Millimeter-Wave VNA Characterization using Modulated Signals

5G implementations will require wider bandwidths and probably higher carrier frequencies which will complicate the characterization of power amplifiers and other components. A wide-bandwidth VNA measurement approach with modulated signals can sometimes improve these measurements. Structures, calibrations and example measurement improvements will be discussed.

1 - Introduction

One likely aspect of 5G development is the increased frequency flexibility, in terms of more and higher carrier frequencies, more transitions, and wider modulation bandwidths, of transmitters and receivers. Among the radio components, the power amplifier is often of central interest due to its relative cost and relative importance in determining performance. Thus in a 5G context, characterization and analysis of power amplifier performance can be quite important[e.g., 1)] and will be more challenging for a number of reasons:

- With higher carrier frequencies, stability and repeatability of the measurement can be more difficult.
- Broader band and high frequency devices, and measurement systems, tend to have lower return losses which can affect measurement accuracy. These mismatch effects are one part of a broader power measurement accuracy question.
- Measurement speed can become an issue as the amount of frequency space to be analyzed increases and the number of different parameters to be measured likely increases.
- Practicality of the measurement setup may become an issue as levels of complexity increase.

While output power is obviously a central parameter of interest in PA characterization, other quantities play an important role and take on different nuances in the context of wider bandwidths:

- Compression behavior (AM/AM and AM/PM): how do these characteristics behave across the modulation bandwidth? The compression behavior is almost always a function of the modulated waveform so the variation across traffic levels and dynamic modulation formats is still important.
- Return loss while in compression. Depending on the amplifier topology, the mismatch of the DUT may be power- and modulation-dependent and vary across the modulation bandwidth. This could have an impact on matching networks and overall efficiency.
- Distortion (Adjacent Channel Power (ACPR) and other intermodulation-related quantities): The waveform statistics will almost always dictate nonlinear behavior so modulation characteristics

remain important but now the calibration of the distortion product measurement must happen over a wider bandwidth.

- Desense. Although closely related to other distortion metrics, the gain/phase behavior in the presence of another high-level signal is an important measure. Because of the wide range of possible interferer locations and formats, this characterization process could become significant.
- MIMO topics

With all of the above metrics, being able to cover the parameter space in a reasonable amount of time takes on added importance.

Many tools exist to cover some of these measurement needs and there are many possible permutations[e.g., 2)-5)]. One approach is to use a wide-IF VNA platform. The match characterization and correction capabilities are intrinsic, the inherent ratioing ability helps with stability and accurate power delivery, and normal low-level sweep capabilities can help with measurement speed. When one couples that with broadband/mm-wave architectures to cover all possible carrier frequency ranges with higher dynamic range than is available with some other platforms, there is a possibility of addressing many of the characterization needs. This paper will discuss such a measurement platform, some of its characteristics and calibration concepts, and a number of measurement examples to illustrate the principles.

2 - Measurement Structure and Characteristics

One version of a VNA platform for this class of measurements is shown in Figure 1 and is based on the MS464XB VNA equipped with several options including access loops and a high-speed digitizer (option 035). A modulated source is not part of this instrument but the analysis soft-ware, which resides on the VNA, can control external sources (depending on configuration) such as the MG3710 or MS2830 (ARB side) which may then be upconverted to the desired frequency range using the internal VNA source as an LO or using an external synthesizer. One-path two-port measurements (using one modulated source) are common for many power amplifiers but a dual-drive (shown in the figure) or switched modulation scheme can be used for full two-port measurements. The measurements de-scribed in this paper are one-path two-port. Typically a driver amplifier is also incorporated to provide significant drive level to the amplifier under test. As it is helpful for ratioing stability and power control, the driver amplifier is often inserted in a different position (pre-reference coupler) which can be accomplished with the access loops.

The system LO, distinct from the upconversion LOs, is used to feed the internal receivers. Various versions of the front-end can be configured that would have maximum carrier frequency ranges of 20, 40, 50, 70, 110, 125 or 145 GHz (some with external modules). Depending on how 5G frequency plans evolve, different VNA front-ends may be desirable.

