Power Amplifiers: An overview of Linearity Measurement for 5G and Satcom Applications

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Abstract

Power Amplifiers (PAs) are critical components for communication systems, the PAs amplify the transmitted signal to adequate levels, ensuring the signal is detected by the receiving device, regardless of distance or obstacles. With the growing demand for data, modern communication signals like 5G and broadband satellite communication (Satcom) have complex modulation schemes and wider bandwidth. This complexity makes it more challenging to design power amplifiers that meet performance standards, including efficiency, output power, gain, and linearity.

This paper includes an overview on “in-house” python automation of the flexible characterization setup at CSA Catapult which can be used for carrier frequencies of up to 43.5GHz, and instantaneous bandwidth of up to 1.2GHz. Arbitrary waveforms generated with other platforms can be uploaded into the instrument, while it also offers internal waveform options covering the most common digital schemes as well as 5G OFDM waveforms, and the possibility of inserting notches in the signal for Noise-to-Power Ratio (NPR) measurements. An internal, automatic digital predistortion capability uses the vector generator and analyser in combination to linearize the PA and therefore study its restorability.

1. Introduction

The modern world, in every aspect, relies heavily on communication. Commercial, industrial and military aircraft rely on communication, to navigate the surroundings and ensure effective communication with ground control to take-off and land safely. Everyday people communicate with each other across the globe, work from home and browse the wide web. The entire internet that houses businesses, social media platforms and libraries of entertainment relies on communication. These are just some of the examples of the world’s reliance on communication systems. However, the world is transitioning to become more digital, and this transition isn’t slowing down or stopping. Moreover, the current communication systems must improve and evolve as there are greater demands on communication systems to cover a larger distance, handle more devices and provide faster and more data. This demand can be seen from things like the cloud and smart homes, what require fast speeds and the ability to support multiple devices without any downtime or slowdown.

The structure of communication systems requires multiple devices and components working together seamlessly and effectively to transmit and receive signals. For a signal to be transmitted and received, it must travel over a substantial distance and through an abundance of obstacles. When travelling over a distance the signal experiences path loss. When encountering obstacles such as buildings or natural wildlife like trees, parts of the signal will be absorbed, reflected or refracted which causes the transmitted signal to lose power. To remedy issues like this, communication systems have a critical component called power amplifiers (PAs). The PA increases the power of the transmitted signal, to ensure that the signal can be received at the receiving end regardless of distance or obstacles. This work introduces the basics of power amplifiers and discusses important design factors like efficiency and linearity. It also includes the measurement results related to linearity for a Ka-band GaN MMIC PA.

2. Power Amplifiers

There are different types of amplifiers, depending on their modes of operation, circuit configurations, bias conditions, and drive conditions (e.g. A, B, AB, C, and F). The classes range from entirely linear with low efficiency (class A) to entirely nonlinear with high efficiency (class F). A brief overview of various types of amplification and their suitability for solid-state heating is presented in this section.

2.1. Class A

Class A PAs have conduction angels of 360 degrees, whilst sporting maximum theoretical efficiencies of 50% [1], [4]. Additionally, Class A has the best linearity out of the classes, due to the transistors outputting a wave during all of the input signal's cycle.

2.2. Class AB

Class AB PAs have conduction angels between 180 and 360 degrees, whilst sporting maximum theoretical efficiencies between 50% and 78.5% [1], [4]. Moreover, Class AB's linearity is better than Class B but worse than Class A, which is due to the class suffering crossover distortion. This distortion is due to the transistors not switching off and on at the same time, what cause there to be a moment where the amplifier output nothing.

2.3. Class B

Class B PAs have conduction angels of 180 degrees, whilst sporting maximum theoretical efficiencies of 78.5% [1], [4]. Furthermore, Class B's linearity is better than Class C but worse than Class AB, which is due to crossover distortion. Where the transistors for Class B don't switch on and off at the same time, causing there to be moments of no output.

2.4. Class C

Class C PAs have conduction angels of less than 180 degrees, whilst sporting maximum theoretical efficiencies between 78.5% and 100% (in practice, this is impossible) [1], [4]. Also, Class C linearity is the worst of the classes, due to the PA only transmitting a signal for less than half of the input signal's cycle, which means the PA only transmits parts of a signal and not a full wave, leading to high distortion.

3. Performance Characteristics for Power Amplifiers

The main performance characteristics of a power amplifier include output power, efficiency, gain and linearity. There is usually a trade-off between each of these characteristics, so an understanding of each of these characteristics is essential in meeting the targeted specifications. Amplifier characteristics along with their commonly used modes of operation are introduced in the following sections.

3.1. Efficiency for Power Amplifiers

Efficiency improvements are desirable to reduce the amount of wasted direct current (DC) power. This is even more critical for higher-power PAs, as substantial amounts of DC power can be lost in the form of heat due to poor efficiency, which can raise the PA's temperature and consequently have an adverse impact on its performance.

