Behavioral Modeling of Digital Pre-Distortion Amplifier Systems

By Tim Reeves, and Mike Mulligan, The MathWorks, Inc.

ABSTRACT - With time to market pressures in the wireless telecomm industry shortened designed cycles are of the essence. One of the most intensive components to design in the wireless telecomm realm is the power amplifier assembly. This is a multi-discipline design challenge that incorporates both digital and analog design into the same assembly. In order to meet these design timelines, accurate high level behavioral models that can serve as the amplifier assemblies' "executable specification" need to be developed at the commencement of the design cycle. Herein a methodology is presented that begins with a high level behavioral model of an RF amplifier and then incorporates this RF amplifier into a Digital Pre-Distortion (DPD) algorithm. Key performance characteristics such as Error Vector Magnitude (EVM) and Adjacent Channel Leakage Ratio (ACLR) are characterized. Finally, the digital pre-distortion approach is incorporated into a communications system that is based on IEEE 802.16-2004 and key system performance parameters such as bit error rate (BER) are evaluated for different signal to noise ratio (EbNo) values.

Traditional RF design methods

Today's wireless communication systems and subsystem components are built by multidisciplinary teams. The overall system or subsystem behavior is the responsibility of the project technical lead for individual components or the system architect for large scale integrated systems. Implementation of each subassembly into a component's main assembly involves specialized design teams including experts in signal processing, RF engineering and other technical disciplines. Smooth integration of these discipline specific teams is the key to success.

In the past, the design process began with the subsystem component architecture team developing a paper specification that guided the work of each of the various design and implementation disciplines: embedded software, digital hardware and analog hardware. Any flaws in the paper specification could not be detected until running the design in various hardware and software simulators, or, worse yet, at systems integration and verification. At this stage problems were prohibitively expensive to correct.

This approach, which was sufficient when system and subsystem designs were relatively simple, is all but obsolete now. As the complexity of RF systems and subsystems increases, the complexity of implementing these systems and subsystems increases. For example, a Digital Pre-Distortion (DPD) amplifier assembly is compromised of multiple design disciplines including embedded software, digital hardware and RF hardware subsystems each of which are technically complex. The complexity of specifications required to define the latest DPD Amplifier assemblies make the use of a text document to capture these specifications obsolete.

The risk of producing a specification that cannot be implemented for subsystems like DPD Amplifier assemblies is too great to ignore. For example, when designing a DPD Amplifier assembly capturing the non-linear effects of the RF Amplifier and evaluating the ability of the DPD algorithm to compensate for those impairments requires a system level simulation environment. Otherwise these system-level interactions are difficult to detect for discipline specific design teams. Also, when engineering teams work in isolation it is difficult to explore design alternatives and find an optimum solution.

Technical leads have realized that written documents are inadequate and that early system simulation is essential. However there are very few commercially available software packages that have the ability to model embedded software, digital hardware and analog hardware simultaneously. The ability to bring these varied technical design disciplines into a single simulation environment is the focus of this paper.

Model-Based Design delivers executable specification

Project technical leads are using Model-Based Design to create executable specifications. These are superior to text-based documents because they can simulate the behavior of the proposed design. In the document-based design era, the probability of the written specification containing flaws was rather high and these would only emerge during the decoupled design phase. In contrast, with Model-Based Design one builds an executable model, which is the specification of the system, and then bases the design on it. The design portion of the project includes implementation tasks such as partitioning, circuit level design, encoding the behavior in programming code and compilation. The advantage is that an executable model can be validated, and a validated model makes the design phase far more straightforward.

Frequency and Time domain analysis

Algorithm architects develop their algorithms in the time domain which is conducive to creating signal flow diagrams. In contrast, RF engineers typically refer to the frequency response of the RF component or subsystem, in terms of network parameters as well as frequency-dependent noise and non-linearity. RF Engineers also specify hardware, design circuits, run simulations, and perform physical testing. For performing circuit simulations, RF Engineers typically work in the frequency domain and within a frequency passband. The output from these simulations is incompatible with the baseband complex time domain modeling methods that algorithm architects and signal processing engineers use.

