Calibration of a Gigahertz-Bandwidth Vector Signal Generation and Analysis System

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Abstract — **The calibration procedure for a vector signal generation and analysis system with over 1.6 GHz Bandwidth is described. To achieve the desired bandwidth, two software filters (a prefilter and a postfilter) are used to correct the non-uniform frequency responses in the system. We describe techniques for obtaining the response functions of both the signal generator and the signal analyzer. The measured response functions are used to construct the filters to achieve the flat frequency response. Finally a 1-Gsymbol/s 32-QAM raised-cosine-filtered waveform is generated to demonstrate the application of the system.**

I. Introduction

The increasing need for high-data-rate (HDR) links in military and commercial communication systems, coupled with the limitations on available spectrum, is resulting in renewed interest in high spectral efficiency modulations such as quadrature-amplitude-modulation (QAM). For designers of components and in particular power amplifiers to be used in such systems, it becomes increasingly important to test the components as close to their system operating condition as possible [1]. Furthermore, there is a growing interest in developing wideband nonlinear models for microwave power amplifiers and wideband nonlinear equalizers based on such models to achieve high efficiency operation of the amplifiers [2]. Vector signal systems, because of their flexibility in generating a wide range of RF and microwave waveforms, are ideal for these tasks. Commercial vector systems can be purchased from many sources, but they tend to have only limited bandwidth.

The recent development of commercially available high-speed long-record-length digital oscilloscopes and arbitrary waveform generators (AWGs) has made it possible to construct a vector signal system with multi-GHz bandwidth. Yet to realize the desired bandwidth, techniques must be developed to characterize and compensate for the frequency response of the system over the bandwidth. In particular, because of the difficulty in implementing uniform-frequency interpolation filters in the digital-to-analog conversion, AWGs tend to have non-ideal response [3]. In this paper, we will describe a procedure for correcting this non-ideal response together with those of other components in the system to achieve the necessary bandwidth. In Section II, the overview of the system is given. A detailed calibration procedure is listed in Section III. An application of the system is given in Section IV.

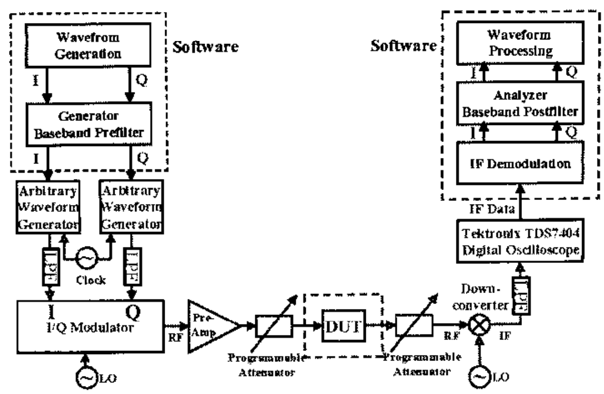

Figure 1. Schematic of the Ultra-Wideband Vector Signal System.

II. Overview Of the System

A schematic of the GHz-bandwidth vector signal generation and analysis system is shown in Figure. 1. The key components of the system are two synchronized AWGs (Analogic DBS2050s) running at 2.4 Gsamples/s and a digital oscilloscope (Tektronix TDS7404) running at 10 Gsamples/s.

The system is divided into two parts: the signal generator is from the baseband waveform generation to before the device-under-test (DUT); the signal analyzer is from after the DUT to the captured waveform processing. Most of the signal processing tasks are achieved by means of software digital signal processing. These include baseband waveform generation and IF signal demodulation as well as waveform processing. Furthermore, in order to compensate for the frequency characteristics of the generator and the analyzer over the broad frequency bandwidth of the system, two software filters are also implemented in the system: the prefilter is applied to the baseband waveform before it is downloaded to the AWGs to cancel out the non-uniform frequency response of the generator hardware; the postfilter is

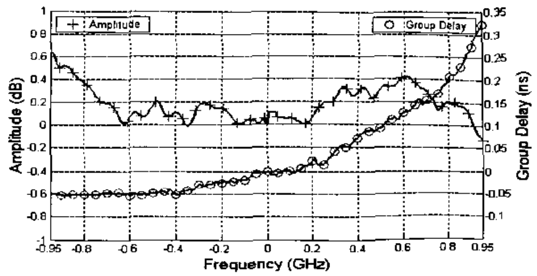

Figure 2. Amplitude and Group Delay Response of the Analyzer.

