A New Approach for Accurate System Level RF-Transceiver Front-End Modeling

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Abstract **– The development of wide-band systems for high-speed data transmission requires extensive and accurate modeling and simulations on system level. The methodology of algorithmic and baseband modeling is already established well, whereas the integration of RF parts is usually done very improper. This paper introduces modeling of RF components to be used in transmitter and receiver architectures, based on the equivalent baseband modeling approach. Two types of modeling approaches are proposed with example and usage merits. The models consider non-idealities like nonlinearity, noise introduced by the block, etc. Methodologies of detailed RF modeling are explored for low noise amplifier (LNA), basically using the S-parameter design approach. The model generates amplifier stability, noise figure, and constant gain circles along with various other factors.**

1 INTRODUCTION

The degrees of freedom to specify and partition the modern communication systems have increased. In parallel more precise system and block specifications have to be generated out of a more detailed system simulation. With SystemC it is possible to describe sophisticated communication systems completely and the areas of front-end, digital baseband and software can be considered on a common development platform with interfaces between these disciplines. SystemC comes along with a methodology that can be used effectively to create software algorithms, cycle-accurate models of hardware architecture, interfaces of SoC and system-level design [5]. The usage and the benefit of SystemC for Front-End modeling will be discussed in more detail in further sections. Based on previous work results on improving the top-down design flow of RF-Communication systems and increasing the modeling precision of RF building blocks on system level, [6]-[12], the capability of SystemC was evaluated against already achieved milestones in modeling precision. The CoCentric System Studio (CCSS) also facilitates such system level simulation [4] but is tool dependent.

At first, the concept of baseband simulation is presented, and then its usage in one of the modeling approaches, parameterizable analytic model (PAM), is explained with an example. The more accurate modeling scheme, physical back annotation model (PBT) that uses bottom up approach is described later with its application and limitations.

2 THE CONCEPT OF EQUIVALENT BASE BAND SIMULATION

Simulations building usually involves competing aims such as accuracy of the results and minimizing usage of computer resources, which are measured in terms of memory and run time. Practicality demands that a simulation not be too massive in terms of memory requirements and that a run of interest not be overly time consuming. Run time is the factor that tends to be the most limiting, especially during the design process, where dozens or hundreds of runs may be needed to work out all the system tradeoffs and sensitiveness.

The large ratio between carrier frequency and signal frequency in wireless communication systems is a big problem in system simulation. The high carrier frequency implies a very high sampling rate. The consequences are low simulation performance, requires high computational throughput and memory. The backbone of baseband simulation is to translate carrier frequency to zero, thus requires less sampling rate that depends on the signal bandwidth but not on the carrier frequency as shown in Fig 1. The modulated carrier signal $x(t)$ is described as:

$$x(t) = r(t)\cos(2\pi f_c t + \phi(t)) = \Re\left|r(t)e^{j(\phi(t)+2\pi f_c t)}\right| \qquad (1)$$

where $r(t)$ is the amplitude modulation, $\phi(t)$ is the phase modulation and f_c is the carrier frequency. The signal that contains information is independent on the value of carrier frequency, therefore, the term including the carrier frequency can be separated from the signal part. The signal

$$v(t) = r(t)\,e^{j(\phi(t))} \qquad (2)$$

evidently contains all the information related variations and is low pass in nature, which is the *complex low-pass equivalent* or the *complex envelope* [1]. For the baseband signal the carrier frequency, f_c, is converted to zero, with $s_i(t) = r\cos(\phi)$ and $s_q(t) = r\sin(\phi)$ then $v(t)$ becomes

$$v(t) = s_i(t) + js_q(t) \qquad (3)$$

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where $s_i(t)$ is the inphase component and $s_q(t)$ is the quadrature component of the baseband signal. The magnitude (or amplitude) and phase can be calculated from these signals at any time.

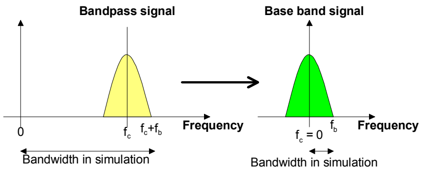


Figure 1: Passband and baseband representation of signals

The main drawback of the baseband simulation approach is that the out-of-band effects such as harmonics, frequency dependent losses, etc., cannot be represented in baseband signal

3 RF TRANSCEIVER MODELING

In the following subsections two different abstraction levels and their complementary functionality is discussed.

3.1 Parameterizable Analytic Models (PAM)

In PAM, each module of RF system is represented using its low pass equivalent type. It uses hierarchical analytic models in representing the system hence follows top-down methodology. Most of the misalignments that are introduced by the practical components are modeled as parameters. These parameters enable system engineer to tune the component model as required in different scenarios during development. This ability of configuring makes these models unique to represent any kind of architecture. For instance, the system can be represented as ideal one by simply disabling all misalignments and thus this ideal representation can be used as reference to compare other configurations.