3.2. Linearity for Power Amplifiers

Linearity is measured by Adjacent Channel Leakage Ratio (ACLR) and Intermodulation third order (IM3). This measurement metric gives an indicator of how much power leaks from the main channel into the adjacent channels, causing interference. Fig. 1 shows the measurement of ACLR.

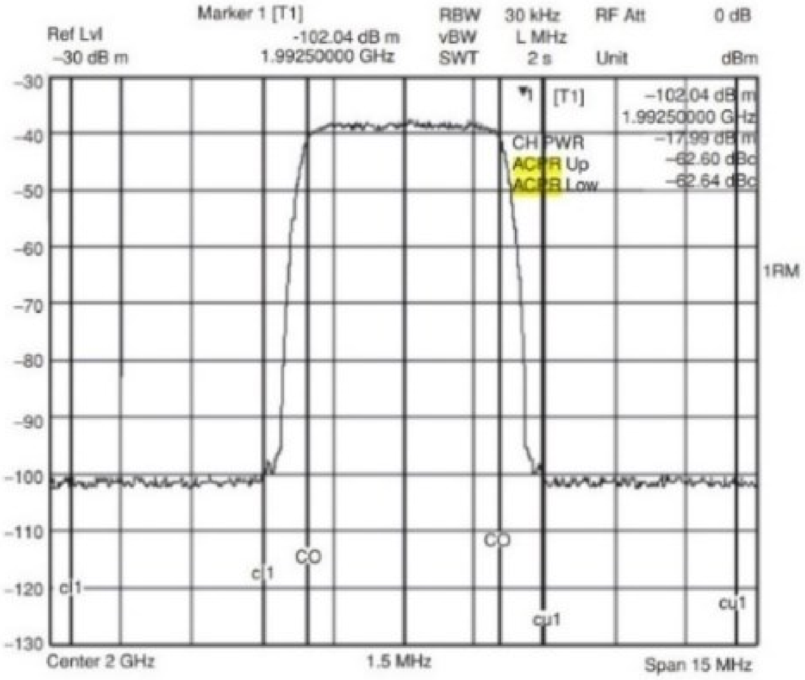


Fig. 1. Displaying of a ACLR test result showing the power in the main channel and adjacent channels. Source: [8].

IM3 is a product of intermodulation distortion (IMD). IMD occurs when two or more signals of different frequencies, enter the input signal port causing the different signals to mix, the output signal transmitted contains signals with different frequencies, that have been formed from the summing or differences between signals [3]. IM3 can be found by a two-tone test. Fig. 2 shows the effect of IMD.

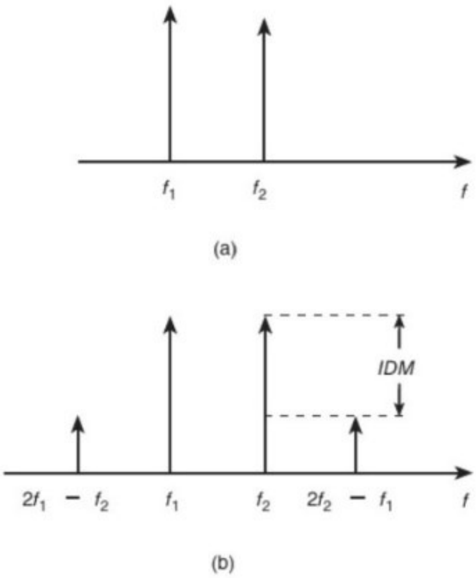


Fig. 2. (a) is two signals of different frequencies at the input port. (b) are the transmitted signals that consist of the original signals and intermodulation products. Source: [3].

For PAs, linearity is important as distortion or changes to the signal can result in data loss and the signal not being recognized by the receiver.

4. Semiconductor technologies

4.1. Silicon Bipolar Transistors

In earlier communication systems silicon bipolar transistors were used, these transistors provided adequate gain and efficiency at low frequencies [5]. However, these transistors suffered from thermal runaway and could not to meet design requirements for better linearity and efficiency [5].

4.2. Lateral Diffused Metal Oxide Semiconductor (LDMOS) Transistors

LDMOS transistors have good linearity, good efficiency, and can operate at higher frequencies and aren't susceptible to thermal runaway due to a positive coefficient of thermal resistance [5]. Additionally, LDMOS transistors are easily adaptable to different voltage supply levels and deliver large amounts of power compared to bipolar transistors [5]. In addition to this, LDMOS transistors are low-cost structures that offer higher gain, better efficiency, linearity and reliability. [5]. LDMOS transistors dominate the high-power amplifier market ranging from low frequencies (MHz) to 4GHz [5].

4.3. Gallium Arsenide (GaAs) High Electron Mobility Transistors (HEMTs)

GaAs HEMTs are used in communication systems due to their high electron mobility, direct bandgaps and high electrical resistivity. These devices can be designed to operate close to their breakdown limits compared to other transistors [6]. However, the GaAs HEMTs suffer from low thermal conductivity [6], which means that thermal design requires careful attention.

