TX system-level analysis by behavioral modeling of RF building blocks: the IEEE802.11a and IEEE802.15.3a case studies

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***Abstract*—The paper highlights some of the newest results achieved in the framework of the *Transmitter Modeling for wideband access transmitters* work package within the IST-EU Network of Excellence TARGET. Two cases of study have been considered to discuss the outcome, namely the IEEE 802.11a WLAN and the IEEE 802.15.3a UWB. A specific discussion about the subsystem modeling requirements in terms of key parameters allow the construction of subsystem models capable of numerical efficiency and accuracy. The subsequent insertion of such subsystem behavioral models allows fast and accurate co-simulations of complete transmitters for the performance investigation.**

***Index Terms*—Behavioral modeling; System level analysis; WLAN; UWB.**

I. INTRODUCTION

Broadband wireless access applications such as WLAN, UMTS, LMDS, WSN, etc…, require low cost, power efficiency and system-wide optimized transceivers. Moreover, a high flexibility is required when wireless terminals will have to cope simultaneously with several standards, which is one of the main objectives in 4G communications aiming at the integration of different applications. This paper is aimed to highlight the effects of the transmitter's subsystems on the signal processing for some of the above applications. Conventionally, most of the Tx corrupting effects are related to the power amplifier (PA), while the remaining sub-systems are considered mostly ideal. Here we consider the PA embedded in a complete non-ideal system, i.e. a system where analog and digital sub-systems interact, introducing their corrupting effects during the transmission process.

The goal is twofold. Firstly, the investigation of the key sub-systems and the identification of the most critical features, which therefore have to be accurately modeled. Secondly, a proper sub-systems' specifications trade-off preventing severe and too conservative specifications for the PA. This opens the door to new efficient simulation strategies of mixed-signal architectures by means of a detailed behavioral modeling of the different subsystems. In most cases, behavioral models are the only solution to perform an optimization of system level parameters such as Bit Error Rate (BER) or Error Vector Magnitude (EVM) in acceptable CPU times.

Behavioral models should not hide too many details, otherwise important signal-degrading effects are not seen in the simulations. On the other hand, they should be as easier as possible and associated with a straightforward identification procedure.

In this paper we propose an analysis strategy to the selection of the best suited model approach for a given subsystem and application. Next paragraphs will deal with the description of this vision, along with practical examples.

II. TX SYSTEM-LEVEL SIMULATION STRATEGY

In order to describe in details the technique, we refer to two wireless applications that exhibit different requirements in terms of subsystems specifications, namely the WLAN working under the IEEE 802.11a standard [2] and the Ultra Wide Band transmitter working under the recommendation IEEE 802.15.3a [3]. The data provided in remaining sections will deal only with the analysis of the physical (PHY) layer. Figure 1 reports the proposed analysis strategy flow.

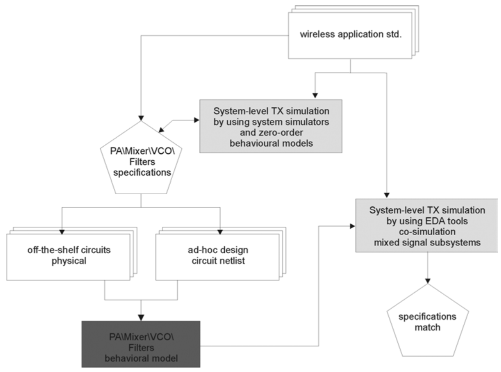

Fig. 1: flow chart of the system-level analysis strategy

Two distinct analysis phases are observed. The first one is based on a simple and schematic modeling of the main building blocks, henceforth we will refer as zero-order behavioral models. This class of models considers static non-linearities which in some cases are embedded in dynamic linear blocks. Such models are aimed to identify the main specifications of the transceiver sub-systems. The second phase is performed by using commercial mixed-mode co-simulations engine tools capable to implement the use of more accurate behavioral models. The scenario is realistic, provided the reliability of the behavioral models, from either circuit-netlist defined or physical subsystems.

A. High Level Analysis

The first step of the system analysis considers pure system simulator tools, e.g. Matlab\Simulink, typically based on a visual language. They have recently reached high degree of flexibility in describing modern communication systems, allowing even a real time simulation of the adaptive capability of the system. The latter is a feature of dramatic importance as it allows adjusting the modulation and coding scheme, frequency, power and data rate parameters to counter communication interferences and channel changes. Such a simulation environment causes severe constraints in the subsystems models, thus often preventing the use of the most accurate techniques. At this level of the analysis, the subsystems are characterized by the following features:

- driving amplifier and power amplifier: Pin/Pout AM-AM and AM-PM distortion, ideal matching, noiseless,
- mixer: pure voltage multiplier characterized by the AM\AM and AM\PM; frequency constant conversion behavior;
- synthesizer: static VCO including the MHz/V parameter and phase noise;
- filter: modeled by a two-port, 4 parameter broadband linear model
- channel: multipath, addictive noise and Doppler effects
- base-band: Boolean implementation of MAC and ideal description of the base-band section of the PHY layer.

