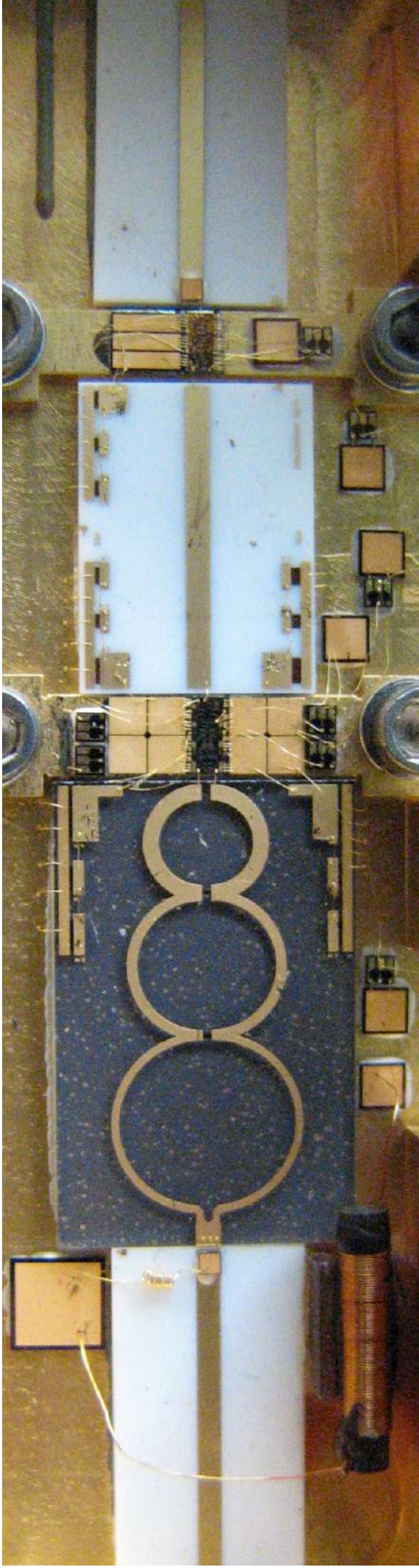
AMCAD Engineering
White Paper

Advanced Modeling for Computer-Aided Design

Power amplifier behavioral modeling for system level simulation



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SUMMARY

This paper addresses the crucial importance of adopting advanced behavioral models for power amplifiers in simulating complex electronic systems. As the performance requirements of modern systems continue to evolve, the efficiency and accuracy of the design and simulation phase become paramount. A comprehensive analysis of behavioral models is conducted to highlight the limitations encountered by each type of model. The impact of these limitations will be emphasized through a specific case study related to the modeling of a Wi-Fi 6 Extended amplifier. This case can be generalized to all types of integrated systems for RF communications and other emerging applications.

INTRODUCTION

In the dynamic and constantly evolving field of radio frequency (RF) communication systems, power amplifiers hold a central position. Their importance is crucial in a multitude of applications, ranging from wireless communications to radar systems. The performance of these systems is intrinsically linked to the characteristics of the amplifiers used, such as their linearity, efficiency, and bandwidth. To ensure effective and rapid development, RF system simulations must be of exemplary precision.

Recently, the integration of behavioral models to simulate power amplifiers has become indispensable. These models must take into account the nonlinear behaviors and significant memory effects of the amplifiers. A memory effect indicates that a circuit's response to a given signal is affected not only by the current characteristics of the signal but also by its past attributes. This phenomenon can be attributed largely to thermal and trap effects within the semiconductor materials used in the amplifiers.

The accurate simulation of these phenomena is a considerable challenge, making the process more complex and time-consuming. It must anticipate the influence of signal dynamics and their bandwidth on the actual performance of the system. Moreover, it is essential to consider the potential effects of impedance mismatches between different circuits, which can affect the entire system.

Although behavioral models offer a precise prediction of the performance of a complex architecture, they also pose challenges in terms of complexity and work time for designers, especially if the tools used are not adequate. Engineers must find a balance between these factors to develop an optimal and efficient system design methodology.

This white paper focuses on the importance of integrating various phenomena into a robust behavioral model for power amplifiers. We will discuss the VISION tool which addresses these aspects. The input data for this model can come from actual measurements or circuit-level simulations. In the latter case, it is necessary to solve the equations at a detailed level, involving all the elementary components of the circuits.

While circuit-level simulation is a benchmark in terms of accuracy, it is impractical for designing complete systems, which may include thousands of circuits, each comprising hundreds of components. The simulation time would become prohibitive, especially with modulated signals.

To overcome this challenge, the behavioral model for system simulation offers a higher level of abstraction, avoiding consideration of each circuit element. This significantly accelerates the simulation speed. The challenge then lies in the development of behavioral models for each circuit, which offer a significant gain in terms of simulation time while maintaining accuracy comparable to that of component-level circuit simulations.

CASE
STUDY

Power Amplifier Description

As mentioned in the introduction, the behavioral model can be derived from measurements (via IQSTAR test bench control software) or through simulations conducted at the scale of each elementary circuit.

To showcase the capabilities of such a modeling tool, an amplifier circuit designed in the Pathwave ADS software provided by Keysight Technologies (Figure 1) is used as a candidate. This circuit is intended to amplify a signal carried at a frequency close to 5.9 GHz, for "WiFi 6 Extended" type signals. Thanks to this extended frequency range, WiFi 6E can deliver significantly higher speeds of up to 11 Gb/s, as well as lower latency.

This GaAs MMIC design example delivers an output power of 27dBm as a saturated gain of 9.5dB when biased at 6V, and has a power added efficiency up to 50%. The design's sole purpose is to illustrate a typical example, where phenomena of non-linearity and RF memory are observed, and it does not claim to be a circuit with a finalized design for serving this application. Indeed, to highlight the nonlinear effects which can occur in such circuits, the original biasing circuit has been modified to underline the impact of low frequencies memory effects.

The circuit incorporates two field-effect transistors, along with conventional adaptation and biasing circuits. The specifics of this design are not addressed as such in this paper.