4.4. Gallium Nitride (GaN) High Electron Mobility Transistors (HEMTS)

GaN HEMTs are wide bandgap semiconductor transistors that provide high output power at high frequencies, can withstand high temperatures due to good thermal conductivity and are the preferred devices at higher frequencies of operation [7]. GaN transistors can potentially operate at frequencies of up to 300GHz (currently the technology performance is limited to ~40GHz for PAs), [7]. This means that GaN devices are preferred over LDMOS and GaAs HEMTs devices for the 5G frequency range 2 (FR2, 24.25GHz to 52.6 GHz), [9].

5. An overview of Power Amplifier Measurement Setup

5.1. Equipment for Power Amplifier Measurement

Various instruments and components are involved in the measuring process of PAs such as circulators, attenuators, as shown in Fig. 3.

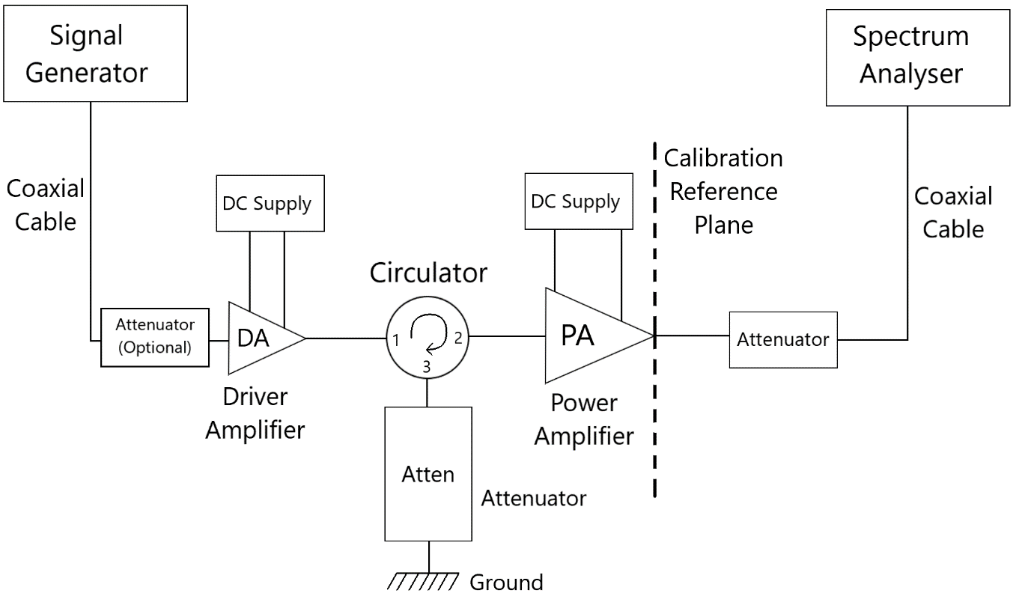


Fig. 3. Block diagram of power amplifier measurement setup at CSA Catapult. Source: Primary.

Attenuators act as a load as they dissipate the power of the signal, so that the signal can be safely read without damaging the equipment. However, the rating and direction of these components needs careful attention in the setup. A circulator is positioned between the driver amplifier and the power amplifier. The circulator is a three-port device that restricts the direction of the signal to go one way. The circulator protects the driver amplifier from the reflected signal.

Additionally, as seen in Fig. 3, a spectrum analyser is used to measure the signal's power density spectrum [8], [2]. This data can be used to examine the amplifiers performance at certain frequencies. A power meter or a vector network analyser (VNA) can also be used for the same purpose. Power meters obtain values of power dissipation, where the results can be used to determine the efficiency of the amplifiers [2]. VNAs measure the S-parameter's phase and magnitude [8]. This data is valuable as it can be used to describe the characteristics of the amplifier circuit. Although directional couplers and tuners aren't shown in Fig. 3, these components can be used in the measurement process. Directional couplers separate the reflected signal and forward signal and send them in different directions [2]. This can be useful when measuring the reflected signal and forward signal separately.

5.2. Power Amplifier Measurement Calibration

Calibration deals with any unknown parameters and systematic errors introduced by components and ensures that the results obtained are accurate. Calibration involves the procedures of Short-Open-Load-Through (SOLT), Thru-Reflection-Load (TRL) and Short-Open-Load-Reciprocal (SOLR) [2]. Calibration procedures are a series of two-port and one-port standards that are conducted to perform calibration, these standards are simple passive devices whose attributes and properties are known, so their behaviour is easily assessable [2]. The two-port standards include a line and thru ; the line is a transmission line with known electrical length and impedance whereas the thru standard is a transmission line with zero length [2]. For one port standards, there's open circuit, short circuit and matched terminations [2]. In terms of procedures, SOLT makes uses of the standards short circuit, open circuit, load and thru, TRL uses the standards of thru, line and reflection.

