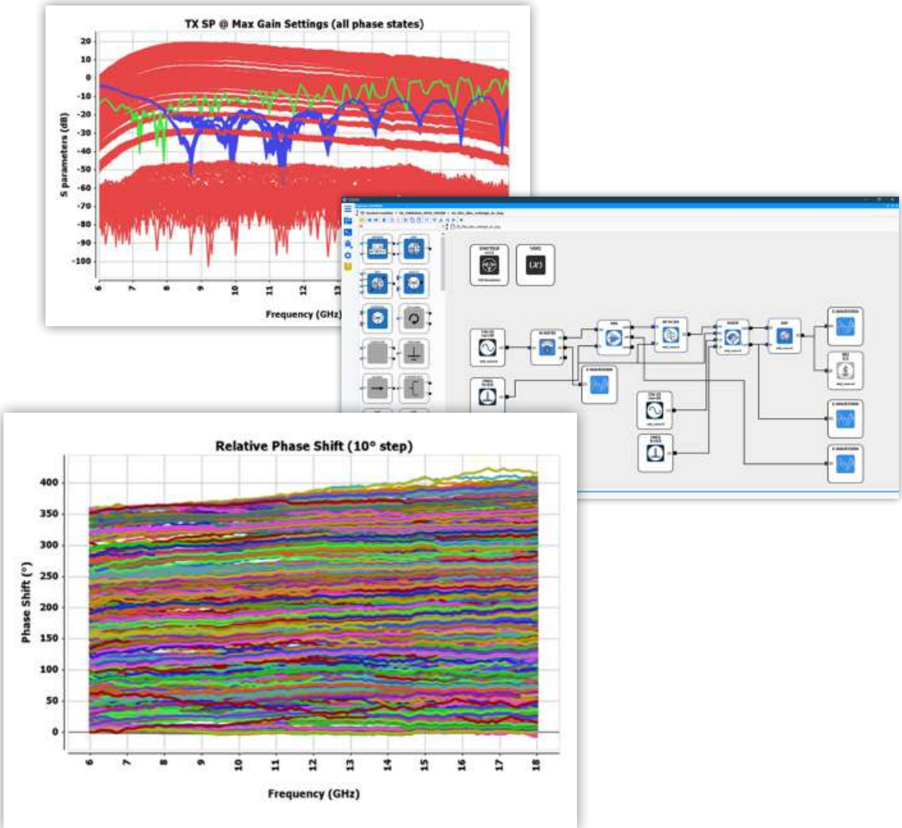
White Paper

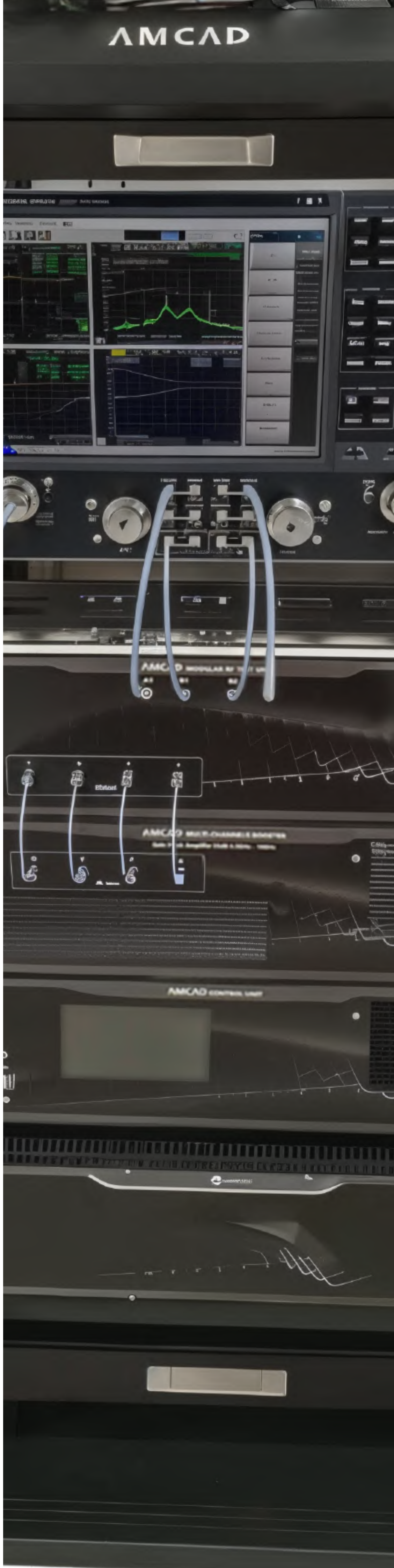
RF Beamformer Measurement Modeling and Simulation



AMCAD Engineering,
a Dassault Systèmes Company

In partnership with
AMCAD SAS

Helping our customers to design smart and safe communication systems !



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PREAMBLE

This white paper describes a test bench and modeling solution for the accurate modeling of RF beamformers. These systems-on-a-chip (SoC) enable the design of advanced communication systems based on antenna beamforming technologies. Due to the cost of manufacturing such a prototype, the aim is to provide system designers with equivalent behavioral models of the SoC in order to evaluate the performance of the virtual twin before manufacturing the real prototype.

We are extremely pleased to inform you that AMCAD Engineering has been acquired by Dassault Systèmes and has joined its SIMULIA brand dedicated to simulation on May 30, 2024. AMCAD Engineering will complement SIMULIA's leading 3D simulation capabilities, by adding the modeling and characterization capabilities for the active network part and will be able to extend the footprint of the radio frequency simulation technology provided by SIMULIA CST Studio Suite.