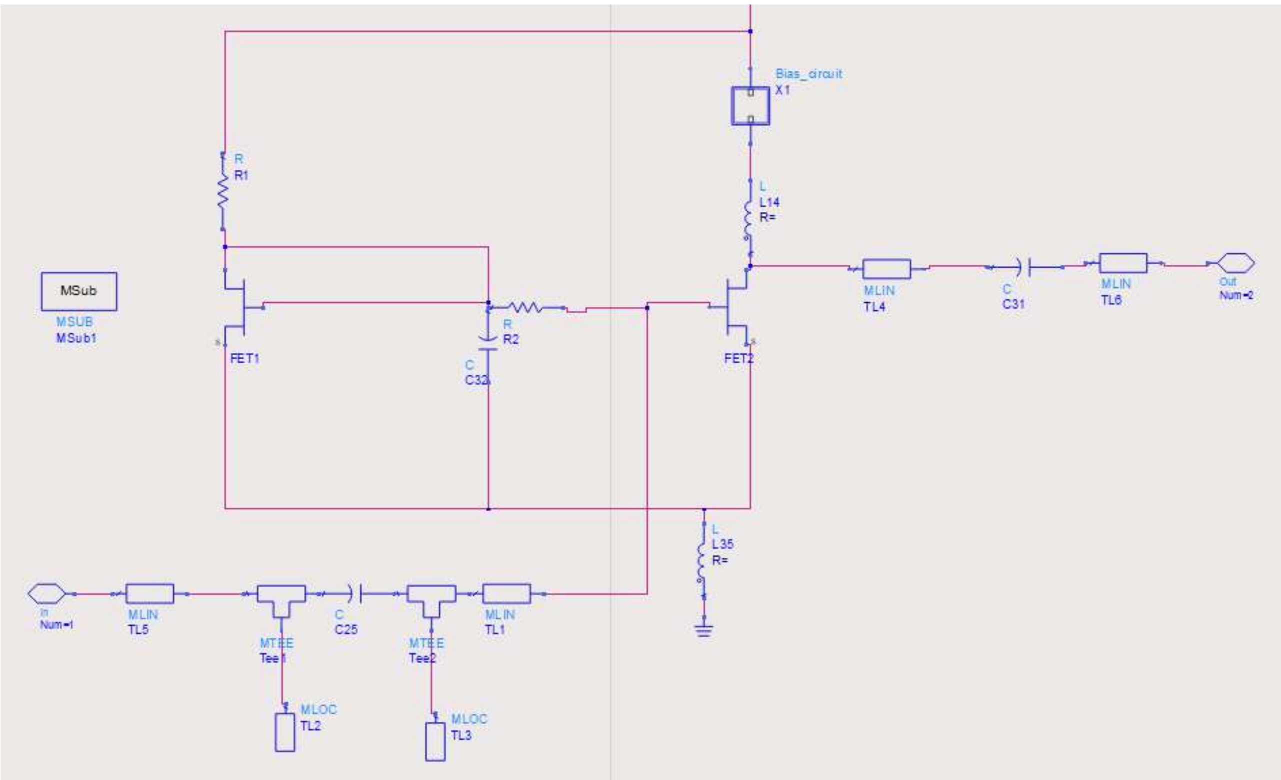


Figure 1: *WiFi 6 RF Amplifier Designed in Keysight Technologies' Pathwave ADS Software*

Small-Signal CW Characterization:

S-parameters

In the initial stage, it is important to analyze the bandwidth of this amplifier. The S-parameters provide a fundamental description of the circuit's behavior in a linear regime. They allow for the assessment of the circuit's ability to amplify the incident signal and the study and optimization of its matching to a reference impedance of 50 Ohms.

In our case study, the S-parameters are obtained from an AC simulation using a low-amplitude CW signal, with varying carrier frequency. This characterization helps determine the frequency response and define the operating bandwidth of the amplifier (***Figure 2***).

Here, the reflection coefficient S11 is minimized at the frequency of 5.9 GHz. It is considered that the amplifier must maintain an S11 parameter value below -15 dB, defining an operating bandwidth of approximately 800 MHz (~13.5%), ranging from 5.5 GHz to 6.3 GHz. Within this bandwidth, a variation of approximately 1 dB in gain, represented by the S21 parameter, is observed in ***Figure 3***.

The variation in the frequency response of the amplifier is a significant marker of high-frequency memory effects (HF). High-frequency memory effects in RF power amplifiers refer to the phenomenon whereby the amplifier's behavior is influenced by its previous input and output signals. This dependency becomes particularly crucial in scenarios involving high operating frequencies. The delayed time response of the circuit, due to the physical properties of internal components, becomes noticeable and starts to influence the immediate shape of the output signal. Several factors contribute to these memory effects, including:

- Reactive components: Capacitive and inductive elements in the circuit lead to energy storage that depends on the history of the excitation signal, influencing the instantaneous operating state of the amplifier.
- Transmission line effects: At high frequencies, the signal wavelength becomes comparable to the physical dimensions of the internal structure of the amplifier, highlighting undesirable phenomena. This scenario causes signal reflections, standing waves, and other phenomena that depend on the previous states of the signal.

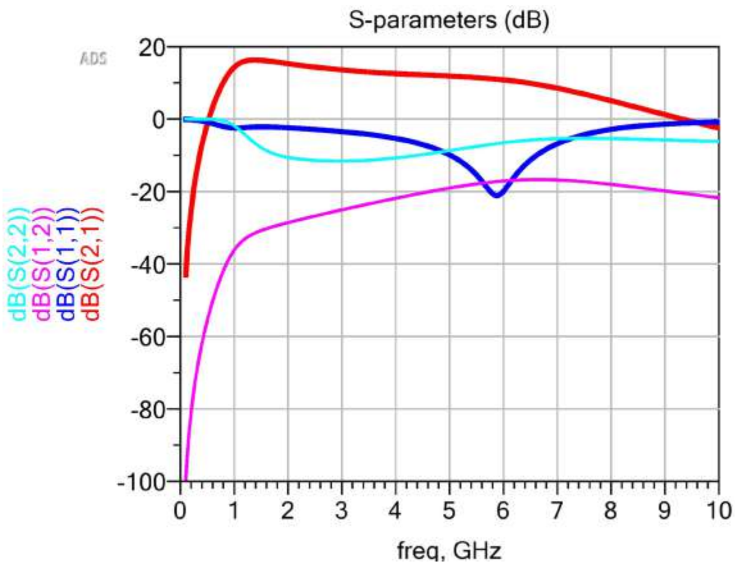


Figure 2: *Wideband S-parameters (100MHz to10 GHz)*

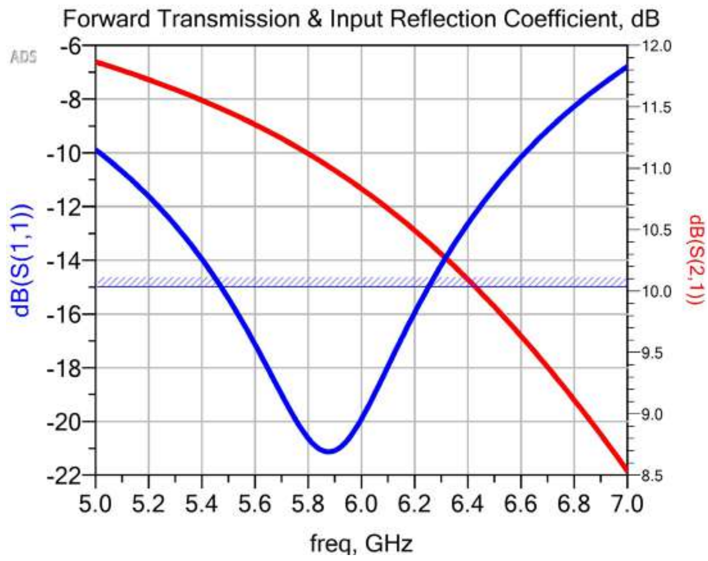


Figure 3: *S11 and S21 parameters (5 GHz to 7 GHz)*

High-frequency memory effects in power amplifiers are a critical phenomenon that affects the performance of modern communication systems, especially those handling wideband or complexly modulated signals. This effect, intrinsically linked to the temporal and frequency properties of components, is particularly significant in the input and output matching networks of amplifiers. These networks, designed to optimize power transmission, possess reactive characteristics that can introduce variable phase delays (***Figure 4***).

In the context of modulated signal amplification, this memory effect can result in significant signal distortion, as the amplifier reacts differently based on the input signal's history, altering the linearity of the frequency response and causing irregularities in the amplitude and phase of the amplified signal.

These variations can degrade signal quality by causing synchronization errors between different signal components, resulting in an increase in the Error Vector Magnitude (EVM). The EVM is a crucial and widely used quality factor for evaluating the linearity of the amplification of a modulated signal.

Figure 4: *Phase of S21 parameter (degree) et group delay (second)*

Large-Signal CW Characterization

(50-ohm conditions)

Non-linearity in power amplifiers refers to the deviation of the output signal from the amplifier compared to an ideally linearly amplified signal with respect to the input signal. This deviation becomes particularly evident when the amplifier starts to saturate (***Figure 5***). This behavior leads to various forms of distortion, such as the generation of harmonic frequencies and intermodulation products for multifrequency signals. This significantly impairs the quality of the amplified signal and the system's performance. Signal distortions are critical in radio communication systems, where the spectral shape of the signal emitted by the antenna must adhere to strict regulatory mask requirement in the frequency domain to avoid disrupting or interfering with adjacent communication channels. Simulation with a single-frequency carrier signal, also known as a one-tone simulation, is a fundamental technique. By sweeping the power of this signal, engineers can obtain valuable information about the linearity characteristics of the amplifier and observe phenomena such as saturation based on the incident signal power. The AMAM curves represent amplitude modulation to amplitude modulation characteristics. The amplitude modulation relative to phase modulation is referred to as the AM/PM characteristic. This non-linear behavior is also identifiable in other characteristics such as DC power consumption and power-added efficiency (***Figure 6***).

