2. 1.1~6 GHz down-converter.

Fig. 3. 6~26 GHz down-converter.

nals. An integrated low-noise amplifier (LNA) increases sensitivity by lowering the system noise floor. The band from 1.1~6 GHz is then sequentially up-converted to a first high intermediate frequency in 16 subbands of around 325 MHz bandwidth and then finally down-converted by a second mixer.

The block diagram of the 6~26 GHz down-converter is shown in Fig. 3. The input band is subdivided into 5 ultra-wide subbands with bandwidths between 3 and 5 GHz. The preselection bands are switched via low-loss single-pole-quintuple-throw (SP5T) PIN-diode switches. An integrated, broadband LNA amplifies the input signal and increases the system sensitivity. The amplified signal is then down-converted by a broadband mixer with low conversion loss and a low phase-noise local oscillator signal generated by a PLL-synthesizer.

The system noise figure strongly depends on the insertion loss of the passive components before the LNA, as the system noise figure F is defined by [11].

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \dots + \frac{F_N - 1}{\prod_{k=1}^{N-1} G_k}, \quad (2)$$

where G_i is the available power gain of stage i and F_i is the noise figure of stage i . This has been a major design rule in the design of the hardware components. The implemented SP5T PIN-diode switches e.g. exhibit a low insertion loss of below 3.6 dB for all paths. The isolation exceeds 30 dB over the complete frequency range from 6~26 GHz. The measured scattering parameters are shown in Fig. 4.

Table 1. Measurement of the noise floor.

Frequency / MHz	Power spectral density / dBm/Hz
6000	-160.4
10000	-158.6
14000	-157.5
18000	-153.8
22000	-150.1
26000	-150.1

Fig. 4. Measured insertion loss (straight line) and isolation (broken line).

To characterize the system noise floor, the noise voltages V_N are measured at distinct frequencies using the average detector, a 120 kHz IF filter bandwidth and a matched input and the respective noise powers P_N were calculated. The resulting powers are normalized to an IF bandwidth of 1 Hz and the resulting power spectral density values are given in Table 1. The system exhibits a low noise floor power spectral density of below -150 dBm/Hz in this frequency range.

CISPR 16-1-1 requires an IF dynamic range of over 40 dB for measurements above 1 GHz. For the detector calibration in CISPR Band E above 1 GHz, pulse-modulated sinusoidal signals are used. The difference in level between the peak and average detector measurements of

Fig. 5. Measured pulse-modulated signal.

a pulse-modulated signal is defined as the IF dynamic range. A pulse generator fed a pulse-modulated sinusoidal signal with a frequency of 25 GHz to the system input. The signal pulse width was set to $1 \mu\text{s}$ and the pulse period to 40 ms. The measured spectra are shown in Fig. 5.

The measurements indicate an IF dynamic range of around 52 dB for an IF bandwidth of 120 kHz. As CISPR 16-1-1 requires the use of a 1 MHz IF-bandwidth for measurements above 1 GHz, the IF dynamic range for a 1 MHz IF-filter should be above 61 dB. The system IF dynamic range exceeds the CISPR 16-1-1 requirements by over 20 dB.

IV. Time-Interleaved System

The second system presented in this paper increases the bandwidth of the initial time-domain system to 4 GHz by the use of a time-interleaved sampler. Time-interleaved (TI) sampling was introduced by Black and Hodges [12] as a solution for increasing the sampling rate of a system. By increasing the sampling rate F_s the receiver bandwidth BW is also proportionally increased as stated by the Nyquist relation.

$$BW \leq \frac{F_s}{2}. \quad (3)$$

The principle idea of the TI-sampling concept is to use several ADCs in parallel to sample the same input signal. To ensure that the input signal is uniformly sampled the phase of the ADC driving clocks should be equally shifted. The architecture of the system is plotted in Fig. 6. A major challenge in the design of the presented system arises from ADC channel mismatch effects. Different categories of mismatches can be specified, but the main effects that have been encountered and studied are the offset, gain, and phase mismatch. Extensive work has been done to characterize the effect of the mismatches [13]. It was found that the three mis-

Fig. 6. Time-interleaved ADC system.

Fig. 7. Measurement of spurious-free dynamic range.

matches add artefacts to the spectrum. These spurious spectral components will decrease the spurious-free dynamic range (SFDR) of the system. The phase mismatch generates a spurious component at $k \cdot F_s/M$, while phase and gain mismatches both generate spurious components at $F_{in} + k \cdot F_s/M$, where M is the number of samplers, F_{in} is the frequency of the harmonic input signal and $k=1, 2, \dots, M$.