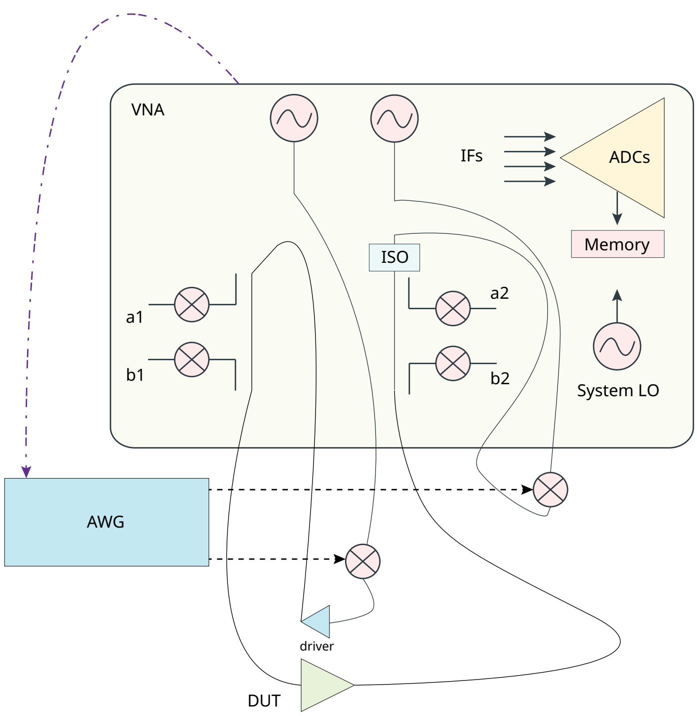


Figure 1: A block diagram of the VNA-based modulated measurement setup is shown here. External synthesizers can be used in lieu of the internal sources for upconversion LOs. Only one modulation/ upconversion path is needed for 1 path-2 port measurements.

Of central importance to the measurement class is the behavior of the receiver. The front-end downconverters have reasonably wide IF bandwidths and feed into a 200 MHz wide IF strip ending in a 400 MSPS analog-to-digital converter. The front-end converters have a third order intercept point (IP3) generally exceeding 35 dBm (when referred to the port)[6)] which enables the meas-urement of quite low ACPR products. This IP3 is available even in broadband versions of the instrument (reaching to 110 GHz and above) which covers all of the potential 5G bands discussed to date that we are aware of. The linearity further downstream is also not compromised so a high linearity analysis is continuously possible.

At the opposite end of the amplitude range is the noise performance. One may not normally think of this much in terms of power amplifier characterization but measure-ments such as ACPR may stress the noise floor performance as well if the distortion products from the DUT are small. A VNA, or other heterodyne conversion platform, has some advantages over a pure time domain platform in this regard. While the noise figure in this test configuration is not small (due to front end coupling loss and the need to handle higher powers), the converter noise figure is not extremely high even up into the mm-wave range and an overall dynamic range exceeding 90 dB on a 1 MHz BW basis is possible. The combination of linearity and reasonable noise floor performance is also beneficial for desense measurements which similarly stress both amplitude extremes.

From a functional point-of-view, it is also useful to note that four ADCs operating pseudo-independently are availa-ble so full ratioing and certain MIMO measurements are possible and with receiving channels having over 120 dB of isolation. The latter point may be useful for eliminating leakage induced nonlinearities in the measurement system (which is possible in certain MIMO measurements). The data analysis paths for the different receivers are also independent so one can analyze different time and frequency epochs within each receiver path.

3 - Calibration Topics

Common to any measuring receiver is the concept of as-signing absolute power which we will term a 'receiver calibration.' This must be done over the instantaneous analysis bandwidth as well as the carrier frequency range. These two frequency lists are essentially orthogonal (at each carrier frequency, one must have a calibration over the instantaneous bandwidth) which can increase the size of calibration data when covering large frequency ranges. Such calibration table management is inherent to the VNA platform.

A second level is to incorporate mismatch correction during the receiver calibration itself as well as in applying to the DUT power measurement. This concept is illustrated in Figure 2. The correction during the receiver calibration is to account for mismatch of the source and receiver (as well as of the power sensor used for calibration transfer in some cases). During the DUT measurement, the correction is between the DUT mismatches and those of the system itself. This process can be important since many broadband power devices may have only 10 dB return loss so the correction effects can exceed 1-2 dB.