Prior to the acquisition by Dassault Systèmes, AMCAD Engineering has transferred all its hardware and buy/resell business to AMCAD SAS, an independent company, which will handle all hardware activity. AMCAD Engineering, now a Dassault Systèmes company, will focus solely on its software business as of May 30, 2024.

The two entities have established a strategic partnership that enables them to jointly develop turnkey solutions comprising software and hardware. In this white paper, find out how AMCAD Engineering and AMCAD SAS have jointly developed a solution to accelerate the design flow of complex beamforming systems.

INTRODUCTION

Active antennas have brought a paradigm shift in modern communication systems. Their real-time signal processing capabilities enable adaptive responses to changing network conditions, minimize interference, and maximize signal reliability. The result is improved quality of service, higher data throughput, and reduced latency, all of which are critical for applications like autonomous vehicles, augmented reality, and remote healthcare services.

One of the most prominent applications of active antennas is in mobile communication networks. The advent of 5G technologies has placed greater demands on the reliability and capacity of wireless networks. Active antennas are pivotal in boosting signal strength and ensuring seamless communication, particularly in densely populated urban areas and regions with challenging geographical features.

Satellite communication systems also benefit from active antennas due to their ability to enhance signal quality and reliability. In applications where communication with satellites in geostationary orbits is required, active antennas can mitigate signal degradation and interference, contributing to improved global communication capabilities.

Active antennas employ advanced circuits like beamformers to dynamically adjust the magnitude and phase of the signal sent to the antenna. The radiation pattern is optimized for wireless connections to steer the signal in a particular direction. This is crucial for supporting ever-increasing wireless devices and ensuring efficient data transfer while reducing the power consumption of tomorrow's communication systems.

ACTIVE ANTENNA
Architecture

Communication systems employing active antennas rely on a combination of several critical components to achieve efficient signal transmission and reception. The primary elements include antennas, power amplifiers (PAs), and phase & amplitude-controlled shifters.

Beamformers are integral to active antenna systems, particularly in scenarios requiring adaptive beam steering. They enable the system to adjust the direction of the radiated or received signal dynamically, optimizing signal quality and reducing interference.

The common beamforming techniques are:

- Digital beamforming relies on complex algorithms and multiple antennas to steer the signal direction electronically. This technique is prevalent in 5G and radar systems for sub 6GHz systems where the multi-channel RF signal can be directly managed by digital System on Chips (SoC)
- Analog beamforming employs phase shifters to manipulate the signal's phase, directing it to the desired direction. It is often used in point-to-point communication links at millimetre wave frequencies.
- Hybrid beamforming combines digital and analog beamforming elements to strike a balance between complexity and performance. It is utilized in various wireless communication applications.

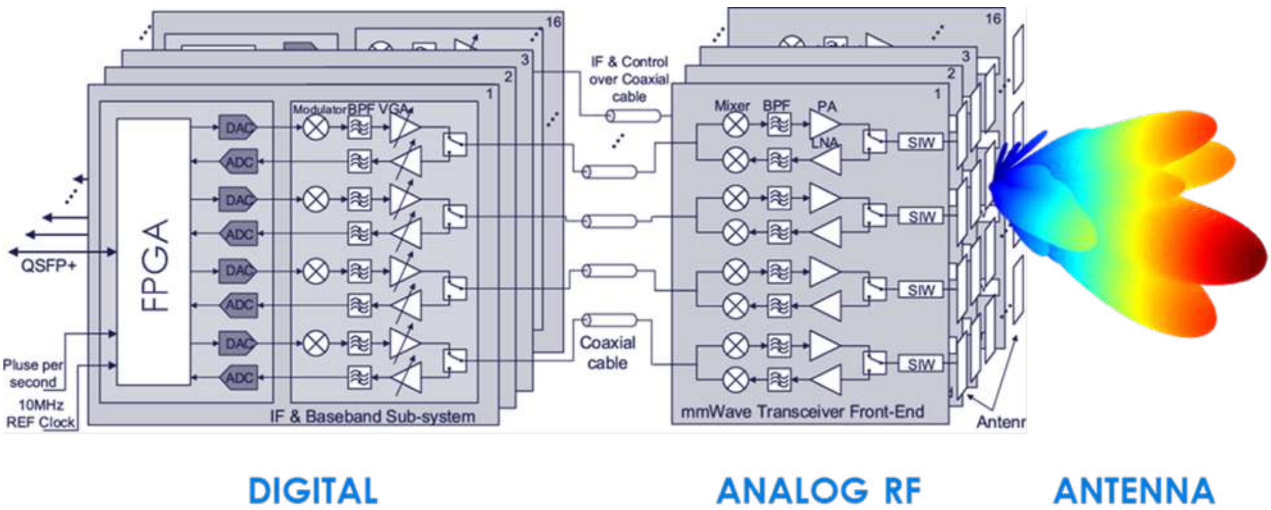


Figure 1 : *Diagram of Active Antenna Architecture with Digital and Analog RF Components*

System Design
CHALLENGES

The design of modern communication systems necessitates a meticulous approach that goes beyond the integration of individual components.

In the first branch of the V-model development cycle, the top-down process splits the overall system performances into sub-circuit specifications. The system architect must then balance the performances of each building block to achieve a robust and cost-effective solution.
In the second branch, the bottom-up design process must assess the global system performances once each building circuit has been chosen.

