Testing High-Speed Digital Interfaces with Automated Test Equipment

Jose Moreira and Hubert Werkmann
Verigy
jose.moreira@verigy.com hubert.werkmann@verigy.com

Abstract

For high-speed digital applications the DUT loadboard performance is critical. Even using state of the art materials and design techniques it is not possible to completely eliminate the DUT loadboard effects. One approach to compensate for the DUT loadboard loss is to use de-embedding.

This paper provides two sample sections which are reprinted from the up-coming book "Testing High-Speed Digital Interfaces with Automated Test Equipment" by Jose Moreira and Hubert Werkmann with permission from Artech House, Inc. The book will be published in July/August 2010.

http://www.artechhouse.com/Detail.aspx?strBookId=1996

Key Words – High-Speed Digital Basics, High-Speed Interfaces Standards, ATE Instrumentation for Digital Applications, Tests and Measurements, Characterization, Production Testing, Support Instrumentation, Test Fixture Design, Advanced ATE Topics

1. Signal Path Loss Compensation: De-Embedding

Time domain de-embedding or time domain deconvolution [1] corresponds to a post-measurement step where measurement data is processed to remove the effects of the test fixture loss or the bandwidth limitations of the pin electronics receiver (assuming that those effects are known and have been measured or simulated). The idea is to assume the test fixture and the pin electronics to be a linear time invariant (LTI) system (see for example [2] for a proper treatment of LTI systems). One simple model for the loss a signal suffers when traveling from the DUT I/O package pad to the measurement instrument is shown in Figure 1.1 where the DUT output goes through a low pass filter representing the test fixture (and the DUT socket) and then another one representing the bandwidth limitations of the ATE pin electronics.

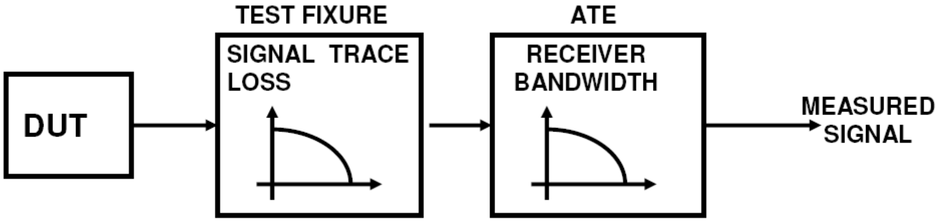

Figure 1.1: Modeling the measurement of the output of a DUT through a test fixture and a bandwidth limited ATE pin electronics.

One straightforward approach to measure the real output waveform of the DUT would be to compensate for the signal degradation by "inverting" the effect of the "low-pass filters" on the measurement setup by an appropriately designed "high-pass" filter as shown in Figure 1.2. This filter would be applied by means of a software algorithm on the measured data. In order to obtain this de-embedding filter we need to formalize the problem by using a black box approach as shown in Figure 1.3.

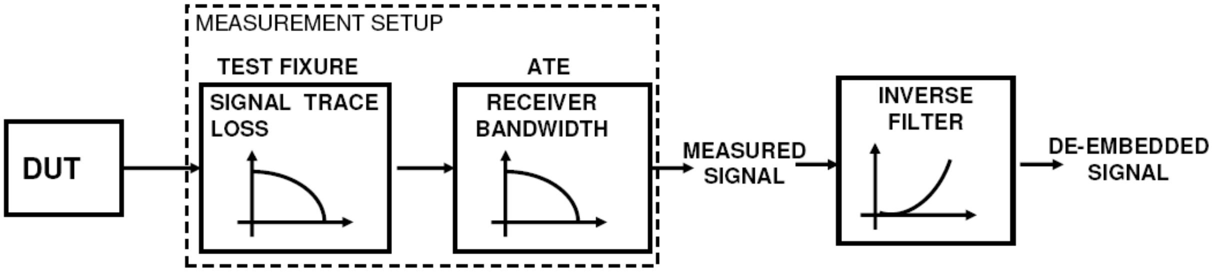

Figure 1.2: Obtaining the original DUT output through an inverse filter applied on the measured data.