Bridging the gap between analysis in the time and frequency domains

Using a multi-domain simulation environment allows one to bridge the gap between the frequency and time domains. With Simulink and Model-Based Design, the RF domain of the DPD Amplifier assembly can be defined and simulated at the system level. This allows one to verify the DPD algorithm as well as the RF amplifier before going to detailed designs in either the analog or digital domain.

Use of a pre-built RF domain offers major advantages. The design space can be explored rapidly by altering parameters or algorithms as well as doing full passband analysis. The goal of this analysis is to determine what component performance characteristics are required to achieve desired subsystem or assembly performance. In this way, the systems architect can generate the specification at a high level. These specifications guide the next stage: detailed circuit design.

The RF engineer can pass back realistic data generated either by a circuit-level simulator or from test equipment to the systems architect in order to verify the RF design in a systems context. This allows the architect to verify the proposed design will meet system level metrics like BER or ACLR. Again, the RF domain in Model-Based Design forms the bridge between the time domain tools used for signal processing and the frequency domain tools used by RF engineers. The conversion is more sophisticated than a simple inverse FFT from frequency domain to time domain. Real passband frequency responses are converted to their complex-baseband equivalent impulse responses. This allows the simulation to step forward at the symbol period, rather than being bogged down by stepping at the tiny carrier wave period.

Example: Applying Model-Based Design to DPD Amplifier Assemblies

Figure 1 shows an end to end model of a wireless communications link based on the IEEE 802.16-2004 OFDM physical link. It includes the baseband and RF sections of the transmitter and baseband section of the receiver. The RF section of the transmitter is a high level behavioral model of a DPD Amplifier Assembly. The overall system performance of this communication system can be evaluated with the behavioral model implementation of the DPD Amplifier Assembly. Additionally, forward error correction, channel models and an OFDM transmit and receive scheme are all included in this model.