One pivotal aspect of this process involves system-level simulation, which critically evaluates system performance before physical realization. Engineers can anticipate and address issues using advanced simulation tools and techniques, leading to more efficient and reliable communication systems. In addition, because several thousands of circuits can be deployed for large-scale antenna architecture, accurate system simulations can assess the overall performance while considering the different circuits' spread of performances. Realistic simulations can also be used to optimize the digital control of the communication system in case of RF circuit failures.

The choice of components, such as transistors, capacitors and inductors, to design circuits like filters, power amplifiers and other circuits is possible thanks to the different models available in the circuit-level simulation software. However, accurate circuit models are lacking when integrating multiple system-level circuits. Moreover, as the communication systems are meant to use complex wideband signals, the simulation of the entire system manages a huge quantity of data, preventing simulation from going down at the component level to manage the computing resources and simulation time efficiently.

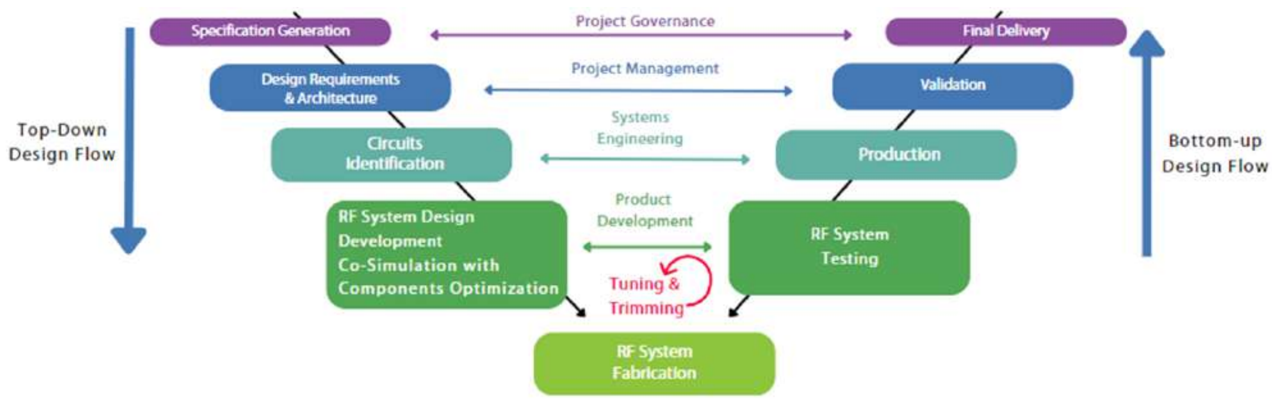


Figure 2 : *Flowchart of Top-Down and Bottom-Up System Design Approaches*

System designers need accurate Circuit Models based on accurate measurements.

While robust simulation solutions are already provided to simulate RF antennas on the one hand or RF circuits on the other, there is a lack of an accurate solution to simulate the overall system behavior when the RF front-ends drive the antennas.

Because of Antenna coupling effects, RF power amplifiers can be submitted to a reverse RF signal in Tx mode. Indeed, some interactions and interferences between multiple antenna elements can drive the output of amplifiers while the PA was designed to be loaded on 50 Ohm impedance. These effects significantly impact system performance by causing an active load pull effect on the RF-Front end, changing the amplitude and phase expected at the output of each amplifier, and altering the intended radiation pattern. Therefore, models must be able to predict such behavior.

Just as there can be no accurate system simulation without a reliable circuit model, there can be no accurate IC modelling modelling work without reliable, complete and exhaustive RF characterization.

This article intends to focus on the measurement prerequisites needed to drive such a system design flow.

In this example, an ADAR1000 beamformer IC, working in X-band, and provided by Analog Devices was used as a measured circuit candidate.

The measurement step of such a SoC can be time-consuming, and the next section will elaborate more specifically on this point, to the extent that some beamforming IC manufacturers provide only a subset of the measurements (S-parameters only) with a few values of phase and gain variations, leading to incomplete data to validate a design. Moreover, the beamforming still needs to be iteratively calibrated on OTA chambers, which adds to the overall cost of the design.

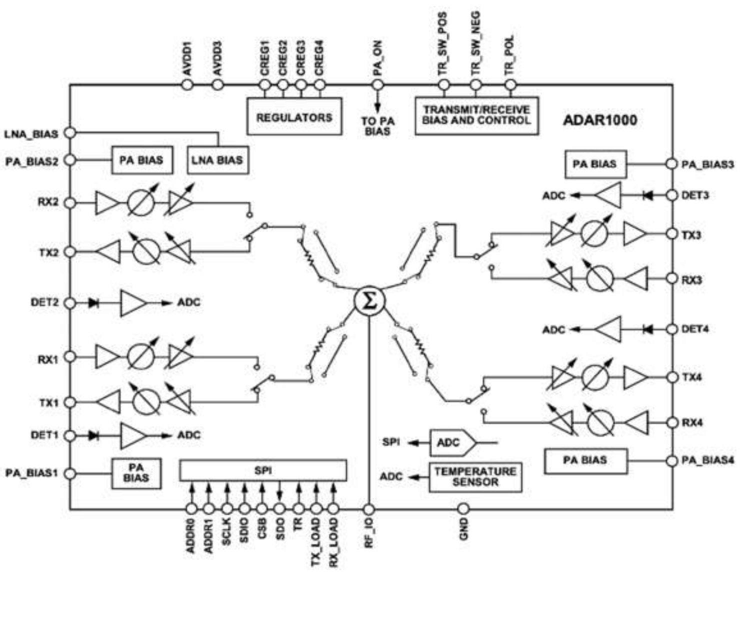


Figure 3 : *Block Diagram of ADAR1000 Beamformer IC*

Image 1 : *ADAR1000 Beamformer IC from Analog Devices*

AUTOMATED TEST EQUIPMENT
makes SoC characterization easy.