Noise figure budgeting can be done by making all other misalignments to their ideal values except noise figure and simulations can be performed for such a representation. Presently, the noise modeling is limited to white noise with zero mean. Similarly, gain, linearity etc., budgeting can be done. Thus, these models are modular. This kind of modeling ideally suits in developing correction algorithms in digital baseband to counter the analog component misalignments. Since the digital baseband modules and these models use the same environment, by combining both of them, the required performance of an algorithm can be investigated in early design cycle itself. The advantages of this approach are: efficient in terms of simulation as the carrier frequency in simulation is zero, includes parameterizable errors that can be described in terms of analytic equations (such as phase and amplitude imbalance, bias, phase and frequency errors, attenuation and reflection losses at ports etc.). Models the noise behaviour and non-linearity of the component.

3.1.1 PAM Example

The PAM approach is used in establishing data flow set up for the direct conversion transceiver that uses many primitive and hierarchical models, implemented and analyzed in System Studio and SystemC. The set up used in CCSS/SystemC is depicted in Fig. 2. Hierarchical blocks are double lined and normal blocks are primitive models. This partitioning into different blocks enables the simulation of system level parameters (like BER, constellation variation, etc.) on front end block parameters like amplifier non-linearity, or mixer imbalance, etc.

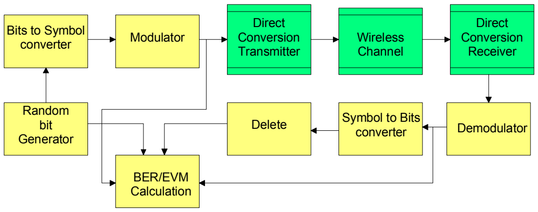


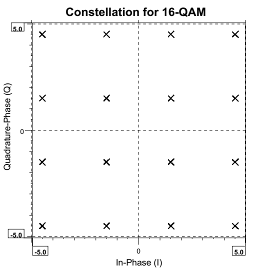
Figure 2: Direct conversion transceiver set up.

The Random bit Generator model uses primitive polynomial (modulo 2) that generates bits in each sample and is implemented by 31-bit shift register. The recurrence relation used is guaranteed to produce a sequence of maximum length. The Bits to Symbol converter pairs up the N (parameterizable) bits to output a sequence in the range of 0 to 2^N-1. Symbol to Bit converter performs the reverse operation. Depending on the requirement different models of modulators, such as QPSK, QAM, etc. are used. For successful operation the corresponding demodulator must be selected. BER module calculates bit error rate. The best performance factor for the set up shown in Fig. 2 is error vector magnitude (EVM) measurement. The EVM model uses a reference signal to determine the error vector and magnitude of the received signal. Wireless channel model uses a free space propagation model [3] for attenuation that is proportional to frequency of operation and line of sight distance between the transmitter and receiver. Rayleigh fading is used to model the multipath effects. Channel noise is modeled as Gaussian.

The hierarchical model capturing the behavior of direct conversion transmitter consists of DAC, filter, baseband amplifier, mixer, filter, power amplifier, and antenna blocks. The DAC model normalizes the input value to the specified value, and the repetitive spectra after sampling is filtered out by a filter. Quantization noise can be added optionally. In baseband and power amplifiers, the amplification of the signal depends on the gain, 3rd order intercept point and 1-dB compression point. The mixer model includes inaccuracies like bias, quadrature and imbalance errors along with phase noise and conversion loss. As there is no separate model for local oscillator the phase noise model is used in the mixer itself. The antenna is modeled with antenna gain. All models include noise addition and reflection losses to model matching imperfection.

The direct conversion receiver consists of antenna, LNA, mixer, filter, baseband amplifier and ADC. After passing the transmission channel the received signal is picked up by the antenna and fed to the low noise amplifier (LNA). Antenna model is almost same as that of transmitter. The LNA is modeled with amplification features such as gain, non-linearity and non-idealities that are common for all blocks. The S-parameter design approach [7] is used to check the amplifier stability, to find out the information about noise figure, constant gain and stability circles, to calculate unilateral figure of merit and simultaneous source and load matching impedance for optimum performance of amplifier. In addition to the transmitt-er mixer, the receiver mixer incorporates frequency error generation and correction models. The first one generates the specified amount of error in degrees taken as a parameter and the latter, takes from the input port to carryout the correction operation. These primitive models use the relation ($\omega = d\phi/dt$) between angular frequency, ω, and phase, ϕ, in imple-mentation. A two-stage baseband amplifier and ADC follow the mixer. The model of the latter one includes ADC quantization noise. The data samples are denormalized to retrieve the original values. Because of unmatched filter response and other factors exact retrieval of data symbols (as fed to DAC) may not be possible. As a consequence, an error occurs due to incorrect sampling. A timing error detection model is used to overcome this problem. This model uses integral control to track the errors. An interpolator is used to calculate the exact sample value.

