Mixed Analog-Digital Instrumentation for Software-Defined-Radio Characterization*

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Abstract—**This paper presents a new type of analog-digital mixed-domain instrument that is specially tailored for software-defined-radio characterization.**

The instrument allows the utilization of analog instruments such as vector signal analyzers and network analyzers to characterize components based in the digital domain, such as analog-to-digital converters or field-programmable gate arrays. In this paper a study of the implementation of the mixed-domain instrument is also given.

Index Terms—**Software defined radio, nonlinear systems, analog-to-digital converters, electronic measurements.**

I. INTRODUCTION

SOFTWARE-DEFINED radios (SDRs) typically utilize signals in both the analog and digital domains. For receiver front ends, the input is analog and the output is digital. For transmitters such as class S amplifiers [1], the input is digital and the output analog. Instrumentation that is normally used for analog components typically does not provide enough information to characterize the system adequately since much of the signal exists only in the digital domain.

In this paper, we analyze a proposed mixed-domain instrument that allows the user to simultaneously evaluate the overall radio path in both analog to digital domains. We propose techniques for synchronization of the acquired signals and describe temporal alignment of the two types of measured signals.

Key parameters of the digital domain measurements, where the bit pattern is the fundamental signal of interest, include nonidealities such as offset/gain error, integral nonlinearity (INL) and differential nonlinearity (DNL) [2]. In the analog domain, important figures of merit include voltage standing wave ratio (VSWR), gain, etc. [3].

With the advent of SDR and cognitive radios, the study and evaluation of wireless standards from a radio hardware point of view is currently a very important theme in the test and measurement community. This has driven the instrumentation industry to develop instruments such as vector signal analyzers, capable of operating in the analog and/or the digital domains. Nevertheless, in a typical SDR, the two involved domains are important and present all of the time, (see Fig. 1).

As can be seen from Fig.1, the radio signal passes from the analog to digital domain during the frequency conversion process. During this process, problems typical of those encountered in the analog domain appear in the digital part. For instance, we would like to continue to have information on the input noise figure, or the VSWR of the input stage, even if the output is no longer analog but is a digital version of it. Additionally, in the digital section information such as INL, DNL, spurious-free dynamic range, etc., is important.

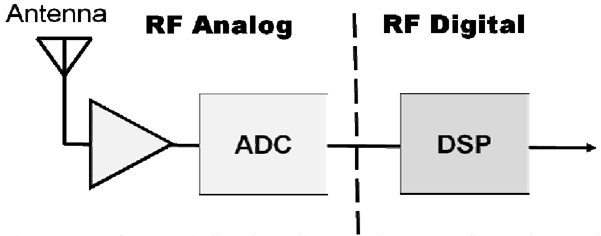

Fig. 1. Software-defined radio receiver configuration. The received signal is amplified and the RF signal is digitized directly by the analog-to-digital converter (ADC). The baseband signal is further processed by the digital-signal-processing (DSP) chip.

Recently, some approaches to this type of measurement were proposed by combining a large number of instruments, including logic analyzers, oscilloscopes, and vector signal analyzers (VSAs) [4]. While we can acquire information from all these instruments, that information is normally not coherent or synchronized in time with the original test signal. This means that while power information about the signal or information about demodulated signals can be obtained, we cannot characterize from a vector point of view (amplitude and phase) the device under test. For instance, we cannot characterize a function similar to S_{21} in a network analyzer.

In this paper, we will start by presenting the new instrumentation idealized solution. In Section III, a laboratory implementation of this ideal approach will be given, based on common instruments from the laboratory. Since a common time base is needed, advanced triggering solutions are presented for time alignment in Section IV. In Section V measured data will be presented for an SDR device under test. Finally some conclusions will be drawn.

II. SDR INSTRUMENTATION

As referred to above, measured quantities such as those already used to quantify analog measurements continue to be valid in SDR, for instance, input VSWR, gain, bandwidth, nonlinear effects, etc. Thus, the same approach as is used for standard analog instrumentation will be followed here, developing a concept similar to an analog/digital S parameter. Fig. 2 presents the fundamental concept for this type of instrument.