A comprehensive set of measurement data is required to model such a chip accurately, covering various combinations of phase and attenuation settings for each channel. In the case of the ADAR1000 chip monolithic IC, its RF beamforming integrated circuits (ICs) feature individual phase and gain adjustments for all four TX (transmit) and four RX (receive) channels. A 7-bit resolution control allows an adjustment of the phase and the gain over 128 values each in addition to a fixed 15 dB attenuation ON/OFF toggle, leading to 32768 possible states (measurements) per channel and a total of 262144 sets of measurements for the entire chip. In addition, the chip may have to be measured in linear conditions to get the S parameters, for example, but also in nonlinear conditions for various operating conditions to get a full picture of the SoC behavior. In such conditions, an Automated Test System becomes mandatory.

Compared with the characterization of other passive or active RF circuits (Filters, amplifiers, mixers, etc.), the ATE system for beamforming ICs needs to control the chip and the instruments. Indeed, automated parametric tests must be done by sending specific commands to the IC controller to vary the channels, the attenuation levels and the phase shifting before each measurement to speed up the process.

The ATE system proposed in this whitepaper is a turnkey combination of hardware from AMCAD SAS and software from AMCAD Engineering. The hardware was chosen based on its capabilities to perform all the measurements needed for a complete characterization of the chip, which includes:

- For the TX
- S-parameters
- Large signal characterization over the RF frequency bandwidth
- 2-Tones Characterization to estimate video bandwidth and Intermodulation performances
- Load Impedance VSWR Control to estimate the impact of antenna mismatch effects on the TX path performance and Tx/Rx switch isolation
- Wideband signal analysis (ACPR, NPR...)
- For the RX side
- S-Parameters
- Noise measurement
- Nonlinear behavior when the reception channel is saturated

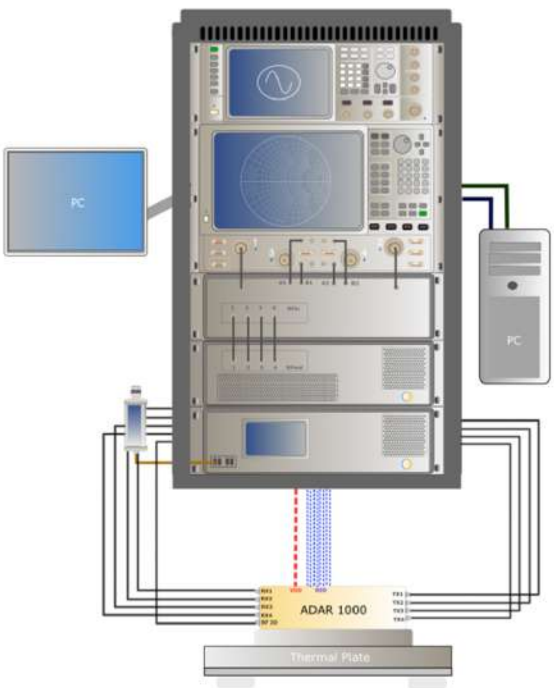


Figure 4 : *Block Diagram of Automated Test Bench*

A Vector Network Analyzer (VNA) stands as the singular instrument that comprehensively offers measurement solutions to the diverse requirements in characterizing integrated RF circuits. It distinguishes itself by accommodating a spectrum of measurements, from small signal analyses to 1-tone and 2-tone large-signal measurements. Encompassing active sources with magnitude and phase control and wideband signal analysis permits an impedance variation at the output of the RF-Front ends to simulate antenna mismatch effects. With its built-in spectrum mode, the VNA not only performs a comprehensive characterization of the circuit under complex wideband signals used for communication applications measuring figures of merits like ACPR, but it also allows measuring the Noise Power Ratio (NPR) for very wideband signals used to assess the quality, linearity, and performance of satellite communication systems where the transmission of signals over long distances demands high-quality signal integrity. (See [AMCAD Engineering's IQSTAR brochure] for NPR measurement capabilities).

This setup is designed to provide high- accuracy, flexibility, and efficiency, ensuring that engineers and researchers can conduct long measurements with the utmost precision and convenience.

The intent is also to limit the number of human manipulations of the bench to ensure a maximum characterization speed, minimum manipulation errors and guaranteed repeatability from bench to bench or site to site.

Three rackmount units were designed by AMCAD SAS and added to the system on top of the VNA to achieve automation.