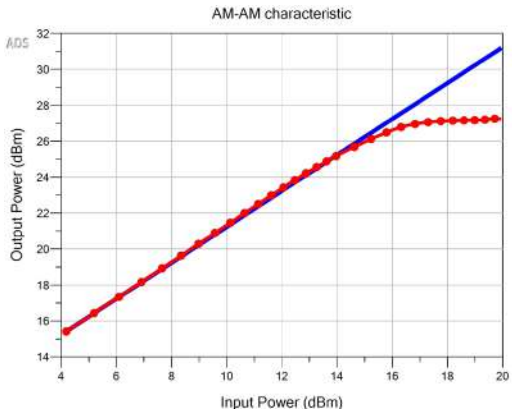


Figure 5: *Output Power vs. Input Power in dBm (Linear case in blue, PA characteristic in red)*

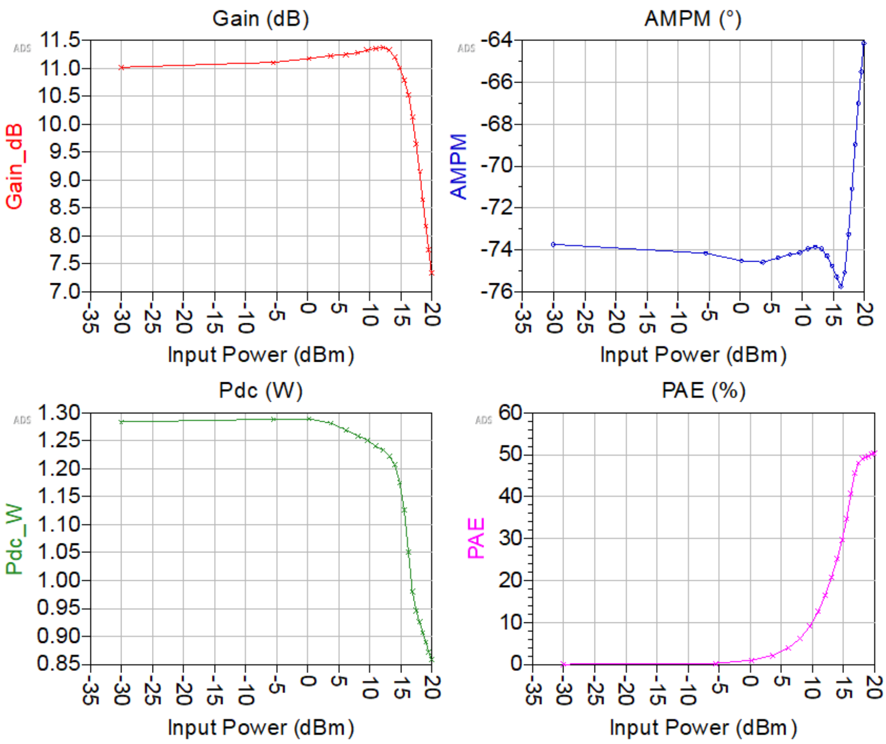


Figure 6: *One-Tone Characteristic at 5.9 GHz*

This kind of simulation is performed for various carrier frequencies within the amplifier's operating band to evaluate its nonlinear behavior, as illustrated in ***Figure 7***. The results reveal a noticeable dispersion in the amplifier's characteristics based on the carrier frequency and power level, a direct consequence of the high-frequency memory effects discussed earlier.

This dispersion can be influenced by the interaction between the inherent nonlinearity of the amplifier and high-frequency memory effects, introducing increased complexity in the device's behavior deviating from the theoretical ideal. A more in-depth examination of this issue is presented in ***Figure 8***, illustrating the frequency dispersion of the amplifier gain at various input power levels under 800 MHz bandwidth. This analysis unveils significant disparities in the amplifier characteristics, particularly when compared in a linear regime versus high-signal conditions.

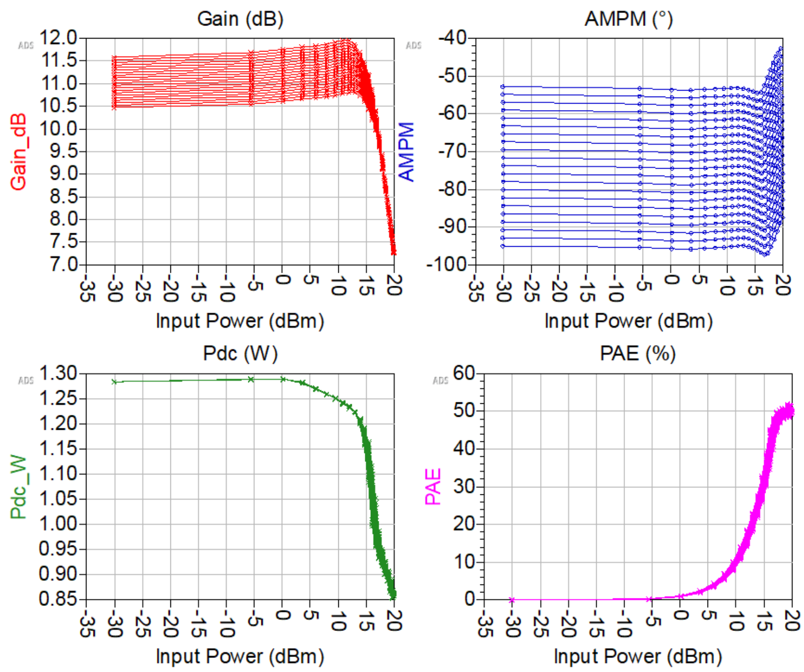


Figure 7: *One-Tone Characteristics within the Operating Bandwidth of the Power Amplifier*
F-start=5.5GHz, F-stop=6.3GHz, F-step=40MHz

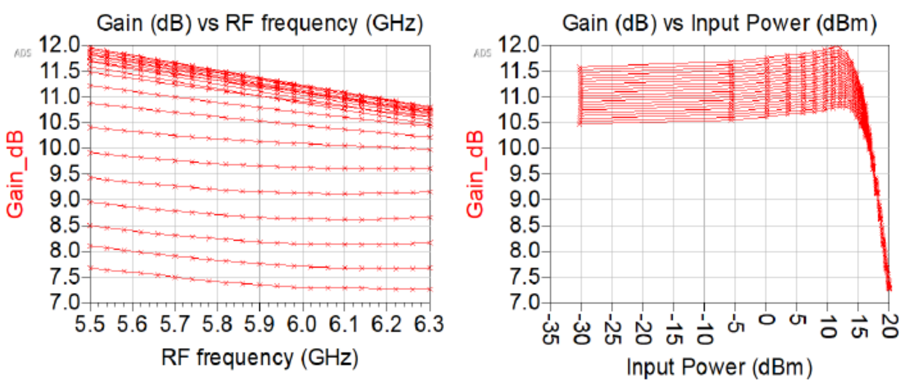
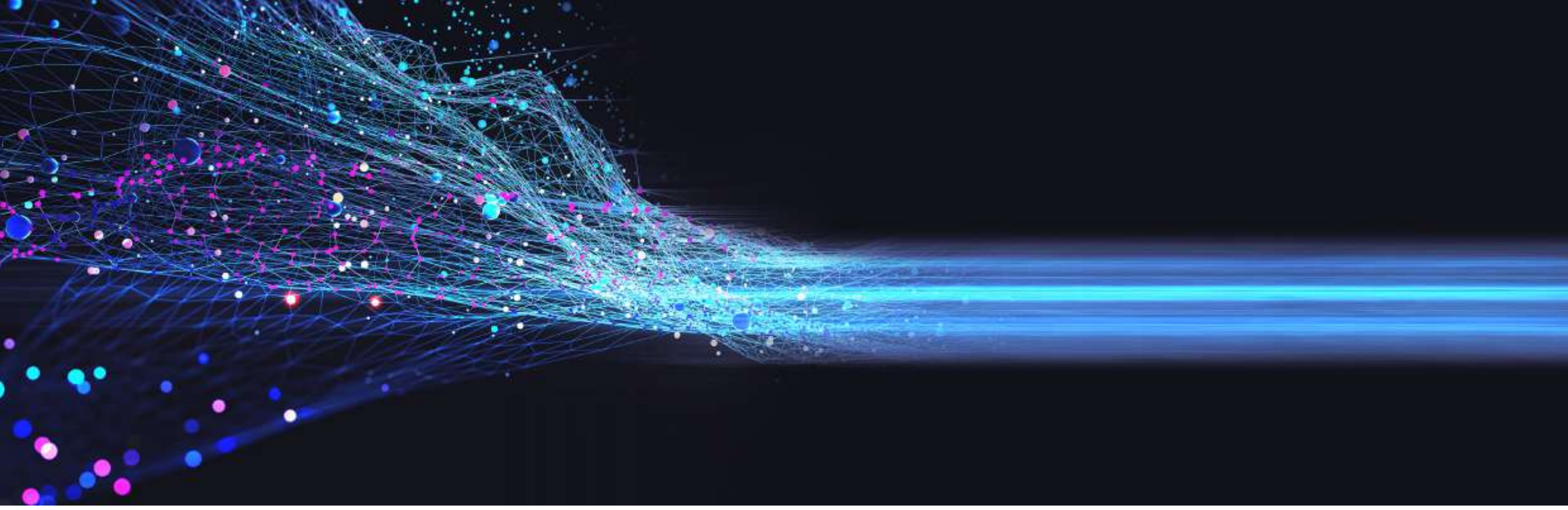