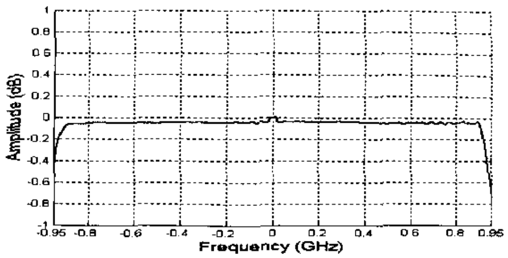

Figure 3. Measured Amplitude Response of the Analyzer with Postfilter.

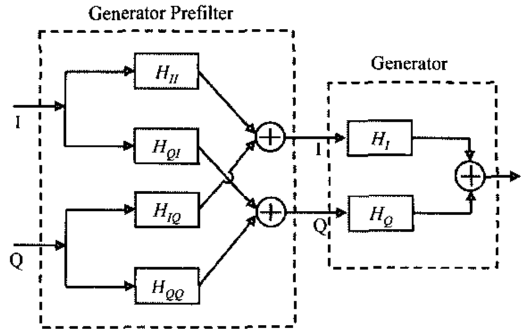

Figure 4. Block Diagram of the Generator Prefilter and the Generator.

applied to the demodulated waveform emerging from the analyzer to compensate for the frequency response of the analyzer hardware. The signal generation part of the system uses the conventional I/Q modulator configuration. The offset levels of the I and Q AWGs can be adjusted to cancel out the carrier leakage in the I/Q modulator.

For all the measurements presented in this paper, the LO frequency for the I/Q modulator is set at 5.25 GHz and the down-converter LO frequency is set at 6.5 GHz. The digitized IF signal is demodulated with a software LO frequency of 1.25 GHz.

II. Calibration of the System

The overall calibration strategy is to calibrate and compensate for the frequency response of the signal analyzer first, and then to use it as a perfect analyzer for calibrating the signal generator.

A. Analyzer Calibration and Compensation

The amplitude and phase response of the analyzer are characterized separately and the phase response is measured in group delay format. The amplitude response is measured by scanning the frequency of a frequency synthesizer connected to the input of the analyzer over the desired bandwidth. The amplitude response of the analyzer can then be obtained by digitizing the corresponding down-converted IF waveform. The output power of the synthesizer is also monitored with a power meter so that the amplitude of the record waveform can be normalized. The group delay response of the analyzer is obtained by combining the group delay of all the components in the analyzer which are characterized individually with a vector network analyzer. The most critical of these is the down-converter mixer. The mixer is characterized using a technique described in [4] which requires the use of two additional mixers and at least one of these mixers must have a reciprocal frequency response. Our measurements have indicated that, even though the reciprocity condition is only approximately true for amplitude responses (~0.5 dB difference in the two directions for LO=6.5 GHz), it is a very good assumption for group delay responses (~10 ps for the same condition). In constructing the phase response of the analyzer, we have ignored the phase response of the digital scope, which should be negligible for the IF frequency range.

The overall amplitude and group delay responses of the analyzer are shown in Figure 2. The information is used to construct a postfilter so that the combined response of the analyzer and postfilter is flat from –0.9 to 0.9 GHz. After the postfilter was implemented, the amplitude response of the analyzer was re-scanned, with the resulting flattened response is shown in Figure 3.

B. Generator Calibration and Compensation

For signal generator calibration, its output is directly connected to the analyzer input, bypassing the DUT.

A general representation of a vector signal generator is shown in Figure 4. The I and Q channels of the vector signal generator are characterized by two impulse response functions H_I and H_Q. Note that both the I and Q inputs are real numbers while the response function can be complex. Ideally, these two response functions should both have, (1) the same amplitude in the time-domain except for a 90° phase difference; (2) flat response in the frequency-domain over the desired bandwidth of the