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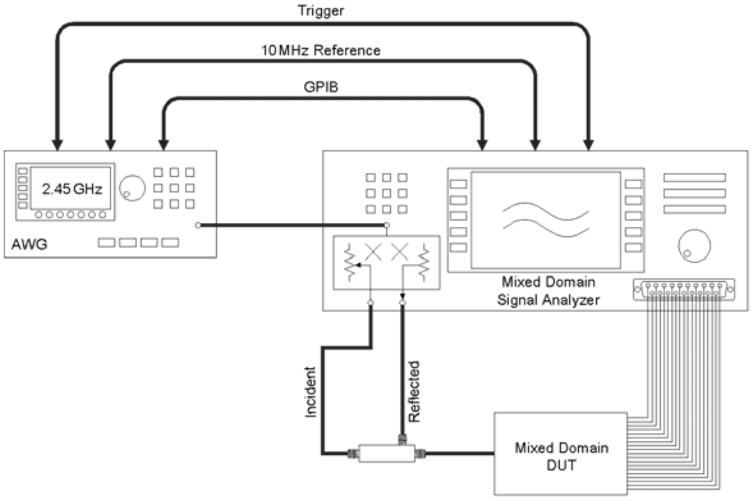

Fig. 2. Mixed-domain instrumentation in which an arbitrary waveform generator (AWG) excites the mixed-domain DUT.

As seen in Fig. 2, the analog channel has the channel configuration of a network analyzer, while the second channel is a digital channel, where the input signals are no longer analog ones, but are actually bit sequences. This will allow us to measure important information such as the reflection coefficient at the input port, since

$$\rho(\omega) = \frac{V_{ref}(\omega)}{V_{inc}(\omega)} = S_{11D}(\omega)\,, \qquad (1)$$

where $V_{ref}(\omega)$ and $V_{inc}(\omega)$ are the incident and the reflected waveforms at port 1 (analog signal) and S_{11D} is an analog S parameter. Thus similar quantities can thus continue to be defined in this scenario as the $S_{21D}(\omega)$ which allow us to measure the "gain" of the DUT from an RF point of view.

Other important information related to amplitude and phase change can now be gathered. For instance, the linear transfer function relating input to output signal is given as

$$H_L(\omega) = \frac{V_{dig}(\omega)}{V_{inc}(\omega)} = \frac{\frac{1}{T}\int_{-T/2}^{T/2}[2^{n_1(t)} + \cdots + 2^{n_N(t)}].V_{ref}.e^{-j\omega t}\,dt}{\frac{1}{T}\int_{-T/2}^{T/2} v_{inc}(t).e^{-j\omega t}\,dt}\,. \qquad (2)$$

This format can also be used to compute other forms of nonlinear transfer functions, such as those for systems containing all-analog components. Such transfer functions can be based on higher-order statistics for nonlinear distortion evaluation [5].

In fact, what we are measuring is nothing more than a time-domain signal, whether in the analog or in the digital domain. The need to time align signals measured with this instrument is the same as for quantities that we measure using analog instrumentation. External alignment signals should continue to be used, including GPIB, trigger, and signal reference, since those will be based on the time alignment of the overall signals. The next section presents one possible implementation of this ideal vision by using regular laboratory instrumentation.

III. LABORATORY IMPLEMENTATION

In order to implement the mixed-domain instrument using a laboratory arrangement, we have assembled a version using individual measurement equipment, as presented in Fig. 3.

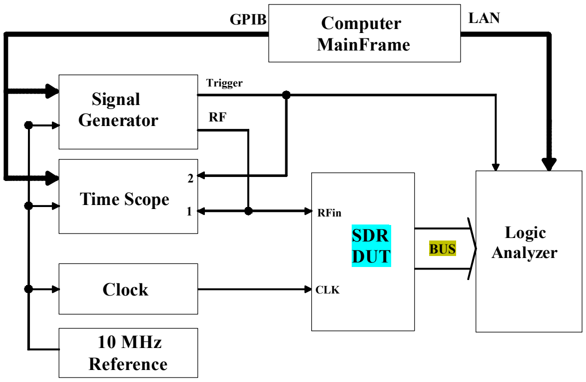

Fig. 3. Laboratory setup of a mixed-mode instrument.

As shown in the figure, for the analog part we use a time-domain instrument such as an oscilloscope or a microwave transition analyzer (MTA). We use a logic analyzer to sample the signals in the digital domain.

These two systems are then synchronized using a common 10 MHz reference and a trigger signal that allows time synchronization between signals. We do this because we will measure the input and output signals at different times and they should be synchronized afterwards in post processing.

Even though we use the same sampling frequency for both instruments, extra care should be used for the correct selection of this quantity. If different sampling frequencies are used for the analog scope, the digital scope, and for the DUT, then interpolation and/or decimation should be used carefully in order to guarantee a similar time base for all the signal components.

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In the case implemented in our scenario, we have used a similar sampling frequency of 20 MHz for all the instruments. We should also guarantee that all the signals are synchronous, that is we should guarantee that we are actually measuring the signal at the same instant of time. The next section is devoted to this problem.