6. Power Amplifier Measurement at CSA Catapult

Fig. 4 shows the power amplifier measurement setup at CSA Catapult utilising a Rohde & Schwarz SMW 200A vector signal generator while the spectrum analyser is a Rohde & Schwarz FSW signal analyser, which can support signal frequencies up to 43.5 GHz [10]. The signal generator and spectrum analyser are synchronised by an internal, automatic digital predistortion capability to linearise the PA [10] and controlled by "in-house" python scripts. The device under test (DUT) in Fig. 4 is a Ka-band GaN Monolithic Microwave Integrated Circuit (MMIC) PA, that's capable of output power greater than 6 W in the 26 to 31 GHz band, which is mounted on an evaluation board with coaxial launchers for the measurements [10].

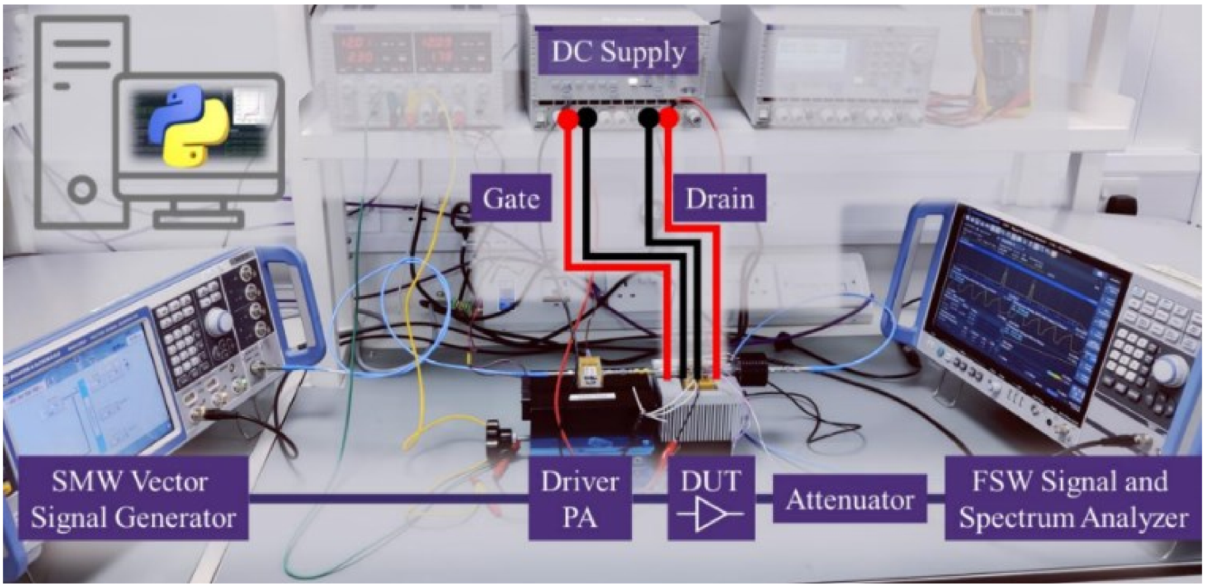


Fig. 4. Photograph of the Ka-band GaN MMIC PA measurement setup at CSA catapult, with a block diagram on top to provide more information. Source: [10].

6.1. Two-tone measurements

Two-Tone measurement consists of sending two signals, carriers, into the DUT. The measured output shows IMD products of third order (IMD3) due to the DUT's non-linear properties. The two signals are sine waves at different frequencies that are levelled to be the same amplitude before entering the DUT, which is conducted by pre-characterizing the driver amplifier and performing necessary levelling [10]. The DUT is operated at a centre frequency of 27.5 GHz, while experiencing different carriers spacings of 2 MHz to 300 MHz and a range of different powers levels. Fig. 5 below shows the results of the measurement where Carrier-to-Intermodulation Ratio (CIMR) is the measurement unit.

