Automated Testing Toolbox for Power Amplifiers and Antennas

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1. Abstract

The telecommunications industry is facing increasing energy consumption demands. Next-generation communication systems, i.e., 5G, require stringent performance specifications to meet the growing data requirements. Testing power amplifiers (PAs) and antennas, crucial components in these systems, is labor-intensive and time-consuming due to repetitive changes in testing parameters. Such solutions exist, namely commercial equipment, however, they are expensive and restricted. This research addresses the challenges of manual testing of power amplifiers and antennas by developing an automated toolbox. The toolbox was packaged as a MATLAB application to interface with the existing equipment in the ARES Lab, utilizing the built-in communication protocols provided by the equipment to establish control and acquire data. The toolbox was designed with a user-friendly interface that allows users to control the testing parameters. The toolbox automates parametric frequency, bandwidth, and input power sweeps for PA testing. It also includes features to control the anechoic chamber positioners for antenna pattern measurements. Comprehensive data sets are generated, and visuals provide valuable insights into the performance of the PA and the antenna radiation patterns. This enables efficient data acquisition and eliminates the need for manual labor. The developed software solution enhances collaboration, reproducibility, and knowledge sharing within the research community. The automated testing toolbox offers an efficient, cost-effective alternative to expensive commercial solutions. Future work involves expanding the toolboxes, adding more utilities to the application, standardizing the code, and extending compatibility to multiple test equipment models.

2. Introduction

With the advent of 5G communication systems, the need to shift away from the current paradigm is increasing. This shift is driven by the new era of wireless communication standards and the telecommunications industry demands. Power amplifiers (PAs) and antennas are critical components of these modern communication systems, playing vital roles in signal transmission and reception. With these emerging technologies, highly efficient and linear PAs as well as high-performance antennas, must meet these new industry standards. Our project aims to address these evolving needs by developing an automated toolbox for parametric testing of power amplifiers and antenna gain measurements, providing more efficient and accurate characterization methods.

Characterizing PAs involves measuring various key parameters such as saturation power, compression points, gain, drain efficiency (DE), power-added efficiency (PAE), adjacent channel power ratio (ACPR) and error vector magnitude (EVM). These metrics quantify the performance of the PA, and its contribution to the transmitter system. Similarly, antenna characterization includes measuring gain, efficiency, and radiation patterns. These parameters quantify how well the antenna can transmit and receive electromagnetic waves and how much of the input power is turned into output power. Traditional testing methods for both PAs and antennas are time-consuming and prone to human error.

Recognizing these challenges, Cai et al. developed an automated testing system using LabVIEW to enhance the efficiency of power amplifier data collection [1]. We used their work as an initial model for the automated testing toolbox presented in this report. Building on these principles, our project integrates both power amplifier and antenna measurements into a single automated platform. By leveraging MATLAB instead of LabVIEW, this toolbox provides a more versatile programming environment, which improves user interaction and functionality.

Packaged as a MATLAB App with a user-friendly graphical interface, the toolbox allows for intuitive control of testing parameters and visualization of measurement results, offering a more accessible and enhanced user experience compared to the command-line interface typical of LabVIEW applications.

Recent advancements in PA and antenna design have increasingly focused on optimizing efficiency, linearity, and gain across wide bandwidths, fitting into the newer telecommunication standards. Advanced PA architectures such as the Class B Doherty power amplifier (DPA), show an improvement in backoff efficiency, and gain expansion when using a two-tone modulation mechanism [2]. At the 2021 High-Efficiency Power Amplifier (HEPA) student design competition, Lyu, Cao, and Chen's worked on a highly efficient and linear Quasi-Balanced DPA. They developed a novel design methodology using a quadrature coupler-based output network that would consider the AM-AM expansion and AM-PM improvement[3]. Their design achieved a gain of 13 dB at 3.485 GHz, and a PAE of 57.2%. Modulated signals such as LTE and 5G were also assessed and their results were superior, earning them first place in the competition.

Similarly, Chen and Peroulis presented an adaptive GaN PA for octave-bandwidth applications, incorporating a tunable matching network (OMN) using varactors with high breakdown voltages

[4]. The PA demonstrated a DE of 64-79% and a PAE of 55-72% at maximum power, with dynamic load modulation providing over a 15% efficiency improvement at 10 dB back-off. Their paper is thorough in its analysis of varactor diodes and the PA's performance, making it a valuable reference for those looking to implement similar technology. The well-documented experimental results and consideration of device parasitics offer a solid foundation for future research and development in this area.

The need for high-performance antennas capable of delivering significant gain at elevated frequency ranges has intensified in recent times. Designing compact antenna solutions with substantial gain is crucial for realizing compact, efficient communication systems. Abdelaziem et al. made notable progress in this area by proposing an innovative antenna architecture that leverages Mu-near-zero (MNZ) meta surface (MS) structures to achieve high gain [5].

MNZ-MS are a class of engineered materials designed to exhibit unique electromagnetic properties. Unlike traditional materials, which are characterized by their inherent physical properties, metamaterials derive their behavior from their structure rather than their composition. This allows them to manipulate electromagnetic waves in ways that natural materials cannot, such as achieving negative permittivity and permeability, which can enhance the performance of devices like antennas. Research is still being done to document how these materials can be used for antenna miniaturization, gain enhancement, and improved isolation in wireless communication systems [6].

