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Cover Feature
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Improving System Simulation Accuracy with Measurement-based Behavioral Mode

Wissam Saabe
AMCAD Engineering, France

Zacharia Ouardirhi and Tony Gasseling
AMCAD Engineering, Canada

With communication systems evolving quickly, the main challenge for manufacturers is to design intelligent, secure and energy-efficient systems. This development is driven by the traffic generated by the various uses of mobile communications and new associated applications, necessitating the frequent introduction of new technologies to meet these requirements. The arrival of the new 5G standard has brought a radical change in the architecture of base stations with the development of active antenna systems (AAS).

To understand the complexity of these new communication systems, ***Figure 1*** shows an abstract high-level representation of the system where the problem is broken down into three parts:

- The antenna made up of many radiating elements
- The RF front-ends composed of various analog functions (like power amplifier (PA), low noise amplifier (LNA), mixer, filter and phase shifter)
- The digital modules that manage the signal processing (DSP), the beamforming control algorithms, and the non-linearity compensation of the RF circuits (DPD).

This system's design decomposition results in the interaction of several specialized teams with various levels of maturity (R&D or production, for example) and in an asynchronous design time. Controlling the cost of the overall project can be challenging if a dependency exists between these teams. For example, the sizing and adjustment of the PA linearization system entrusted to the DSP team can only be made when the circuit team produces the PA. Thus, these cascaded tasks that are required for the prototyping of certain elements result in a long time to market.

If the overall system does not meet the targeted specifications due to poor coordination between teams, very costly and time-consuming testing and adjustment phases may be necessary after the demonstrator has been manufactured. This cycle of development and production is illustrated in ***Figure 2***.

TOP-DOWN DESIGN FLOW

In Figure 2, the "Top-Down" design flow of the system consists of breaking down the system's global specifications into sub-specifications. The work of the system architect then consists of defining the sub-specifications of each circuit, making up the overall solution by balancing the constraints on each block as well as making it possible to optimize the design and production costs of the entire chain.

The more the specifications tar-

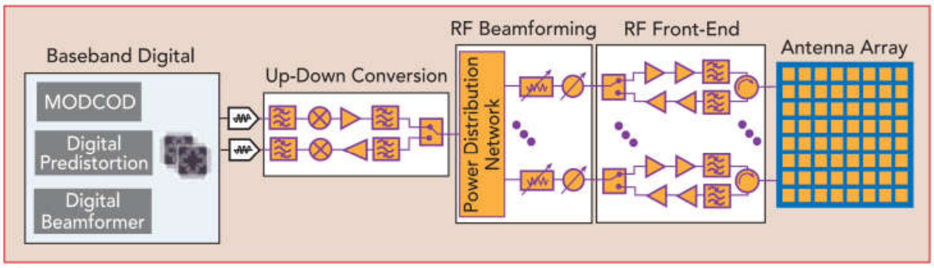
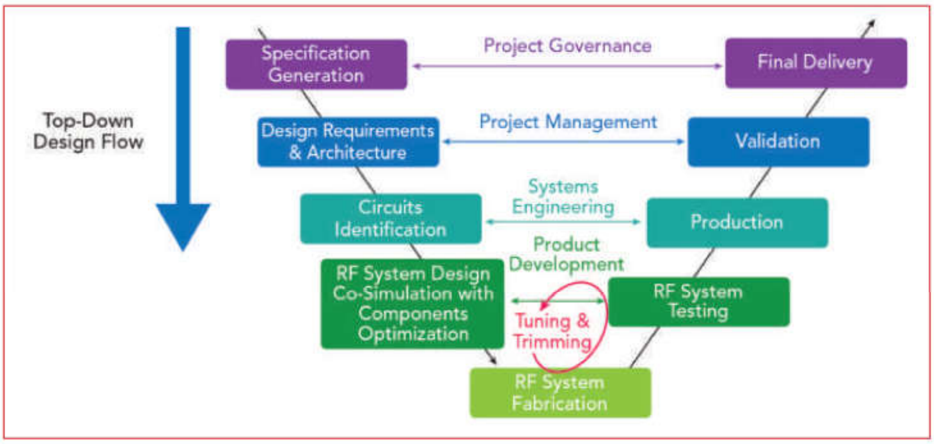
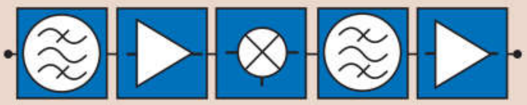


Fig. 1 Active Antenna System architecture.



