LINEARIZATION OF RF FRONT ENDS

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Linearization, as a concept for improving signal integrity in radios, has been around for the best part of 100 years (at least dating back to Black's Feedforward patent, filed in 1920's). A golden period of innovation followed for 80 years, until the turn of the century, when the now quasi-ubiquitous DPD (digital pre-distortion) became the architecture of choice.

DPD has been widely adopted, no more so than in Mobile Communications – initially in infrastructure, more recently in mobile devices. The advent of 5G, with mm-/u-Wave implementations potentially enables alternative techniques.

This paper provides a review of the subject matter, including; a linearization classification system, an overview of the limits and goals of linearization and a measurement example.

Background

The RFFE

The RFFE (Radio or RF Frontend) is a PHY-layer concept (Figure 1).

In the transmitter, the RFFE is responsible for conditioning (e.g. modulating, frequency shifting, filtering, amplifying) wanted data onto a carrier, suitable for transmission across a medium. In the receiver, the reverse operation.

The RFFE, comprises a number of functional blocks, e.g. DAC/ADC, modulators, mixers, filters and amplifiers. The RFFE might be built with varying degrees of integration; monolithic, multi-chip module, or completely from discrete components.

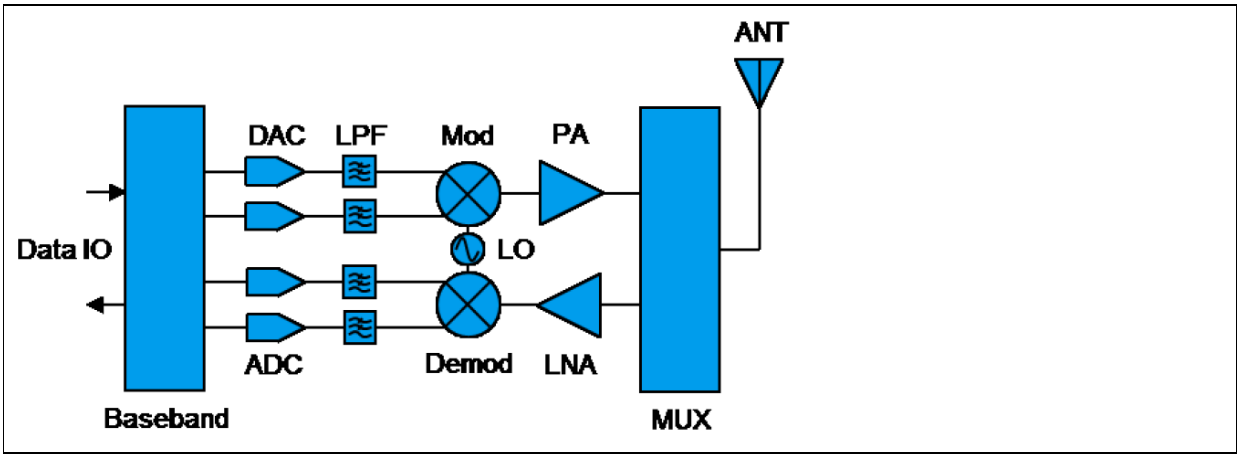


Figure 1 - Simplified architecture of transmit/receive frontend.

This conditioning process, performed by the functional blocks, introduces errors; e.g. distortions and noise.

Important macro parameters for the RFFE include operating power, efficiency, linearity and bandwidth.

- Linearity requirements are usually regulated for a given system; they protect other third parties, including other users of a communication system (but don't necessarily guarantee sufficient link quality for the intended users).

- Efficiency on the other hand, is a market force; e.g. "Talk-time" in mobile devices. Even when supply energy is bountiful, wasted energy always ends up as heat, which needs to be managed. That costs.

What is Distortion?

Non-noise Distortions can be broken down into three types, causing variations in the complex gain (amplitude and phase of transfer) in different domains (Figure 2):

- Non-Linear (complex gain variations as a function of amplitude)
- Linear (complex gain variations as a function of frequency)
- Memory Effects (complex gain variations as a function of time)