Figure 8: *One-Tone Characteristics within the Operating Bandwidth of the Power Amplifier*
F-start=5.5GHz, F-stop=6.3GHz, F-step=40MHz



Two-Tone Characterization

(50-ohm conditions)

This section of the document highlights the often overlooked aspect of low-frequency memory effects (LF) in radiofrequency (RF) power amplifiers and underscores the importance of the two-tone test diagnosis, particularly through the analysis of the asymmetry of third-order intermodulation (IM3) sidebands (***Figure 9***).

By elucidating how these memory effects subtly alter amplifier performance and how they can be precisely detected through this testing methodology, a deeper understanding of these low-frequency memory phenomena is sought. Low-frequency memory effects in power amplifiers arise from various sources such as thermal and bias networks, charge trapping in active devices, and power-induced distortions. Unlike high-frequency memory effects, they manifest over longer time scales, also impacting the dynamic behavior of amplifiers. These effects can degrade the linearity of the amplifier and compromise the energy efficiency of the system.

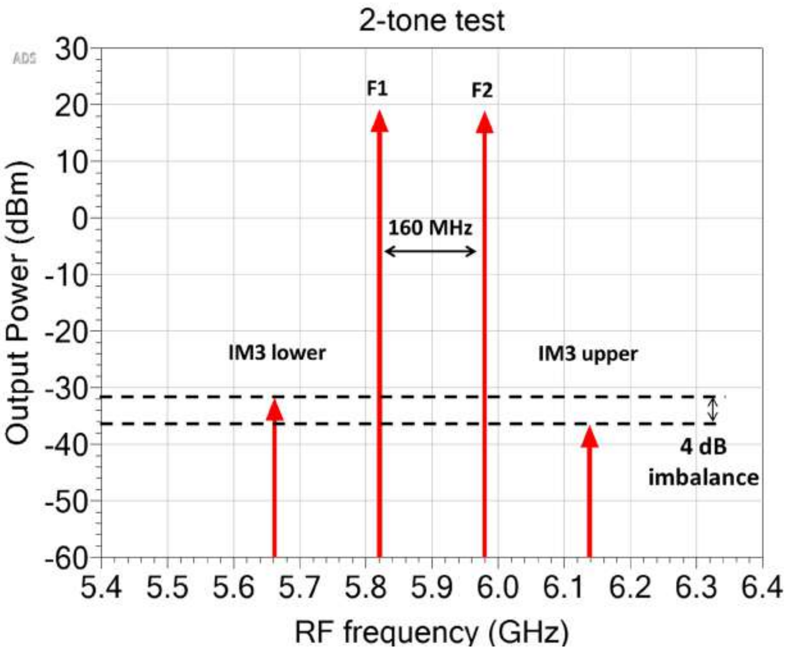


Figure 9: *PA Output spectrum stimulated with 2-tone signal*

Figure 10 and ***Figure 11*** critically illustrate variations in gain based on the separation between the two carrier frequencies of the signal and the third-order intermodulation product ratios (IM3) it generates depending on the input power. These graphs highlight interactions between the intrinsic nonlinearity of the amplifier and LF memory effects. A particularly revealing phenomenon observed is the distinct asymmetry between the levels of intermodulation created to the left and right sides of the two carrier frequencies at the output of the amplifier. This asymmetry is a compelling indicator of LF memory effects that significantly influence the properties of the amplified modulated signal.

Furthermore, this 2-tone analysis facilitates the identification of the presence of resonances at specific spacing intervals between the two carriers. These resonances are not only artifacts of amplifier nonlinearity but also a direct consequence of LF memory effects, dynamically modulating the amplifier's response based on the input signal history. The presence of these resonances underscores the significant disruption induced by memory effects in the intended behavior of the amplifier, especially in the context of a 2-tone test signal, commonly used to evaluate the performance of communication systems.

These results emphasize the importance of considering LF memory effects in the design and development of amplifiers, particularly for applications requiring the simultaneous management of multiple carriers or wideband signals. They also serve as a precursor to potential correction strategies aimed at optimizing the linearity of the amplifier and its overall performance in complex communication scenarios. Behavioral models will also need to faithfully represent these phenomena.

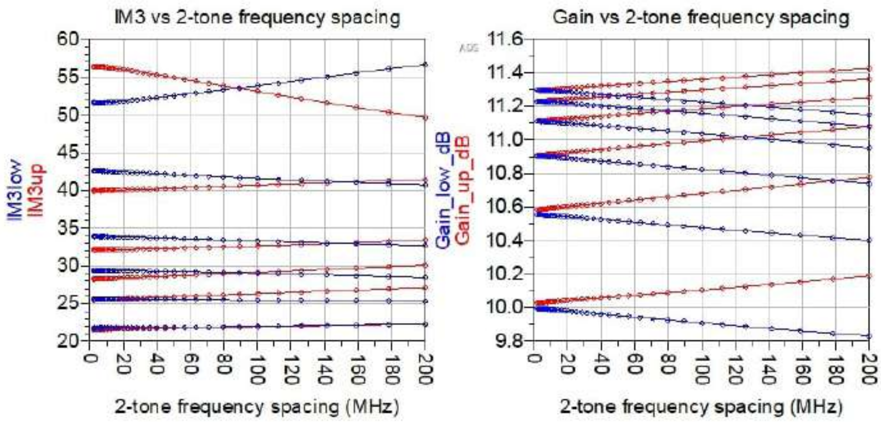


Figure 10: *Gain of carrier F1*

Individual carrier gain and IM3 ratio as a function of 2-tones frequency spacing.

