CHARACTERIZATION OF SDR/CR FRONT-ENDS FOR IMPROVED DIGITAL SIGNAL PROCESSING ALGORITHMS

Diogo C. Ribeiro, Pedro Miguel Cruz, and Nuno Borges Carvalho

Instituto de Telecomunicações - Universidade de Aveiro (DETI)
Campus Universitário de Santiago, 3810-193, Aveiro, Portugal

ABSTRACT

This paper will demonstrate the importance of performing unified mixed-signal measurement and characterization procedures. It will be shown that a joint analog and digital analysis has a strong impact on future (radio-frequency) RF components and devices. This is mostly due to the fact that today's circuits and systems are evolving in the way of integration into a single module, which makes the separation of analog and digital analysis impossible to be done.

Some details about mixed-signal instrumentation are introduced by showing representative laboratory measurement arrangements. They allow to obtain correlated information of analog and digital portions of mixed-signal systems, which are essential to retrieve the commonly named transfer functions. This information will make possible to produce better designs of the entire radio front-end, as well as, the implementation of optimized digital signal processing (DSP) algorithms to compensate the analog impairments.

***Index Terms*—** Digital signal processing, linear measurements, mixed-signal instrumentation, nonlinear characterization

1. INTRODUCTION

In general, more and more radio access technologies tend to be supported in single chip devices, especially when addressing mobile terminals design, including a wide variety of applications as for instance, cellular networks, wireless local area networks (WLANs), positioning and navigation, broadcasting services, short-range personal communications, among several others.

In what concerns to the specific radio front-end design, there are two conceptual alternatives: 1) separate low-cost, compact radio implementations for each access technology (Fig. 1a), or 2) single flexible and reconfigurable radio hardware that should be multi-standard and multiband. This fact have imposed that integrating more and more the radios would benefit the cost and final size of individual hardware implementation. The advantages on lower costs, better integrability and increased energy-efficiency are achieved through more assembled electronics (allowed mainly by current improvements in silicon processes). This applies to all analog electronics existent in a radio front-end and especially to complete radio-frequency (RF) modules that now include analog and digital portions together, see Fig. 1b.

The idea created by Mitola [1] some years ago, called software defined radio (SDR) and recent advances of this technology into the cognitive radio (CR) field, were already anticipating the need for integration of analog RF front-end designs with the digital counterpart.

Basically, what was initially idealized and is now being made is to move some of the analog functions to the digital domain. Moving such selectivity and other functionalities to digital domain has been enabled by the continuous developments in digital signal processing circuitry, which allow the simplification of the analog front-end, more integration, an increased flexibility and reconfigurability. However, on the other hand, it implies higher demands for the remaining analog components (naming amplifiers, mixers, analog-to-digital converters (ADCs)), which have now to be wideband and demonstrate higher dynamic range to capture several incoming signals.

To help on this issue the development of sophisticated digital signal processing (DSP) techniques for mitigating the dominant impairment effects in transmitter and receiver stages is now a strong case study. Obviously, joining these two different worlds calls for expertise on both sides of the analog-digital interfaces and for a higher synergy between the radio engineering and baseband DSP communities. Thus, it is a key function to find the proper balance and partitioning between analog and digital signal processing in general.

As well, the instrumentation and measurement sector is being forced by those advancements and the instrumentation arrangements should also follow this evolution by integrating analog and digital measures together. In this way, it is important to construct tools at the simulation level that permit RF engineers to design better hardware analog or mixed-signal front-ends, but at the same time, potentiate the understanding of the entire RF chain and its functioning to digital-side

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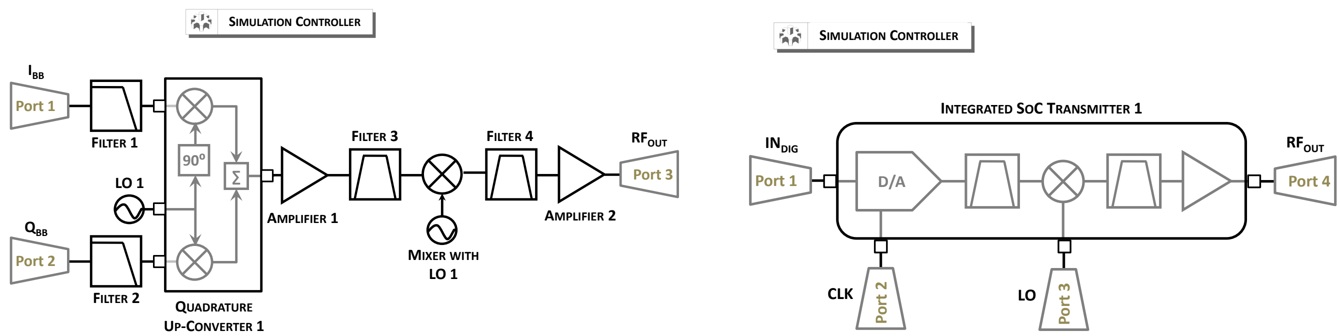


(a) (b)

Fig. 1. System-level simulation of: (a) a completely analog super-heterodyne transmitter and (b) an integrated mixed-signal RF transmitter module.

engineers. This will be exactly the main focus of this work.