An additional effect of this level of correction comes in transmission phase (as would be used in AM/PM analysis) and group delay. While it may appear secondary, the mismatch correction can have a perhaps non-intuitive impact since the mismatch may represent a significant pole-zero collection that affects transmission phase flatness. A simulation example is shown in Figure 3 where the group delay through a V-band amplifier is being studied (after de-embedding of a measurement fixture which is yet another analysis step). With proper match correction, the group delay is extremely flat for this device across the band. Without that correction, the flatness appears to be nearly ten times worse. While the effect of this flatness variation will vary with system architecture (including the modulation choice), the significant effect of the measurement approach may not be unusual.

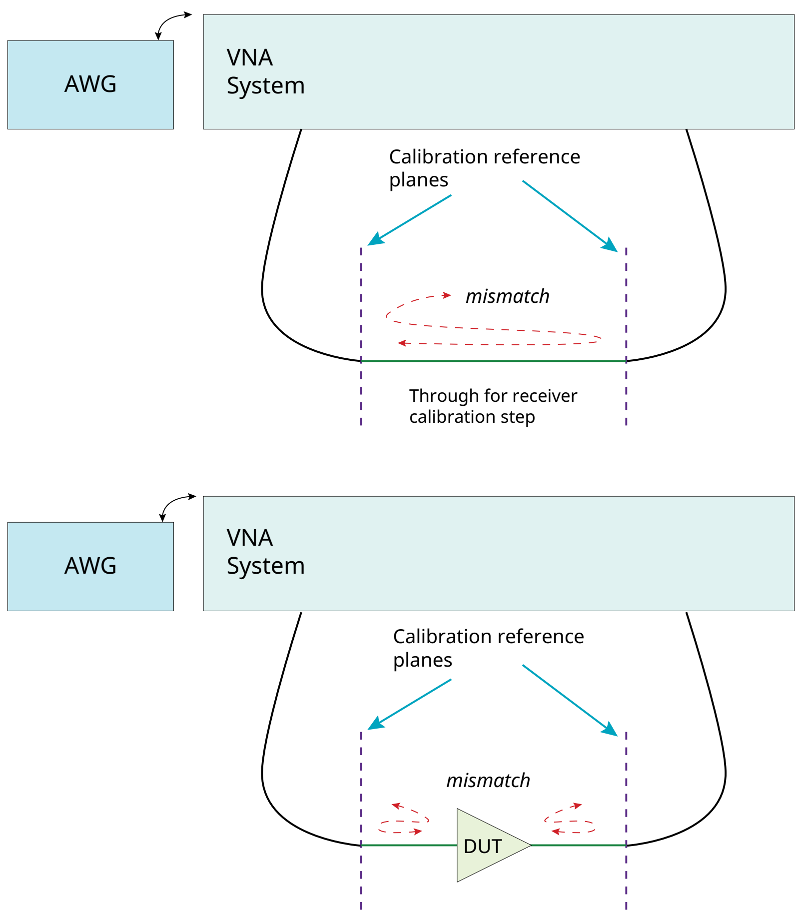


Figure 2: A schematic of the correction processes during multiple measurement phases can be important.