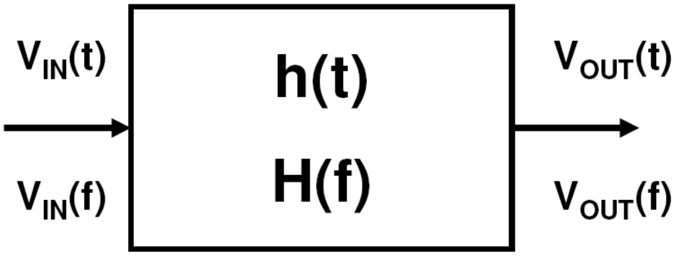

Figure 1.3: Black box model of the de-embedding problem: *h(t)* is the time domain impulse response of the measurement system and *H(f)* is the frequency domain transfer function.

The output function (V_{OUT}) can be computed by the following equations in the time and frequency domain where * represents the convolution operator:

$$V_{OUT}(t) = h(t) * V_{IN}(t) \tag{1.1}$$

$$V_{OUT}(f) = H(f) \cdot V_{IN}(f) \tag{1.2}$$

The de-embedding problem consists in computing the original input waveform function V_{IN} by using the measured output waveform function V_{OUT} and the system transfer function H. In the frequency domain this is represented by the following equation:

$$V_{IN}(f) = \frac{V_{OUT}(f)}{H(f)} \tag{1.3}$$

The frequency domain is used since a convolution in the time domain is simply a multiplication on the frequency domain. The time domain waveform can then be obtained from $V_{IN}(f)$ through an inverse Fourier transform.

One open question is how to obtain the system transfer function $H(f)$ since it is typically unknown. If the test fixture loss is the only item to be de-embedded, then one approach is to obtain the insertion loss of the test fixture. The measured insertion loss (S21) will then correspond to $H(f)$.

To include the ATE pin electronics receiver in the model, it is typically necessary to obtain the $H(f)$ model first in the time domain since this is how a high-speed digital ATE receiver works. One way to measure the transfer function $H(f)$ is to use a test signal like a step function and measure the resulting step function with the ATE receiver (e.g. a step signal that is injected at the DUT socket). The $H(f)$ function can then be computed by dividing the Fourier transform of both step functions:

$$H(f) = \frac{V_{OUT}(f)}{V_{IN}(f)} = \frac{FFT\{V_{OUT}(t)\}}{FFT\{V_{IN}(t)\}} \tag{1.4}$$

The previous discussion shows the basic theory behind time domain de-embedding or deconvolution, but it is important to realize that there are several technical details regarding the Fourier transform of step functions, causality and stability of the numerical algorithms that are outside the scope of this book. Reference [3] provides an excellent discussion of time domain deconvolution.

Figure 1.4 shows one example of a stimulus step response (generated with a bench pattern generator and measured with a high-bandwidth equivalent time oscilloscope) and the step response measured by the ATE pin electronics which is degraded by the test fixture loss and the pin electronics bandwidth limitations. Both measured step responses are then used to obtain the frequency response of the measurement setup *H(f)* through the Fourier transform of the step waveforms as shown in Figure 1.5.