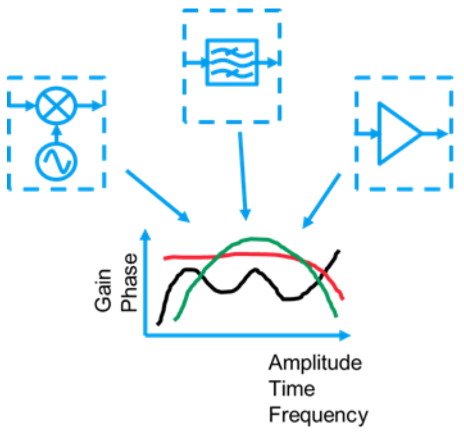


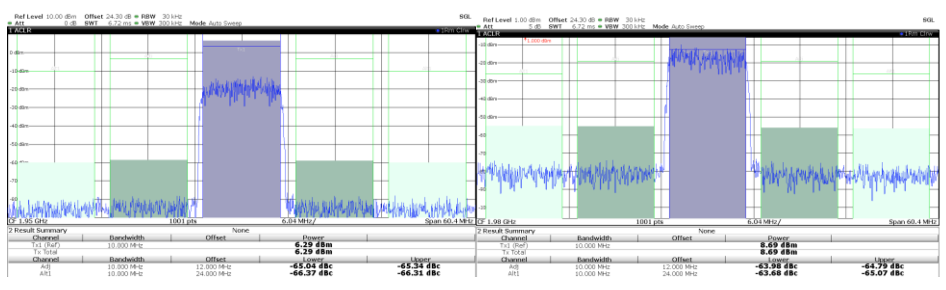
Figure 2 - Example frontend components and distortions

All devices or components in an RFFE contribute to all of the distortions, but the proportions and dominant types vary.

- RF Filters exhibit predominantly Linear distortion (Figure 3)
- RF Amplifiers and RF Mixers contribute heavily to non-linear distortion (Figure 4)

A non-distorting device would exhibit flat (i.e. constant) complex gain characteristics in amplitude, time and frequency domains.

Generally speaking, linearization is taken to mean the correction only of non-linear (amplitude domain) effects caused by devices. In practice, the linearization schemes may be capable of compensating for linear and memory effects too, and in doing so, ensure better identification and correction of non-linear distortions.



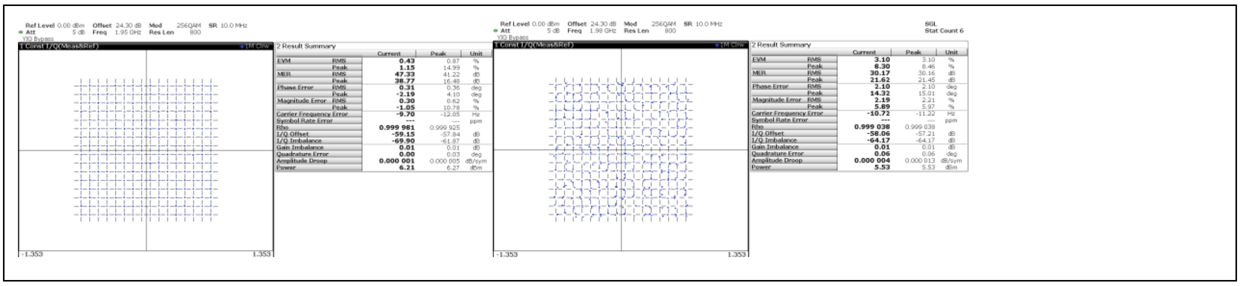


Figure 3 – Linear distortion: Commercial bandpass filter, spectrum and 256-QAM IQ signal played through in mid-band and at the band-edge