▲ Fig. 2 **V-Model design cycle based on experimentations.**



	RF Filter	LNA	Mixer	RF Filter	PA
Stage	1	2	3	4	5
Gain (dB)	–3.5	12.1	–7.3	–0.8	21.2
NF (dB)	3.5	1.8	5.6	0.8	7
OIP3 (dBm)	Inf	20	Inf	Inf	Inf

▲ Fig. 3 **Preliminary system simulation made during the V-design cycle.**

geted for an element of the chain are restrictive, the more the cost of this circuit is important. The system architect indicates which specific circuits have to be developed and which circuits are already available on the shelves that have to be integrated.

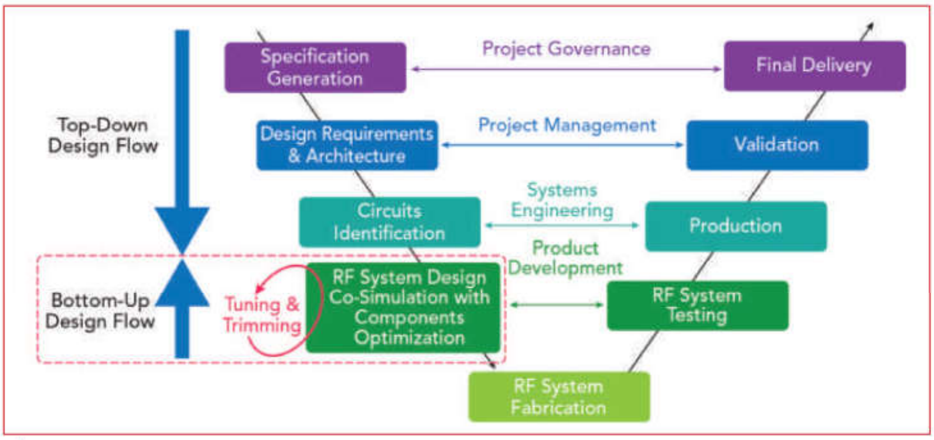
The sizing of each circuit is therefore very important. Theoretical models of each circuit can be used to pre-estimate the overall performance. Thus, the optimization of the communication system design requires simulation tools to evaluate and validate the global performance with more or less theoretical models indicating the gain, the noise factor or even the linearity criteria of each element (see ***Figure 3***).

Different options are available to the production team once each circuit composing the system has been used. The historical method is to conduct a first system assembly and see if it meets the targeted specifications. Depending on the sophistication and complexity of the signals processed by the chain, optimization and engineering phases are necessary to achieve the desired performance, as illustrated in the feedback loop in Figure 2. Depending on the system's complexity, each iteration can represent several months of work and hundreds of thousands of dollars, or even more if it is an active antenna composed of several thousand elements.

MODEL-BASED SYSTEM ENGINEERING

The preferred method of system architects now is to anticipate, as early as possible, the impact of each technological choice on the entire chain, even before the production phase, to avoid any pitfalls. Recently, manufacturers have been leaning toward a design methodology called "Model-Based System Engineering (MBSE)."[1] The approach consists of including models to support the tasks of the definition of specifications, design, analysis, verification and validation of the system at all stages of development.

Precise models for each element of the chain are then necessary. As illustrated in ***Figure 4***, the iterative loops for refining the specifications are conducted only during the simulation and are no longer in the post-manufacturing stages. In this case, total confidence is placed in the accuracy of the circuit models in the system simulation. It then makes it possible to implement a genuine bottom-up design flow



▲ Fig. 4 V-Model design cycle based on a Model-Based Design approach.

methodology, consisting of checking the overall specifications of the system before production.

The top-down design methodology has largely proven itself in designing ICs for the digital part of systems.[2] This approach makes it possible to conduct the synthesis of the circuit from the specifications. It integrates a bottom-up verification phase through dataflow simulations in the time domain (timed dataflow). These simulation techniques have proven effective due to their speed and reliability, thanks to the high level of abstraction of the digital blocks by a high-level description language.

Similar approaches are desirable for the analog part of the system, but considering critical effects coming from the RF/microwave circuits in this type of simulation is more problematic. Taking into account behaviors such as non-linearity, memory effects and mismatches, are essential for verifications at the system level. Unfortunately, circuit-type simulations have proven to be unsuitable at this high level of abstraction because of the significant computational effort and the resulting long simulation times to process wideband modulated signals.