Their design, which places an MNZ-MS layer above a patch antenna source, demonstrated a peak gain of 13.13 dBi at 26.3 GHz, representing an impressive gain enhancement of more than 5 dB compared to the patch antenna alone. This significant improvement in gain, combined with the compact form factor, positions the MNZ-MS antenna as a promising solution for realizing high-data-rate 5G communication systems.

In conjunction with these advancements in power amplifier and antenna designs, the development of an automated testing toolbox has become increasingly vital. By building upon the concepts from [1] and incorporating additional functionality, this project aims to provide a comprehensive solution for efficient characterization of power amplifiers and antennas in the context of evolving 5G technologies. Packaged as a MATLAB application, the toolbox streamlines the testing process by automating parametric sweeps and data acquisition, thereby improving efficiency and accuracy compared to traditional manual methods.

The primary goals of this project are to (a) integrate both power amplifier and antenna measurements into a single automated platform, (b) increase the efficiency and accuracy of data collection by automating multiple testing runs, and (c) create a versatile toolbox that can accommodate various PA designs, antenna types, and testing environments. By leveraging MATLAB instead of LabVIEW, this toolbox offers a more versatile programming environment that enhances user interaction and functionality while offering a cost-effective alternative to expensive commercial solutions.

3. Methodology

3.1. VISA Interface

What makes the automation process possible is that each instrument can be connected to the testing computer, enabling data transfer between each device. The main idea behind instrument automation is to connect effectively via a communication protocol to an instrument, then using the Virtual Instrument Standard Architecture (VISA), standard commands for programmable instruments (SCPI) can be sent to control the instrument. VISA is a software protocol created by Keysight and National Instruments for communicating with instruments regardless of their communication protocol (LAN, USB, GPIB, RS-232) [7]. SCPI are built on the foundation of IEEE-488.2 and provide a common language between devices and instruments, making it easier to interface with them. Since SCPI is hardware independent, SCPI strings can be sent over any instrument interface that supports it [8].

To utilize VISA and connect to the instruments four software prerequisites must be installed first. This includes:

1) Keysight IO Libraries
2) Keysight Connection Expert
3) Keysight Command Expert
4) MATLAB with Instrument Control Toolbox

The first software installs the drivers needed by VISA to establish connection to the instruments. The second software is a connection manager for all your instruments, this tool allows you to scan and add instruments once you connect them to your computer. Connection Expert gives you information about the device such as manufacturer, model, and VISA address. The process of building the initial code was to first program each instrument to do their job, e.g., signal generation. This was first done in Command Expert which provides each connected instrument's SCPI sets, which come with documentation making it easier to decide what commands to use and how to use them. The program also features an option to export the SCPI sequence into different programming languages, including MATLAB, Python, and C. After establishing the sequence of strings for each instrument, the resulting code was exported into MATLAB which allowed us to use the sequence dynamically.

One early problem we faced when exporting code was that MATLAB would warn us that the code was not up to date and in the future, it would not be supported. The cause of the problem was that Command Expert was referencing the original VISA interface, meanwhile MATLAB had updated its Instrument Control Toolbox, introducing the new VISAdev interface. This did not set us back, as MathWorks provides documentation to transition code from VISA to VISAdev [9]. The following table includes the major changes that we had to implement for our code to successfully run in MATLAB.

Table 1: Transitioning Code from VISA Interface to VISAdev Interface

VISA Interface	VISAdev Interface	Purpose
visa()	visadev()	Connect the instrument
fprintf()	writeline()	Write to the instrument
fscanf()	readline()	Read from the instrument
query()	writeread()	Write and read at the same time
binblockread()	readbinblock()	Read binblock data
clrdevice()	flush()	Flush data from memory
fclose()	delete() & clear()	Disconnect the instrument

Soom after becoming accustomed to the SCPI strings, the process got significantly easier, allowing us to combine each instruments commands together to form complex code capable of setting parameters, running the measurements, extracting, processing, and visualizing the data, and handling each instrument gracefully.

3.2. SCPI Strings

As previously mentioned SCPI strings allow an instrument to be controlled programmatically mirroring the utilities that come with the physical inputs to the instrument (touch screen, buttons). There are two types of SCPI strings,

:KEY and :KEY?

The former is called a command string and is reserved for when we want to write to the instrument and not receive anything back. The latter is called a query string and is reserved for when we want to read data back from the instrument. In this case :KEY represents the name of an instrument's feature such as measuring something, setting parameters, and more. SCPI strings can also take in parameters,

:KEY <parameter>

Complex SCPI strings can be made by combining several features and parameters into one string,

:KEY1:KEY2:KEY3? <parameter1> <parameter2>

All instruments which adhere to the VISA standards share a small set of SCPI strings. These strings can be found in all instruments. These were useful and were employed in the application for distinct reasons discussed in the table below. They have a different form to previous SCPI strings,

*KEY and *KEY?