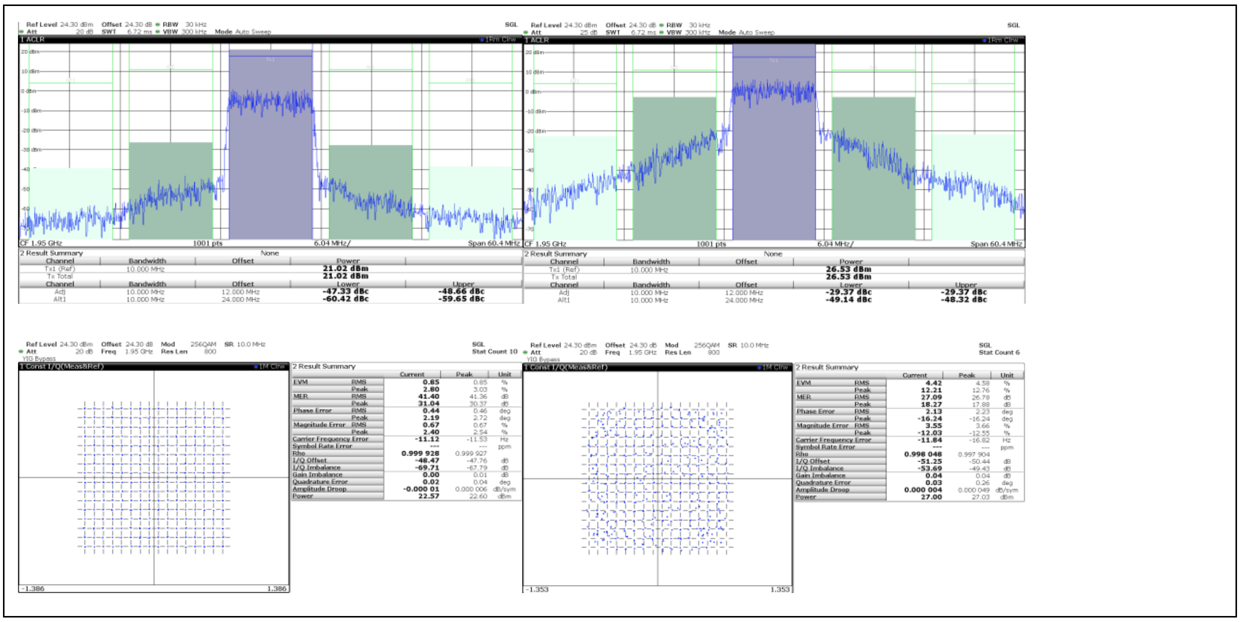


Figure 4 - Non-linear Distortion: Commercial amplifier, spectrum and 256-QAM IQ signal played at a low-power and high-power level

Linearization & Methods

What is Linearization?

Linearization is the reduction of distortion in an RFFE to acceptable levels.

There are a plurality of linearization techniques in the literature [1], including:

- Feedforward [2]
- Feedback
  - Direct [3]
  - Cartesian [4]
  - Polar [5]
- Predistortion
  - Analog [6]
  - Digital

Each of the mentioned techniques, and others, offered slightly different features, advantages and implementation challenges.

Classification of Linearization

In an attempt to make sense of the plurality of techniques, a classification method is presented. Example motivations for this exercise are (i) to understand general features, in order to help identify which might be the best choice for a particular application, or (ii) complementary methods, schemes that can mutually improve linearity.

The proposed classification is performed according to whether (i) the correction signal is Predicted or Measured/Extracted and (ii) whether that correction is applied to the Input (Pre-) or Output (Post-).

Thus, a 2x2 matrix is formed (Figure 5), but the draft classification has only 3 members, thus far:

Feedforward = Measured/Post-correction

Feedback = Measured/Pre-correction

Predistortion = Predicted/Pre-correction

A 4th (and as yet unpopulated) category has been identified, using Predictive/Post-correction.

Linearization Methods

		Impediment Generation	
		Predicted/Synthesized	Measured/Extracted
Correction Location	Pre-source	Digital Pre-distortion Analog Pre-distortion	Cartesian Feedback Polar Feedback
	Post-source		Feedforward Fixed Filtering (e.g. Band Pass)

Figure 5 - Proposed classification of Linearization techniques

The 4th Method: Predicted/Post-Correction

It transpires that this 4th category has been the subject of quite extensive research itself.

The most significant contribution was already addressed by Popovic et.al [7], proposing three types of multiple path transmitters; Envelope-schemes, Doherty and Outphasing.

A further search of the literature for these transmitter types yielded yet more variations. Building a Venn diagram (Figure 6) from these three basic types allows for a further consolidation of the literature.