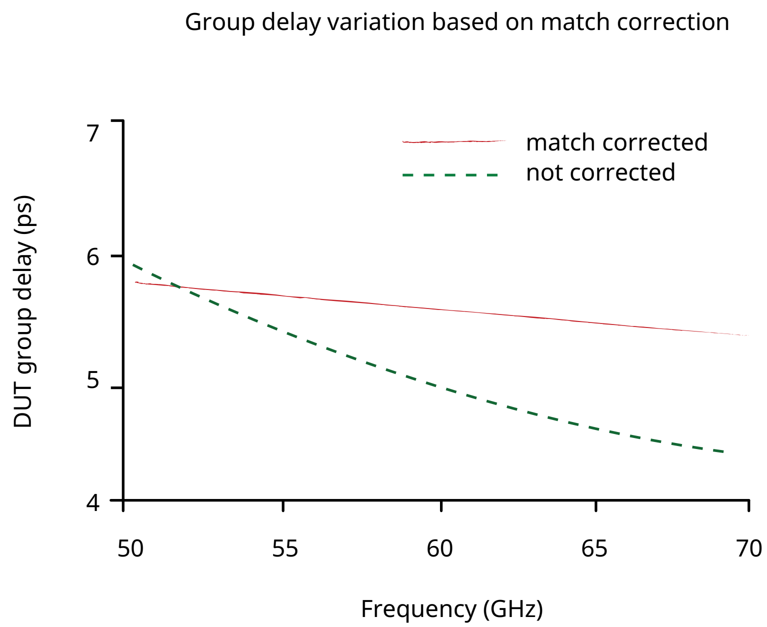


Figure 3: The result of a group delay measurement simulation based on calibration choice is illustrated here.

Some of these correction capabilities seem routine for a user coming from a network analysis background. They are perhaps less common in many versions of power spectral analysis where calibrations may be limited to the factory-based variety referenced to an instrument port coupled with a nominal cable loss correction. The multi-level and frequency aware calibration capabilities in this measure-ment structure can add to the accuracy and usefulness of the modulated characterization results.

4 - Example Measurements and Scenarios

As a simple first example, consider the output power measurement of an amplifier excited with a 60 MHz band-width signal (here modeled with a 23 tone multisine signal). Of interest is the flatness of in-channel power and, at least observationally, the adjacent channel power behavior from device intermodulation effects. This measurement was done with the above system with a VNA match-based cor-rection discussed and with only a normalization calibration. The results are shown in Figure 4. Although the results with this normalization calibration are somewhat deviant, it should be pointed out that in some other systems, even this level of calibration (frequency-by-frequency and at the DUT reference planes) is not available and an even coarser result may be observed.

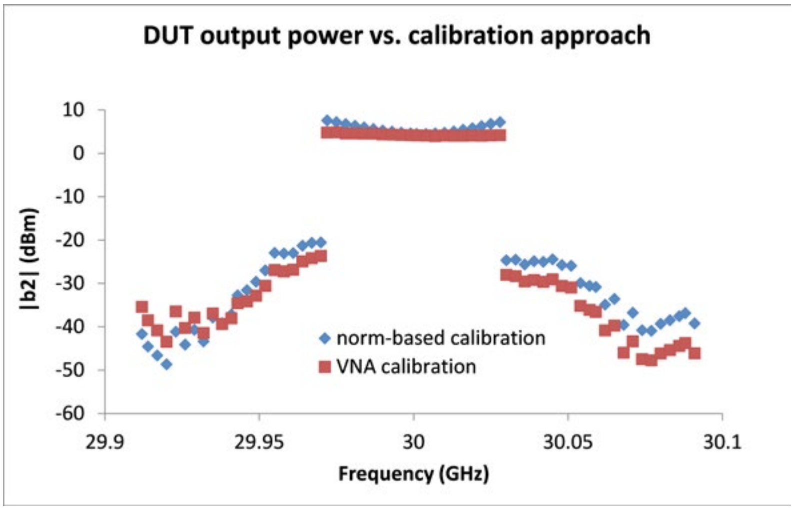


Figure 4: A plot of modulated output power is shown here with a VNA calibration and with one based only on normalization (as might be seen in other instruments).

One can see in-channel mismatch effects with the normalization only approach that can distort interpretation of the data. This effect extends to the adjacent channel regions as well. A study of the return loss of the device provides an even more obvious difference since a normalization calibration on a return loss measurement will be uncertainty challenged in all but the simplest of setups. This comparison is shown in Figure 5 and the differences are more obvious. With too simple a calibration approach, the return loss could be seriously underestimated in parts of the channel bandwidth. Note that this measurement is only plotted within the modulation bandwidth. For certain DUTs, where the input stage is compressing, return loss artifacts may also appear in the adjacent channels but that was not the case here.