Input power swept from 10dBm to 15dBm / 1 dB step

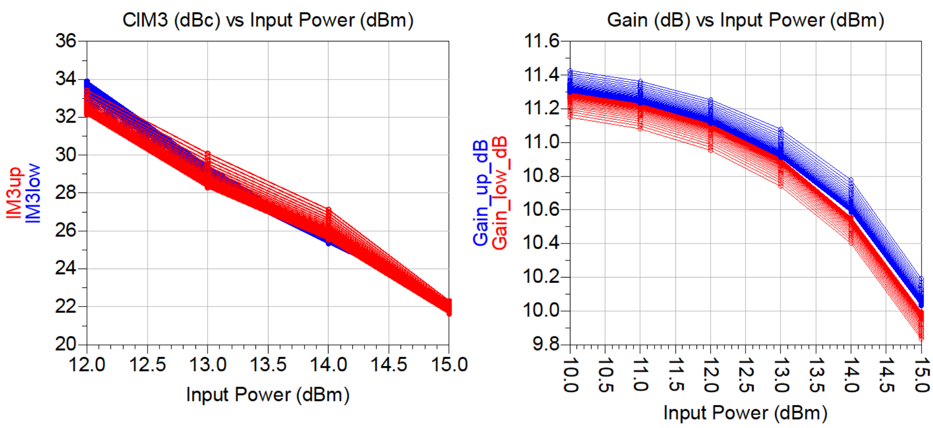


Figure 11: *Gain de chaque porteuse et rapport CI3 en fonction de la puissance d'entrée*

Individual carrier gain and IM3 ratio as a function of input power and carrier's tone spacing

Continuous Wave Characterization under Mismatch Conditions (Load-Pull Effect)

Load-pull characterization is a technique used in the design of power amplifiers (PA). It essentially involves simulating or measuring the effects of varying the load impedance presented to the amplifier to understand its impact on performance parameters such as output power, efficiency, and linearity. This methodology is crucial in the design of RF and microwave amplifiers, where the device's performance is strongly influenced by the load impedance presented to the circuit.

Each amplifier is designed to operate optimally for a load impedance reference, typically equal to 50 Ohms. Mismatches between circuits and this reference impedance can significantly affect circuit performance. Load-pull characterization involves varying the load impedance over a specified range and observing the amplifier's response, usually in a complex impedance plane (Smith chart).

Key parameters such as output power (Pout), power-added efficiency (PAE), and gain are measured for each impedance. Advanced simulations or measurements also take into account other factors such as ACPR and EVM, which are essential for evaluating linearity, especially in communication systems. These load-pull simulations help designers anticipate the performance of a power amplifier in different real-world scenarios, such as impedance mismatches resulting from antenna usage. This evaluation and design optimization process enables the development of power amplifiers that maintain reliable performance even under non-optimal load conditions, essential for robust systems.

In this paper, a load-pull simulation is performed, where the load impedance has been systematically varied according to the coordinates specified in the Smith chart, illustrated in ***Figure 12***.

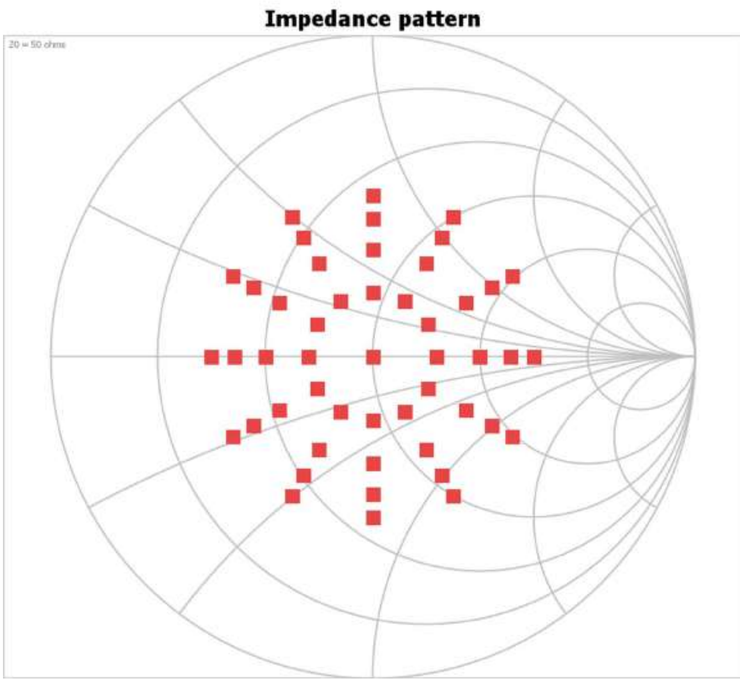


Figure 12: *Load impedances presented during simulation*

This rigorous methodology allows for a detailed one-tone characterization at the carrier frequency of 5.9 GHz, following the procedures presented earlier. Crucial insights are possible through the analysis of the amplitude modulation in amplitude (AM-AM) and amplitude modulation in phase (AM-PM) curves, documented in ***Figure 13a*** and ***Figure 13b***, respectively.

These visual data are revealing, showing noticeable variations in amplifier characteristics that are directly attributable to changes in the load impedance. Specifically, the results demonstrate that each impedance point on the Smith chart corresponds to a unique set of amplifier behaviors, manifested by differences in AM-AM and AM-PM curves. These differences indicate nonlinear responses of the amplifier, which are crucial criteria for evaluating performance in terms of distortion and power conversion efficiency.

Figure 14 illustrates, using the Smith chart, the contour lines representing both the output power (Pout) and the Power Added Efficiency (PAE). This graphical representation is crucial for determining the optimal load impedance that maximizes Pout (MXP) and PAE (MXE) for a given level of input power and at a specific RF frequency.

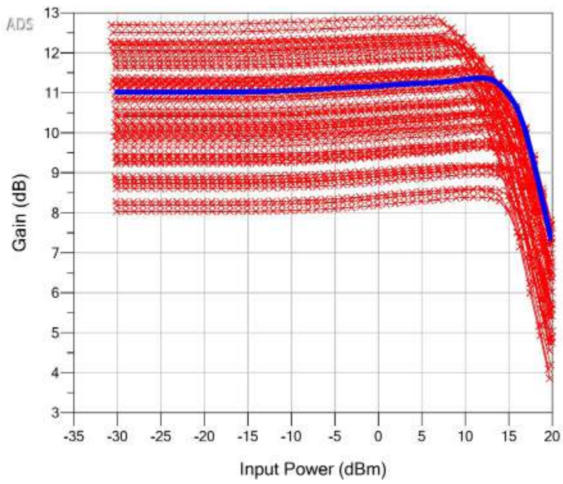


Figure 13a: *Gain as a function of input power (on 50-ohm load in blue and on mismatched load in red) @5.9 GHz*

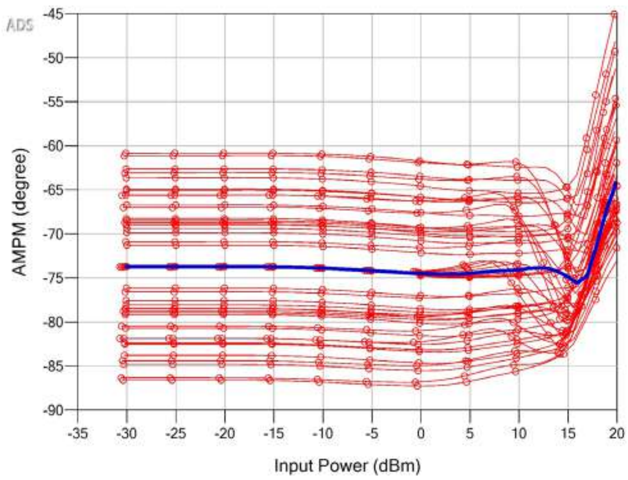


Figure 13b: *AM-PM on 50-ohm load (in blue) and on mismatched load (in red) @5.9 GHz*

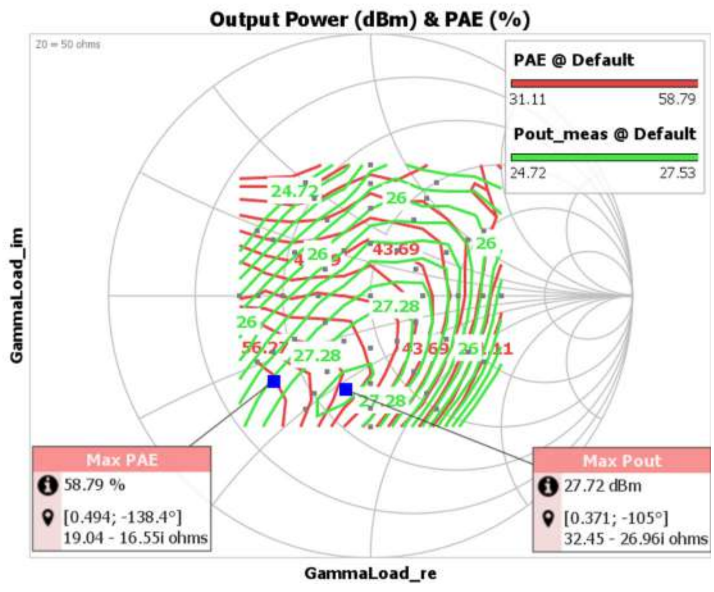


Figure 14: *: Coutours of output power and PAE with locus of MXP & MXE load impedances / Pin =18dBm @ f=5.9GHz*

Continuing this exploration of the internal dynamics of the amplifier under different conditions, closer attention is directed towards an analysis of the reflection coefficient at the input of the amplifier, a parameter that has proven to be of substantial importance for a comprehensive understanding of amplifier behavior. The results of this investigation are summarized in ***Figure 15a and 15b***.