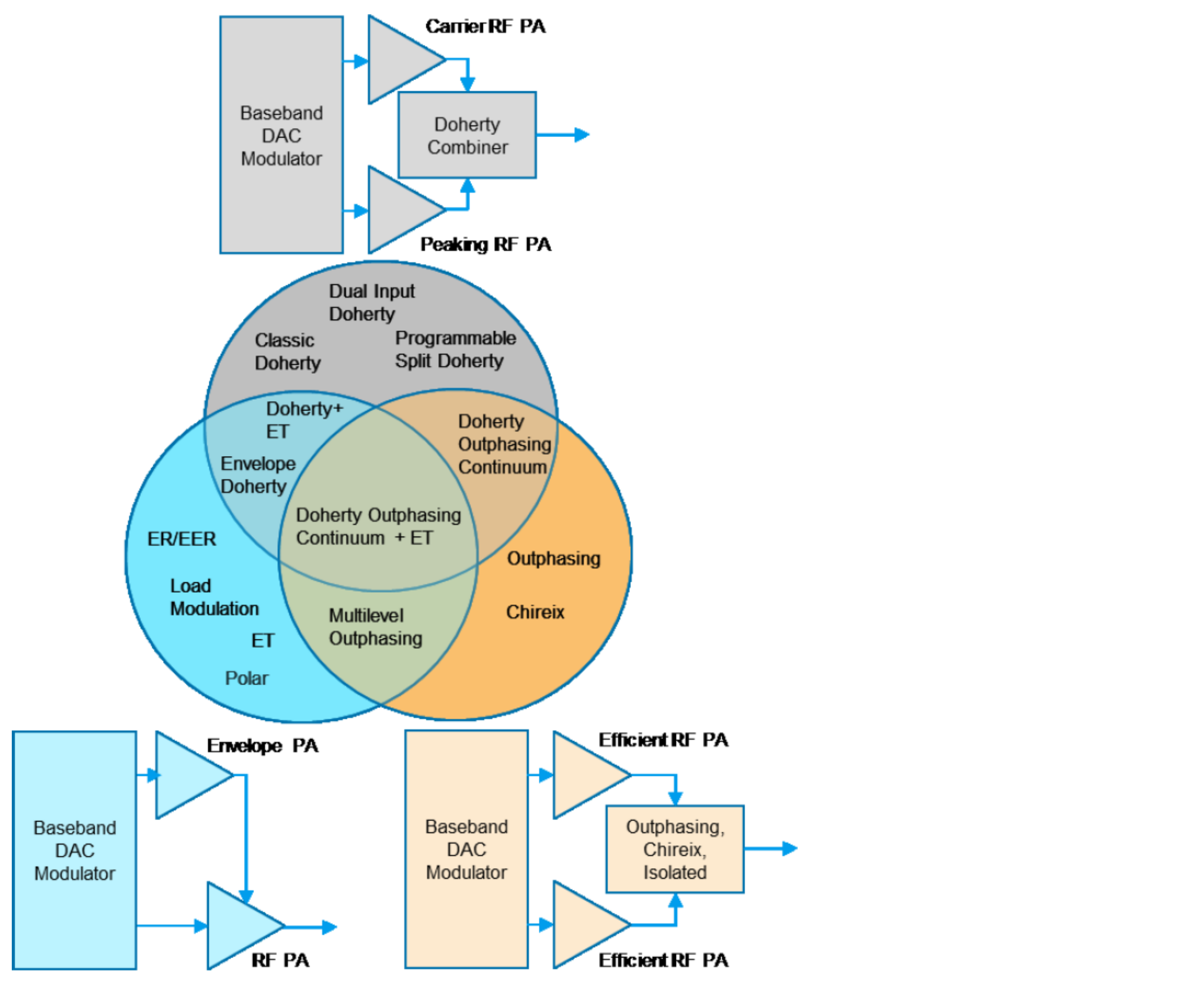


Figure 6 - Venn diagram classifying plurality of Predictive Post-correction architectures from the literature

Incidentally, the Venn consolidation yields a total of seven categories. Examples in the literature were found covering six of those; but a concept covering all three was not. And so (for a short period), the identification of (for example) a Doherty-Outphasing-ET amplifier would appear to be novel.

Linearization Effects

The Limits of Linearization

Perfectly linearized results in zero AM-PM and an AM-AM characteristic divided into two regions of operation; constant gain and constant output level.

This is, in effect, the response of a "hard limiter" or "hard clipper" response (Figure 7). An incident signal is passed unmodified, until such time as envelope excursions impinge on the programmed clipping level. Excursions exceeding that clipping level are not passed.

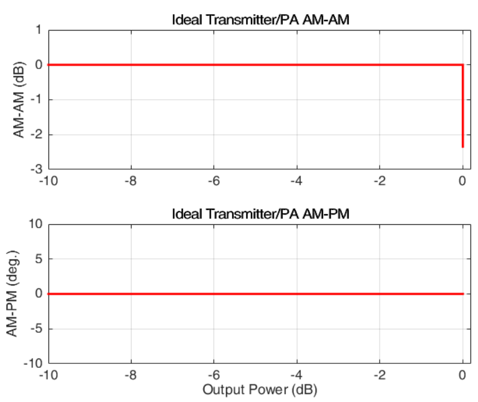


Figure 7 - AM-AM and AM-PM of a hard clipper/limiter

Hence, a perfectly linear RFFE preserves PAPR through the device, i.e. PAPRo=PAPRi. (Note – the opposite is not true, that equal PAR at the input and output does not constitute perfectly linearity!)