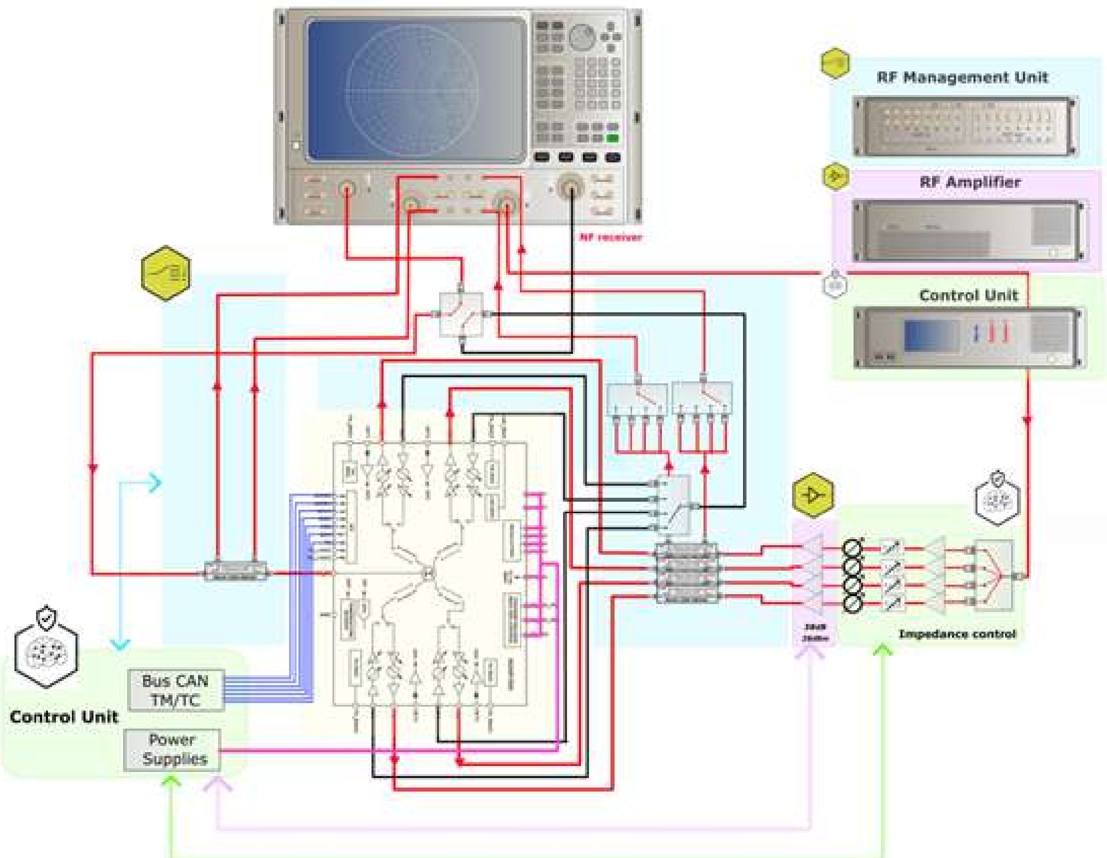


Figure 5 : *ATE Schematic Diagram with the DUT in the Center*

RF MANAGEMENT UNIT

Given the architecture of the beamformer and the multiple configurations of the VNA to achieve different measurements, the RF management unit routes the RF signal through different paths or measurement configurations related to transmitters (TX) or receivers (RX), using a switch matrix. Test engineers may be called to configure various connectorized passive components like filters, switches, and couplers to meet specific testing needs in an automated testing system. One of the key challenges when setting up such a system is twofold: firstly, ensuring effective control of all the switching elements, and secondly, managing the inherent path losses associated with these configurations. Therefore, conducting a thorough study and optimizing the mechanical integration of these components is paramount to minimize these losses.

AMCAD SAS developed a dedicated solution using a selected switch matrix control for multi-channel component testing integrated into a 3U chassis. The standard rackmount chassis includes relays, power dividers and couplers for the measurements. The RF switch matrix links each channel and its respective output to the VNA and is controlled through USB.

Such a switch matrix comes with a high-level control user interface provided by AMCAD Engineering's IQSTAR software to get calibrated data at the SoC reference planes in absolute magnitude and phase information for both linear and nonlinear conditions.

RF AMPLIFIER UNIT

The RF Amplifier unit is an important block of the test bench. Finding power amplifiers with the required power level and frequency bandwidth of the application is not always possible. Therefore, a manual connection of different modules is mandatory, which defies the purpose of an automated system. For such an application, a multi-channel amplifier was designed to drive the output of the 4 Tx channels to reproduce the active VSWR effects caused by the different elements of the active antenna for various beam steering. Conversely, these 4 channels can be advantageously used to drive the input of the 4 inputs of RX channels.

With the AMCAD SAS RF amplifier unit, all the peripherals are controlled and checked to ensure the proper operation of the power amplifiers. Moreover, status feedback is implemented to monitor parameters like supplied voltage, current consumption, temperature, etc. Thanks to a dedicated communication protocol with the measurement software, any malfunction or deterioration of the modules and peripherals is caught immediately.

CONTROL UNIT

Beamformer ICs often have control interfaces, such as SPI (Serial Peripheral Interface) or I2C (Inter-Integrated Circuit), through which a microcontroller or other external device can communicate with the IC. The control interface allows external devices to configure the IC's settings and adjust the beamforming parameters. When it comes to instruments, the bench can be quite heterogeneous. Some are controlled through LAN, others through USB or GPIB, if not proprietary communication protocols.

To solve this issue, AMCAD SAS designed a control unit to manage effectively all the modules, instruments and devices connected locally, standardizing the connected parts of the bench, facilitating the control and increasing the reliability.

The control unit acts like a broker between the low-level test instruments and the high-level measurement software, allowing filtering the low-level continuous monitoring of security parameters (voltage, current, die temperature…), without breaking the logic of the measurement software.