To enable accurate and fast system simulations, a reliable behavioral modeling solution for each RF circuit is necessary to simplify each circuit's description without losing quality concerning the knowledge of the behavior of each block. This uses mathematical equations describing the relationships between each circuit's input and output ports.

These equations are used for accurately reproducing the behavior of the observed circuit, either from measurements obtained on a test bench or from more physical circuit simulations, where each elementary component constituting the circuit itself makes the object of precise modeling beforehand.

In recent years, many efforts have been made on this topic that we describe here. This article is mainly interested in PA behavioral modeling for system simulation, which is critical in analyzing and optimizing communication systems.

RFPA BEHAVIORAL MODELING

Various specialized commercial software allows the communication system's architecture design to evaluate the performance in terms of bit error rate throughout a transmission chain. These simulators are a timed dataflow type and allow the efficient simulation of information encoded in the form of a digital signal in the time domain. However, the simulation can only be realistic if it considers the degradation caused by the analog front-end blocks, particularly by the PAs.

Unfortunately, designers face a lack of effective methodology to properly model PAs at the system level, either from measured or simulated data at the scale of each circuit. Although circuit-type models make it possible to obtain realistic behaviors on relatively simple signals (CW, two-tones) thanks to analysis techniques in the frequency domain (Harmonic Balance Method), the problem is too big to

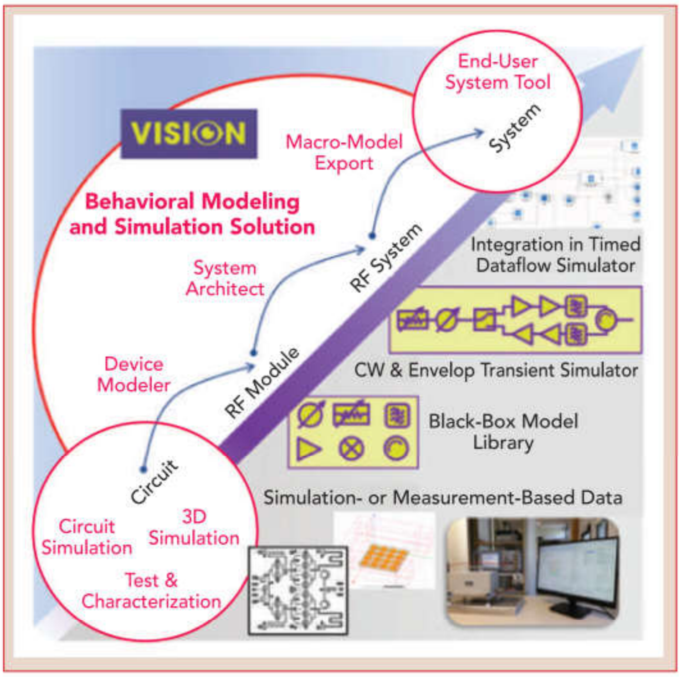


Fig. 5 A comprehensive modeling workflow.

be solved in the time domain, especially with the Envelop Transient (ET) method, resulting in prohibitive simulation times. Simulation convergence problems can also be observed. Means of characterization in measurement now make it possible to know the real performance against application signals. On the other hand, the quantity of data quickly becomes important if one wishes to measure each variation of circuit parameters (load impedance, bias, temperature) and the signal (average power, peak-average ratio, bandwidth).

Currently, models proposed in these system simulators can accurately reproduce the circuit's behavior only for stimulation conditions relatively close to those used to extract the model. For example, the Poly Harmonic Distortion Model,[3] defined as a non-linear extension of

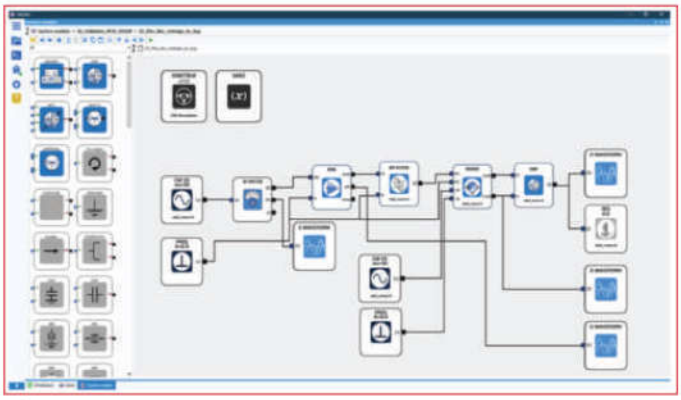


Fig. 6 System simulation schematic.

the S-parameters. This model is treated in the system simulator as the static non-linear gain of the device. Even though this model proves to be relatively precise for simulating the circuit's response when the latter is excited by a CW signal, it quickly exhibits significant inaccuracy when simulated with modulated signals.