First of all the mandatory frequency planning and a preliminary set of sub-system specifications of the system architecture are defined. The latter can be initially guessed starting from the normative specifications and selecting the off-the-shelf subsystems and\or ad-hoc circuit solutions designed for the specific purpose. At this level the superior numerical efficiency of the zero-order model is the only available instrument to reach the goal.

The next phase consists in the investigation of the system performance sensitivity with respect to some of the subsystems' specifications. For example, in order to assess the influence of the TX linearity on the system performance, the main peer-to-peer communication parameters, such as BER or EVM, are simulated and observed at different PA P1dB and with different channel models. A further analysis may consist in adding artificial degrees of long-term memory effects, by cascading filters to amplifiers and mixers, and observing the corruption of the EVM or the BER. If a meaningful sensitivity to the low-frequency memory effects is not observed in some subsystems, e.g. in mixers, behavioral models can be identified without taking this feature into account.

B. System Level Analysis by means of Higher Order Behavioral Models

According to the results obtained in the first simulation step, a deeper investigation and verification is performed by using appropriate behavioral models of the main sub-systems. These models should cover accurately the relevant signal degrading effects investigated at the previous level, while, at the same time, they should not be too complex such that simulations are slowed down too much. Furthermore, the construction of such models should not be too time-consuming although complex measurement set up and post processing are often required.

The treatment of the extraction procedure of such kind of behavioral models is still a subject that stimulates new researches and it is beyond the scope of this paper. We will refer to available literature for the description of the higher-order behavioral model adopted in the next description. In this phase we concentrate on the capability of such a model to describe the complex performance of the system in terms of EVM, BER and spectrum mask. In some cases the data are compared with the one obtained with circuit-level simulation.

III. The Cases of Study

A. IEEE 802.11a WLAN

The first example considers the case of the IEEE 802.11a WLAN; the use of the zero-order models allowed the definition of a system architecture based on a double up-conversion with image rejection and an amplifier chain constituted by a driver and a PA. The 1st stage LO frequency is 650 MHz; the channel selection is then obtained by tuning the 2nd stage LO frequency in the range 4.530-5.155 GHz. Final amplification is obtained by means of a two stage amplifier; the second stage has a variable gain in order to properly set the output power according to IEEE specifications [2].

System sensitivity is investigated by varying meaningful subsystems parameters and observing the resulting EVM and BER. Figure 2 reports the analysis of the BER as a function of the Input Back-Off (IBO) in different channel and Doppler spread conditions in the case of a 54Mbps link with a 30 dB Signal to Noise Ratio.

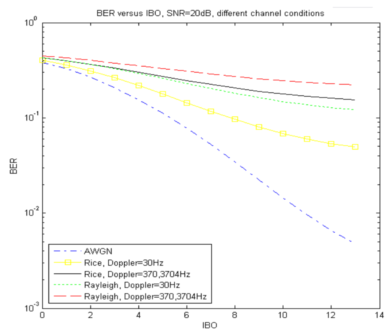

Fig. 2: BER versus PA IBO in with different channel models, for the WLAN link

Notice that at low Doppler level, in both Ricean multipath and AWGN (only Gaussian noise, not multipath) channels, an IBO augmentation is clearly perceived by the users as a data rate increase. It can be concluded that in presence of high Doppler and/or Rayleigh multipath (not line-of-sight), it is not recommendable to increase IBO: users may percept a battery reduction without significant compensation in data rate improvement. The system designer may conclude that an accurate channel characterization is mandatory in the WLAN system level simulation.

The impact of the signal source phase noise (PN) was investigated in terms of EVM, by simulating the IEEE 802.11a transceiver with a noisy oscillator, in presence of a PA with an output IP3 ranging from 10dBm to 40 dBm.

Simulation results are reported in Fig. 3. The single-side carrier ratio (SSCR) profile of the oscillator was set as shown in Table I.