3.1.2 Simulation results



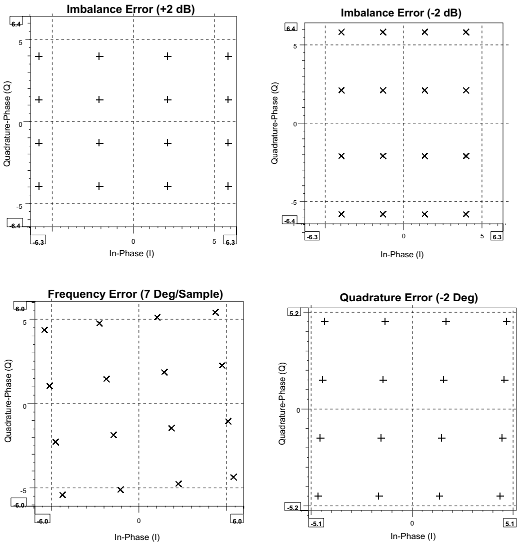


Figure 3: Simulation results of PAM.

The above direct conversion transceiver set up is simulated in CCSS for several misalignments with different modulation schemes. The simulation includes various errors with and without noise in the PAM approach. Some simulation results for 16-QAM-modulation scheme are presented in Fig. 3.

3.2 Physical Back Annotation Model (PBT)

This second approach captures the exact input-output behavior of the system. In this approach, a RF subsystem is developed in a simulation environment (such as ADS2002) that allows precise (even physical) modeling of RF component. Then the model is tested for its full specifications. Once the model found to be compliant to specifications, the input–output behavior in the required power range is captured. These measured values are back annotated to the system level using a table. A special model template is developed in SystemC to use this table as a lookup table, by using interpolation if needed, for the particular model or system. In this approach, the model in SystemC for almost all front-end components is same, just the look up table is changed according to the requirements. This model suits well for modeling single tone response. In the extended approach it requires many data tables to capture the multi-tone or frequency band effect in simulation. In such a case, filters are used to model the frequency dependency variation. The analog circuit is simulated for the frequency band of interest and the data in different cases are captured as said above. The suitable interpolation filter(s) is/are designed to capture the effect of frequency dependency. Then the model looks as shown in Fig. 4, a data table and a filter. The filter is designed to meet the requirements of the amplifier frequency response in a pre-defined band. For single tone, this approach is verified for power amplifier. The amplifier's AM-AM and AM-PM nonlinearity is shown in Fig. 5.

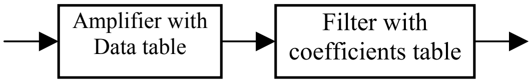


Figure 4: PBT model of an Amplifier.

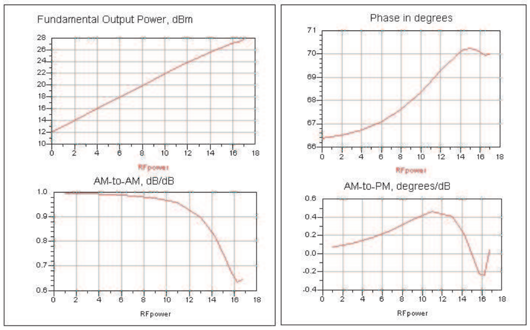


Figure 5: AM-AM and AM-PM response of the amplifier used in PBT model (simulated in ADS).

Merits: The PBT modeling approach can represent exact input-output behavior of the component/ system captured for single tone; a single look up table can even represent an entire system, provides guaranteed response, the model represents many effects that were considered in the RF simulator and requires less simulation or runtime. The drawbacks: misalignments are not parameterizable, no tuning is possible at the system level as the lookup table is fixed. But the new lookup table with required parameters can be generated from the RF simulator very easily, more look up tables and filter(s) are required to capture the frequency dependent variation. This approach needs RF simulator to generate component response.

4 CONCLUSIONS

As each presented approach (PAM and PBT) offers essential benefits, it is better to support both approaches for implementation and to combine them in complementary manner to obtain full advantages. The best strategy is to use PAM approach at first while deriving initial specifications or developing algorithms, etc. Once the circuits are developed then data tables can be generated for the required blocks from simulation. After generating data tables, earlier PAM models are replaced with one or more PBT models with appropriate data. Now, the simulation is performed with the same test environment but with more accurate models. This resembles the traditional top-down and bottom-up approaches used in most system designs to utilize the advantages of both.

Acknowledgements

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