As before, the data is collected during load-pull simulations where not only does the load impedance vary, but also the input power to the amplifier. This dual sweep has revealed inherent complexity in how the amplifier responds to external stimuli. Unlike the initial assumption that the reflection coefficient might remain relatively stable across load and power variations, the data clearly indicates that this parameter is, in fact, a variable that impacts the amplifier's operation and, by extension, affects the behavior of other circuits placed upstream of the amplifier.

Here as well, the behavioral model of the amplifier must reproduce these effects.

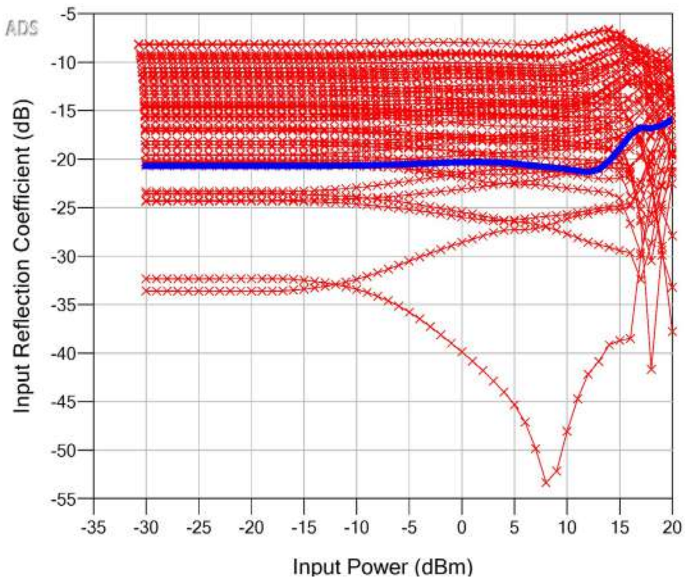


Figure 15a: *Reflection Coefficient at the Input of the Power Amplifier on a 50-ohm load (blue) and on mismatched loads (red) @5.9 GHz*

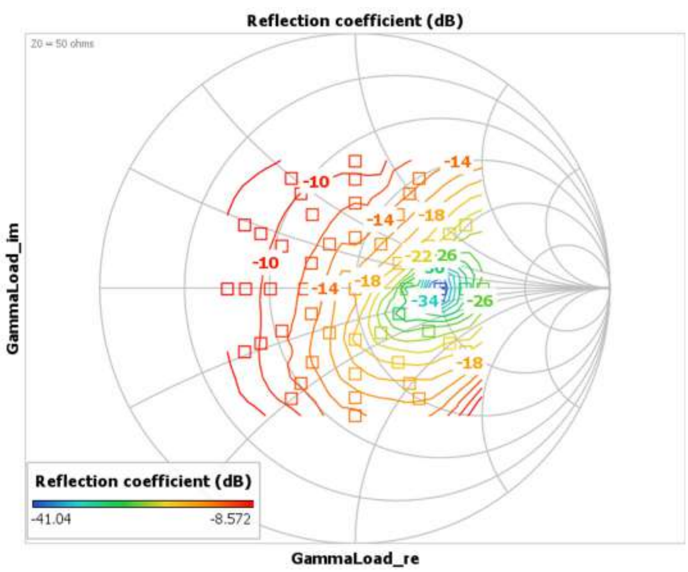


Figure 15b: *Contour lines of reflection coefficient Pin =18dBm @ f=5.9GHz*

Characterization using Modulated Signals

Characterizing a power amplifier using modulated signals is an essential step for circuit optimization under application conditions. These modulations allow testing the linearity of the amplifier, a crucial performance criterion to maintain signal integrity, especially in communication systems where distortion can lead to interference with adjacent radio channels and signal degradation.

In this part of the document, transient envelope simulations are performed to capture the output waveforms of the amplifier. The goal is to examine distortions resulting from the phenomena discussed in earlier sections. The analysis will be conducted on a power amplifier (PA) connected to a reference load of 50 ohms. However, it is important to note that, in practical situations, power amplifiers often face loads that are not perfectly matched to 50 ohms. By characterizing the amplifier under these more realistic conditions, a better assessment of its operational behavior can be obtained.

In the given example, the circuit is designed to amplify a signal conforming to the IEEE 802.11ax standard, commonly referred to as Wi-Fi 6E, which is applicable for the 6 GHz band. his standard demonstrates the capability of handling modulations up to 1024QAM (MCS 10 and 11) within a 160 MHz bandwidth, leveraging OFDM/OFDMA technologies. For the scope of this study, OFDM/OFDMA processing has been excluded to facilitate a more streamlined approach in signal generation and its subsequent post-processing. It is noteworthy that, despite these modifications, the circuit achieves a Peak-to-Average Power Ratio (PAPR) of 6.6 dB. This level of PAPR is substantial enough to markedly stimulate the nonlinear response characteristics of the power amplifier that is being evaluated.

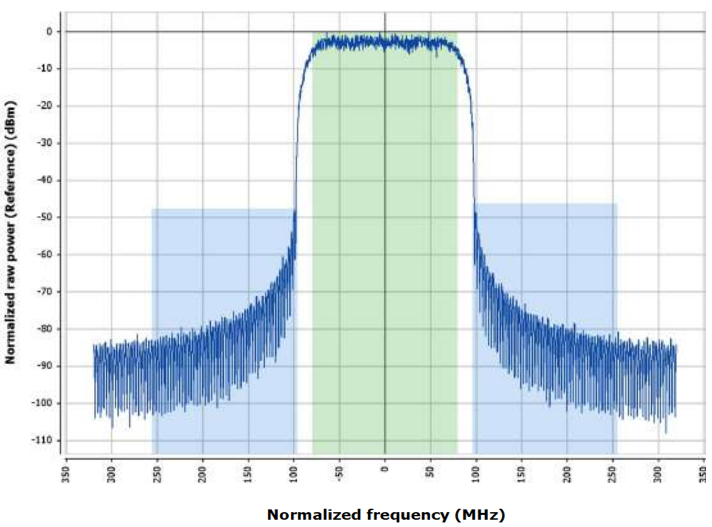


Figure 16a: *Input spectrum with higlighted center and adjacent channels*

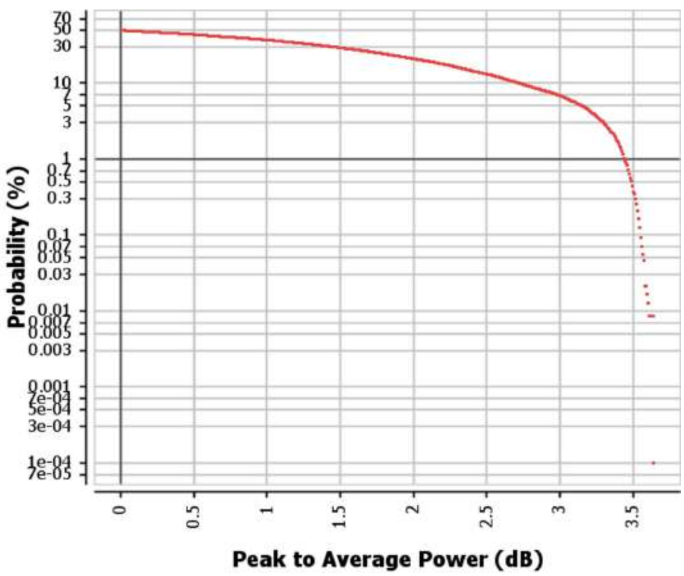


Figure 16b: *CCDF curve as function of PAPR*

Characterization using Modulated Signals

Figure 17a illustrates the output spectra when the amplifier is connected to a perfectly matched 50-ohm load and a 75-ohm load. Compared to an ideal 50-ohm load, this represents a VSWR of 1.5 and a reflection coefficient of 0.2.