The paper is divided into a first approach to mixed-signal systems evaluation, followed in section 3 by the discussion on novel instrument arrangements for mixed-signal environments. Then, in section 4 a couple of application examples are shown, including a commercial integrated receiver and an integrated transmitter. Finally, some conclusion and outlook will be presented.

2. MIXED-SIGNAL SYSTEM EVALUATION

The mixed-signal system representation proposed in this work follows the idea of considering the existence of scattering (incident and reflected) waveforms at each input/output of the device that is being analysed. This procedure is similar to what is typically done to represent fully analog RF systems.

An illustrative representation of a generic mixed-signal SoC transmitter using the proposed approach is sketched in Fig. 2. This approach tends to be very effective for a fast and easy application onto current RF/Microwave simulators, and also provides a clear projection of the device characteristic behavior to RF engineers used to deal with this type of designations.

Additionally, the techniques used on traditional RF measurement equipment (or adapted arrangements of those) can continue to be employed in the proposed mixed-signal instrumentation, as a way to correctly read the analog portion of the device. This fact is very important since the kind of devices being tested in this work are composed of analog and digital parts of radio front-ends. So, knowing that radios operate at high or very high frequencies, the same type of issues faced when measuring fully-analog RF devices, such as multiple reflections, also have an impact on the considered mixed-signal measurements.

By using this kind of approach based on the incident and reflected scattering waves, several linear and nonlinear quantities being solely employed onto analog blocks, can now be extended into the characterization of such mixed-signal SoC devices. For example, in the depicted integrated mixed-signal transmitter a very interesting measure would be the RF_{out} port reflection coefficient to evaluate the connection to an antenna piece. Thus, this is obtained by relating the incident and reflected signals at the RF analog port ($a_{RF}; b_{RF}$), given by:

$$\rho(\omega) = \left.\frac{b_{RF}}{a_{RF}}\right|_{a_{LO}=\beta;\, a_{CLK}=\alpha;\, a_{DIG}=0;} \tag{1}$$

In the same way of thinking, the remaining incident and reflected waveforms could as well be related between them in order to obtain transfer function like information. For the purpose of comparing the digital-side waveforms ($a_{DIG}; b_{DIG}$) to the analog counterparts, it will be converted conceptually to a voltage waveform. Also, at this port, a perfect RF match is considered by assuming that no reflected signal exists and so, b_{DIG} is equal to zero.

For instance, a transfer function between the digital input (a_{DIG}) and the analog output at RF port (b_{RF}) can be defined as the equivalent "gain" for the depicted integrated transmitter. Obviously, this measure could be obtained for different clock (a_{CLK}) values and local oscillator (a_{LO}) excited frequencies and power levels. This could be of huge interest when one expect to have functional models for mixed-signal RF parts existing in a laboratory, which need to be simulated and optimized as a way to improve its overall functioning.