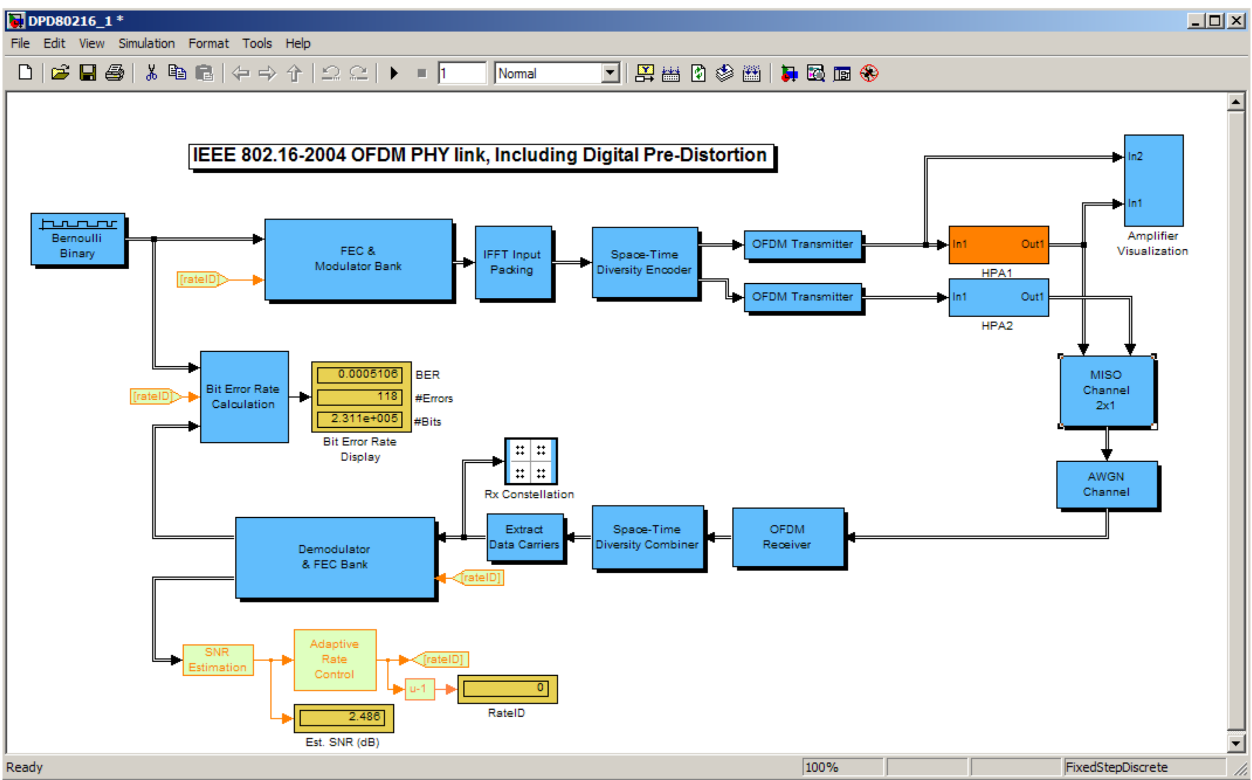

Figure 1. End-to-end model of a wireless communications link based on the IEEE 801.16-2004 OFDM Physical link.

Figure 2 shows a more detailed view of the top-level block "HPA". At these levels in the block diagram hierarchy it can be seen that the Power Amplifier assembly is represented by a behavioral model of both a RF amplifier and a DPD algorithm.

The RF amplifier behavior is modeled as a single complex baseband equivalent block based on the Saleh Amplifier model in which both AM - AM and AM - PM are characterized. For this Amplifier the performance characteristics can be implemented as shown in Figure 3. The model shown in Figure 4 can be used to visualize the input versus output characteristics of the amplifier.

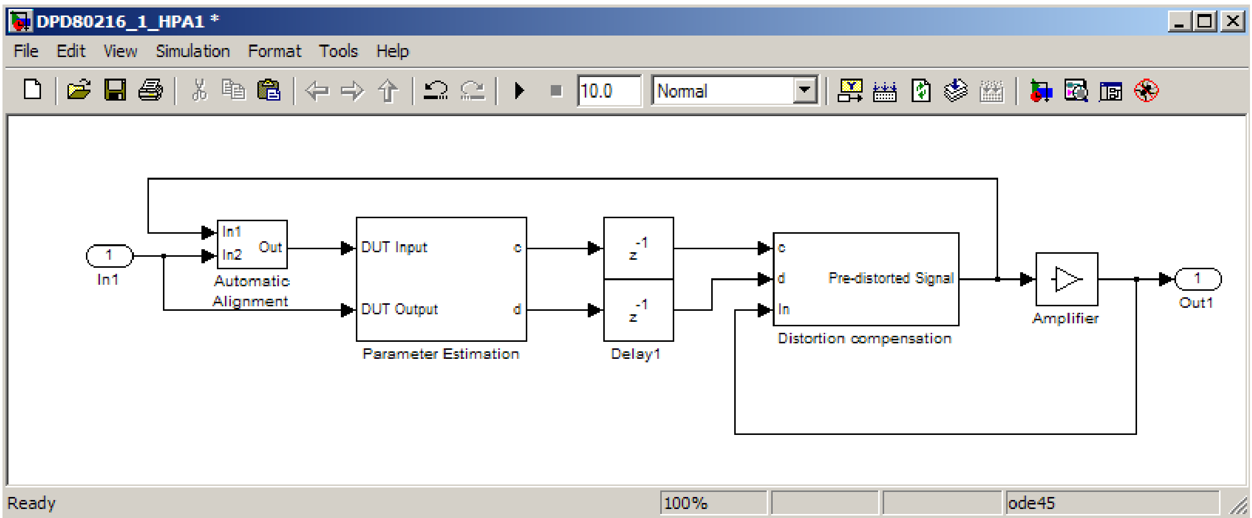

Figure 2. Under the top-level of the HPA block are both the DPD implementation blocks and the RF Amplifier behavioral model.