Table 2: Common SCPI Strings Across Instruments

Command / Query	SCPI String	Purpose	When To Use
Identification Query	*IDN?	Returns a string that uniquely identifies the instrument. Including brand, model, and serial numbers.	After connecting the instrument, one can use the command to verify the instrument.
Reset Command	*RST	Resets most instrument functions to factory-defined conditions.	After connecting the instrument unless working with a preconfigured environment.
Clear Status Command	*CLS	Clears the registers from the status byte.	When measuring sweeps, such that the next set of data is not compromised.
Operation Complete Query	*OPC?	The query returns the ASCII character one when all pending operations have finished.	Especially helpful when debugging the QUERY Interrupted error from the instruments.
Wait Command	*WAI	Prohibits the instrument from executing any new commands until all pending overlapped commands have been completed.	Like *OPC? but this approach is less dynamic.
Data Format Commands	:FORM:BORD: SWAP :FORM:DATA <type>,<bits>	Defines the type and format of data that is returned after a trace measurement. These commands are required to query the data.	Swapped endianness is preferred on most modern computers.

There are three types of data to be chosen. REAL,32 is best for transferring substantial amounts of data. REAL,64 is slower but has more significant digits than REAL,32. For these types use readbinblock(), because they transfer data in block format. The last one is ASCii,0 easiest to implement, but slow, used when you have small amounts of data to transfer.

Table 3: Specific SCPI Strings Across PA Instruments

Instrument	Command / Query	SCPI String
Power Supply	Set voltage, current limit, and supply mode	:APPLY <mode> <voltage> <current>
	Measure voltage	:MEAS:VOLT:DC? <mode>
	Measure current	:MEAS:CURR:DC? <mode>
Signal Generator	Set frequency	:SOUR:FREQ:CW <frequency>
	Set RF power	:SOUR:POW:LEV:IMM:AMPL <power>
Spectrum Analyzer	Set center frequency	:SENS:FREQ:CENT <frequency>
	Set span	:SENS:FREQ:SPAN <span>
	Set sweep points	:SENS:SWE:POIN <points>
	Set reference level	:DISP:WIND:TRAC:Y:SCAL:RLEV <reference>
	Initializes the type of sweep entered by the user. Available types are single, continuous or hold.	:INIT:CONT <type>
	Starts the sweep	:INIT:IMM
	Fetch trace data	:TRAC:DATA? <trace>

Table 4: Specific SCPI Strings Across Antenna Instruments

Instrument	Command / Query	SCPI String
Vector Network Analyzer	Set start frequency	:SENS<cnum>:FREQ:STAR <frequency>
	Set end frequency	:SENS<cnum>:FREQ:STOP <frequency>
	Set sweep points	:SENS<cnum>:SWE:POIN <points>
	Create a measurement	:CALC<cnum>:PAR:DEF:EXT <mnum>,<mname>
	Display the created measurement	:DISP:WIND<cnum>:TRAC<mnum>:FEED <mnum>
	Start a sweep	:SENS<cnum>:SWE:MODE <mode>
	Select measurement to populate with data	:CALC<cnum>:PAR:SEL <mname>
	Fetch trace data	:CALC<cnum>:DATA? SDATA
	Fetch the frequency data from trace	:SENS:X:VAL?
	Delete all existing measurements	:CALC:PAR:DEL:ALL
EM Center	Get current position	1<slot-letter>:CP?
	Set speed	1<slot-letter>:SPEED <speed>
	Seek angle	1<slot-letter>:SK <angle>
	Stop movement	1<slot-letter>:ST

For the VNA, cnum is the channel number which defaults to one if not specified, mnum is the measurement number, and mname is the name of the measurement. For the EM Center which controls the anechoic chamber, the tower and table are in slot one, however the table is in letter A, and the tower is in letter B.

3.3. Application Structure

The application began as a collection of separate MATLAB files and functions, each responsible for specific tasks such as controlling the instrument, acquiring data, and processing data. Leveraging MATLAB's App Designer framework for creating a graphical user interface (GUI), the initial code was integrated into the framework for a more user-friendly experience. Since the application functions as a class, it is organized in two main structures.

1) Properties: There are two property blocks. The first block oversees all properties that correspond to app components. MATLAB manages this block automatically, and stores all components (buttons, tables, panels). The second block oversees all properties that correspond to global variables. In this block, the instrument objects are initialized, as well as the data parameters. Any variable that is initialized in this block is made global and can be accessed at all moments within the application.
2) Methods: There are four method blocks. The first block includes all helper functions used throughout the application. The second block includes all callbacks that manage component events, these callbacks execute dynamically when the user presses a button in the application. The last two blocks include all methods that relate to app components, MATLAB manages these blocks automatically.

Key functions that manage the data collection and processing include:

1) measureRFOutput.m: Measures RF output power and DC power.
2) measureRFParameters.m: Calculates gain, DE, and PAE.
3) measureSParameters.m: Measures S-parameters, and frequency values.
4) measureAntennaGain.m: Measures Antenna gain using the Friis transmission equation.

These functions are located within the application's workspace, allowing the application to call them even if they are not in the main code. This allows users to interact with a cohesive interface rather than running multiple scripts, but at the same time have access to these files to modify them, as necessary.