In this example, the potential of linearization is illustrated.

Starting with a classical OIP3 specified non-linear component (which might be a mixer or amplifier, for example). Highly linear devices are marketed as "high IP3". Typically this means that the OIP3 level is 10-15 dB higher than the P-1dB or PSat of the device.

Two example IM3 levels (-72 dBc and -52 dBc) are calculated and plotted in Figure 8. These IM3 levels are extrapolated to give an OIP3 level. Considering the power per tone relative to the device PSat, this device exhibits a 12 dB ratio.

Next, a two-tone signal is "played" through a hard clipper – whose PSat value is equal to the previous. The IM3 values, relative to the power per tone of one of the two carriers, is calculated across a range of values.

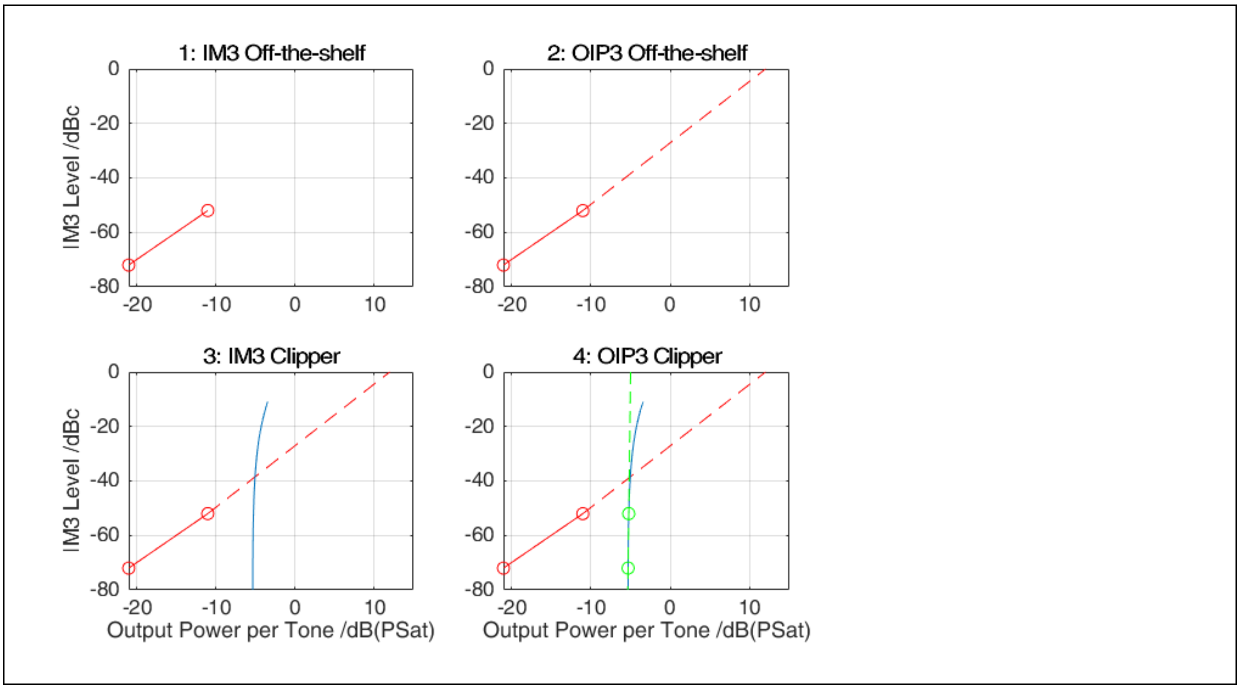


Figure 8 - (1) IM3 v Power per tone for an off-the-shelf mixer (2) Extrapolated OIP3 for that mixer (3) IM3 for a hard clipper with same power capability (4) OIP3 extrapolation for that hard clipper

Unless the PEP of the two tone signal actually stimulates the clipping action, then no distortion is generated. The clean, or PAPRi, of a two-tone signal is 3 dB. With no clipping, there is no distortion and PAPR is preserved through the device.

As the drive level increases, such that the PEP impinges on the clipping level, distortion (IM3) increases and the PAPRo reduces. All the IM3 is generated over a small dynamic range.

Using the same -72 and -52 dBc IM3 levels and the same linear extrapolation demonstrates that this device actually has a very low OIP3. Lower, not only than the marketed linear device, but lower than the PSat/P-1dB of the device itself.