MEASUREMENT SOFTWARE

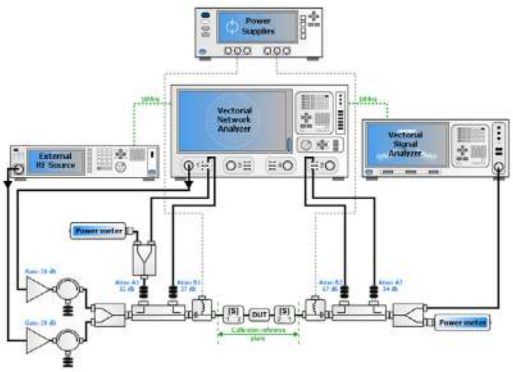


Figure 6: *Schematic of IQSTAR ATE System Setup*

Characterizing complex circuits like amplifiers and complex Integrated circuits requires more than just an instrument. An accurate and repeatable calibration procedure must be used to extract the measurement at the circuit reference plan. Moreover, multiple sweeps must be performed with the required measurements, including frequency, power, bias, impedance, tone spacing, etc.

As specified in the previous sections, the ATE system includes different instruments and modules that do not always share the same communication protocols. Therefore, measurement software must be Instrument-agnostic to extract all the measurement parameters.

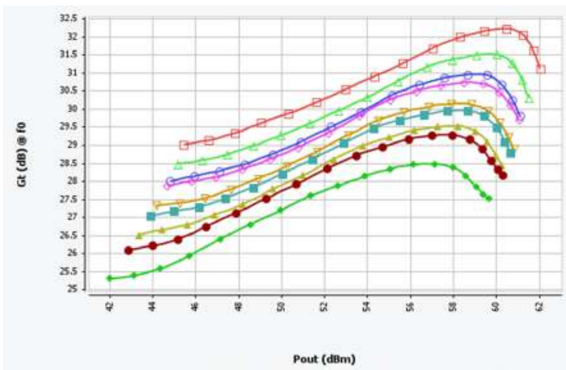
Thanks to the support of more than 1000 instrument software drivers, IQSTAR software is a turnkey solution for circuit characterization. It allows full customization of the bench schematic using a setup editor.

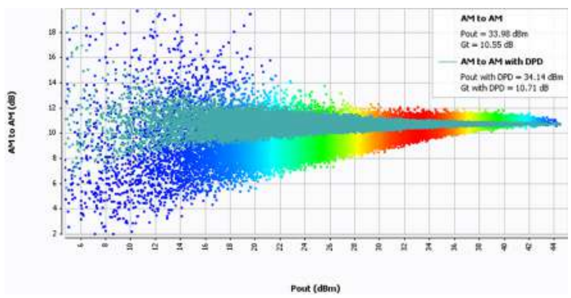
The complete characterization flow of IQSTAR includes the following:

- Calibration process: Ensuring a bench-to-bench or site-to-site measurement repeatability and data coherence.
- Different measurement configurations:
  - S-Parameters (CW and Pulsed)
  - 1-Tone (CW and Pulsed)
    - Power and frequency sweeps
    - Gain Compression
    - Constant VSWR testing
    - PAE
    - Harmonics
    - Spurious detection
    - Spectrum traces
  - 2-Tone
    - Intermodulation
    - Video Bandwidth
  - Modulated Signal and IQ Analysis
    - ACPR
    - EVM
    - CCDF
    - NPR
    - Dynamic AM-AM
    - Dynamic AM-PM
    - Spectrum
    - DPD analysis

Figure 6 & 7:

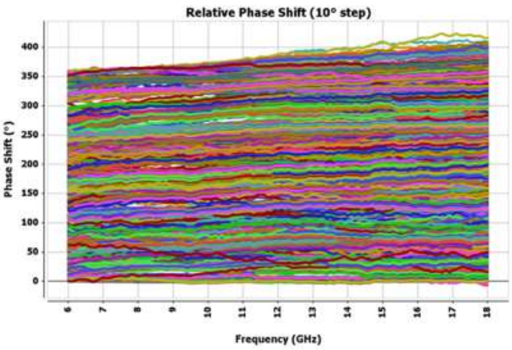
Gain Compression Measurement Graph / ACPR vs. Power Measurement Scatter Plot

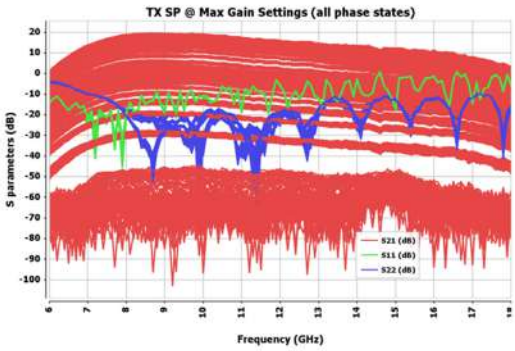




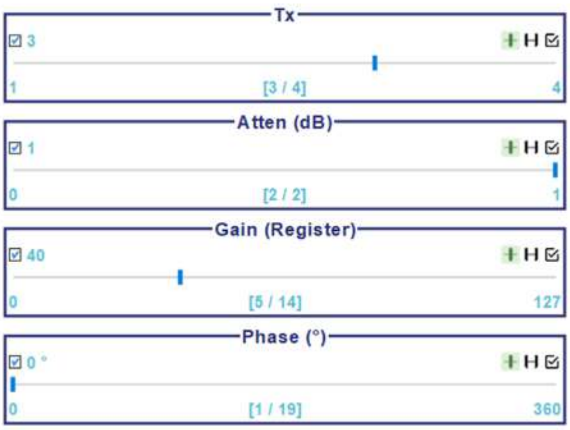
Automation and test sequencing are necessary to ensure complete testing without human intervention and minimize all sources of errors. Switching between different channels and sweeping the gain and phase variables on the chip, the system can produce all the measurement data obtained from the VNA.