Table I: Oscillator SSCR Noise profile

Frequency Offset	SSCR [dB/Hz]
1 kHz	ΔP (Sweep Variable in dB)
10 kHz	ΔP – 30 dB ($1/f^3$ region)
100 kHz	ΔP – 50 dB
1 MHz	ΔP – 70 dB

According to the typical PN data of many off-the-shelf VCOs working in the same frequency range, 10 kHz has been set as the corner frequency between the $1/f^3$ and the $1/f^2$ regions. The SSCR has been swept from -70 dB to -30 dB. If the linearity of the PA is not critical (OIP3 > 30 dBm), the IEEE specification (-25 dB for a 54 Mbps link) is accomplished if the noise power of the 1 kHz offset tone is at least 45 dB below the carrier power. Moreover, a SSCR in excess of -60dBc/Hz at 1KHz offset is enough to minimize the link sensitivity from this parameter.

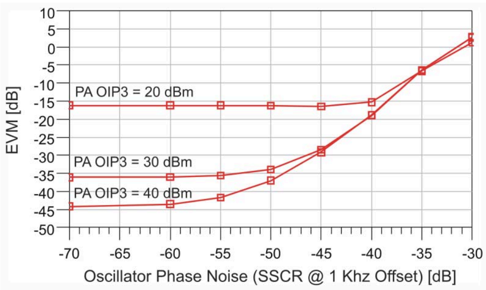

Fig. 3: EVM versus Oscillator Phase Noise for different PA Output Third Order Intercept values

In the case of the WLAN phase noise will be the only feature to be preserved by the behavioral model.

Figure 4 reports the effects of the PA and Mixer linearity on the transmitter's EVM.

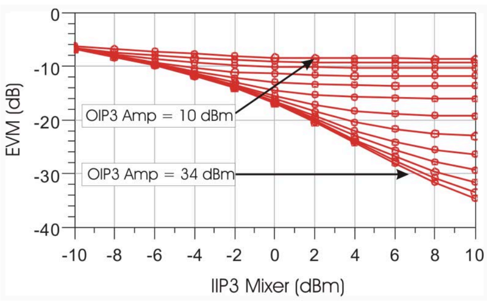

Fig. 4: EVM versus Mixer IIP3 and Amplifier OIP3

Mixer's Input Third Order Intercept (TOI) has been swept from –10 dBm to +10 dBm, while the Output TOI of the Power Amplifier ranges from 10 dBm to 34 dBm. As it can be seen, provided that the system performances are not heavily degraded by one of the two blocks, a trade off is available between mixer and amplifier properties in terms of linearity.

From the above graphs, it can be concluded that the four subsystems, namely the VCO, the PA, the mixer and finally the channel model, simultaneously determine the overall performance of the TX. The features that have to be considered are those investigated above, plus the memory effects, at least for the PA.

B. IEEE 802.15.3a

The second example considers the case of the UWB transmitter. It is based on a single IQ up converter driven by a synthesizer, whose architecture is the one proposed in [3]. The power level are such to determine a transmitted power density below -41.3 dBm/MHz in the 3.168 GHz 4.752 GHz band. From the mixer point of view, if a single stage up-conversion scheme is chosen, this implies an extremely low LO leakage. The transmitter architecture adopted in this work is based on an active balanced mixer; this choice allows a lower LO level (around -10 dBm) and, at the same time, it provides a good LO rejection to the output port. Moreover, if the active mixer's properties in terms of conversion gain and linearity are compatible with the maximum allowed output power level (-10.3 dBm), no more amplification is needed and the mixer can be directly connected to the Tx antenna. In the simulation setup the baseband part of the transmitter is supposed to produce the In-phase and quadrature signals with a power level of around -15 dBm each. Taking into account the losses of the IF and RF filters, this value implies a total Tx chain Gain of approximately 4-5 dB. The first test considers the combined channel model and TX linearity. Similarly to the WLAN case different channel model have been considered, the only difference consists in the incorporation of the gain in the frequency conversion subsystems. The sensitivity of the UWB radio to both the channel and the linearity of the system for a 200Mbps link is reported in Fig. 5. In this case the results suggest to investigate the effects of the mixer linearity.

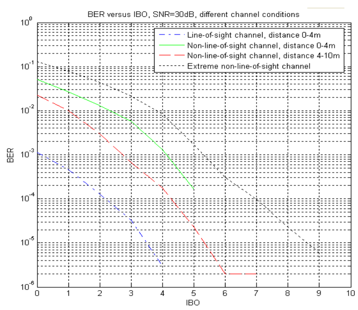

Fig. 5: BER versus PA IBO in with different channel models, for the UWB link.