A system with 3 ADCs was implemented driven by a single clock signal with the frequency $F_s=2.7$ GHz. Using the time-interleaved architecture the input signal is effectively sampled at a rate of $3 \cdot F_s=8.1$ GS/s which yields a system bandwidth of more than 4 GHz. Each ADC has programmable serial registers to control the gain, offset and phase of the sampling clock. To overcome the problem of the mismatches between different ADCs, automatic calibration routines were implemented to find the optimum register settings [9]. Fig. 7 shows the measured spectrum of a harmonic test signal with a frequency of 2.4 GHz. The measurement shows, that a SFDR of 45 dB is achieved. This fulfills CISPR 16-1-1 requirements for EMI measurement systems above 1 GHz.

V. Emission Measurements

Measurements of electronic consumer devices and electric household appliances were done in a fully-anechoic room using the presented systems. The radiated emissions of a microwave oven were received with a broadband horn antenna in a distance of 3 m. The time-domain EMI measurement system described in Sec. II and III was used and the corresponding antenna factor and transducer factors were applied to give the electric

Fig. 8. Measured spectrum of a microwave oven.

field strength. The measured spectrum weighted by peak and average detectors is shown in Fig. 8. The spectrum shows the magnetron's fundamental at around 2.45 GHz and several higher harmonics up to 18 GHz. The scan using an IF-filter bandwidth of 9 kHz and a frequency resolution of 50 kHz took around 120 s.

The microwave oven's radiated emissions are non-stationary. Therefore the time-domain measurement system's real-time spectrogram is very well suited to show the time-behaviour of the emissions. The bandwidth up to 26 GHz allows to measure the 4th harmonic of the magnetron's radiated emissions, which is located at around 9.83 GHz. The spectrogram is shown in Fig. 9.

The E-field strength reaches levels of above 80 dB μ V

Fig. 9. Spectrogram of the 4th harmonic of a microwave oven.

Fig. 10. Spectrogram of Wi-Fi communication between two mobile phones.

/m while the magnetron is periodically turned on and off because the microwave was set to a medium power setting. The time-domain system's real-time spectrogram reveals that the free-running oscillator's output frequency drifts by nearly 30 MHz.

Fig. 10 gives the measured spectrogram of the Wi-Fi communication between two contemporary mobile phones. The two phones formed a wireless network and files were transmitted via the file-transfer-protocol (FTP). The real-time spectrogram allows for the examination of the time-behaviour. While the Wi-Fi network was idle for the most part, the transmission of a file, lasting from 2 s to 6 s, can be observed.

The EMC standard DO-160F defines limit lines for the conducted interference signals on supply lines. The presented time-domain EMI measurements system allows to conduct those measurements due to the implementation of the required IF filter bandwidths. The supply lines of a personal computer's power supply were measured using a current clamp with a bandwidth from 10 kHz to 1 GHz. The measurements are shown in Fig. 11. For the measurements, the peak detector was chosen with a dwell time of 100 ms. The scan time for the DO-160F scan from 150 kHz to 30 MHz was around 4 s, while this measurement would take over 1.5 hours with a traditional heterodyne receiver.

The conducted interference currents in the frequency range from 150 kHz to 30 MHz clearly exceed the limit lines defined in DO-160F. The measured power supply would not be suitable for use with sensitive equipment defined in DO-160F.

An emission measurement of a household mixer was

Fig. 11. Measured spectrum of the conducted interference currents on a PC power supply line.

Fig. 12. Spectrogram of a household mixer.

carried out in a fully-anechoic room using the TI-ADC system described in Sec. IV. A 1 MHz CISPR-defined IF-filter was used. The 3-D plot of the spectrogram of the measured emissions is shown in Fig. 12. The time-interleaved system can measure broadband emissions beyond the bandwidth of a single ADC. A narrowband spurious signal can be observed at 2.7 GHz due to remaining offset mismatches between the clock signals. This behaviour will be addressed in future work.