The output power capability for -52 dBc IM3 (in this case) may be increased with linearization by up to 5.8 dB. For -72 dBc, the increase is 15.7 dB.

Be wary of using IP3 as a figure of merit for RFFE linearity, especially when testing linearized systems.

Linearization Goals

Linearization is most optimally applied (at least in Transmit applications) when it enables the RFFE to operate with a PEP (peak envelope power) that reaches the RFFE saturated output level. This way, every bit of paid-for periphery is utilized.

Certain amounts of distortion are, however, tolerable and allowable.

With the onset of hard clipping, distortion begins to appear. At the same time, PAPRo is reduced, PSat is fixed and therefore Pavg continues to increase.

Increasing Pavg is beneficial. If too much linear power is achieved, then a smaller periphery may be used, or a lower power supply voltage.

Although Linearization does not in itself modify the operating energy efficiency of the RFFE, it can produce a net improvement in efficiency by increasing the utilisation of the RFFE:

- higher absolute operating output level or dynamic range, from a given RFFE (typically accompanied by a higher efficiency) (more bang for your buck)

- allowing a smaller scale RFFE to achieve the same output (the same bang for less bucks)

The goals of Linearization are therefore:

- Ensuring that PEP reaches PSat either at, or before, the breach of linearity requirements

- Ensuring that output PAR is minimized, maximizing PAvg, for a given level of distortion

Linearization Example

In this case, an off-the-shelf VSAT Ku-band BUC (block up-converter) was appraised using instrument based DPD (digital predistortion). The BUC comprises at least one instance of each of the building block elements (mixer, filter and amplifier).

Before performing the unlinearized and linearized measurements, two value-adding steps should be followed.

1. In the first step, a measurement must be made of the PA's saturated output level. This also has to be performed with a representative signal, especially regarding bandwidth.

2. A calculation should be performed of the response of the hard clipper to the test signal and distortion metric.

In this case, the test signal was 64-QAM (10 MSym/s and rrc= 0.1) creating a PAPR of 6.1 dB.

A calculation of spectral regrowth was done in MATLAB®, performing a power sweep through the clipper, calculating ACLR and PAPR for various clipping levels. Figure 9 shows that the target -40 dBc ACLR was met with a PAPR of approximately 4.1 dB.

The time domain waveform before and after the clipper, with the -40 dBc ACLR level is also presented. Note how the clipping action creates a "ZOH" (zero order hold) type characteristic in the waveform.

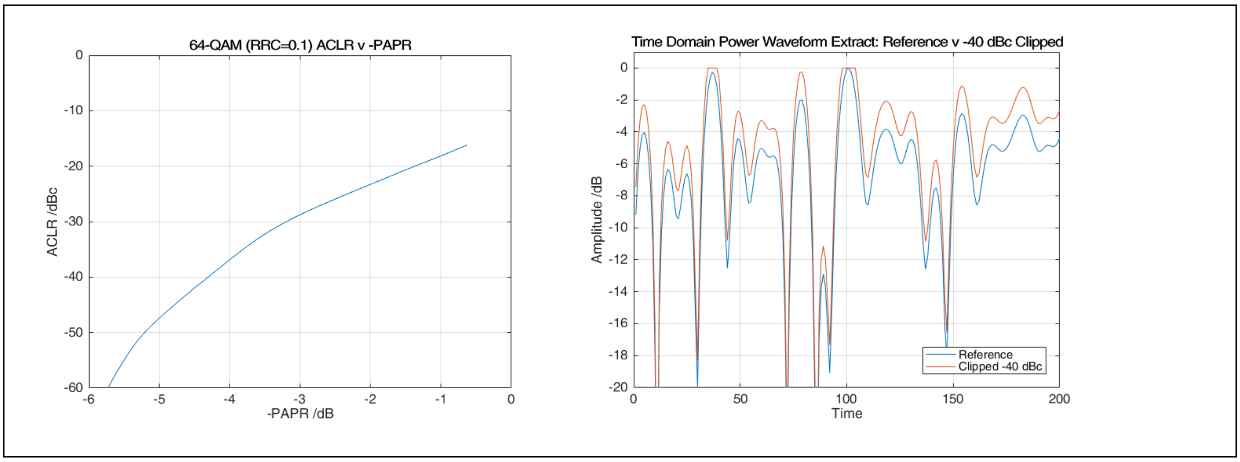


Figure 9 - (1) ACLR v PAPR (Output) for a hard clipper under 64-QAM test signal excitation. (2) time domain representation of the clean and clipped waveform

A power sweep measurement of the amplifier is now performed (Figure 10), measuring average power, ACLR and PAPRo.