Finally, it is important to stress that the explained ap-

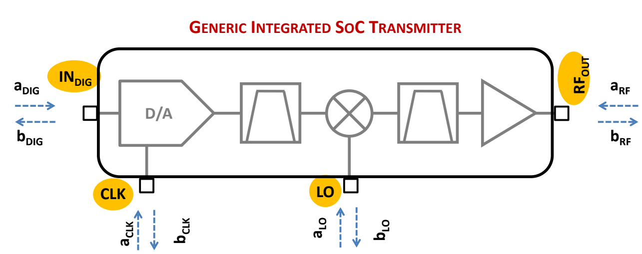
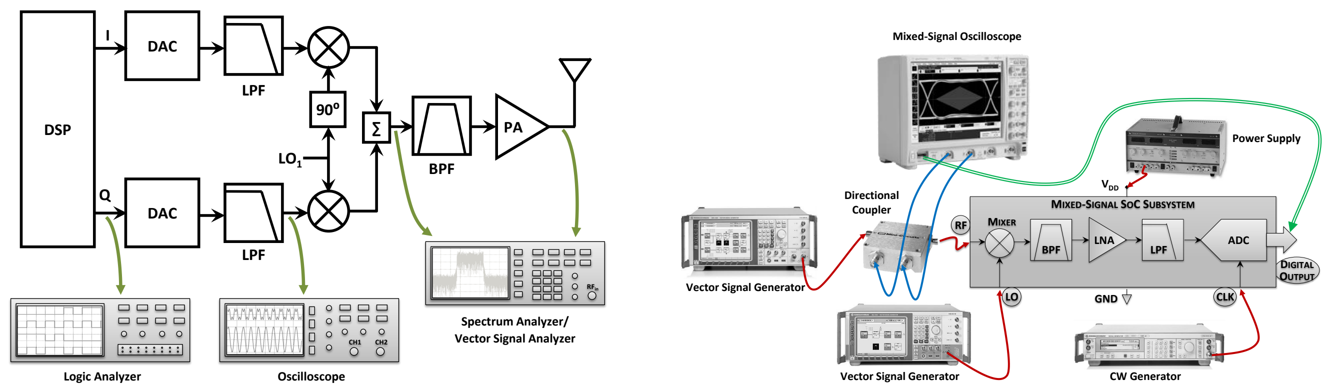


Fig. 2. System-level scattering waveforms applied to a generic mixed-signal SoC transmitter.



(a) (b)

Fig. 3. Combination of several instruments employed in: (a) a complete transmitting chain, from [2] and (b) a mixed-signal SoC receiver, from [3].

proach would allow as well the application into nonlinear characterization scenarios.

3. MIXED-SIGNAL INSTRUMENTATION

As mentioned in the introduction, the devices to be tested are moving away from single-purpose, hardware-centric entities with limited capability to multipurpose, integrated on a chip, software-centric entities with endless capability. Thus, it is rather important that the test and measurement systems evolve in the very same way, making the switch from traditional instruments commonly divided by the type of signal to measure (RF analog, RF digital, DC, optical, and so on) to a software-defined architecture that integrates all the relevant measurement hardware in a single measurement instrument.

At the same level of importance is the connection of produced measurement test benches to the available behavioral modeling tools, i.e., to bring it into a simulation level. The increasing system complexity and improved performance demanded by the new digital communication standards require signal processing techniques and tools that permit an efficient CAD/CAE design process. The complete identification of linear and nonlinear systems is a challenging topic not only from the formal modeling point of view but also from the practical extraction side where the impairments of the real systems have to be accounted for.

In last years the instrumentation industry started to address the integration of analog and digital waveforms in the same instrument and the first approach appeared as mixed-signal oscilloscopes (MSOs), [4], which are capable of operating in the analog and digital domains at same time allowing time synchronization of both signals in a single instrument. However, MSOs use asynchronous sampling to acquire the digital data, which means they sample again the digital signal with their own clock. As explained on [5], this way the magnitude and phase information retrieved from the captured signal could be completely corrupted.

Other suggestions from the instrumentation industry to measure a complete transmitting RF chain employs a set of several instruments, [2], see Fig. 3a. However, there is no simple way to test and characterize such a complex mixed-signal integrated system.

In a different view, the first iteration to address an instrument that joins analog and digital information on a basis of scattering waveforms has been realized in [6]. There, it has been discussed issues like signal timing, synchronization requirements and some solutions were proposed, for example, embedding a trigger signal in the test excitation. Also, the proposed architecture addresses the properties of a configuration having a vector network analyzer (VNA) for the analog part and a logic analyzer for the digital counterpart. However, some important problems remained unsolved such as a calibration procedure for this type of mixed-signal instrumentation. Exactly to address those open issues, later on in [7] a calibration procedure for such type of measurement instrument has been developed.

Recently, in [3] a different framework for the characterization and modeling of single-chip mixed-signal system-on-chip (SoC) systems has been uncovered based on the desired scattering waveform baseline. The utilized measurement setup is fully supported on a MSO in conjunction with some external hardware, including signal generators, a directional coupler and a power suplly, see Fig. 3b.