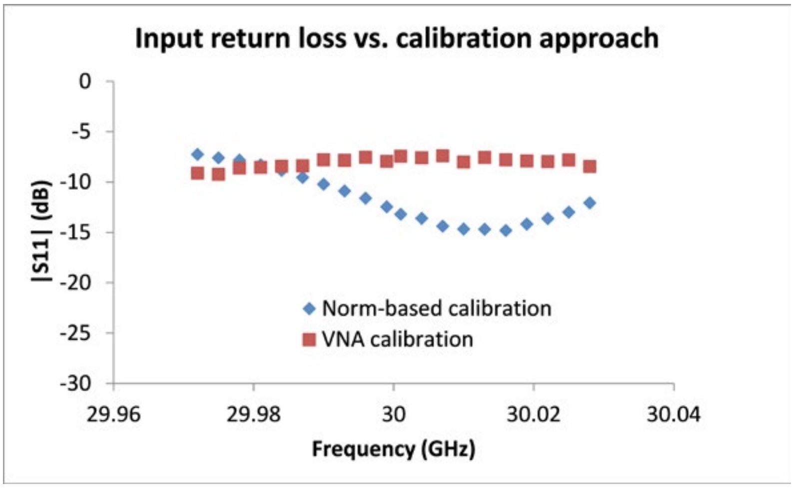


Figure 5: A plot of in-channel return loss for a modulated signal driving a device into compression is shown here. The normalization-only approach produced an overly optimistic result.

Transmission phase is also frequently of interest since deviations from linearity (or lack of flatness in group delay) can cause extreme error vector magnitude (EVM) defects in all but the simplest modulation methods. A measurement of this phase deviation for a 60 GHz amplifier is shown in Figure 6, again with two different calibration choices. With the usual VNA calibration, the phase deviation was no more than about 3 degrees over the bandwidth. With only a normalization calibration, the perceived deviation reached as much as 9 degrees. This could lead one to conclude that more modulation quality degradation would occur in the system than would actually occur.

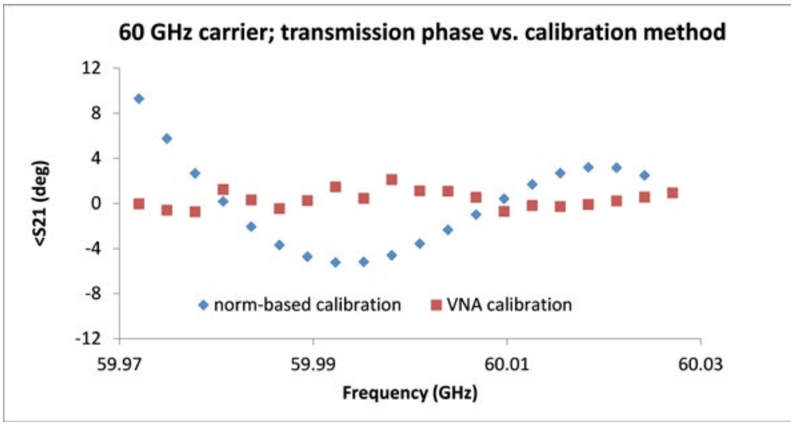
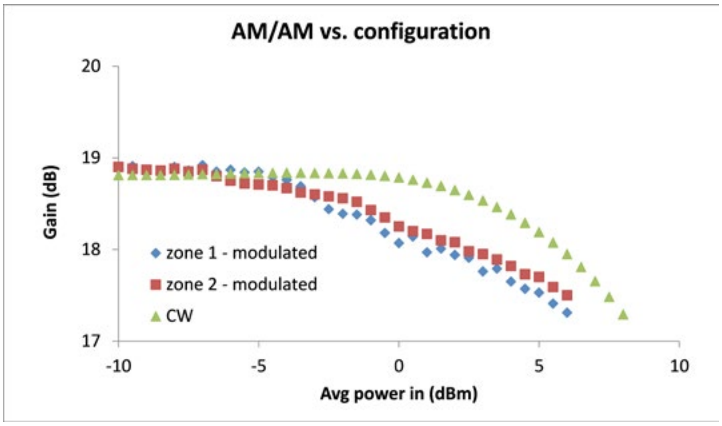


Figure 6: Transmission phase (normalized to 0 degrees) is shown here for a 60 GHz channel measurement with the two calibration approaches. The impact of the calibration change tends to increase with carrier frequency.