Differences in average output power between matched and unmatched loads are on the order of 0.6 dB. Additionally, spectral regrowth on adjacent channels, measured by the Adjacent Channel Power Ratio (ACPR), also varies between the two cases and can be observed in ***Figure 17a***. The AM-AM (amplitude modulation-amplitude modulation) dynamic characteristics presented in ***Figure 17b*** also reflects these behavioral divergences.

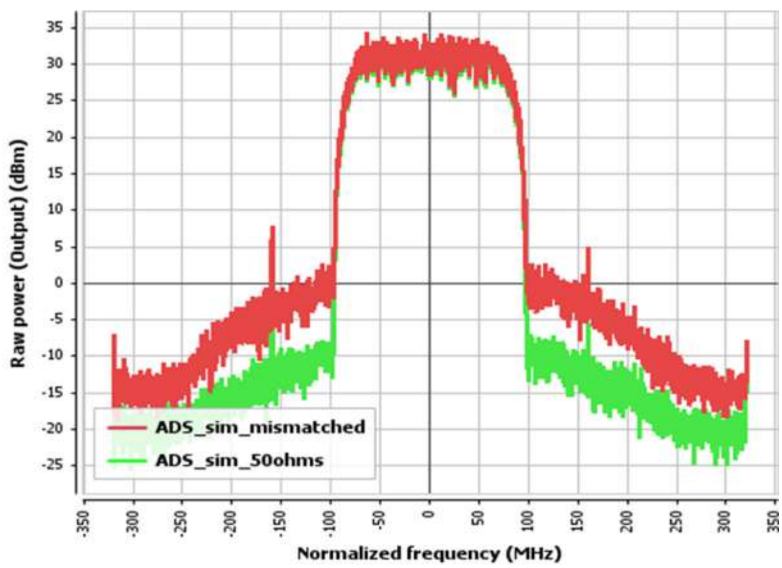


Figure 17a: *PA output spectrum in matched (green) and mismatched (red) conditions*

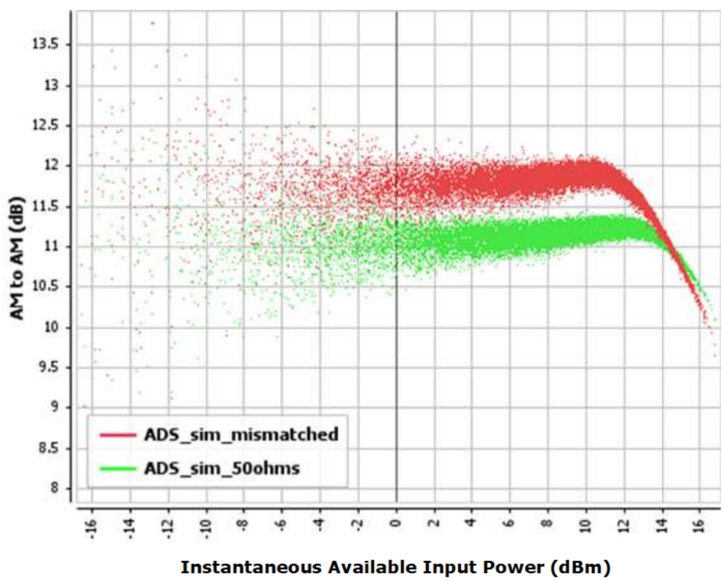


Figure 17b: *Dynamic AMAM in matched (green) and mismatched (red) conditions*

Metrics such as Average Vector Error (EVM) and Bit Error Rate (BER) are particularly well-suited for evaluating the performance of digital communication systems.

EVM quantifies the difference between the modulated output signal and an ideal amplified signal. Low EVM values indicate high fidelity (***Figure 18*** and ***Figure 19***). BER (Bit Error Rate) provides a direct measure of transmission quality by assessing the probability of errors in binary data transmission. A low BER also indicates high transmission quality.

Therefore, EVM and BER serve as critical indicators of an amplifier's performance in the context of digital communication systems. They offer detailed insights into signal quality, data transmission reliability, and help identify areas for improvement in amplifier design. In the scope of this investigation, EVM will serve exclusively as the metric for assessing linearity. However, the BER can of course be calculated by post-processing in the VISION tool presented in this document or in another system simulation environment.

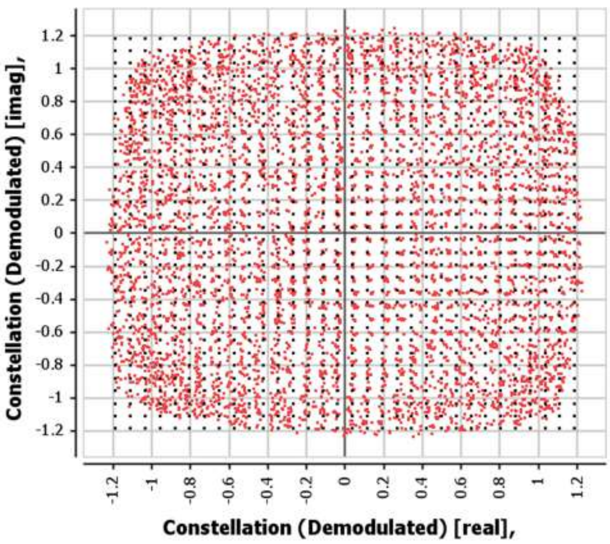


Figure 18: *1024QAM constellation signal (reference in black, PA output signal in red)*

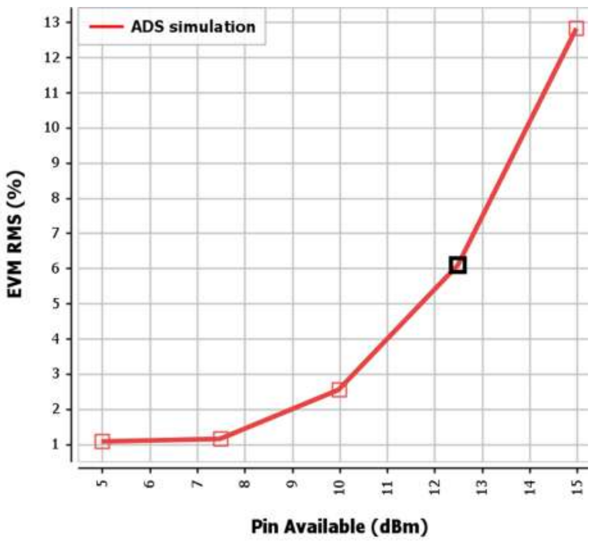


Figure 19: *EVM versus average input power (black square marker corresponding to constellation plotted in Figure 18)*

HPA-U-HF Modeling and Simulation

The evaluations of the behavioral model of this amplifier involve comparing the alignment of results from a circuit simulation and a system-level simulation. Additionally, a comparison of simulation times will be conducted.

The initial model proposed is the most basic VISION model. This model is designed to simulate the nonlinear behavior of the amplifier connected to a matched 50-ohm load, taking into account only high-frequency memory effects. It is named the HPA-U-HF model (High Power Amplifier Unilateral High-Frequency memory effect model).

For the identification phase, it is necessary to extract the model parameters from AM-AM (amplitude modulation-amplitude modulation) and AM-PM (amplitude modulation-phase modulation) data within the operational frequency band of the PA loaded with 50 ohms. ***Figure 20*** illustrates the remarkable precision with which the model reproduces the AM-AM curves across the entire range of powers (-30 to 20 dBm) and frequencies (800 MHz bandwidth).