Conversely, the Generalized Memory Polynomial Model[4] makes it possible to faithfully reproduce the output of a circuit subjected to a modulated signal. Nevertheless, the extraction of the model is only possible from measurement data due to the limitations of circuit simulators (ET simulation) and the accuracy is guaranteed only for signals having the same characteristics as the identification signal (bandwidth, average power, frequency, PAPR).

Many models presented in the literature[3] are based on variants of the Volterra series or Neural Networks. However, no implementation of these models is available in commercial simulators. Even when integrating custom models is possible, it requires specialized skills that only a few engineers master, creating a real risk for manufacturers in developing and maintaining these models.

Finally, manufacturers find themselves without an effective procedure to virtualize the behavior of their communication system realistically and benefit from all the

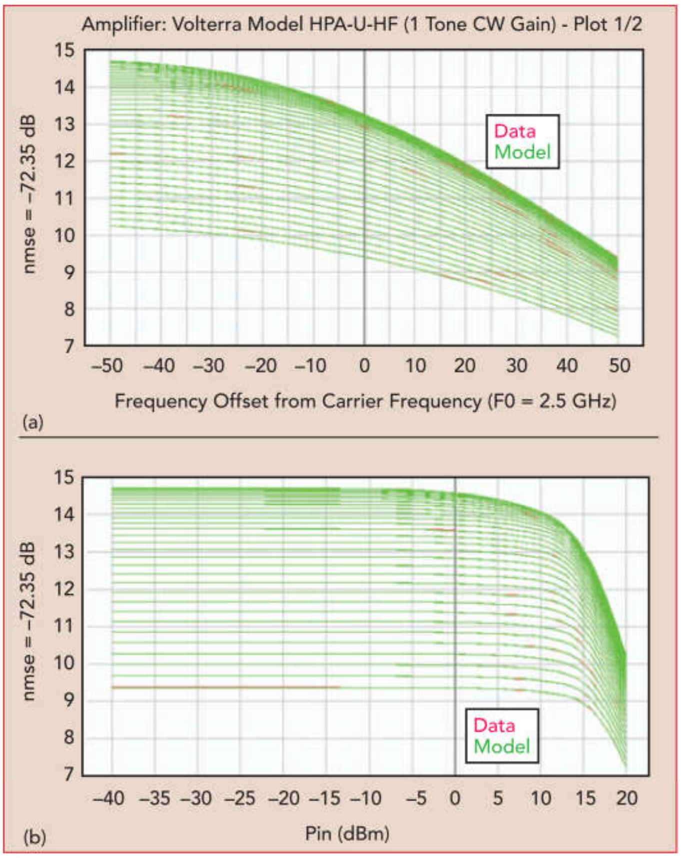


Fig. 7 **Power amplifier non-linearity modeling integrating the frequency dispersive aspects.**

advantages that the MBSE approach can bring for different use cases without the RF signal statistics being perfectly known in advance. Therefore, the solution to solve this challenge is to have available circuit behavioral models that are more general in terms of their use while limiting the complexity of the extraction procedure.

COMPREHENSIVE MODELING WORKFLOW

A comprehensive modeling workflow needs to offer a practical solution to extract, simulate and use these behavioral models in system simulators. An example of this is the VISION modeling tool. A key point offered by this procedure is to be able to extract a model from measurements or simulation results obtained at the circuit scale (see ***Figure 5***). For example, a behavioral model of a linear circuit can be obtained by a simple S-parameters characterization using a VNA or a circuit simulation.

Since this frequency-domain characterization is not directly compatible with a dataflow type system simulator, a "Device Modeler" tool can automatically create a description function in the time domain, as shown in ***Figure 6***. The user can apply this model directly in the "System Architect" environment using an "ET" simulation with broadband application signals and see the impact of the frequency dispersion of the circuit on the signal (ripple, roll-off, etc.).