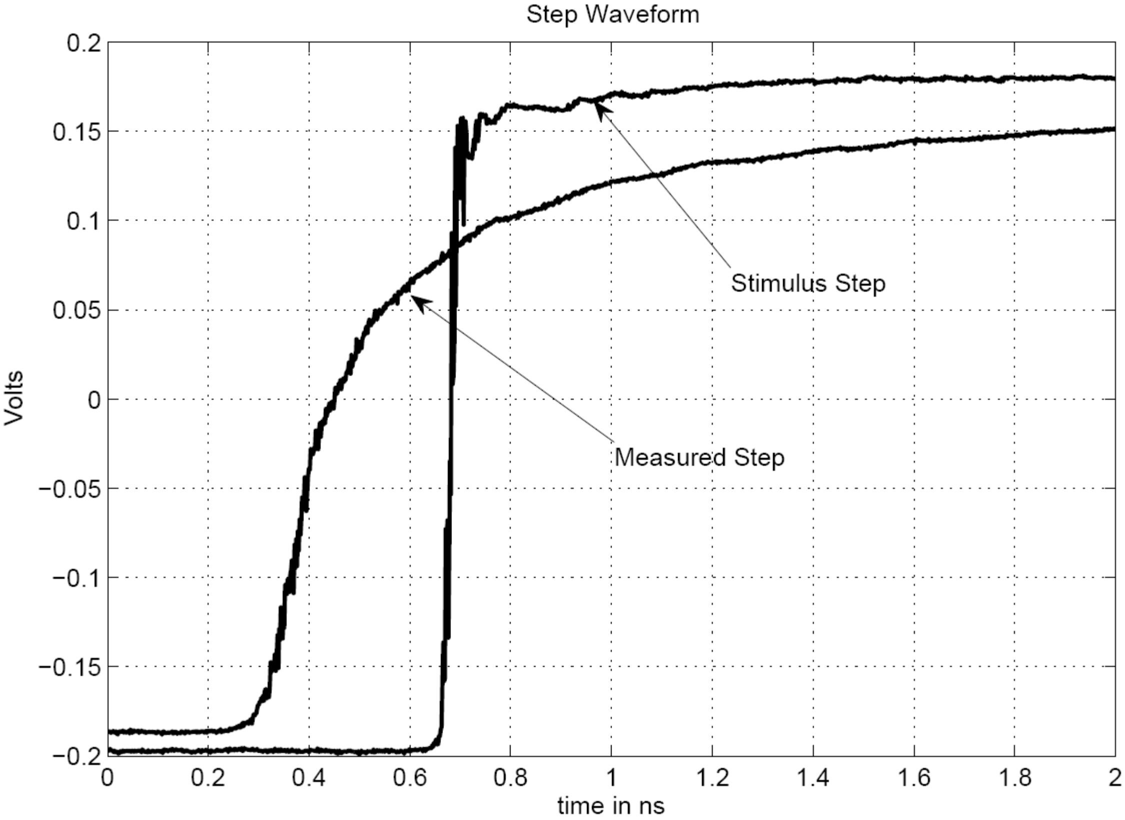

Figure 1.4: Measured step stimulus waveform and the step waveform measured by the ATE pin electronics after a lossy test fixture.

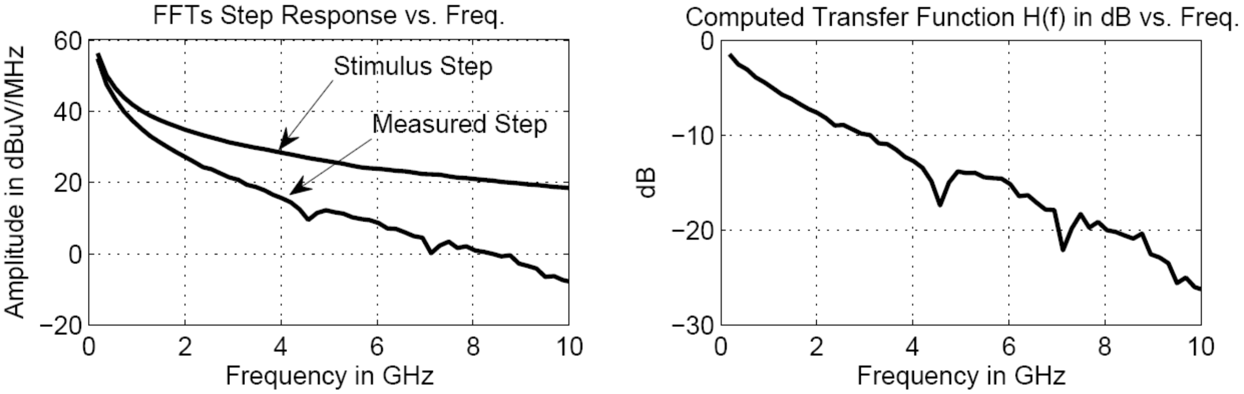

Figure 1.5: Computed FFT of the input and output step responses (left) and computed system transfer function based on the measured step responses (right).

With the knowledge of the computed transfer function *H(f)* it is now possible to de-embed a measured waveform of the DUT. Figure 1.6 shows a comparison of a de-embedded waveform obtained through post-processing of the measured waveform with the transfer function *H(f)* as described in equation 1.3.