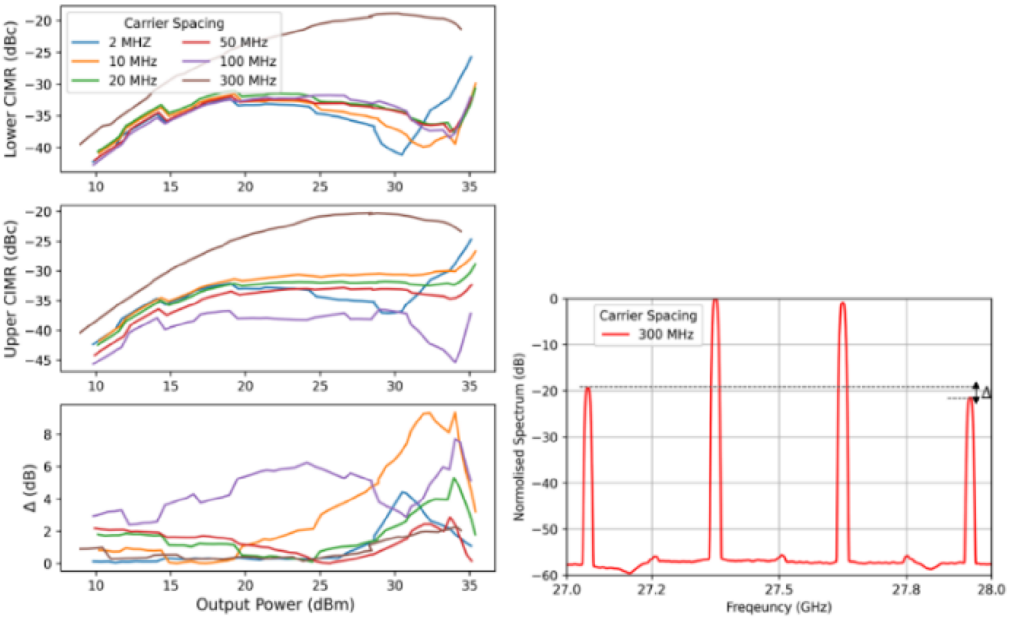


Fig. 5. Two-Tone measurement results at centre frequency 27.5 GHz. The Lower and Upper CIMR (dBc) were measured at different power levels with carrier spacing ranging from 2 MHz to 300 MHz (left). Normalised output spectrum recorded from device with a signal that has carrier spacing of 300 MHz and at peak output power (right). The 'Δ' parameter is the difference between the Upper and Lower CIMR (dB). Source: [10].

CIMR is the ratio between one of the carriers and it's respective IMD product in dB. The results shown in Fig. 5 were captured using a python script. The script was used to extract data, perform calculations and plot data. CIMR measurements were done by capturing the full spectrum and placing markers at relevant frequencies [10]. Fig. 5 displays how at lower power levels the CIMR increases steadily then flattens for most carrier spacings, showcasing typical Class AB behaviour when designed for linearity [10]. Moreover, the flat region is an important characteristic as it relates to robustness of design in terms of linearity against drive level [10]. However, the 300 MHz carrier spacing showcases different behaviours as it displays increased distortion and the flat region isn't seen, what depicts that over wide frequency ranges, PA performance disperses [10].

6.2. ACLR Measurement

ACLR has the advantage of more accurately representing the behaviour of the device in actual communications systems, but a real radio is needed to generate and detect signals [10]. At CSA Catapult, the equipment used can mimic a radio, which means the measurement can be conducted [10]. The measurement is conducted at different power levels with transmission channels (Tx) ranging from 10 MHz to 300 MHz in channel bandwidth, and a test signal that has an 8 dB crest factor (CF) and signal length of 60000 [10]. This measurement was achieved through the software on the spectrum analyser to generate arbitrary test signals with customised parameters such as CF, bandwidth and duty cycle [10]. Python scripts were used to perform calculations and plot data, whereas the spectrum analyser software was used to perform the power sweep, for changing power values [10]. Fig. 6 below shows the results obtained from the ACLR measurements.

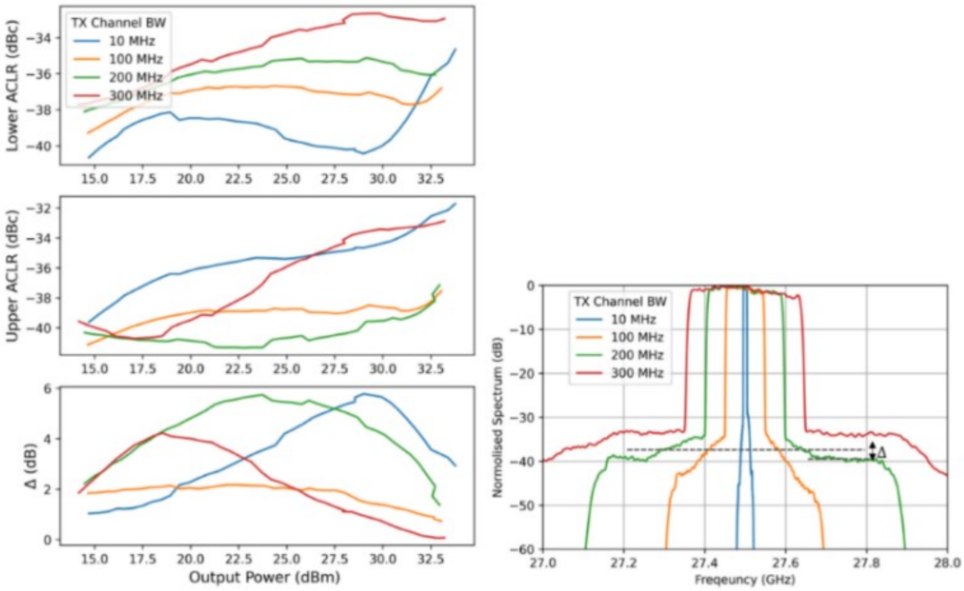


Fig. 6. ACLR measurement at centre frequency of 27.5 GHz. The Lower and Upper ACLR (dBc) were measured at different power levels for transmission channels (Tx) that had a channel bandwidth (BW) of 10 MHz to 300 MHz (left). Normalised output spectrum of DUT at peak power level (right). The 'Δ' parameter refers to the difference between the Upper and Lower ACLR in dB. Source: [10].