PEP may be calculated directly from PAvg and PAPRo. PSat is assumed to be the maximum measured value of PEP, in this case slightly more than 35 dBm.

Note that the clipper and measured device distortion values asymptote, as the device is driven harder and distortions due to quasi-hard clipping in the device increasingly dominate.

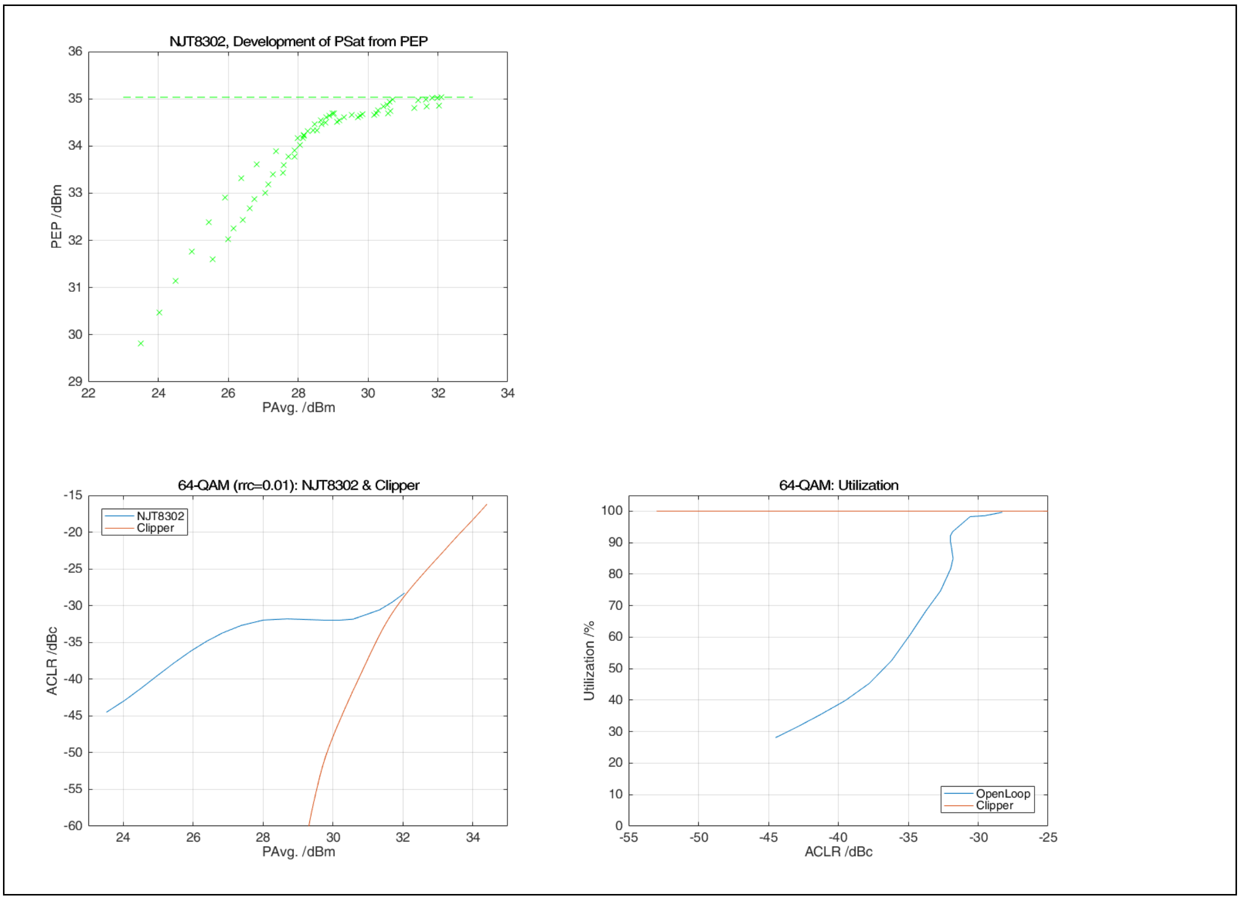


Figure 10 - Measured and theoretical device power sweep showing (1) Peak Envelope Power v Average Power (PAvg + PAPRo = PEP) (2) ACLR v Output Power and (3) PEP/PSat Device Utilisation

Finally, the linearizer is enabled and power sweep measurement repeated, and added to the measurement ensemble (Figure 11).