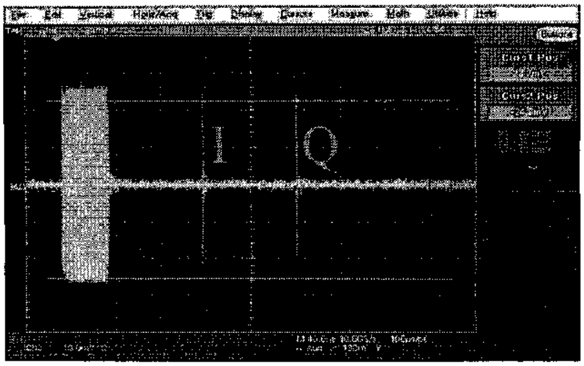

Figure 5. Waveform for Obtaining Response Functions.

generator. To obtain the response functions of the I and Q channels, the two synchronized AWGs are programmed to excite the I and Q channels with delta function impulses during the same waveform but at two separate time instances, as shown in Figure 5. Both response functions have to be probed within the same waveform so that their relative phase can be preserved; yet they have to be separated far enough in time to ensure they do not overlap. Furthermore, a long flat-top pulse is generated in the I channel at the beginning of the waveform preceding the two impulses so that the DC phase in the I channel can be extracted to be used as the zero degree phase reference. The measured response functions are the combined response functions of all the components in the signal generator including AWGs, I/Q modulator, pre-amps and other passive components (Figure 6). It is obvious that they deviate from the two conditions listed earlier in this section for an ideal vector signal generator.

To correct for the component non-idealities, a prefilter network consisting of four software digital filters is placed between the baseband waveform generator and the signal generator. The filters are implemented as FIR filters with real coefficients, an order of 100 and a tap frequency of 2.4 GHz (identical to the AWG clock frequency). The coefficients of filters H_{II} and H_{QI} are determined by the requirement that, if only the in-phase delta function waveform is present, the combined response function of the software filters and the signal generator is purely real with its characteristic as shown in Figure 7. When the generator is excited by only the in-phase delta function, the generator output is given by,

$$r_I(k) = \sum_{i=1}^{M} b_{II}^i \cdot h_I(i-k) + \sum_{i=1}^{M} b_{QI}^i \cdot h_Q(i-k) \quad (1)$$

where r_I is the ideal I-channel response function, h_I and h_Q are the generator response functions and b^i_{II} and b^i_{QI} are the coefficients for filters H_{II} and H_{QI}. Equation (1) is solved using a least-squares algorithm implemented in a MATLAB program. The ideal response function of Figure

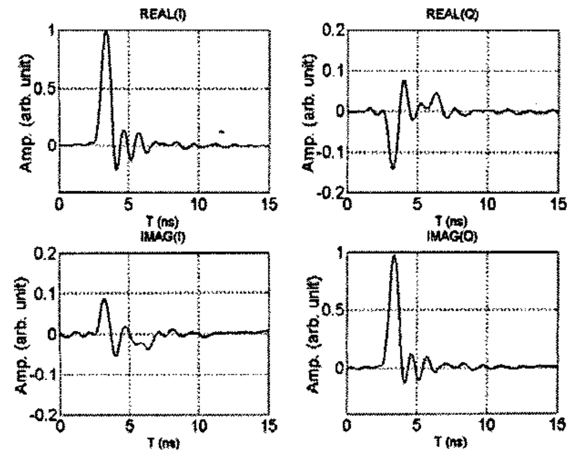

Figure 6. Response Functions of the Generator.

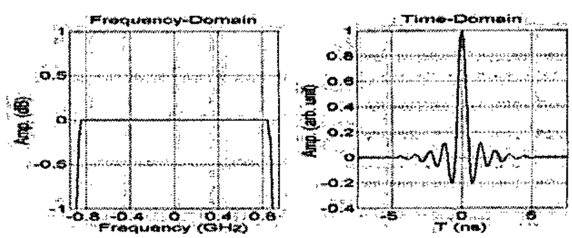

Figure 7. Ideal Impulse Function.

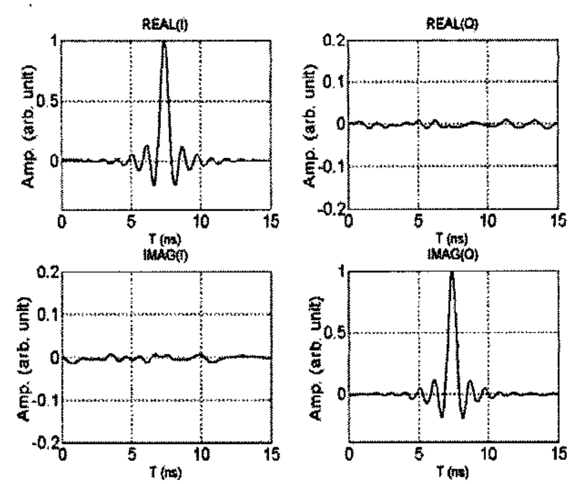

Figure 8. Measured Response Functions with Prefilter.