The trends in Fig. 6 show that ACLR and CIMR are tracking, expressing excellent linearity performance from the PA even under very demanding signals [10]. Moreover, 300 MHz is performing better under ACLR than IMD under same tone spacing, but this could be due to ACLR being an averaged measure over channel while for CIMR, the energy is concentrated at spot frequencies [10]. Overall, ACLR benefits for the very good performance at low spacings [10].

6.3. NPR Measurement

NPR measurement is conducted by transmitting a white noise signal with an in-channel notch to the DUT [10]. This signal can be generated by white noise with a notch filter or a multi-tone carrier signal (with equal magnitude and random tone phases) with a few tones turned-off [10]. Due to the DUT's non-linear properties, distortion will occur causing the depth of the notch to reduce [10]. The measurement data collected is the ratio between the channel power and the notch power [10]. However, this measurement is affected by the position of the notch in the channel, to eliminate this effect a swept notch NPR measurement is done [10]. A swept notch measurement provides a robust assessment of the worst-case linearity situation compared to a fixed centred notch, while also revealing the presence of long-term memory effects present in the PA during the test [10]. Fig. 7 below shows the results from the NPR measurement.

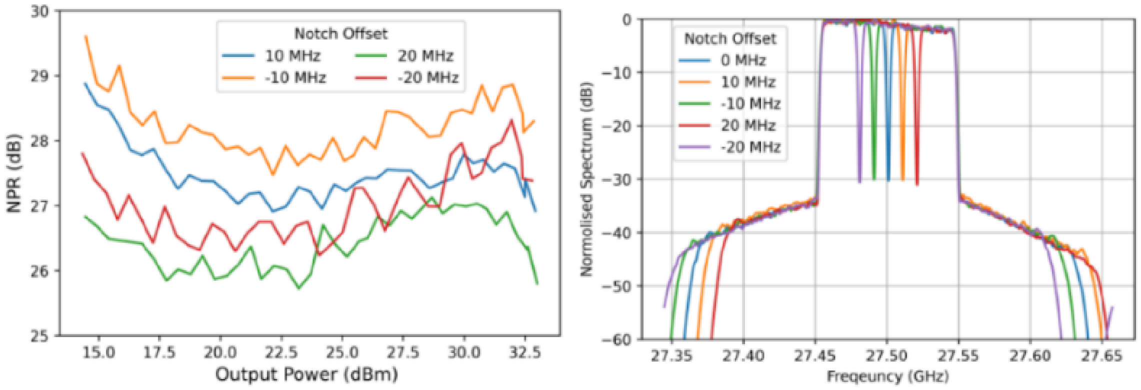
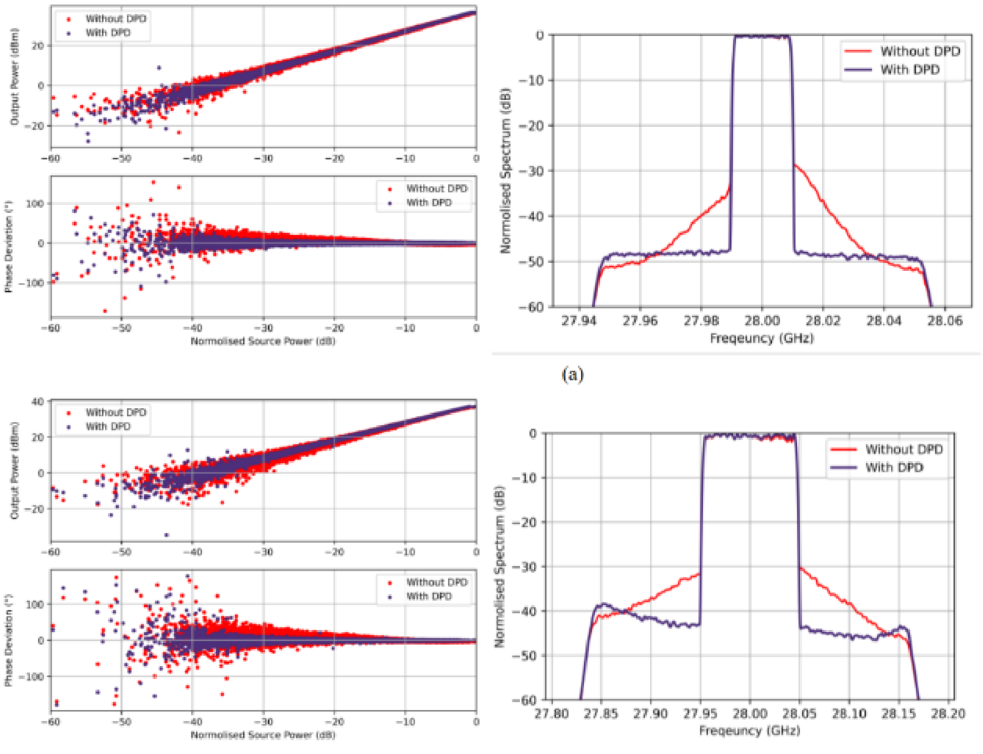


Fig. 7. NPR measurement at centre frequency of 27.5 GHz. The NPR (dB) was measured at different power levels and swept notch positions with a signal that had a 100 MHz bandwidth, 8 dB crest factor and signal length of 6000 (left). The normalised output spectrum is at the peak average power level of 33 dBm (right) Source: [10].