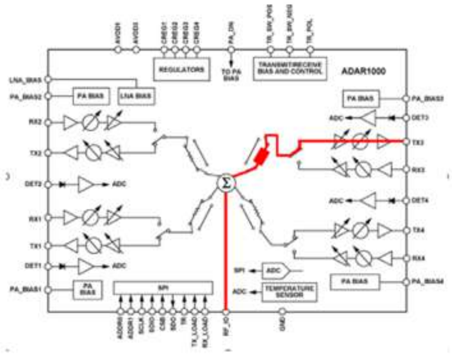
Considering the number of combinations and the necessary sweeps (frequency, power, impedances, channels, measurement type), extracting important information at first glance from a huge quantity of data is difficult. Therefore, a comprehensive Whiteboard reporting tool analysis provided by AMCAD Engineering is the most appropriate solution.

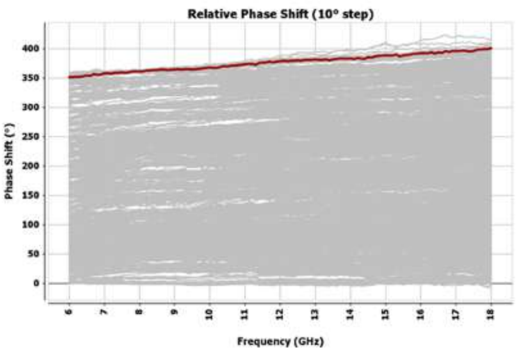


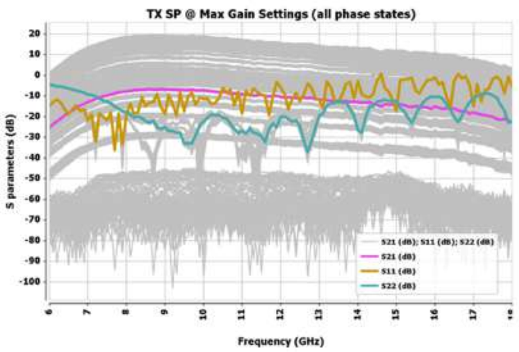


The data is filtered based on user-defined criteria and traced in graphs with adequate attributes. Using controls like sliders, filters, and extractors, the user can easily choose the measurement and stimulus conditions at which he would like to highlight the characteristics of the beamformer.





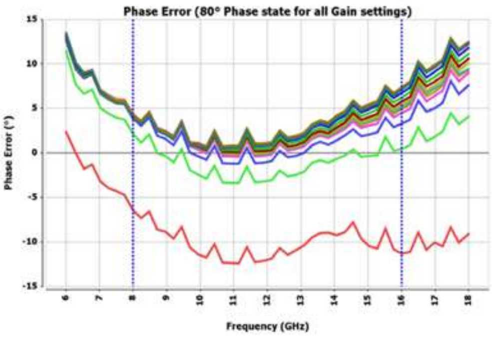




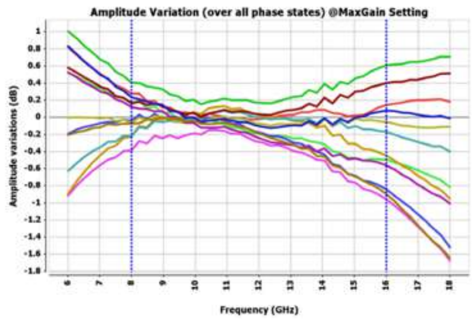
When consulting manufacturer datasheets, where data is gathered on a few graphs and tables, the analysis of the characteristics of the characteristics is very difficult. Most of the data is missing, and if we need to check something specific, chances are that the data is not presented. With the Whiteboard report, the datasheet is interactive, where the graphs are updated from the measurement file based on the user's chosen measurement conditions.

In our example with the ADAR1000 IC, the ATE system highlighted that the phase control may impact the chain gain and vice-versa. Moreover, the attenuator setting also has an impact on the phase variation. So, a closer look at the data shows that the phase variation introduced by the Gain variation can be up to 10 degrees, and the gain variation introduced by the phase setting can be up to 1 dB.

Phase variation introduced by the **VGA** states



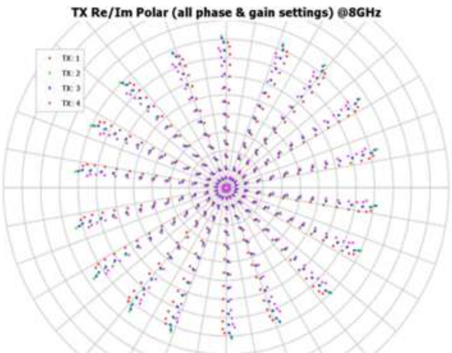
Gain Variation introduced by **phase Shifter** states



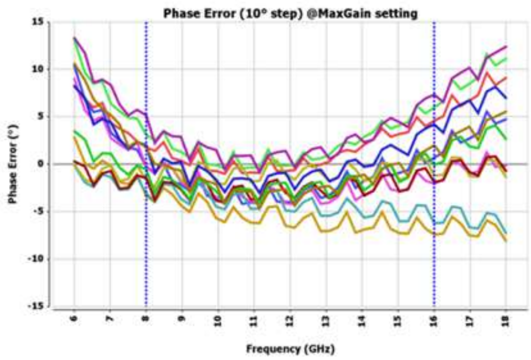
On top, phase and gain dispersion can also be observed between TX paths.