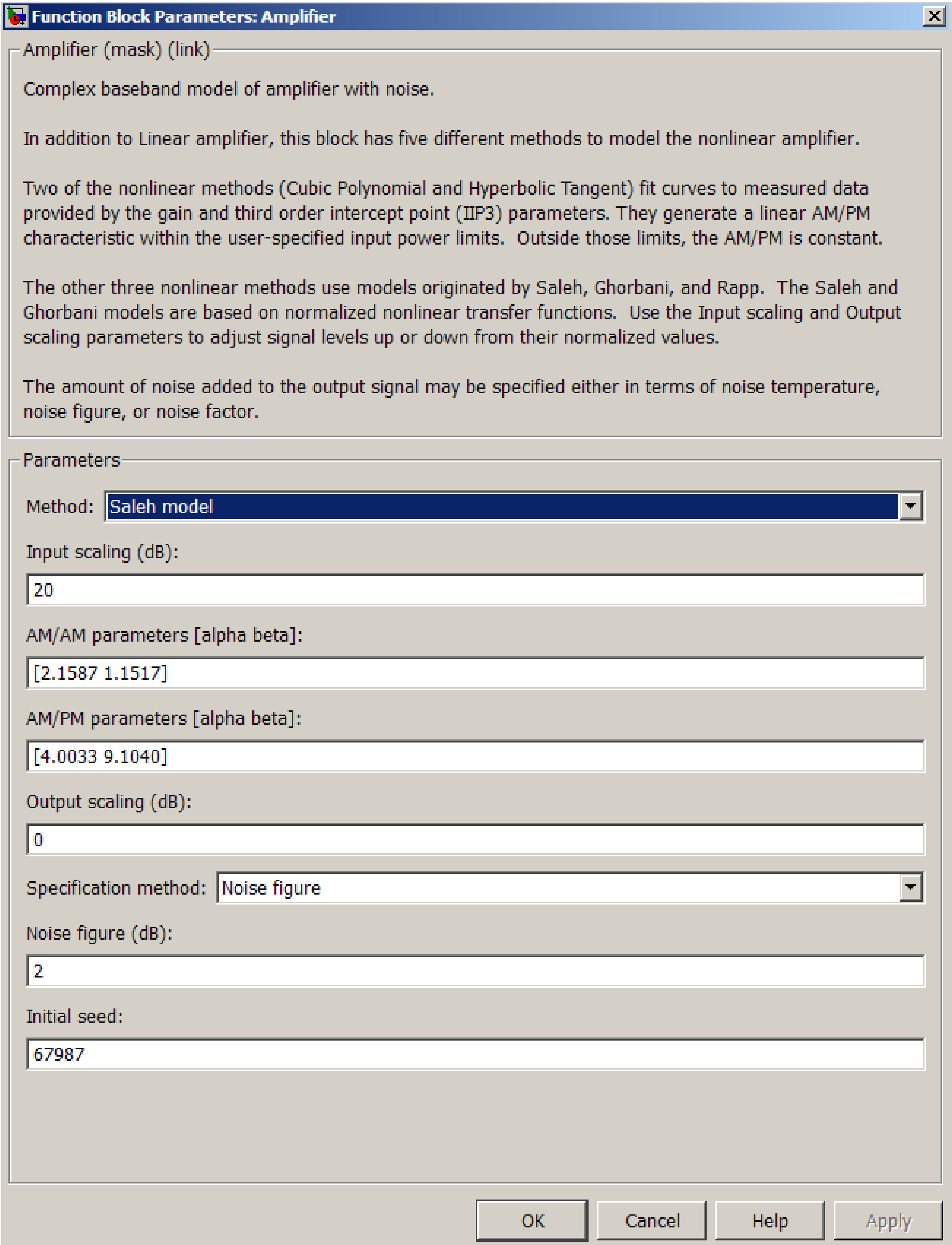

Figure 3. User interface for specifying the RF Amplifier.