For the calculation of NPR, the lowest channel power spectral density (PSD) is used as it gives the worst-case value [10]. In terms of the results from Fig. 7, the DUT shows excellent linearity performance, where the NPR remains reasonably low and flat over a wide output power region [10]. Moreover, the swept notch showcases a worst-case measure where there is limited offset, NPR decreases for larger offset values [10]. These results show that swept notch is useful in determining a robust NPR measure and that the PA only exhibits limited long term memory effects.

6.4. DPD Measurement

DPD is used to examine the PA's ability to linearise. To conduct DPD, the software on the equipment was utilised as it contained an iterative "Direct" algorithm within the FSW spectrum analyser, which dynamically updates the signal generator to achieve the lowest possible error vector magnitude (EVM) [10]. Also, the operation consisted of a very demanding 5G orthogonal frequency-division multiplexing (OFDM) test signal with 12 dB peak-to-average-power ratio (PAPR) [10]. Fig. 8 shows the results of the DPD.



(a)

(b)

Fig. 8. DPD measurement results using 10 MHz (a) and 100 MHz (n) 5G OFDM signal with 12 dB PAPR, average output power was 25 dBm. Source: [10]

Fig. 8 shows the reduction in spectral regrowth at both channel bandwidths while also showing a reduction in EVM, at the same average output power of 25 dBm [10]. These results showcase great predictability [10].

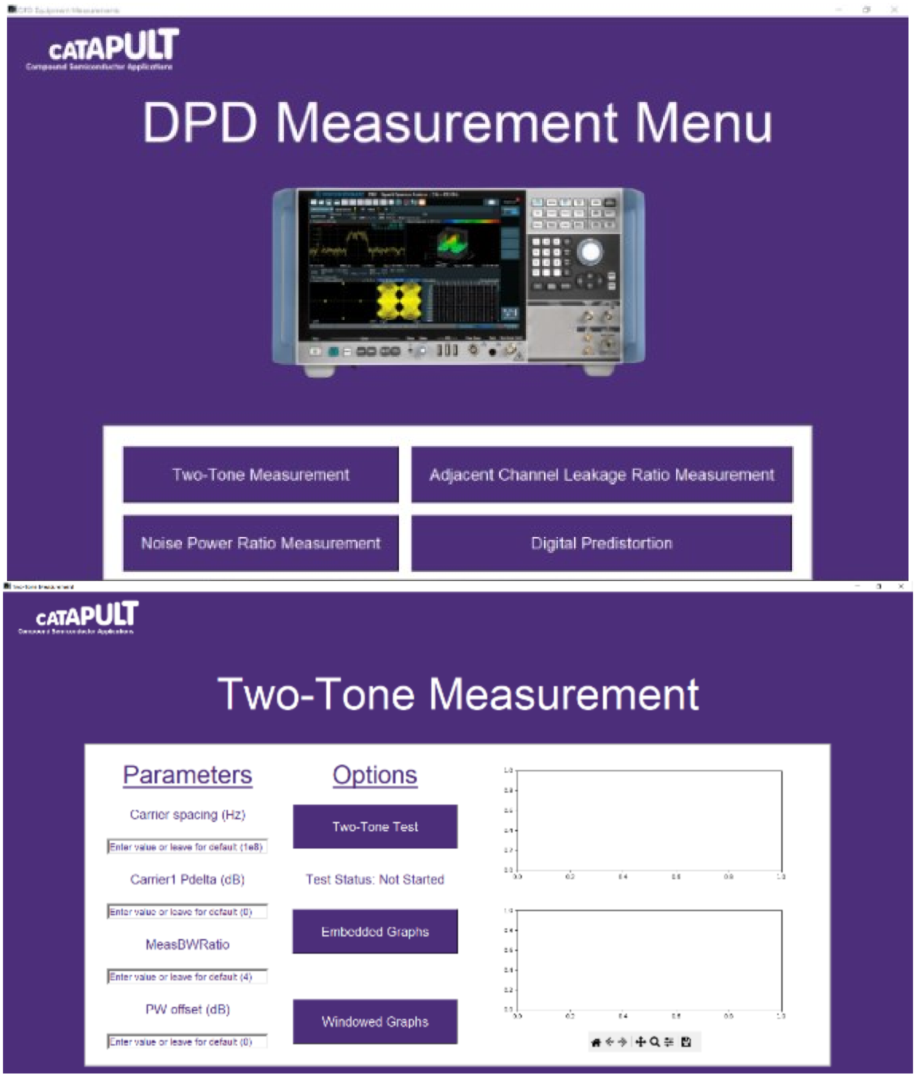
7. Programming Scripts to improve User Experience