IV. TRIGGERING MIXED MODE SIGNALS

One extremely complex problem to resolve in a measurement system like the one that is proposed in this paper is how to synchronize all the different measured signals. In the laboratory measurement set-up that we are using, we do not have synchronized samplers, even though they are all locked to a 10 MHz reference and we are using external trigger sequences whenever possible. The synchronization of all the signals is a fundamental problem that must be resolved if we want to extract the phase relationships between the input and output signals.

The need for external synchronization has driven us to propose the use of an excitation signal that consists of a triggering pulse embedded in the input signal followed by the waveform excitation of interest; for instance, a sinusoidal tone, a two-tone, or a multisine signal (see Fig. 4). Methods such as this were proposed in [5] and [6].

The process of triggering starts by generating a signal in the arbitrary waveform generator that includes a first triggering sequence followed by the waveform to be measured. This signal is generated by first creating the complex envelope waveform, sampled at 20 MHz. This in-phase/quadrature (I/Q) envelope signal is then downloaded to the generator and up-converted to the selected output frequency. The signal is then sampled both at the analog and digital scopes during different time intervals by means of an external trigger that was previously configured in the generator as an external marker.

The measurement process starts by selecting one of the sampled waveforms as the reference waveform, and then referring all the previous waveforms to that reference. For small-signal operation, we extract, for instance, a replica of the trigger signal.

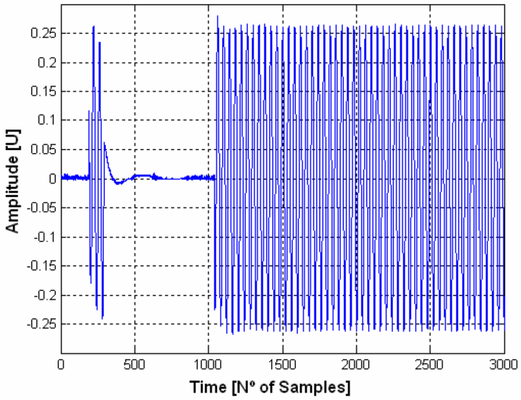


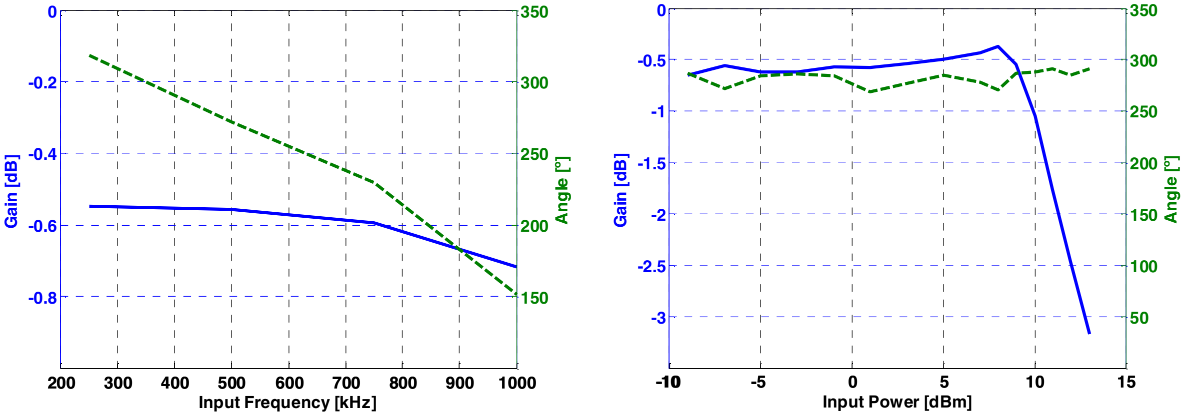
Fig. 4. Excitation waveform, including the triggering sequence initial pulse.

Then in subsequent measurements we correct the trigger signal at the MTA and at the logic analyzer to the reference trigger. This way, all the signals will be synchronous. In each measurement, the first n_{trg} points with the same amplitude are reserved for the signal trigger. Then the generated waveform is corrected according to that trigger and its first periods are deleted in order to eliminate any transient arising from the change of the trigger sequence to the waveform itself. The remaining signal will be our input and output measurement sequence.

V. MEASUREMENT EXAMPLES

In order to clearly show how this instrument can be usefully applied in a laboratory environment, we measured an SDR receiver that consists of a low-noise amplifier (LNA) followed by an 8-bit ADC with a sampling clock of 20 MHz.