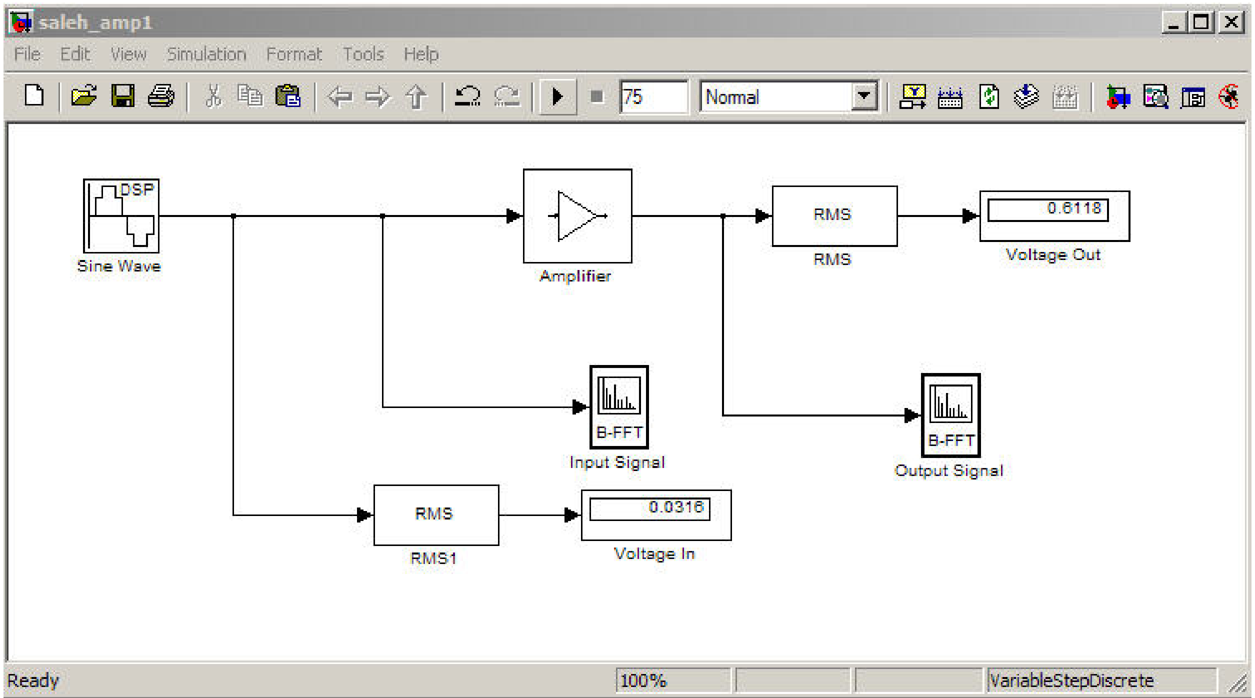

Figure 4. Measuring the output versus input characteristic of the Saleh Amplifier.