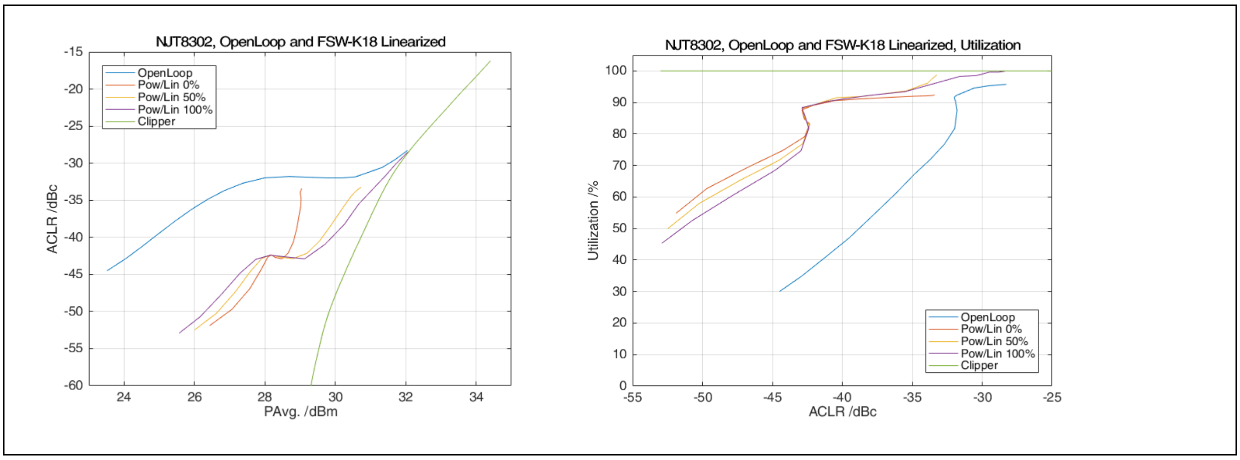


Figure 11 - Raw, Linearized and Theoretical Power Sweeps

A number of observations can be made. The application of linearization in this case, has:

- increased the useful average power of the PA by approximately 4-5 dB
- increased the utilisation of the PA from 45% to 90%.
- achieved an operating power within 1-2 dB of the "theoretical" limit

CONCLUSIONS

Linearization can be effective in improving RFFE performance, its application will continue to play an increasingly important role in the development of high performance RFFE.

However, DPD has become ubiquitous, at least in cellular communications, for a generation of engineers, and it is important not to lose sight of other techniques.

DPD become less interesting when transmit powers are low (e.g. when additional power consumption of DPD becomes a greater part of system consumption), bandwidths are high (DAC and ADC power consumptions are relative to clock speeds), or where there is no access to digital baseband (e.g. receivers, some SatCom ODU).

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GLOSSARY

PAPR: peak-to-average-power-ratio, describes the power ratio of the peak of the envelope of a signal compared to its time average value. Used with suffix "o" denoting output and "i" for input.

PEP: peak envelope power, the maximum instantaneous power achieved by a device when playing a waveform. The sum of PAvg (average waveform power) and PAPR (peak to average power ratio).

PSat: saturated power, the maximum possible power output from a device (not to be confused with PEP). PSat cannot be exceeded.

PAvg: average power, time average power of a waveform output from a device.

ACLR: adjacent channel leakage ratio, a measured of the spectral regrowth or spreading caused by non-linear devices. Similar to IM3, but for modulated signals.

IM3: two-tone, third order intermodulation products, the interaction of two CW tones with a non-linear device causing intermodulation (distortion) products to appear at additional frequencies.

DPD: digital predistortion, a method for predictive, pre-correction linearization of a device by modifying the reference signal in the digital domain, prior to conversion to analog.

BUC: block upconverter, vernacular used in the SatCom industry to describe a transmit component, usually comprising a classic mixer-filter-amplifier RF chain.

ODU: outdoor unit, vernacular used in the SatCom industry to describe the antenna (dish) and connected RF electronics. Complemented by an IDU (indoor unit), housing the digital/modem electronics.

ZOH: zero-order hold, is a mathematical model of the practical signal reconstruction done by a conventional digital-to-analog converter (DAC), holding each sample output value for one sample value (Wikipedia).

PHY-layer, PHY is an abbreviation for the physical layer of the OSI model and refers to the circuitry required to implement physical layer functions (Wikipedia).