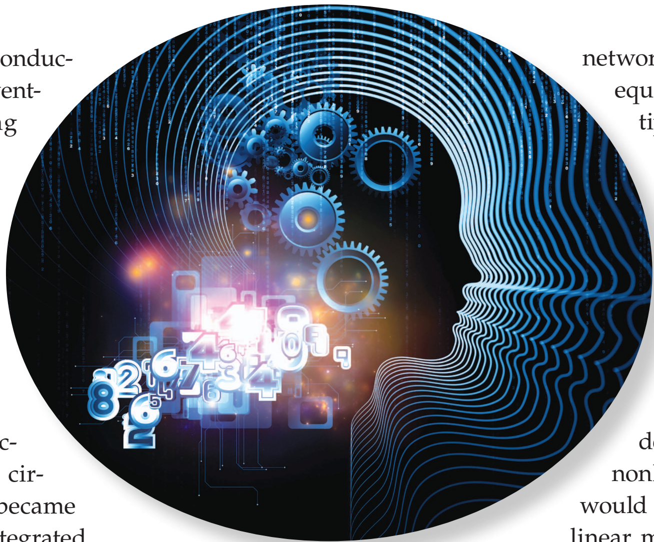
# From the Guest Editor's Desk

## *Microwave Behavioral Modeling—Toward a Universal Device Model Format*

■ José Carlos Pedro





When the first semiconductor devices were invented, device modeling was intended for the understanding of device operation, and so it was restricted to a small set of semiconductor physicists. Up to the late 1960s, microwave electronics was mostly a laboratory art, where hands-on experience and patient adjustment played a major role in the design success. Then, with the advent of circuit simulators, device models became a need for computer aided integrated circuit design platforms. Today, they are common tools in the daily work of all circuit designers.

Models are mathematical representations of the device operation, which are used in both circuit simulators and manual analysis tools. They can be classified as describing the internal device physics—the physics-based models—or only the device's observable input and output port behavior— the so-called behavioral models.

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The goal of this Focused Issue is a focus on the models belonging to the second group. These device models constitute abstract mathematical formulations where a direct relationship between the input and output terminals' observable behavior is sought. Being completely determined by the device's observable behavior, they are known as behavior-based models or simply behavioral models.

The most known examples of behavioral models for linear one-port networks are the Thévenin or Norton equivalents, while for linear multiports we could mention the impedance, admittance, scattering, or transmission matrix models. Unfortunately, the apparent simplicity of the format, measurement (model extraction), and application, of, e.g., the S-matrix, is due to the underlying assumption of the device's linearity. If the device were driven to expose its nonlinear behavior, this simplicity would be lost, and a convenient nonlinear model would become extremely complex because it should be capable of representing a much wider spectrum of all possible nonlinear behaviors.

The fact that behavioral models are not driven by the internal device structure, but established on only its observable behavior, determines their most notable advantages, but also, shortcomings.

Among their advantages, we could mention that behavioral models share a predetermined model format, solely determined by functions' approximation theory, regardless of the device's actual internal constitution. They are thus easily applicable to many different device technologies, so that the same model format can be used for both elementary devices, such as transistors or simply passive components, or for complete circuits or subsystems as amplifiers, mixers complete wireless front ends, etc. Furthermore, they are portable between different simulation platforms, are technology independent, and can be used to protect the device's manufacturer intellectual property rights.

Unfortunately, having no information on the device's internal constitution but only on a (for practical reasons necessarily restricted) set of input–output experimental results, their predictive capability is very poor. This means that the models' representation accuracy is optimum for the excitation used for their identification but is also severely degraded when the stimulus is significantly different from this one. This is known as the poor extrapolation capability of behavioral models, or, in other words, it can be said that behavioral models are the best to store and retrieve measured data but have very limited predictive capability. Furthermore, having no access to the device's internal constitution, or to its governing physics, behavioral models entirely rely on laboratory observations or measurements. Therefore, their quality is heavily dependent on the available microwave instrumentation. Consequently, the need for more accurate behavioral models (especially nonlinear) has pushed the development of new microwave instruments, such as the new class of nonlinear vector network analyzers, as well as the availability of these new instruments has led to the establishment of new behavioral models.

Reliable nonlinear behavioral models of microwave devices are thus highly desirable but also very challenging. This has determined the search for progressively more accurate and general nonlinear behavioral model formats that we have witnessed in recent years. Actually, they are changing the way we were used to seeing microwave electronics, combining contributions from fields as different as approximation theory, system identification, nonlinear optimization, and microwave instrumentation.

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Despite the increased attention that nonlinear behavioral models have been attracting, their relative immaturity, but mostly their mathematical complexity, has precluded their widespread usage. So, we believe that a Focused Issue that can allow the nonexpert engineer to take the first steps into this field and to give a broad, but not too technically deep, coverage of this promising technology can contribute to overcome this potential barrier.

For that, this special section of *IEEE Microwave Magazine* puts together three articles addressing different facets, of complementary nature, of microwave behavioral modeling technology, authored by well-known researchers in this field.

The first article, "Predictable Behavior" by José Carlos Pedro and Telmo Reis Cunha, constitutes an overview that serves as the entrance door to behavioral modeling technology, providing also an introduction to the other two articles. Written in a tutorial style, it starts by the definition of concepts and then reviews the basic properties of behavioral models from a pure theoretical (system identification) perspective. Then, it outlines microwave behavioral models for both time- and frequency-domain signal mapping representations. Finally, it shows how microwave instrumentation plays a key role in establishing different behavioral model formats, their parameter extraction, and, finally, their validation.

The second article, by Edouard Ngoya and Sébastien Mons, is titled "Progress for Behavioral Challenges." Addressing time-domain models, this article focuses its attention on both continuous- and discrete-time Volterra series models. This way, it first classifies system dynamics as short- and long-term memory effects to then illustrate how nonlinear impulse response functions can be derived to represent these important engineering phenomena.

Finally, the third article, "Stretching the Design" by M. Fernández-Barciela, A.M. Pelaez-Perez, S. Woodington, J.I. Alonso, and P.J. Tasker, is devoted to frequency-domain microwave behavioral models. Contrary to the first two articles, which present a more theoretical perspective to the behavioral modeling technology, this one is more committed to the application. Using what is understood today as the best approach to extend the linear S-matrix to the nonlinear realm, this article shows how frequency-domain behavioral models can make a design dream come true: it illustrates how one can design important examples of nonlinear circuits, such as an oscillator, using the same techniques with which microwave engineers were used to treat their linear small-signal circuits.

In summary, these three articles provide the reader with a necessarily brief, but integrated, overview of microwave behavioral modeling so that one can understand the fast pace with which this technology is advancing. However, these three articles are also believed to constitute a valuable tutorial for the interested circuit designer.

We will have fulfilled our goal if, after reading these three articles, the reader gets a more detailed idea of what he can and what he still can't do with behavioral models and is thus in a better position to distinguish highly inflated benefits in advertisement texts from the real advantages and limitations offered by the available microwave device behavioral models.