3.4. Application Algorithm

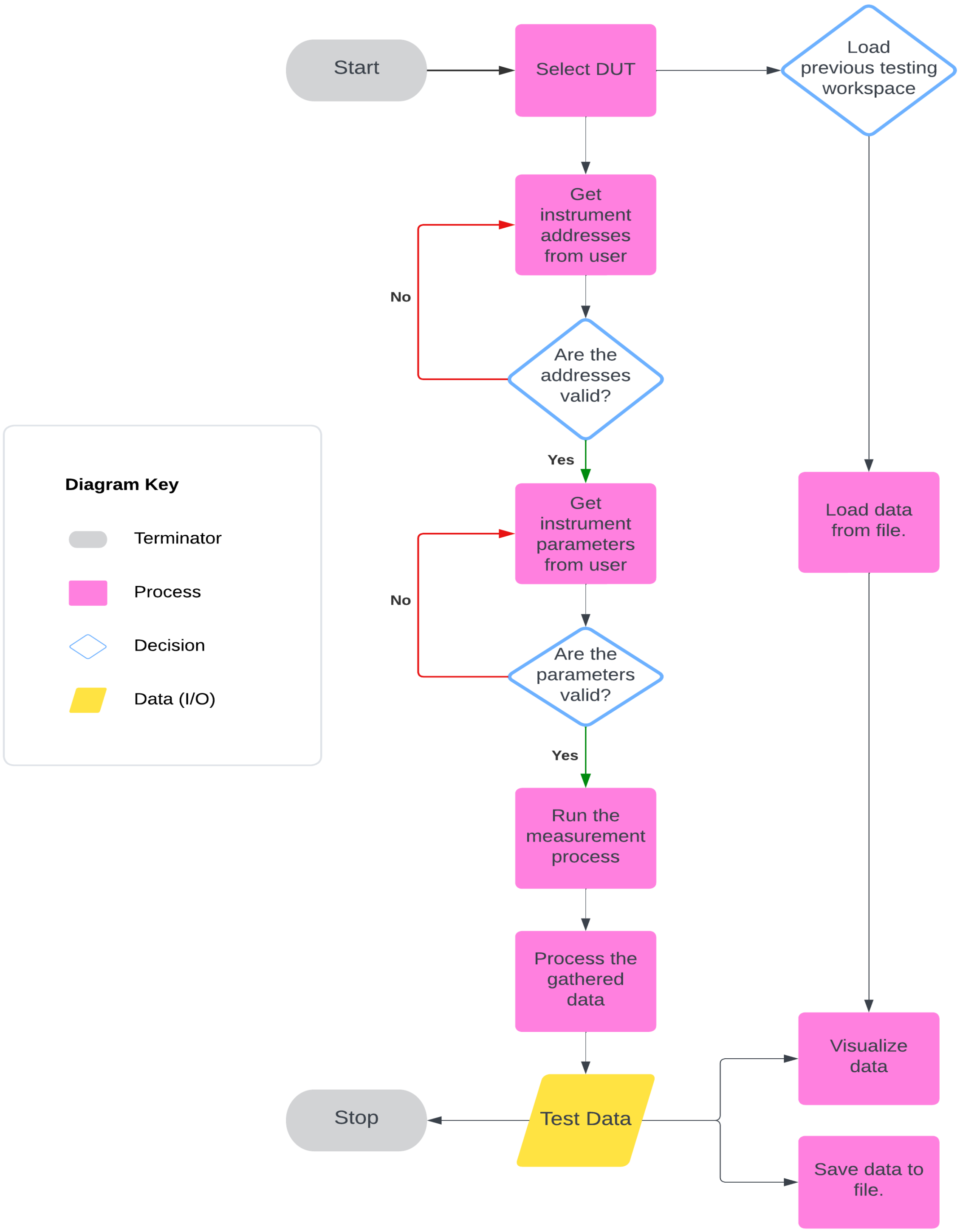


Figure 1: Application Logic Flowchart

4. Results

The application is divided into two main tabs, one dedicated to the power amplifier and the other to the antenna. Figures 2 and 3 illustrate the setup for each component, highlighting the overall design of the application.