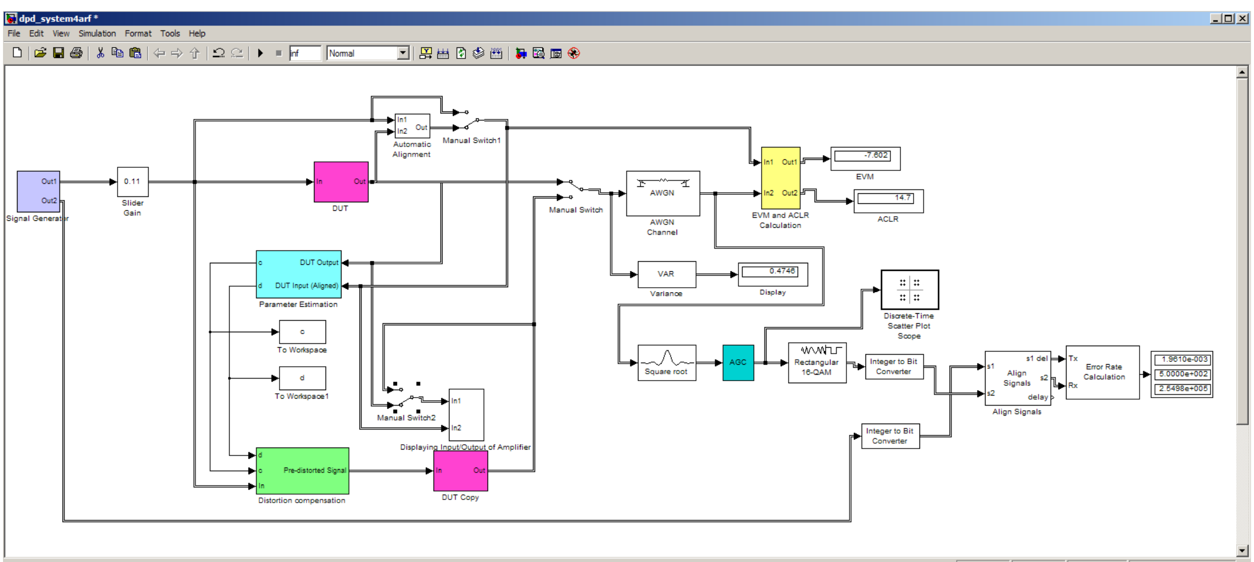

Figure 5. A test bench for evaluating DPD Amplifier Assemblies performance characteristics.

Shifting now to the DPD algorithm and its associated blocks, the algorithm's operation can be broken into three subsystems as shown in Figure 2. The automatic alignment block aligns the input signal to the pre-distorted signal generated. The Parameter estimation block is used for generating coefficients for curve fit polynomials, based off of a least squares fit, for both the amplitude and phase responses. The Distortion Compensation block uses the polynomial to generate a linear AM - AM output and a zero phase AM - PM output signal.

For the DPD Amplifier assembly it is also of benefit to be able to evaluate parameters such as Error Vector Magnitude (EVM), Adjacent Channel Leakage Ratio (ACLR), as well as Bit-Error Rate (BER) as a function of Signal-to-Noise ratio (SNR). Referencing Figure 5, the ability to evaluate all of these parameters can be done in a single model and hence the RF characteristics of the amplifier can be evaluated, in terms of the overall communication systems parameters, very early in the design process. At this point, a quick evaluation of the parameters listed above can be done for a variety of amplifier characteristics and an initial set of amplifier specifications can be done.

After an initial specification of the RF Amplifier has been completed, the RF Blockset library can be used to specify the RF Amplifier with more detailed specifications. In Figure 6, the RF Blockset library is shown that displays the different amplifier blocks available. The S-parameter Amplifier block allows the user to specify small signal S-parameter data as a function of frequency, single point noise figure and non-linear parameters such as IIP3 or OIP3, Output Saturation Power or the 1 dB gain compression point. The General Amplifier block can model an amplifier that is characterized by a data file that is generated either via third party simulation software or from measured data. These blocks can be inserted into the top level communications model and tested. Thus at each stage of the design the communication systems model can be used as a test bench to evaluate the performance of the RF components within the overall system.

Returning now to the original communication system that is depicted in Figure 1, the overall communication systems performance can be evaluated and design decisions can be made. Within the AWGN (Additive White Gaussian noise) channel the Signal-to-Noise ratio can be varied and the system's BER can be evaluated. Once the RF Amplifier is specified the rest of the system can be evaluated and verified. For example the forward error correction scheme can be evaluated as well as the OFDM transmit and receive schemes. Further this environment is conducive to start transitioning these algorithms into digital hardware.