System level simulations in terms of BER versus Mixer 1dB Output compression point for various link ranges are reported in Figure 6. As it can be seen, if the mixer 1dB compression point is higher than -2 dBm the overall performance of the system is not affected by the mixer linearity. This is can be explained considering that, according to the characteristics of the multi OFDM UWB signal [3], a maximum dynamic peak of around +1 dBm is expected on the output of the I/Q modulator. From the modeling point of view, in the UWB case a frequency dependent model for the mixer [4] is strictly required, since in principle a dispersive behavior cannot be excluded on a 1.584 GHz bandwidth. The BER degradation with respect to the in-band ripple is reported in Table II.

Table II: effect of the mixer in-band ripple (200Mbps;5meter)

Total ripple	0	1	3	5
BER%	2.4	2.7	3.3	3.5

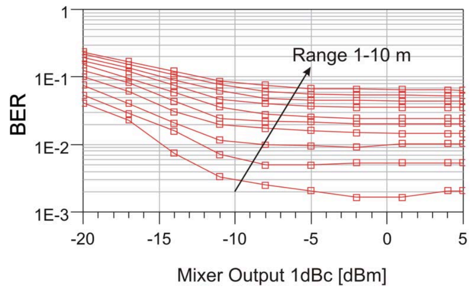

Fig. 6: UWB BER vs. Mixer 1 dBc compression Point

The next step is to consider the non idealities related to the signal source. As far as the frequency hopping in the UWB-OFDM standard is concerned, the VCO (frequency synthesizer) behavioral model must account for dynamics and phase noise (time jitter). Since the number of possible output sates is very low (three different frequencies) we decided not to use a complete VCO nonlinear dynamic model [5], but rather to implement a simple description of the VCO signal, with associated dynamics and jitter, based on standard components at the schematic level (i.e., signal sources, filters, switches, frequency/voltage converters, etc..). The component parameters were computed by fitting the model response to circuit level simulations of the frequency synthesizer.

IV. System Level Simulations

A. IEEE 802.11a WLAN

Behavioral models of the Mixer, the PA and the Oscillators have been used for the final simulation of the WLAN transmitter. In this case the models consider the PA frequency dependent nonlinearities and low-terms memory; the VCO model considers only the phase noise, while the mixer is represented by static multiplier embedded in a frequency dependent dispersive block. Results, in terms of the output constellation for a 54 Mbps link, are reported in Figure 7. The same simulation setup produces an EVM of –28 dB, which is compliant with IEEE specifications (-25 dB).

B. IEEE 802.15.3a UWB

The UWB transmitter has been simulated using ad-hoc behavioral models of the synthesizer and the mixer. The first is described in [5] while the latter in [4]. The latter was designed using SiGe BiCMOS process ad it is able to provide a maximum output power of 0dBm with a OIP3=10dBm and a conversion gain of 4dB. Figure 8 reports the simulation result in terms of the transmitter output spectrum for a 200 Mbps rate. The associated BER for a 5 meter link in a multipath environment is 0.034.

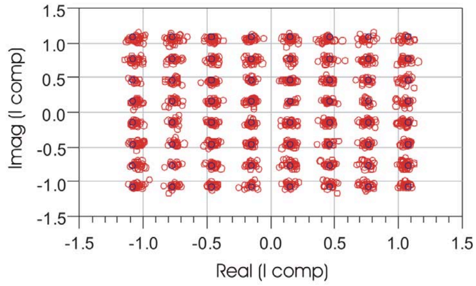

Fig. 7: WLAN Constellation (54 Mbps link)

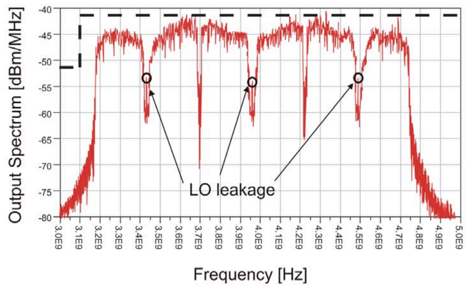

Fig. 8: UWB Transmitter Output Spectrum

V. Conclusion

The purpose of this paper is to document the activity of the Workpackage '*Transmitter Modeling for wideband access transmitters'* exploited in the framework of the IST-EU Network of Excellence TARGET. An effective analysis strategy, with the aim to furnish the instrument of a conscious specification trade-off among all the sub-system specification, has been presented. In spite of the high accuracy of the modeling techniques for the latter, the goal is to identify the more sensitive parameters for a given application and on those concentrate the efforts of the sub-system modeling. The technique can lead straightforwardly to an accurate verification of complete transmitters in their realistic environment.

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