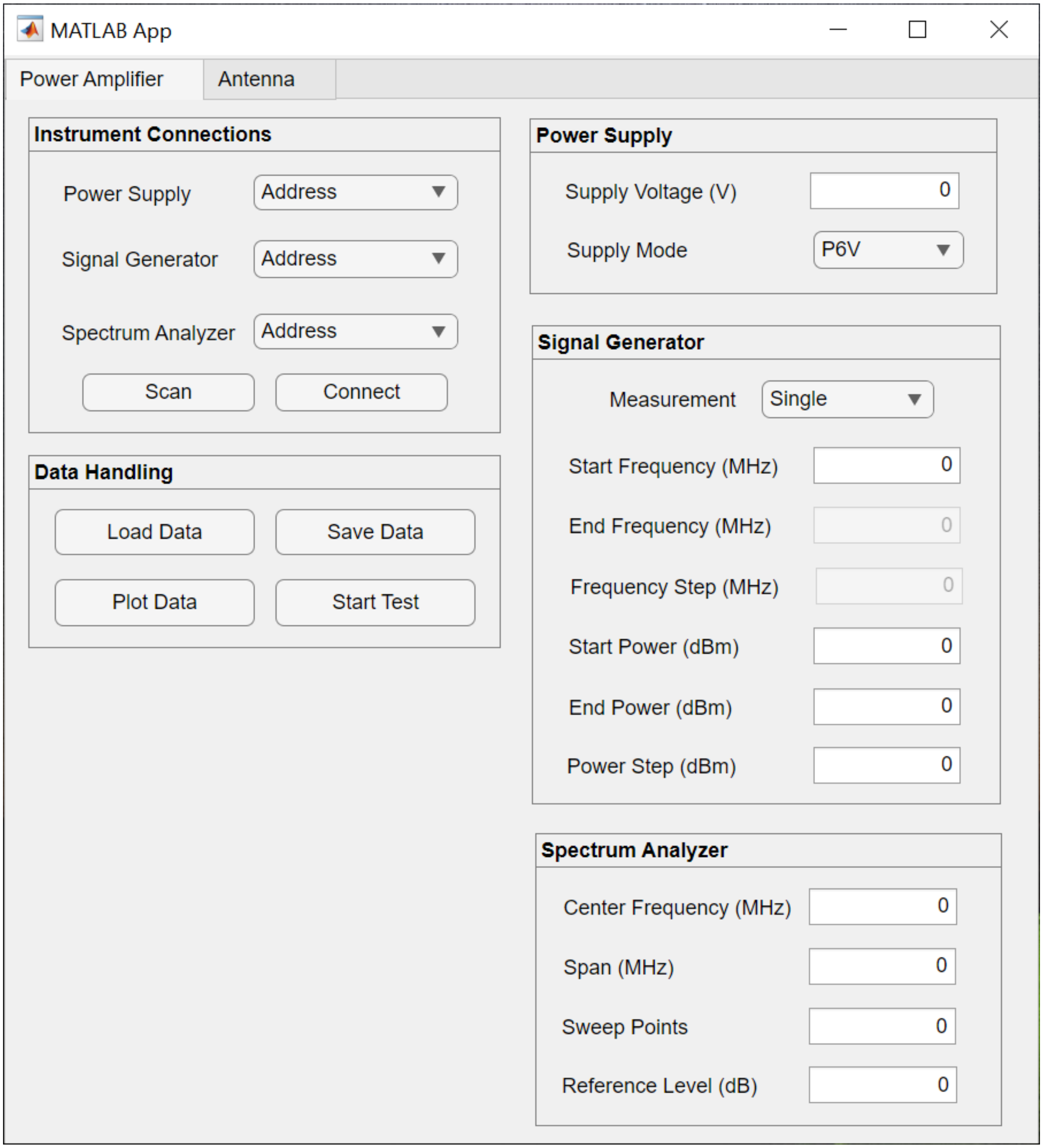


Figure 2: Power Amplifier Application Setup

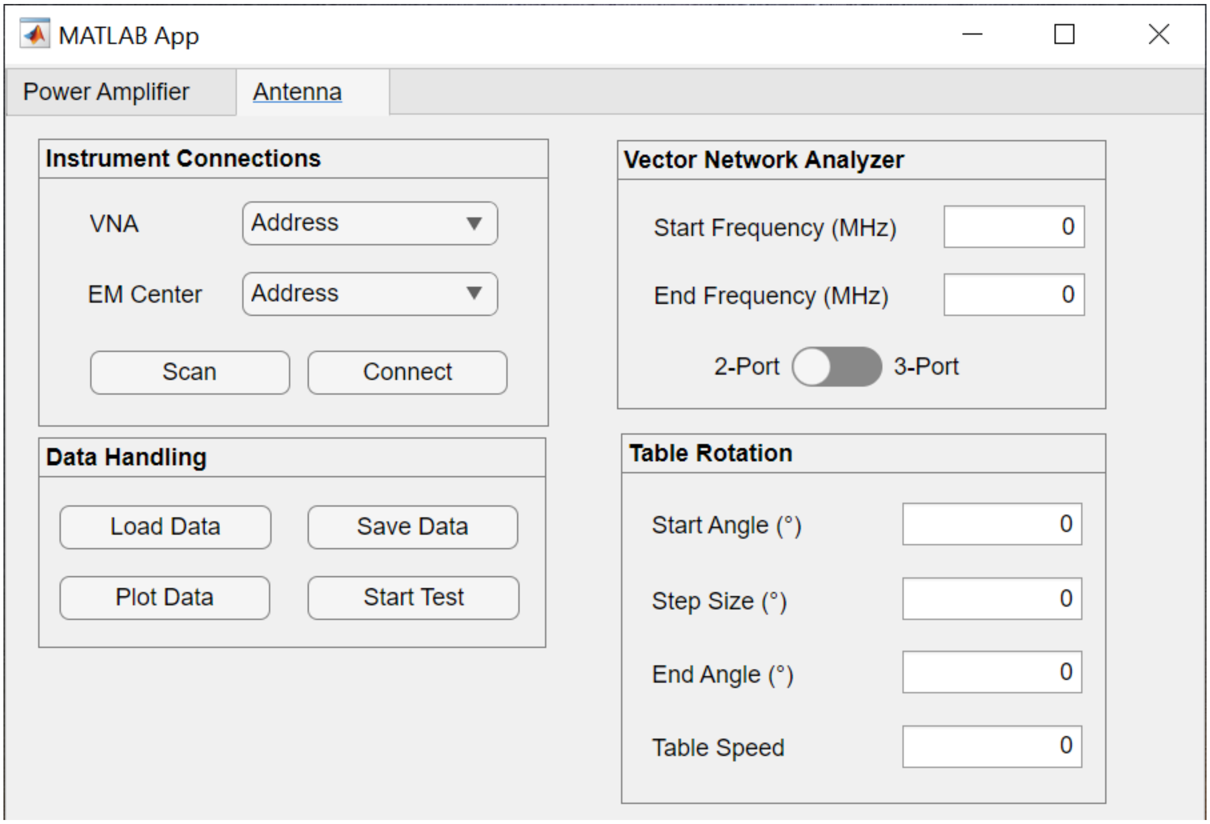


Figure 3: Antenna Application Setup

The application offers two distinct methodologies for PAs: single frequency testing and frequency sweep testing. In the former method, the PA is tested at a specific frequency while varying the input power levels. This method generates two key plots: one showing the relationship between RF input power and RF output power (both measured in dBm), which provides insight into the PA's performance and efficiency; and another plot illustrating Gain, Drain Efficiency (DE), and Power Added Efficiency (PAE) as functions of RF output power, allowing users to understand the trade-offs involved in amplifier performance.