Quasi-linear quantities such as gain compression (or AM/AM) are also of interest. It is well known that this metric can be quite different for CW vs. modulated waveforms (depending on how the power variables are defined) due to differences in device excitation in the peak voltage sense e.g., [7)-9)]. While it is possible to model and calculate the reponse to a modulated signal from CW measurements[e.g., 7)], this can sometimes be more time consuming than a direct measurement. A measurement of a power amplifier at 40 GHz is shown in Figure 7 for both CW and modulated waveforms (with two different sub-channel zones used on the latter using a pseudo-LTE signal). The x-axis is based on average power so it is not surprising that the CW response shows less compression since the peak-to-average ratio is much lower.

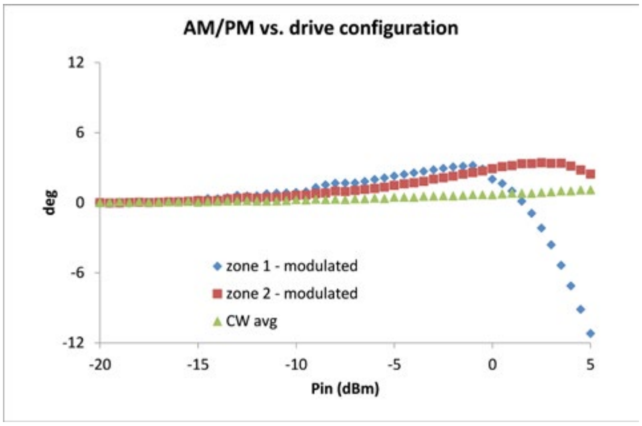
In the modulated measurements of Figure 7, the result is plotted as a function of 'zone' which is a defined as a bin located within the spectrum which allows one to assess another dimension of behavior. The modulated responses show some dependence on location within the channel indicating some symbol dependence of the compression behavior. The 'zone 1' location is in the middle of the modulation bandwidth while 'zone 2' is at the extreme upper edge of the modulation bandwidth. Understanding this variation within the modulation bandwidth can help one better predict system performance for different modulation formats and under different traffic conditions.

Phase deviation with input power (AM/PM) is often also quite important as those phase distortions in channel can degrade modulation quality. A measurement of this is shown in Figure 8 again with CW vs. modulated waveforms (using a pseudo-LTE signal upconverted to 40 GHz). As with AM/AM, the 'zone 1' measurement is in the center of the modulation bandwidth and 'zone 2' is at the upper edge of the bandwidth. The CW difference is not unexpected but the variation with location in the channel spectrum



are somewhat more substantial.

Figure 7: CW and modulated AM/AM measurements are shown here with the 'zones' of the modulated spectrum



discussed in the text. The measurements were at 40 GHz.

Figure 8: As with AM/AM, AM/PM measurements show expected differences when performed with CW vs. modulated signals. The 'zones' used are discussed in the text. The measurement again was at 40 GHz.

Figure 9 shows a difference in AM/PM between normalization-based and VNA calibrated measurements (labeled as 'Delta' on the z-axis) for a modulated signal where both location within the channel bandwidth and the input power are independent variables. The center frequency here was 40 GHz. The change in difference with frequency location (shown as Frequency Offset) is mainly from DUT mismatch effects.

As the DUT match changes with power level, one gets some coupling of the dependencies. This class of measurement is potentially quite valuable in illustrating the dependence on multiple variables and the measurement can be done (relatively) more quickly on a VNA platform due to the integrated sweep engines.