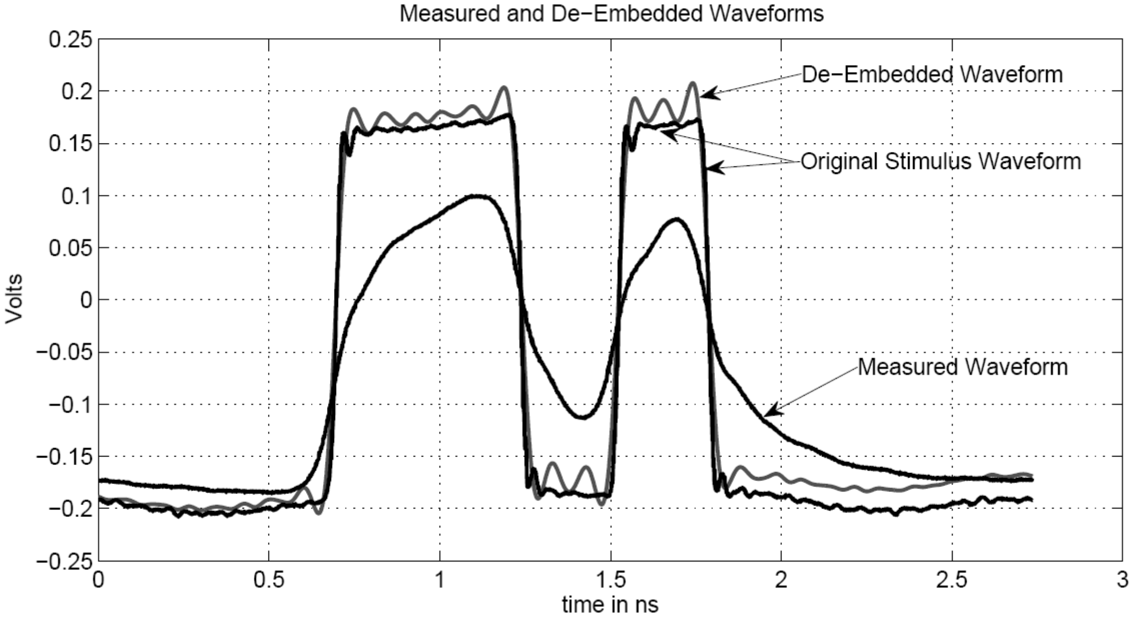

Figure 1.6: Results of applying the de-embedding procedure to a measured 5 Gbps waveform.

This example shows that time domain de-embedding can improve the measured results but it is also important to be aware of the limitations. The first one is that perfect de-embedding in a real application is not possible due to several factors like the random noise inherent to the pin electronics that might dominate in the frequency region where we still want to de-embed a measured signal or the computational issues associated with obtaining the transfer function using a step response. Another challenge in ATE applications is the fact that only time-equivalent (under-sampled) waveforms are measured either by a sampler ATE card or the digital pin electronics. In the pin electronics case there is the additional challenge that digitizing a waveform can be very time consuming. It is also important to note that this type of post processing technique cannot be used to improve measurements that depend on at-speed functional testing like a bathtub curve measurement.

2. Characterization in the Frequency Domain

The previous sub-section discussion can also be used as an approach to measure the performance of an ATE receiver channel in the frequency domain with or without the test fixture loss included or even for characterizing the test fixture performance separately from the ATE driver/receiver channel performance.

Figure 2.1 shows an example of measuring the ATE receiver performance in the frequency domain with a reference test fixture using an external pattern generator that provides a step waveform that is measured by the ATE receiver.

The frequency response of the ATE receiver plus the reference test fixture can be computed from the Fourier transform of the measured step responses as described in Equation 1.4 and shown in Figure 2.1.

If no reference test fixture is to be included and only the receiver performance is to be measured, then the pattern generator should be connected directly to the ATE receiver pogo pin.

If the objective is to measure the frequency response of the test fixture, this can be accomplished either for the drive or receive ATE channels. For the ATE driver channels, one needs to measure the step response at the ATE driver without the test fixture and at the DUT socket with the test fixture docked on the ATE system. The measurement of the driver step response can be done with an external instrument like an equivalent-time oscilloscope. The two measured step responses will then provide the frequency response of the test fixture through Equation 1.4. For the receiver side the process is similar. One measures the step response with the ATE receiver when a pattern generator is connected directly to the ATE receiver pogo pin and when it is connected to the DUT socket on the test fixture. From these two step responses the frequency response of the test fixture can be computed.