Also a phase error of up to 5 degrees compared to the phase command can be observed.

Phase & Gain dispersion in function on TX used



Phase Error setting across frequency compared to command setting



In conclusion, without this thorough analysis, predicting the radiation pattern without a prior calibration would be difficult, if not impossible.

Beamformer ICs are intricate components with inherent imperfections, necessitating thorough characterization. However, given the extensive number of measurements required, even an Automated Test Equipment (ATE) system may not be ideal. For instance, characterizing the S-parameters alone could take up to six days to complete, making it impractical for high-volume production settings. Therefore, a solution based on the chip behavioural model offers substantial advantages. The upcoming section explores these benefits in more detail.

BEAMFORMER MODELING

Efficiency is paramount in a high-volume production environment. Behavioral modeling reduces the time required for characterization and enhances scalability, flexibility, and resource efficiency. It ensures accurate predictions of IC performance, allowing for streamlined production testing and rapid adaptation to manufacturing variations, ultimately improving product quality and reducing costs. Furthermore, this approach accommodates the complexity of the chip architecture, making it a practical and forward-thinking solution for the semiconductor industry.

The modeling solutions available are either based on the datasheet results or issued from measurements. In the case of digital beamforming, the steering angle directly affects the RF Front-end and especially the last amplifying stage, as the mutual coupling between the radiating elements induces an RF signal with a certain power level and phase value. The last stage amplifiers of the RF front end see a variation in the load impedance and, therefore, in their output power. This phenomenon is known as active Load-Pull or active VSWR effects.

Models that do not include the load-pull or bilateral effect cannot predict the impact of such a change of load impedance on output power and phase performance, leading to the wrong prediction of the radiation pattern.

On top of IQSTAR measurement software for controlling ATE systems, AMCAD Engineering's VISION software provides is an advanced RF circuit and system modeling capabilities for RF and MW system design. Designing RF systems intended to be used with wideband modulated signals such as 5G and RADAR or systems featuring a multitude of circuits, like active antennas, can be quite challenging. When evaluating the accuracy of simulations, it becomes evident that the key factor limiting precision lies in the quality of the model employed by the simulator. Despite the potential presence of various memory effects in circuit behavior, these characteristics often remain absent from the model.

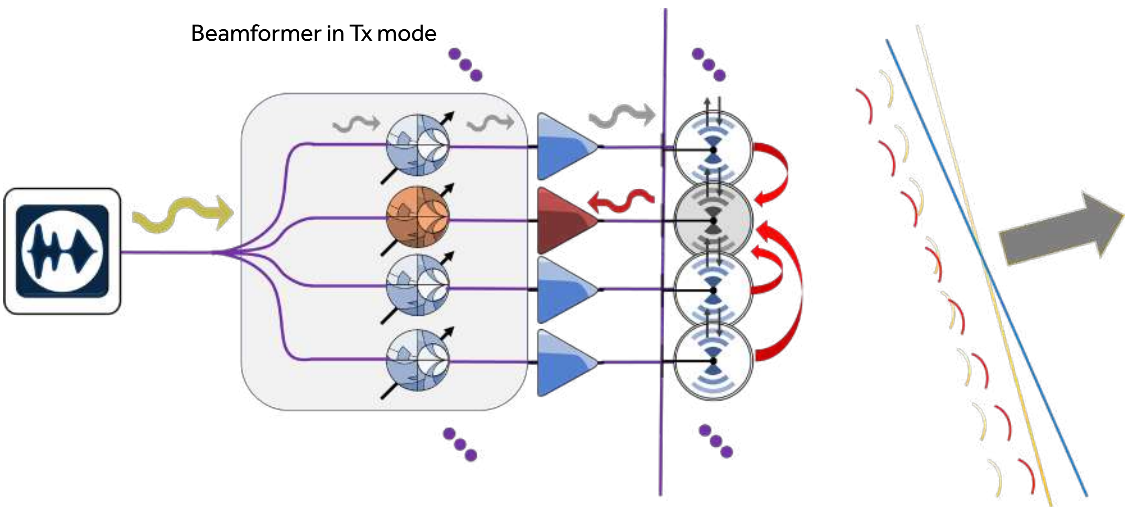


Figure 7 : *Beamformer in Transmission Mode*

AMCAD Engineering

AMCAD ENGINEERING, now a part of the SIMULIA brand of Dassault Systèmes, provides measurement, modeling, and simulation software for improving the performance of RF components and circuits.

The combined AMCAD Engineering and SIMULIA teams are committed to delivering and supporting comprehensive, end-to-end modeling and simulation solutions to accelerate the development of wireless communication systems for civil, aerospace, and defense applications.

AMCAD SAS

AMCAD SAS is a newly established company focusing on test and measurement hardware including the Pulse IV System, Automatic Test Equipment, among others.

AMCAD SAS will remain under the umbrella of the CGD Group, which includes its sister companies, WUPATEC and ITEST.

Dassault Systèmes and AMCAD SAS have entered into a partnership agreement to ensure their respective software and hardware's current and future compatibility and optimization.