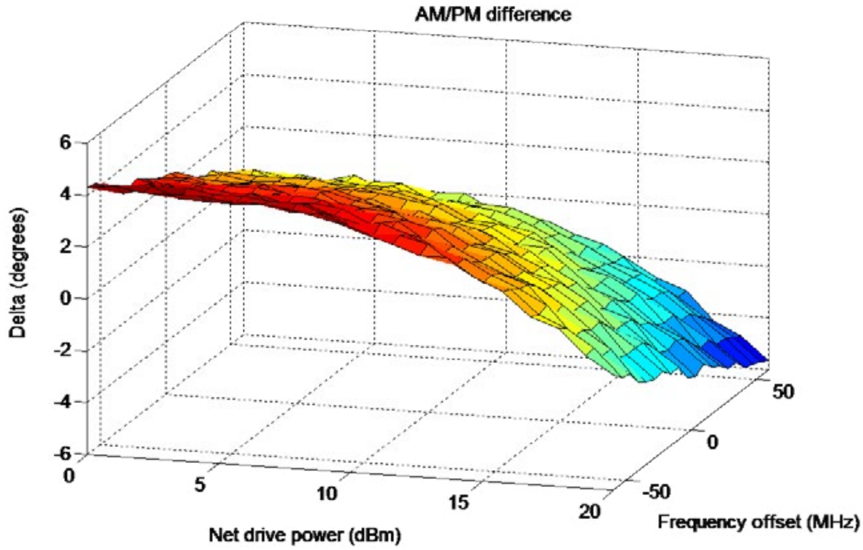


Figure 9: The difference between normalized and ful-ly-calibrated AM/PM measurements is shown here vs. power and the frequency within the modulated bandwidth.

More explicit measurements of adjacent channel power are also typical characterization needs and, of course, a modulated signal is needed in these cases. While the con-tributing nonlinearities can usually be modeled with IMD measurements[e.g., 8] actual measurements of the modu-lated distortion are still often needed. Such a measure-ment is shown in Figure 10 over swept center frequencies using multiple calibration approaches. As the device was measured further from its center frequency, the mismatch distortions increase and the calibration makes more of an effect. Note also the asymmetry of the channel powers which may be due to bias system effects or other topological considerations. This measurement also illustrates the potential value in multi-variate analysis approaches and the instrumentation structure allows this to be done with reasonable speed.

Desense measurments (where a lower amplitude modulated signal is being analyzed in the presence of a higher amplitude signal nearby) show similar effects. The mismatch handling can still have substantive effects and the overall instrument linearity and noise floor affect the achievable measurement range.

5 - Summary

Higher frequency power amplifier measurements, for 5G and related applications, may be able to benefit from a VNA-based wide IF measurement platform operating on modulated signals. Some fundamental platform strengths (signal separation, dynamic range, isolation, multiple receivers....) coupled with appropriate calibration tools have the potential for faster and improved quasi-linear measurements that can be challenging.

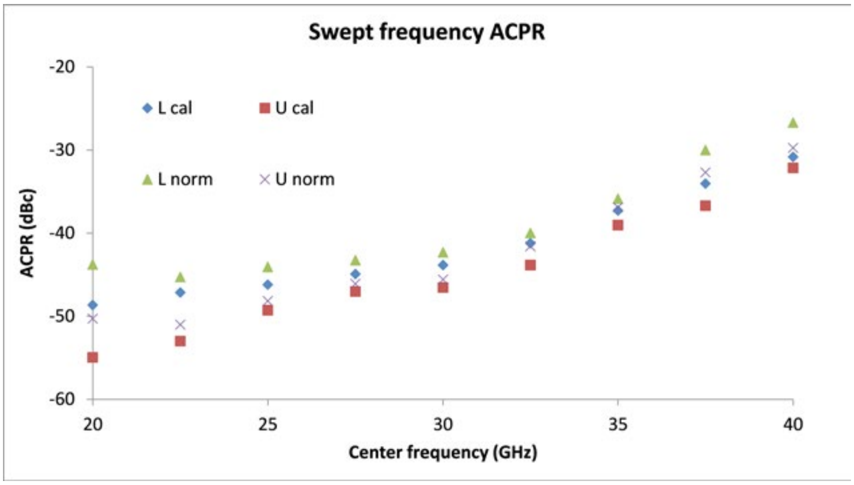


Figure 10: The Adjacent Channel Power Ratio is plotted here for both upper (U) and lower (L) channels with the different calibration choices. The DUT (and setup) match worsened further from the middle center frequency which resulted in a larger correction.

6 - Acknowledgments

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