In the latter method, the PA is tested across a range of frequencies while varying input power levels. This method produces four primary plots: Gain vs. RF Output Power, which shows how the gain changes with varying output power at each frequency; Peak Gain vs. Frequency, highlighting the peak gain achieved across the tested frequency range; Peak Drain Efficiency and Power Added Efficiency vs. Frequency, detailing how DE and PAE vary with frequency to help identify optimal operating conditions; and Compression Points and Saturation Power vs. Frequency, displaying the P-1dB and P-3dB compression points and the saturation power at each frequency, indicating the amplifier's linearity and maximum output capabilities.

Next to the plots, a comprehensive table summarizes the results for each tested frequency. Each row includes the frequency, corresponding compression points, and saturation power, allowing users to easily reference performance metrics at specific frequencies. A notable feature of the application is the ability for users to select which frequencies to plot during the sweep test, enhancing the user experience by allowing targeted analysis based on specific research or application needs.

To demonstrate these features, we evaluated the Mini Circuits ZVE-3W-83+ power amplifier. The datasheet specifies an expected gain of around 35 dB and a supported bandwidth of 2-8 GHz. However, due to signal generator limitations, our testing was conducted up to 4.6 GHz. We used a step size of 20 MHz, enabling us to collect a substantial amount of data. Figure 4 presents all the data plotted across the tested frequency range, while Figure 5 focuses on the frequencies up to the point where significant compression began to occur.