Exporting the model to a system simulator allows the system engineer to obtain more realistic simulation results instead of using the circuit's nominal gain or loss (S21) value. Also, the exported model integrates the solver, which calculates the implicit relations between voltage and current at each model port, thus making it bilateral. More precisely, the incident and reflected waves at each port are available at the system simulator level.

This method allows the global evaluation of a communication system, considering the impedance mismatch of the RF block in a system simulation environment. This methodology described for a linear circuit is completely transposable to modeling non-linear circuits such as PAs. The proposed solutions benefit from the work carried out from the continuous-time modeling theory,[5] which manages large impedance mismatch and short-term memory (see ***Figure 7***).

By completely designing the architecture of the RF front-end in the comprehensive modeling workflow simulator, the system engineer can benefit from the advanced models of each circuit composing the subsystem and from the simulator's capabilities to predict the models' interactions at each architecture node.

These modeling and simulation capabilities pave the way to creating an RF front-end digital twin. This digital twin hosts an accurate representation of reality, which is used for the simulation, optimization and prediction phases at the system level. In addition, the representation stores and is fed by all the available data of each element during all the development phases of the system.

These possibilities have been echoed in several system-level applications. Now an example is presented as a hot topic for system designers: the accurate simulation of the RF front-end architecture of an active antenna. With this type of analysis, the designer tries to understand the impact on the system in the absence of a circulator in the architecture. Removing the circulator reduces the cost and size of the design. On the other hand, the interaction between the anten-

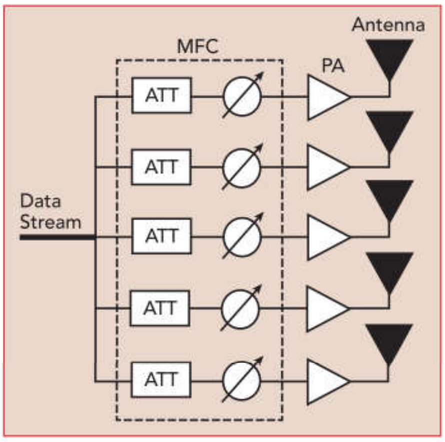


Fig. 8 **Front-end architecture schematic.**

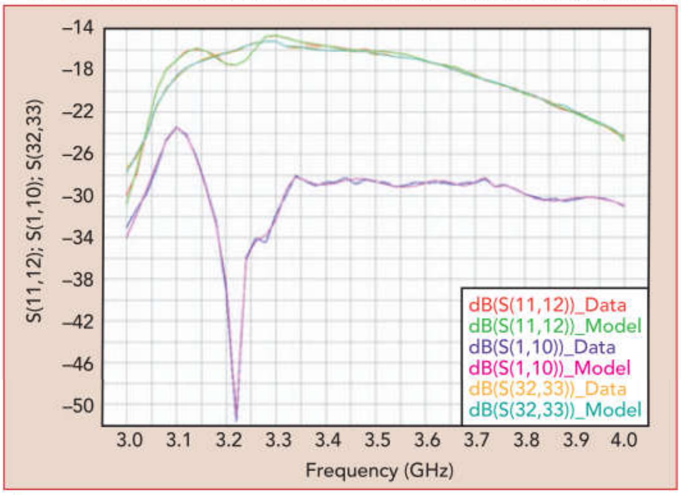


Fig. 9 **Subset of antenna S-parameters.**

na and the front-end creates new interference to the PA, affecting the system's overall performance.

ACTIVE ANTENNA'S FRONT-END SIMULATION

The simulation of a front-end architecture is proposed here to show the benefit of using advanced behavioral models. The front-end module comprises a variable attenuator (DSA) and phase shifter (DPS) to achieve the desired beam's steering. The PAs are located after these devices and connected directly to the ports of the antenna, as shown in ***Figure 8***.

The antenna[6] contains 36 radiating elements and is characterized by an S-parameters matrix. Similarly, the DSA circuits and the DPS have been characterized with S-parameters for different digital control states. This module is controlled by two digital ports with seven and eight bits, representing 32,768 states. Each of them is characterized by S-parameters. ***Figures 9*** and ***10*** show the fits of the S-parameters of each circuit for a given command state and its model.