The first measurement was the equivalent transfer function of the overall system as given in (2). We measured the amplitude and phase change of the output signal for a sinusoidal input signal.



(a)

(b)

Fig. 5. Transfer function of an SDR when the input signal was swept (a) in frequency and (b) in power (solid line – gain amplitude, dashed line –phase).

As seen in Fig. 5(a), the output amplitude is almost constant with frequency, and the phase decreases almost continuously. We next swept the input signal amplitude for a fixed frequency, as shown in Fig. 5(b). These curves represent the AM/AM and AM/PM values, as would be seen in a power amplifier characterization.

Finally, we performed a two-tone test. Fig. 6 presents an interesting aspect of the mixed-mode signal, where the quantization problem is visible in the digital sampled signal. Fig. 7 presents the first-order transfer function and the third-order intermodulation distortion nonlinear transfer function for the two-tone case, where the input power was swept and the distortion products plotted.

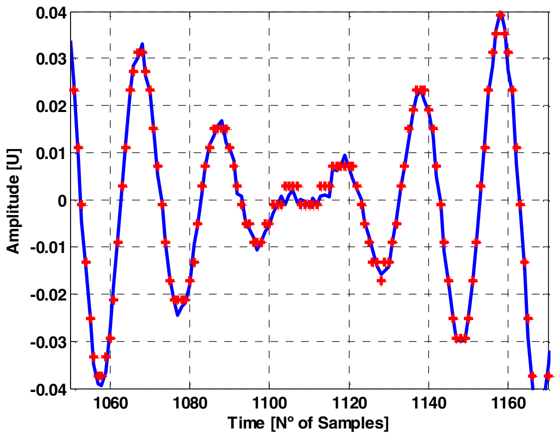
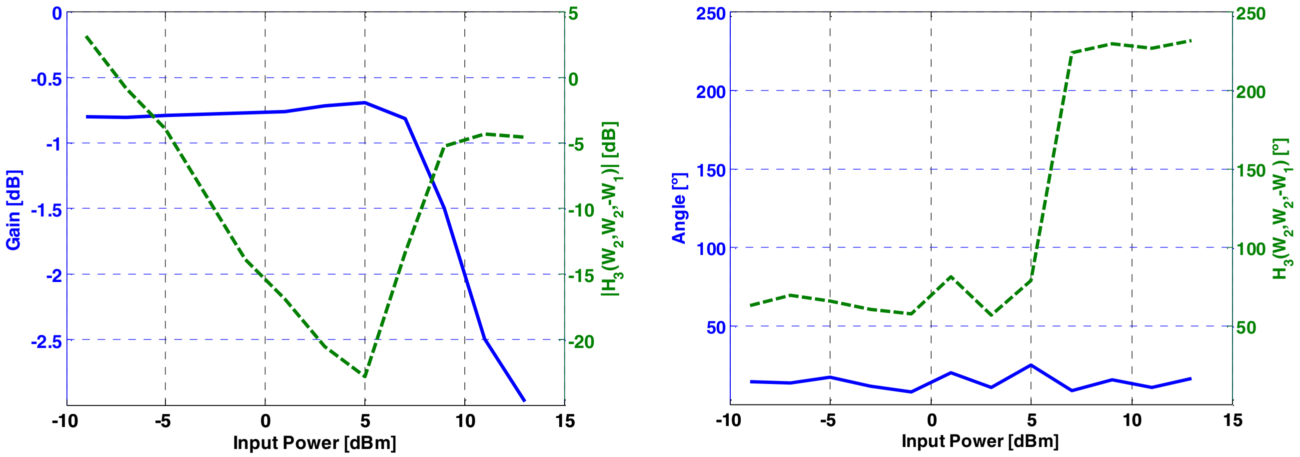


Fig. 6. Time-domain measurement of the analog RF signal (darker line with dots) and the digital sequence (lighter, angular line with dots) for a two-tone signal excitation.



(a) (b)

Fig. 7. (a) First-order (solid) and third-order (dashed) transfer functions; (b) phase of the first-order (solid) and third-order (dashed) intermodulation distortion product relative to the output phase of the fundamental and the corresponding ideal third-order distortion.

VI. CONCLUSIONS

This paper presents a new mixed-domain, analog-digital instrument that is specially tailored to the characterization of SDR systems. The general idea was introduced as well a possible laboratory implementation that utilized typical laboratory equipment. We discussed signal timing and synchronization requirements and solutions. There are some important problems that still have to be addressed, including the development of a calibration procedure and error analysis of measurements made with such systems.

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