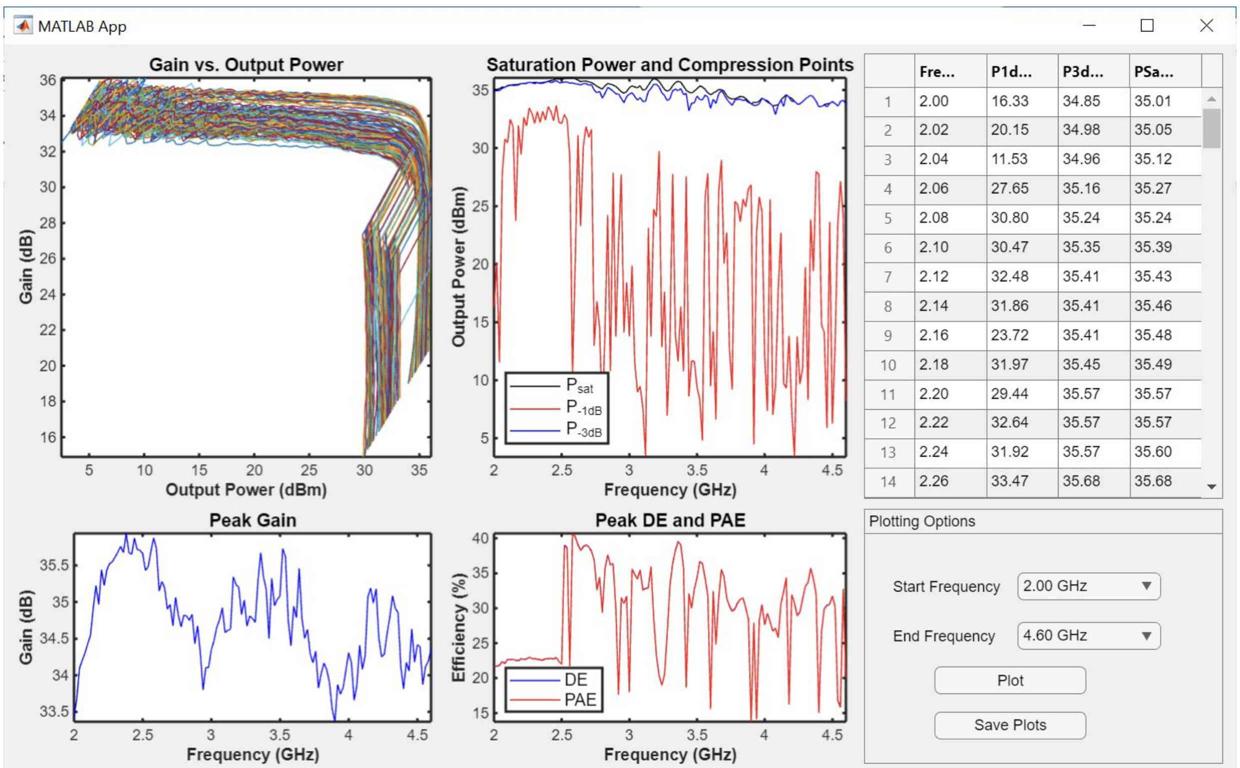
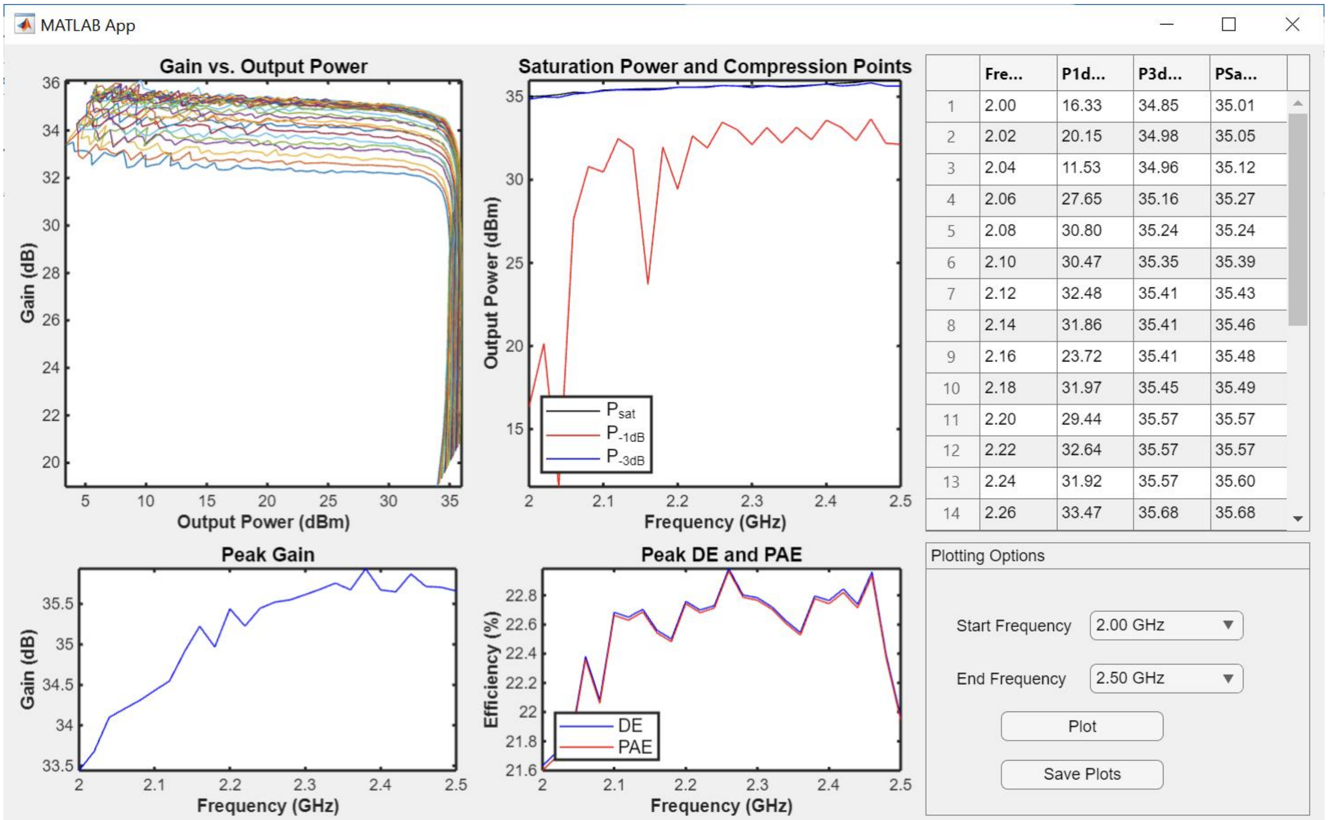


Figure 4: View of Total Sweep Measurement



	Fre...	P1d...	P3d...	PSa...
1	2.00	16.33	34.85	35.01
2	2.02	20.15	34.98	35.05
3	2.04	11.53	34.96	35.12
4	2.06	27.65	35.16	35.27
5	2.08	30.80	35.24	35.24
6	2.10	30.47	35.35	35.39
7	2.12	32.48	35.41	35.43
8	2.14	31.86	35.41	35.46
9	2.16	23.72	35.41	35.48
10	2.18	31.97	35.45	35.49
11	2.20	29.44	35.57	35.57
12	2.22	32.64	35.57	35.57
13	2.24	31.92	35.57	35.60
14	2.26	33.47	35.68	35.68

Figure 5: View of Partial Sweep Measurement

Thus far, the application provides a comprehensive method for antenna testing using 360° table rotation. This method generates four key plots to analyze the antenna's performance. The first plot illustrates the gain versus frequency at a specific angle chosen by the user. The second plot shows the gain versus angle at a particular frequency selected by the user. This allows the user to analyze how gain varies with the angle of radiation, helping to understand the antenna's directivity and radiation efficiency. The third plot depicts the return loss of the antenna, which indicates how much of the waves are reflected, a particularly important metric for evaluating impedance matching networks. Finally, the 2D radiation pattern plot presents the antenna's radiation characteristics in polar coordinates, emphasizing how the antenna radiates energy across different angles and providing a visual representation of the gain distribution. Together, these plots offer a detailed analysis of the antenna's gain, directivity, efficiency, and radiation pattern.