7 is first constructed in the frequency-domain with a flat response from –0.84 to 0.84 GHz. Gradual transition regions are placed slightly beyond the flat frequency band to damp out the sidelobe ringing in the time-domain so that the order of the filters can be kept to a reasonable number. Similarly, H_{IQ} and H_{QQ} can be determined, except the Q channel response will be purely imaginary.

The measured I and Q channel response functions with the prefilter correction are shown in Figure 8. The quality of the response functions are evaluated by the normalized mean-square-error (NMSE) metric given by [2]:

$$NMSE = \frac{\sum_{k=1}^{M} \left| r_{k,measured} - r_{k,ideal} \right|^2}{\sum_{k=1}^{M} \left| r_{k,ideal} \right|^2} \quad (2)$$

where $r_{measured}$ is the measured complex response function at the generator output, r_{ideal} is the complex ideal response function at the same location and k is the sampling point at the analyzer clock frequency of 10 Gsamples/s. The NMSEs for the I and Q channels are 0.11% and 0.14% respectively.

III. Application of the System

To demonstrate the system, the equalized system was used to generated a 1 Gsymbols/s 32-QAM waveform at a 5.25 GHz carrier frequency. The waveform was first generated in baseband with a sampling frequency of 10 Gsamples/s. A raised-cosine filter with a rollover factor of 0.5 was also applied to the waveform and the total bandwidth was therefore 1.5 GHz. The waveform was then re-sampled at 2.4 Gsamples so that it could be passed through the prefilter and downloaded to the AWGs. The constellation plot and the spectrum of the waveform captured by the analyzer are shown in Figure 9, for the case of a thru-connection (no DUT). Approximately 35 dB of dynamic range is achieved. For comparison, the same baseband waveform was downloaded to the AWGs without applying the prefilter. Similar plots are shown in Figure 10 for this case. The deterioration of the signal quality due to inter-symbol-interference is so significant that it prevents the microwave waveform from being useful for testing purposes.

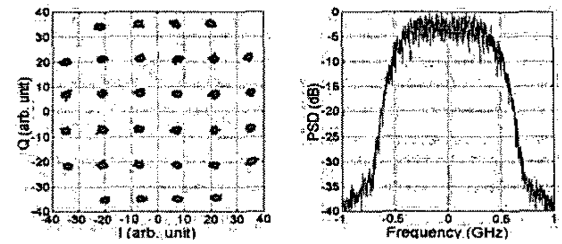

Figure 9. 32-QAM Waveform with Prefilter Correction.

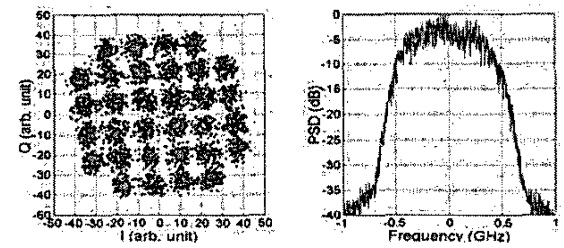

Figure 10. 32-QAM Waveform without Prefilter.

IV. Conclusion

A vector signal generation and analysis system with more than 1.6 GHz of operation bandwidth has been constructed. Although the system uses commercially available state-of-the-art high-speed digital-to-analog and analog-to-digital instruments, a systematic calibration procedure is necessary for it to operate over the desired bandwidth. We have characterized the non-uniform frequency responses in both the signal generator and the signal analyzer. Two equalizing digital filters are implemented in the system to correct for the non-uniformity. The NMSE metric is also introduced and NMSE in the order of 10^{-3} is achieved with the equalization. A 32-QAM 1 Gsymbols/s bandlimited waveform with 1.5 GHz bandwidth was generated with the corrected system and compared with the same waveform generated without the prefilter correction. In subsequent work, this system will be used to characterize the responses of nonlinear power amplifiers (TWTAs and SSPAs) and to develop wideband nonlinear equalizers. [5]

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