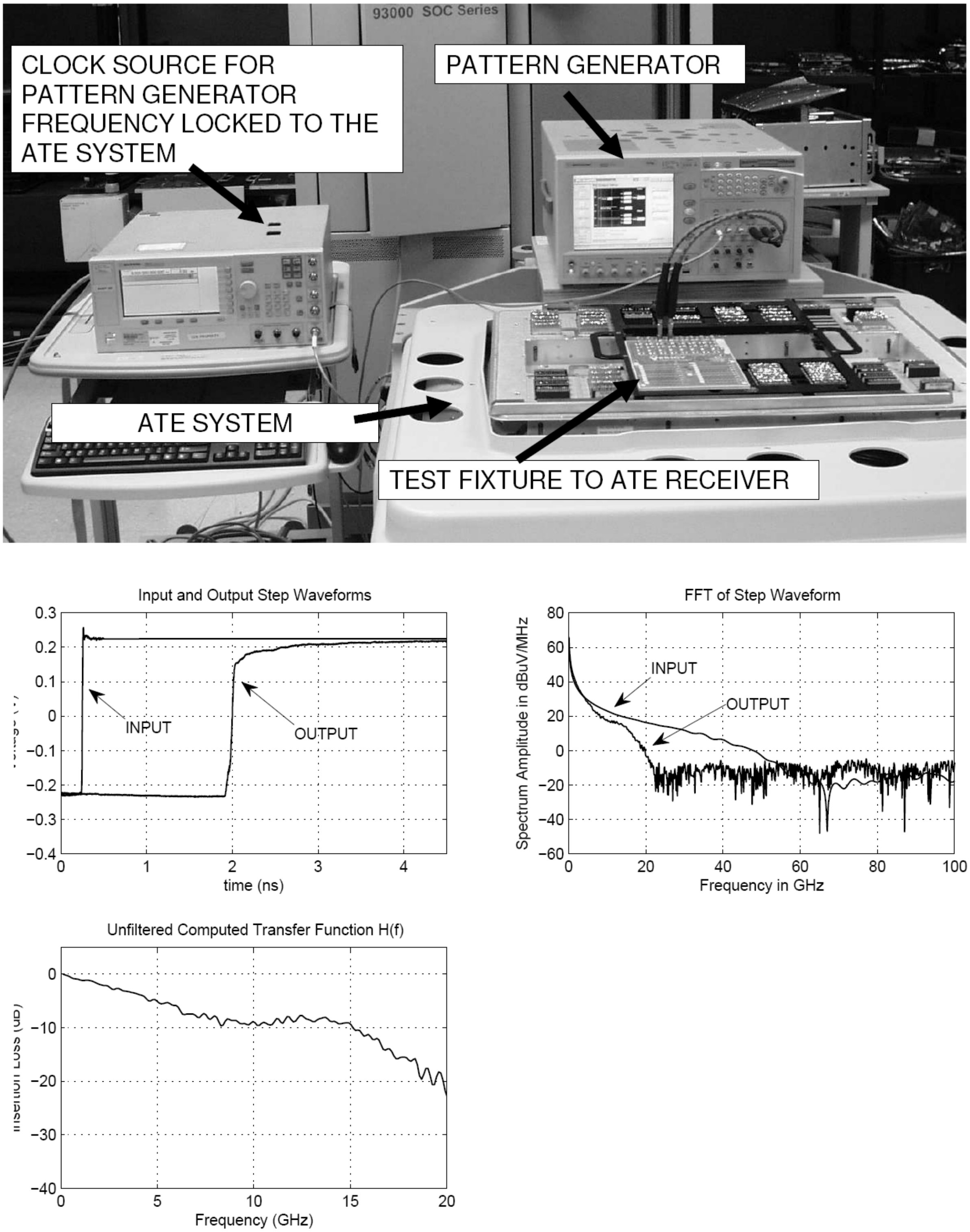

Figure 2.1: **Example of the measurement setup for characterizing an ATE receiver in the frequency domain using a step waveform (top) and the measured step response and computed frequency transfer function of the ATE receiver (bottom).**

3. References

[1] S. M. Riad, “The Deconvolution Problem: An Overview,” Proceedings of the IEEE, vol. 74, Jan. 1986
[2] W. J. Rugh, Linear System Theory. Prentice Hall, 1996
[3] J. R. Andrews, “Deconvolution of System Impulse Responses and Time Domain Waveforms,” Picosecond Labs Application Note AN-18, 2004