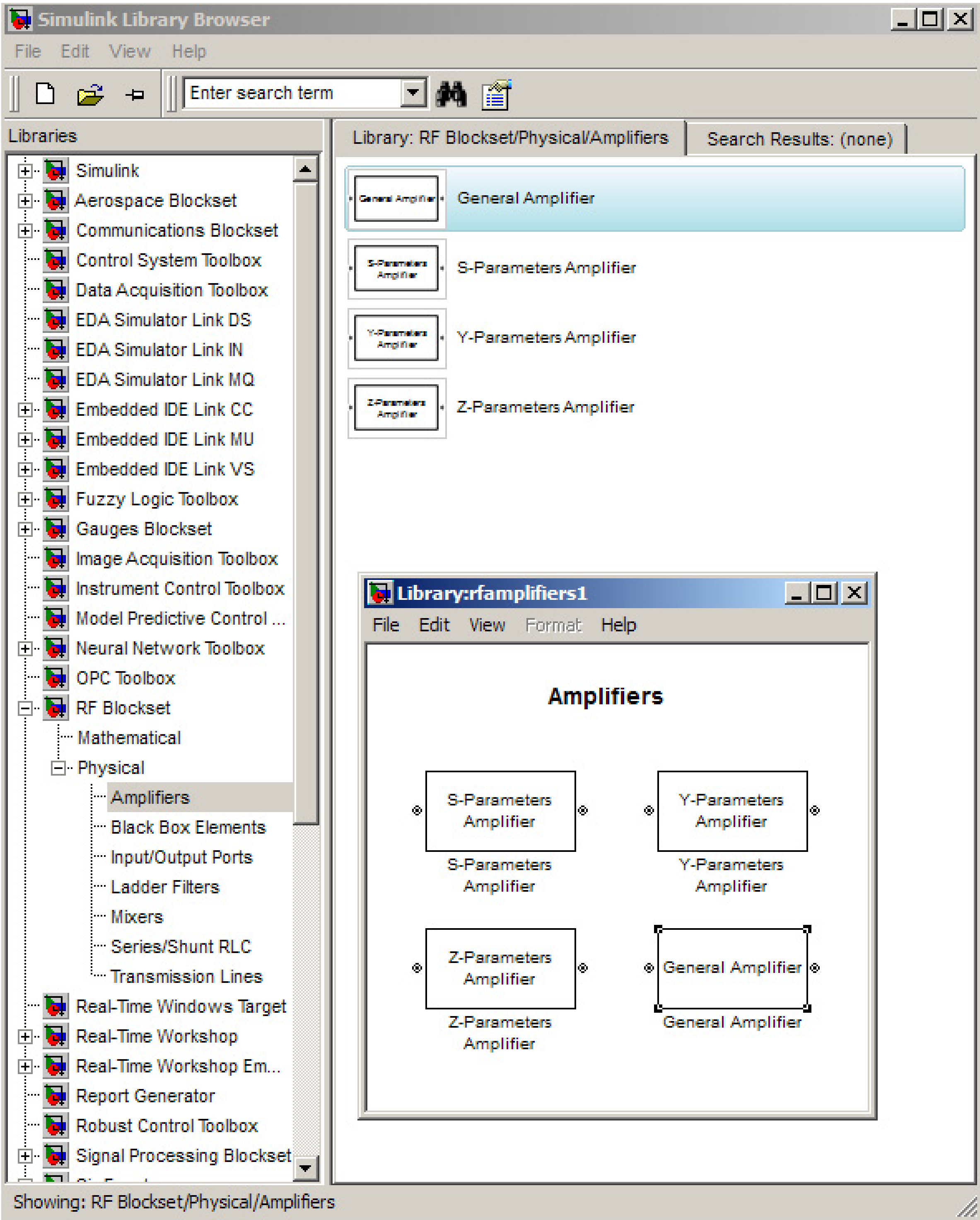

Figure 6. The RF Blockset Physical Amplifier Block Library

Conclusion

This example demonstrates how Model-Based Design makes it possible to develop RF and Signal Processing specifications in a team environment where they can be evaluated at a system level. System architects can build system level models that evaluate the performance of a communication system in terms of EVM, ACLR and BER. RF engineers can provide detailed models of RF components and DPD compensation algorithms, and determine if the proposed design meets overall system performance metrics. This approach to system design allows for the identification, diagnosis and necessary system level corrections to be done and completed at a much earlier design stage than is possible with a more traditional development process. The net result is that problems can be identified and fixed more efficiently and system-level tradeoffs can be evaluated more easily in order to increase performance and reduce cost.