VI. Conclusion

Two system strategies for time-domain emission measurements above 1 GHz and their implementation have been presented. The down-converter system offers a bandwidth from 10 Hz to 26 GHz and has implemen-

tations of all required IF-bandwidths and detectors for measurements according to CISPR 16, MIL-STD-461F and DO-160E. The system exhibits high sensitivity and a dynamic range in excess of 60 dB and is well suited for the measurement of low-level signals near the noise floor and high dynamic signals like radar pulses or broadband transient emissions. The real-time spectrogram allows for the characterization of non-stationary EMI. The time-interleaved system facilitates baseband system operation up to 4 GHz without the need for a complicated RF down-converter assembly. An automatic digital calibration routine minimizes gain, phase and offset mismatches between the ADCs clock signals. Even though the time interleaved system fulfills the dynamic range requirements of CISPR 16-1-1 with an SFDR of 45 dB, it has a lower dynamic range than the down-converter system. For validation of the system operation measurements of electronic consumer devices and household appliances were presented.

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Christian Hoffmann

was born in Ulm/Donau, Germany. He received the Dipl.-Ing. degree in Electrical Engineering from the Technische Universität München (TUM), Munich, Germany, in 2008. From 2008 to 2011 he was working at the Institute for High-Frequency Engineering at TUM, Germany as a research assistant. In 2011 he received a Best Student Paper Award at the 2011 Asia-Pacific EMC Symposium. He is currently employed as an RF Design Engineer at GAUSS INSTRUMENTS GmbH, Munich, Germany, where he is working towards the Dr.-Ing. degree. Christian Hoffmann is a member of the IEEE and VDE. His research interests include measurement techniques in the microwave and millimeter wave regime, microwave and millimeter wave passive and active circuits and digital signal processing. His research is focused on the investigation of electromagnetic compatibility in time-domain above 1 GHz.

Hassan Hani Slim

received the Bachelor of Engineering (B.E.) degree in Computer and Communication Engineering in 2005 from Business and Computer University College (BCU) in Beirut, Lebanon. He obtained his Masters of Science (M.Sc.) degree in Microwave Engineering in 2007 from the Technische Universität München (TUM), Germany. Since 2008 he is working towards his Dr.-Ing. degree at the Institute for High-Frequency Engineering at TUM, Germany under the supervision of Prof. Dr. Peter Russer. His current research is focused on investigations of electromagnetic compatibility (EMC) techniques above 1 GHz, in addition to signal processing techniques and automation routines applied in EMC. Since June 2011 he is working with GAUSS INSTRUMENTS GmbH as a software design engineer. He is a member of IEEE.

Peter Russer

received the Dipl.-Ing. (M.S.E.E.) degree in 1967 and the Dr. techn. (Ph.D.E.E.) degree in 1971, respectively, both from the Vienna University of Technology, Austria. In 1971 he joined the Research Institute of AEG-Telefunken in Ulm, Germany, where he worked on fiber optic communication, broadband solid-state electronic circuits, statistical noise analysis of microwave circuits, laser modulation and fiber optic gyroscopes. With his research group he realized in 1978 the first optical fiber transmission link for 1 Gbit/s worldwide. From 1981 to 2008 Peter Russer has been Professor and head of the Institute for High Frequency Engineering at the Technische Universität München (TUM), Germany. From October 1992 to March 1995 he also has been Director of the Ferdinand-Braun-Institut für Höchstfrequenztechnik, Berlin. From 1997 to 1999 he has been Dean of the Department of Electrical Engineering and Information Technology of the Technische Universität München (TUM). In 1990 Peter Russer has been Visiting Professor at the University of Ottawa, in 1993 he has been Visiting Professor at the University of Victoria and from August to October 2009 he has been Visiting Scientist at the Institut Supérieur de l'Aéronautique et de l'Espace (ISAE) in Toulouse.

The current research interests of Peter Russer include electromagnetic fields, numerical electro-magnetics, metamaterials, integrated microwave and millimeter wave circuits, statistical noise analysis of microwave circuits, time-domain measurement methods in electromagnetic compatibility, methods for computer-aided design of microwave circuits and antennas, quantum nanoelectronics and quantum computing. Peter Russer has published five books and more than 700 scientific papers in refereed journals and conference proceedings. In 1979 Peter Russer received the best paper award from the NTG (German Society for Information Technology). In 1994 he was elected Fellow of the IEEE. In 2006 Peter Russer was elected member of acatech, the German Academy of Science and Engineering. In 2006 he received the Distinguished Educator Award of the IEEE MTT Society and in 2009 the Distinguished Service Award from the European Microwave Association (EuMA). In 2007 Peter Russer received an honorary Doctor degree from the Moscow University of Aerospace Technologies (MAI). In 2010 Peter Russer has been awarded the Golden Ring of Distinction, the highest accolade of the VDE-the German Association for Electrical, Electronic and Information Technologies.