To take into account the mismatch effects induced by the antenna on the PA, the latter was characterized using load-pull measurements. These measurements correspond to

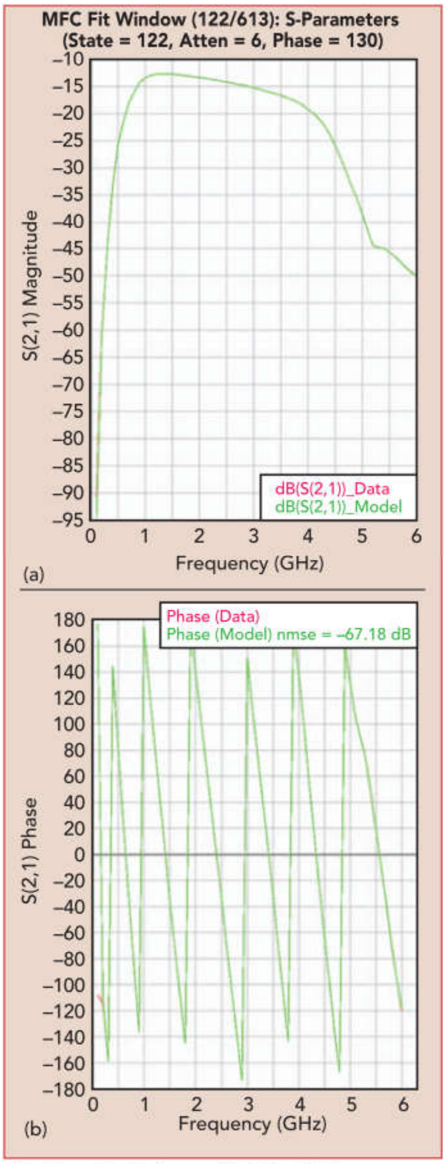


Fig. 10 Subset of DPS+DSA S-parameters.

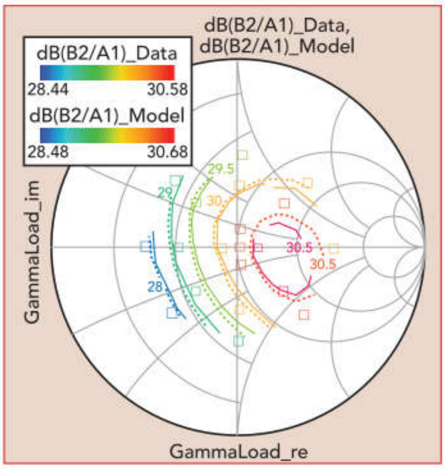


Fig. 11 PA gain contours at a specific compression level.

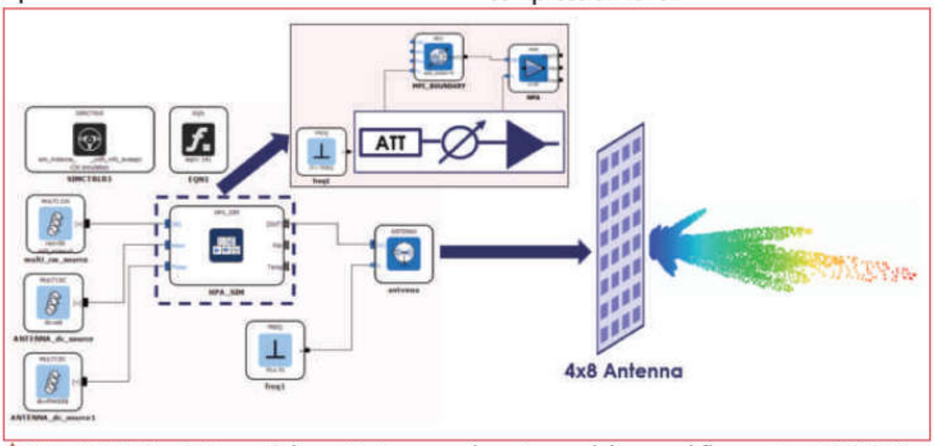


Fig. 12 Active Antenna Schematic in comprehensive modeling workflow system (VISION).

AM-AM and AM-PM characteristics for different frequencies and load impedances. ***Figure 11*** shows the model versus measurement of gain contours at a specific input power.

Figure 12 shows the implementation of the active antenna architecture in a comprehensive modeling workflow system developed. Because the system is described in the form of command buses, the simulation takes into account the interaction between the 36 PAs connected to the 36 ports of the antenna. The active impedance presented by the antenna as a function of the antenna beam steering command is therefore indicated for each PA (see ***Figure 13***).