To demonstrate these features, we evaluated two identical Luxul directional helical antennas. According to the datasheet, these antennas are expected to have a gain of approximately 9.6 dBi across their operating bandwidth of 2.4-2.5 GHz. Using two identical antennas streamlined the application of the Friis transmission equation, simplifying the process of determining the gain of the receiving antenna. At the time of drafting this report, plotting logic for the antenna has not been incorporated into the application, however Figure 6 presents the detailed results and performance characteristics of the described testing setup.

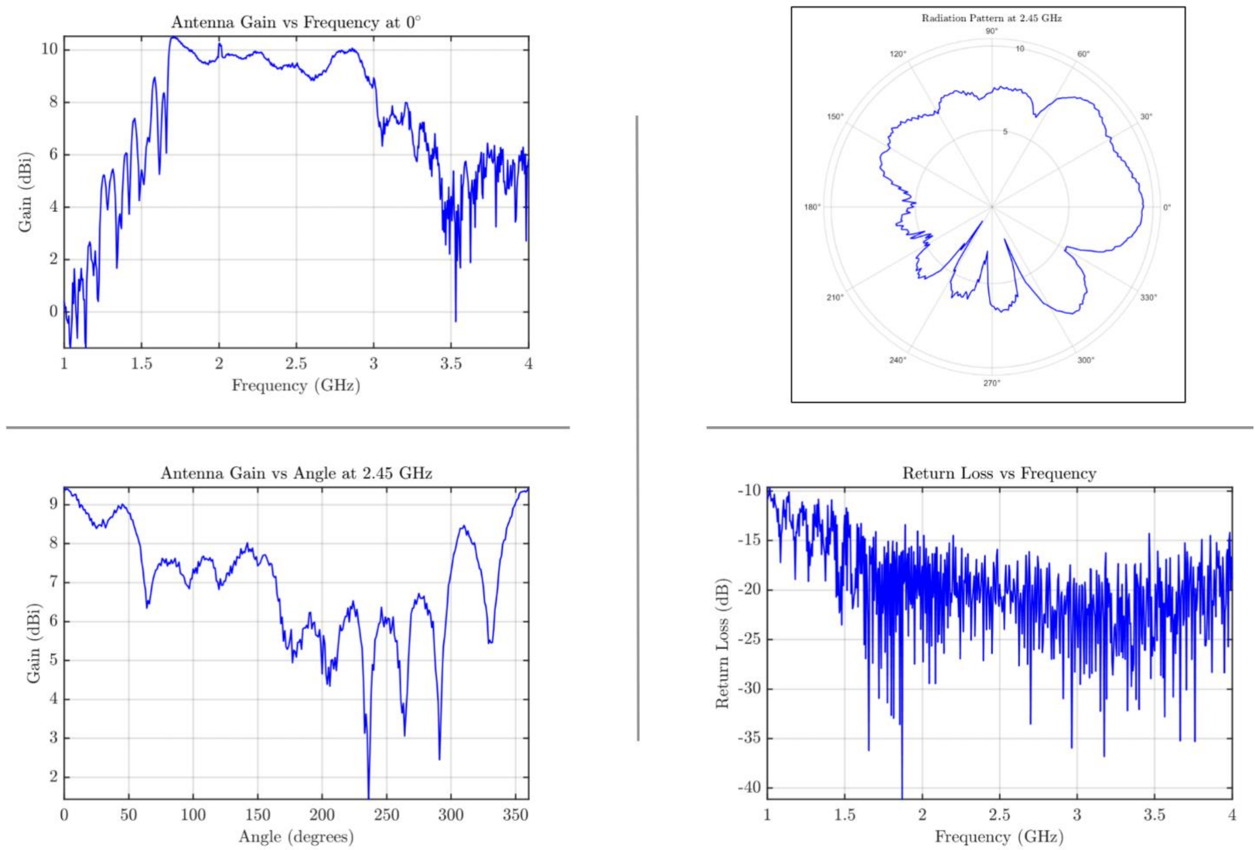


Figure 6: Antenna Characterization Plots

5. Conclusion

The results from the PA testing reinforce the effectiveness of the automated toolbox in characterizing amplifier performance through both single frequency and frequency sweep methodologies. The application's capability to visualize the relationships between input and output power, gain, efficiency, and compression points offers crucial insights for optimizing PA designs.

To further enhance the functionality of the PA testing, we plan to incorporate additional features such as testing for Adjacent Channel Power Ratio (ACPR) and Error Vector Magnitude (EVM). These additions will enable the analysis of modulated signals, providing a more comprehensive evaluation of the amplifier's performance in real-world scenarios where signal distortion and interference are critical factors.

For antenna testing, the next step involves integrating tower rotation into the application, which will allow for the generation of 3D radiation patterns. This enhancement will provide a more complete view of the antenna's radiation characteristics from multiple angles, offering a clearer understanding of its performance. Additionally, incorporating control of the linear slider will enable dynamic adjustment of the spacing between antennas, facilitating more precise and versatile testing setups.

Overall, the application's continuous development promises to significantly reduce testing times while increasing customization options. These advancements will make the tool more adaptable to various testing scenarios, improving the efficiency and accuracy of both amplifier and antenna evaluations. The enhanced features will not only streamline the testing process but also provide deeper insights into device performance, aiding researchers with more effective and optimized designs.

The app and its base code can be found here: https://github.com/bolanosv/RF-Testing-App.

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