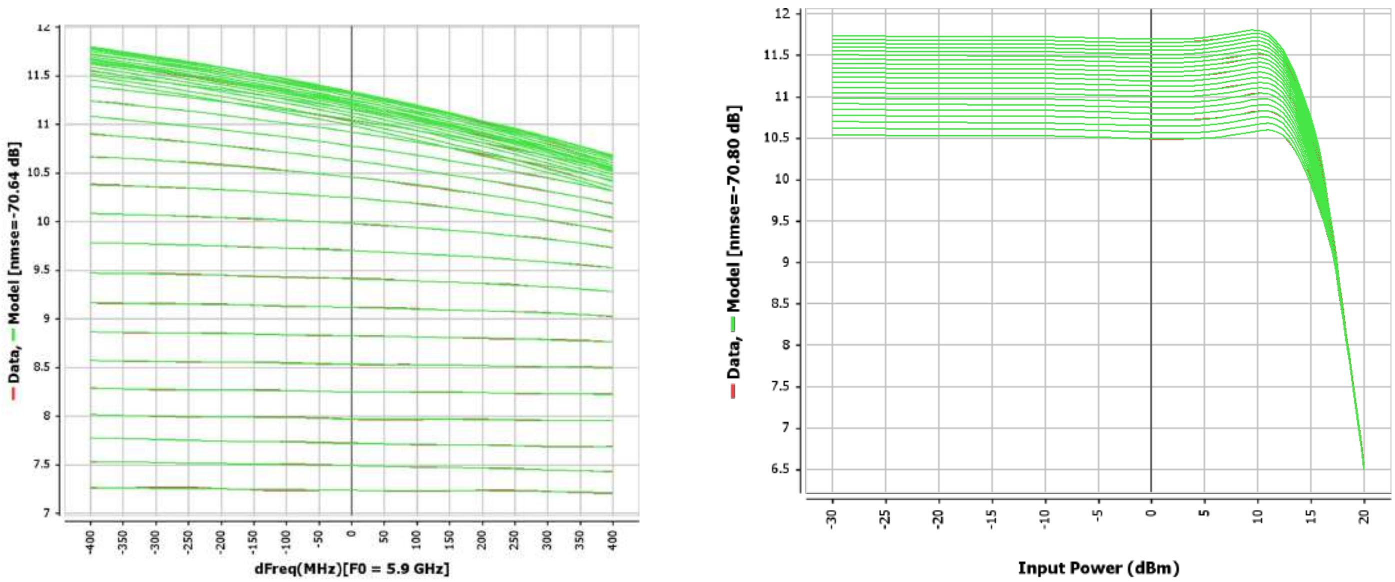


Figure 20: *: AMAM characteristics*

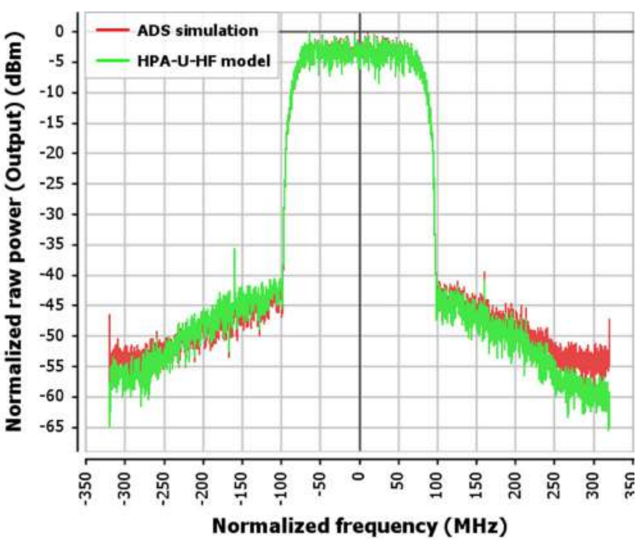


Figure 21: *PA Output spectrum @ 10 dBm average input power*

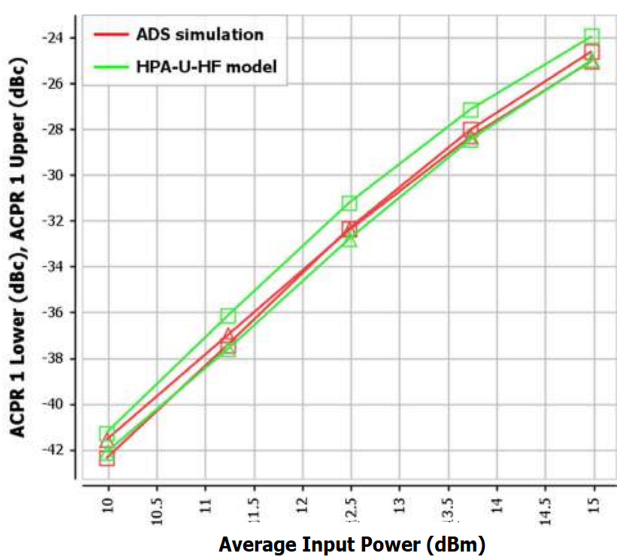


Figure 22: *ACPR lower (square marker) and upper (triangle marker)*

Nevertheless, when simulating this model using the same modulated signal mentioned earlier, the prediction of distortions on the output signal is not satisfactory as that can be seen in spectrum and dynamic AMAM, respectively in ***Figure 21*** and ***Figure 23***. This observation suggests considering a more advanced model that incorporates low-frequency (LF) memory effects.

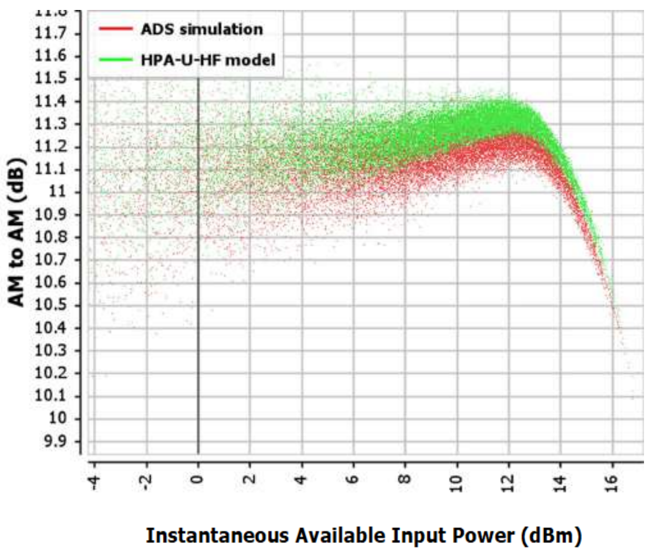


Figure 23: *Dynamic AMAM @ 10 dBm average input power*

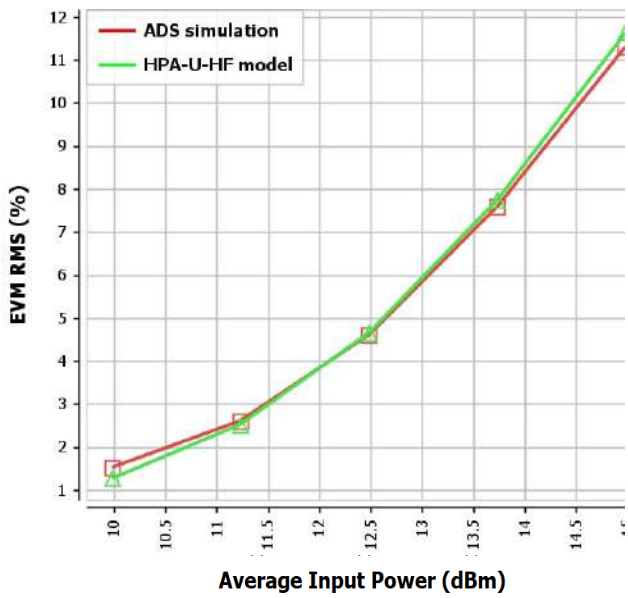


Figure 24: *EVM (Error Vector Magnitude) as a function of input power*

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