Due to the load impedance dispersion, the PA's performance is impacted. A variation of the delivered signal to the antenna in power and the phase may impact the beam steering and the system's overall efficiency. ***Figure 14*** shows the variation of these characteristics as a function of the position of the PA and the angle of the steered beam.

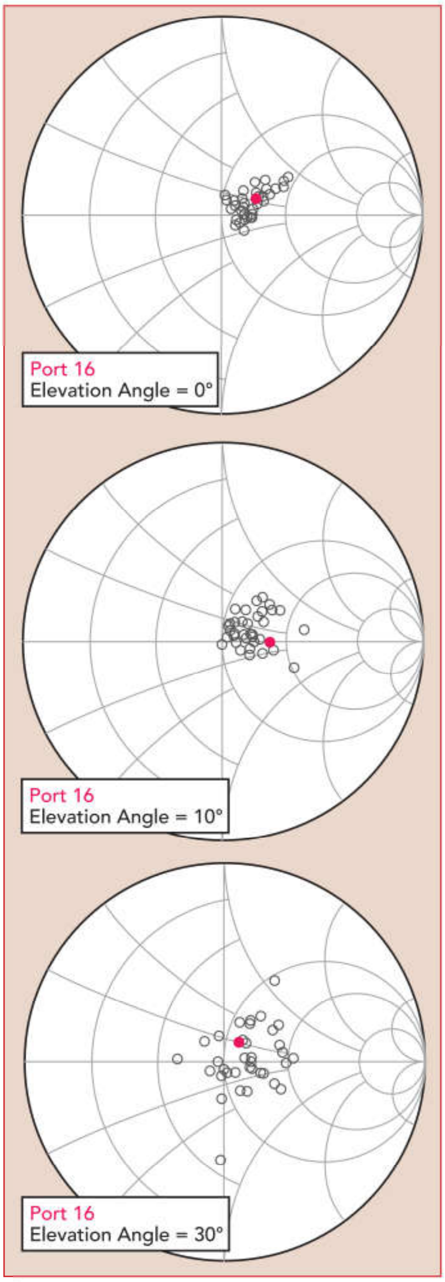


Fig. 13 Reflection coefficient presented to 36 PAs for three different beam steering angles (0°, 10°, 30°).

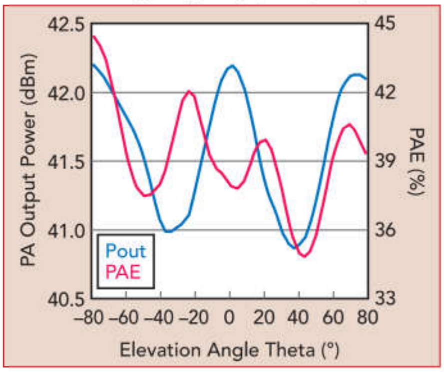


Fig. 14 Pout/PAE vs. theta angle of PA connected to port 16 of the antenna.

This analysis is possible due to the bilateral behavioral model, which takes into account the mismatch at the output of the PA and the solver, which manages a large number of elements of a complex architecture efficiently. Using this type of simulation, the system engineer can explore different architectures and circuit designs to evaluate the best combination to meet system specifications.

CONCLUSION

For several years, CAD tools have offered advanced features to adapt to the evolution of communication systems. The complexity of AAS architectures requires the system simulator to combine analyzes in different fields such as electromagnetic for the radiating panel, electrical for the front-end part and digital for the signal processing blocks. The size of the system is so large that simplifications are made for the modeling of the antenna and the front-end to obtain simulation results in a reasonable amount of time. This impacts the overall performance prediction and does not allow engineers to have sufficient confidence in this system simulation procedure.

The use of reliable behavioral models is increasingly required to fully exploit the system simulation and thus optimize the operating parameters and better size the RF circuits. This article presented an RF circuit behavioral modeling approach that is part of an industrial process that includes measurement or simulation data, quasi-automatic extraction and implementation in an in-house simulator and system simulators.

Moreover, this new approach has been demonstrated in the bilateral modeling of PA in the context of a simulation of the front-end of an active antenna comprising a large number of RF channels. This type of system simulation is fast and allows performance to be assessed based on operational parameters such as input power, frequency and antenna beam in elevation and azimuth angles. Also, other configurations can be evaluated in which the engineer can change antenna designs or RF circuits. These capabilities pave the way for co-design and system validation processes in simulation and enable system designers to reduce development time and market time significantly. ■

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