However, in a mixed-signal system most of its main components are inherently nonlinear. This brings the base instrument into a new laboratorial stage, which claims for the large-signal network analyzer (LSNA) or the much actual nonlinear vector network analyzer (NVNA), both VNA evolutions capable of characterizing the nonlinear behavioral of analog components. Although, the characterization process is a powerful tool, it does not allow to predict the behavior of a component under different signal stimulus. To accomplish this, behavioral models are constructed based on the acquired measured results. The state-of-the-art nonlinear behavioral models are

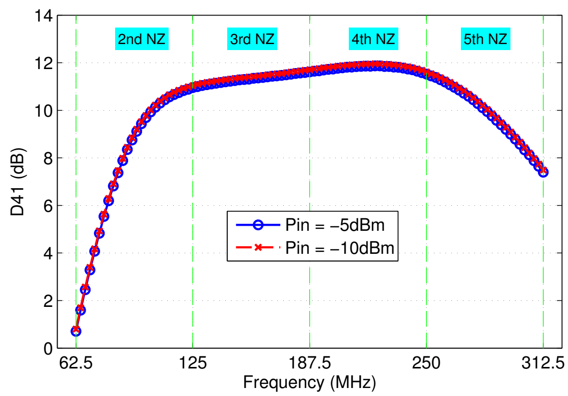


Fig. 4. Magnitude response over frequency of an integrated SoC receiver, for two input powers, from [3].

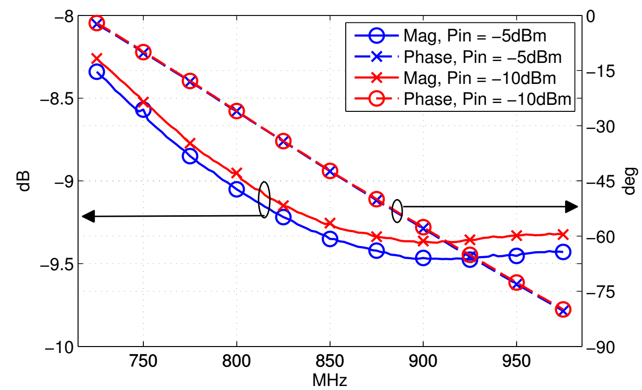


Fig. 5. Reflection coefficient over frequency of the RF port of an integrated SoC receiver, for two input powers, from [3].

assigned to analog components, these models are an obvious extension of traditional scattering parameters and are entitled as X-parameters [8]. In the following section it will be overviewed the application of such a nonlinear characterization for a mixed-signal integrated transmitter published in [9].

4. APPLICATION EXAMPLES

In this section two different examples will be shown. They highlight the need for a complete measure and characterization procedure of mixed-signal devices.

During the design flow of larger systems, which make use of mixed-signal devices, the actual path is most of the time to ignore the non-idealities of these devices. Mainly, due to the lack of tools to completely evaluate and predict the behavior of mixed-signal systems, as already mentioned before.

4.1. Integrated commercial SoC receiver example

In Fig. 4 it is represented the magnitude response of a complete SoC receiver over its operational frequency. As can be noticed, the magnitude response is not flat over the entire receiver bandwidth, it has a shape similar to what is usually seen on band-pass filters (BPFs).

The reflection coefficient of the SoC's input RF port is depicted on Fig. 4.1, where both magnitude and phase are shown. The reflection coefficient was obtained for two different input powers. It can be seen that both and magnitude traces are similar for the two input powers.

By making use of the proposed measurement and characterization framework, the design engineer can use this information to easily compensate the response of system in the digital domain. So that, the cascaded analog and digital magnitude response results in a flat line over frequency.

4.2. Integrated transmitter example

In this second example an integrated transmitter will be characterized. Its nonlinear behavior will be represented by means of X-parameters, as was done in [9]. The analyzed transmitter is composed by a DAC, a reconstruction low-pass filter (LPF) which selects only the 1st nyquist zone (NZ) and power amplifier at the end.

In Fig. 6 are represented the values of four kernels of the X-parameter model over different input powers. In Fig. 6a is represented the magnitude of S and the T kernels which relate the output at the fundamental frequency with the input also at the fundamental frequency. Also, in Fig. 6b the angle of the same kernels is represented. Finally in Fig. 6c is represented the magnitude of S and the T kernels which relate the output at the third harmonic with the input also at the fundamental.

From Fig. 6, it is possible to notice that the gain from the input to the output at the fundamental decreases with the increase of the input power ($|S_{21,11}|$), as expected. Further the conjugate response ($|T_{21,11}|$ increases with the increase of the input power, which is a typical characteristic of power amplifiers [10].

It can also be observed in Fig. 6c that the output 3rd order distortion increases with the increase of the input power ($|S_{23,11}|$), which is once again an expected value result.

It is important to enhance that using the information gather using the proposed framework (in this second example in a form of a model), pre-distortion techniques can be applied at the digital domain in order to reduce the distortion present on the output signal.