7.1. "In-house" Programs for Power Amplifier Measurements

"In-house" programs allow for total control over the measurement process and equipment, compared to the equipment's built-in programs. By using "in-house" programs, any settings of the measurements or equipment can be adjusted, which ensures that the results collected are accurate, reliable and realistic to the device being tested (DUT). Additionally, the increased amount of control over the equipment allows for more data to be collected from the measurements, resulting in more results to describe the behaviour of the DUT. Moreover, measurement results can be presented in a wide variety of ways, the data can be displayed on graphs in the program or exported in different formats such as MATLAB, Excel Sheets or JMP. This is favourable for any entity that wants to execute measurements and get reliable data that can be presented in an understandable or preferred format. Also, “in-house” programs can work with a wide range of measurement equipment, as modifications can be made to the code to account for the equipment’s method of operation.

7.2. Graphical User Interface (GUI) for Power Amplifier Measurements

GUIs have a wide variety of advantages that include accessibility, ease of access and quick run-time, by providing an interface that can be interacted with, instead of interacting with lines of code. Fig. 9 below shows an example of GUIs.



Test Status: Not Started

Fig. 9 In-house Python GUI script, at CSA Catapult, that allows users to execute multiple python measurement scripts, and allows for the execution of Two-Tone Measurement and displays data of measurement. Source: Primary.

Fig. 9 shows the accessibility and ease of use of a GUI. Fig. 9 shows how any measurement can be accessed at the click of a button instead of searching for files. Fig. 9 also shows how the measurement settings can be easily changed without searching lines of code, and any measurement settings that can be modified are indicated. Utilisation of GUIs lead to a faster executing time for measurements as the measurements can be quickly setup and executed. Moreover, due to the interface’s ease of use and accessibility, any entity, with a lack of programming knowledge or experience with the specific program, can easily run the measurements and collect reliable and accurate data.

8. Conclusion

Overall, the research conducted has depicted how PAs use DC power to amplify the RF signal's power and there are multiple performance indicators of PAs, such as distortion, efficiency and linearity that are measured using tools like spectrum analysers or VNAs. Moreover, the performance indicators of distortion, linearity, efficiency are important as the use different of classes such as Class AB and Class B are utilised to obtain higher efficiencies whilst retaining some linear behaviours. Furthermore, an abundance of resources has been poured into GaN HEMTs as they provide high output power at high frequencies. The advantages of GaN HEMTs are shown through the measurements at CSA Catapult what show PAs with excellent linearity under demanding signals. Moreover, "in-house" program scripts and GUIs are shown to be beneficial for measurement as they allow for more control over measurements, to ensure reliable and precise results.

References

[1] M. LeFevre, P. Okrah, L. Pelletier and D. Runton, "RF Power Amplifiers," in *Handbook of RF and Wireless Technologies,* F. Dowla, Eds. Boston: Newnes, 2004, pp. 181-204.

[2] G. Ghione and M. Pirola, *Microwave Electronics*. Cambridge: Cambridge University Press, 2017.

[3] M.K. Kazimierczuk, *RF Power Amplifier***,** 2nd ed. John Wiley & Sons, Incorporated, 2014.

[4] H. Wang and K. Sengupta, "Introduction," in *RF and Mm-Wave Power Generation in Silicon,* H. Wang and K. Sengupta, Eds. Elsevier Science & Technology, 2015, pp. 1-14.

[5] W. Burger and C. Dragon, "Silicon LDMOS and VDMOS transistors," in *Handbook of RF and Microwave Power Amplifiers,* J.L.B. Walker, Eds. Cambridge: Cambridge University Press, 2011, pp. 1-41.

[6] R. Davis, "GaAs FETs – physics, design, and models," in *Handbook of RF and Microwave Power Amplifiers,* J.L.B. Walker, Eds. Cambridge: Cambridge University Press, 2011, pp. 42-102.

[7] R.J. Trew, "Wide band gap transistors – SiC and GaN – physics, design and models," in *Handbook of RF and Microwave Power Amplifiers,* J.L.B. Walker, Eds. Cambridge: Cambridge University Press, 2011, pp. 103-158.

[8] M. Hiebel, "Amplifier measurements," in *Handbook of RF and Microwave Power Amplifiers,* J.L.B. Walker, Eds. Cambridge: Cambridge University Press, 2011, pp. 570-643.

[9] T.H. Brandão and S.A.Jr Cerqueira. (2023, April). "Triband Antenna Array for FR1/FR2 5G NR Base Stations," *EEE antennas and wireless propagation letters* [online]. vol. 22, issue 4, pp. 764-768. Available: https://ieeexplore-ieee-org.bham-ezproxy.idm.oclc.org/document/9964029

[10] E. Azad, S. Pascoe, J. Beardwell, K. Chaudhry, J, Gannicliffe, P. Tasker and R. Quaglia, "Experimental Linearity Tests on a GaN Ka-Band 6-W Power Amplifier for Satcom Using Wideband Signals and Comparing Distortion Metrics," CSA Catapult., Newport, 2023