5. CONCLUSIONS

In this paper we have presented an overview of characterization approaches suitable for emerging RF mixed-signal radios and dedicated measurement arrangements capable to fulfill the user needs mainly at the signal processing and simula-

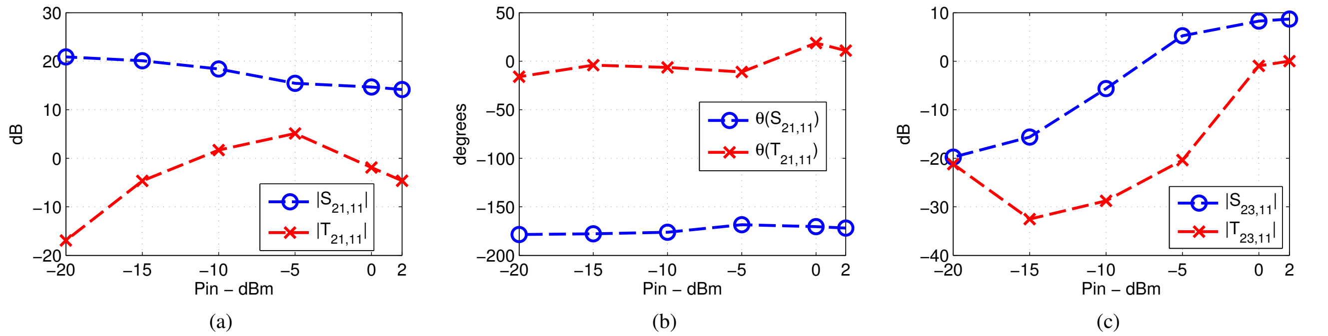


Fig. 6. Some X-parameter kernels of an integrated transmitter over input power, from [9]: (a) Magnitude of $S_{21,11}$ and $T_{21,11}$; (b) Angle of $S_{21,11}$ and $T_{21,11}$; (c) Magnitude of $S_{23,11}$ and $T_{23,11}$.

tion/compensation levels.

It is clear that building a test system to solve the challenges created by current integrated RF modules is no longer a simple problem. It requires a careful evaluation of expanding test requirements and an architecture that can last over time. Thus, it is very relevant to choose a platform that can harness the technology curve while enabling abstraction and integration.

As well, the capability to extract linear and nonlinear information from the measured data is a truly requirement, which would then facilitate the construction of optimized digital signal processing algorithms.

REFERENCES

[1] J. Mitola, "The software radio architecture," *IEEE Commun. Mag.*, vol. 33, no. 5, pp. 26–38, 1995.

[2] Agilent Technologies, *Software Defined Radio Measurement Solutions*, July 2007, Available: http://cp.literature.agilent.com/litweb/pdf/5989-6931EN.pdf.

[3] P.M. Cruz, D. C. Ribeiro, and N.B. Carvalho, "Measurement Setup for Linear Characterization of a Mixed-Signal SoC Wideband Receiver," in *IEEE Radio and Wireless Symposium (RWS)*, Jan 2014.

[4] Tektronix, *Introduction to Mixed Signal Test Solutions*, May 2008, Available: http://www2.tek.com/cmsreplive/tirep/5732/3GW_20213_0_2009.08.06.16.40.57_5732_EN.pdf.

[5] "IEEE Standard for Terminology and Test Methods for Analog-to-Digital Converters," IEEE Std 1241-2010 (Revision of IEEE Std 1241-2000), Jan 2011.

[6] P. Cruz, N.B. Carvalho, K.A. Remley, and K.G. Gard, "Mixed analog-digital instrumentation for software-defined-radio characterization," in *IEEE MTT-S Int. Microwave Symp.Dig.*, June 2008, pp. 253–256.

[7] D.C. Ribeiro, P.M. Cruz, and N.B. Carvalho, "Corrected mixed-domain measurements for software defined radios," in *42nd European Microwave Conference*, Oct. 2012.

[8] Agilent Technologies, *Understanding Component Characterization Using the PNA-X Series Microwave Network Analyzers*, Sep 2010, Available: http://www.agilent.com/about/newsroom/tmnews/background/PNA-X/index.html.

[9] D.C. Ribeiro, P.M. Cruz, and N.B. Carvalho, "Synchronous Frequency Domain Measurements for the Extraction of X-parameters in Digital to Analog Transmitters," in *IEEE MTT-S Int. Microwave Symp.*, June 2013.

[10] J. Verspecht and D. E. Root, "Polyharmonic distortion modeling," *IEEE Microw. Mag.*, vol. 7, no. 3, pp. 44–57, 2006.