Linearization of RF Frontends

White Paper

Widespread adoption of higher order modulation schemes, larger signal bandwidths and higher operating frequencies, to enable higher data throughput in communication links like 5G, places increasingly tough demands on the frontend. Signal fidelity is often enhanced with linearization.

The greater number of RF chains and signal bandwidth in 5G Frontends mean that DPD (Digital Pre-Distortion) may no longer be the default linearization choice; 5G Frontends will be completely different from their 4G predecessors.

The key metrics of Efficiency, Linearity, Bandwidth and Output Power remain, as does the question of how to optimally create the signal with just enough fidelity and power, with a minimum of wasted power. The solution set to that question, however, has never been greater.

Amongst other topics, this White Paper, (i) proposes a classification of Linearization schemes, (ii) introduces the hard limiter, (iii) illustrates linearization of an exemplary mmWave PA using non-DPD techniques, and (iv) introduces a class of linearized transmitters that create their signal and linearity from efficiently generated components.

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White Paper

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1 Introduction

1.1 What is a Frontend?

Raw digital data cannot ordinarily be communicated wirelessly as-is.

That wireless transfer of data is performed using an analog signal. The digital data is encoded onto an analog carrier in a transmitter, radiated through a media and decoded back to the digital domain in a receiver.

This whole conversion and transfer process is performed by the RF frontend (referred to in the OSI model as the PHY-layer frontend). An example RF frontend is shown in Fig. 1-1.

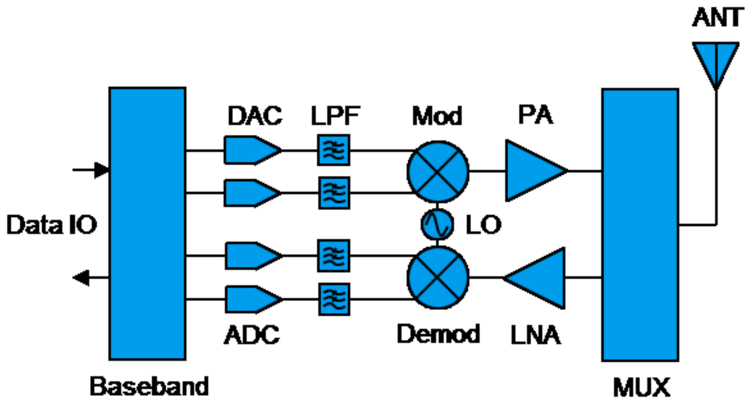

Fig. 1-1: A generic PHY-layer radio frontend

This link may be formed in free- (e.g. using a radio antenna, shown in Fig. 1-1) or confined- (e.g. coaxial-, waveguide or optical fiber cable) media. In duplex or two-way communication, the transmitted and received signals are usually coordinated in an orderly fashion. That coordination typically uses one of the examples in Table 1-1.

Transmit & Receive MUX: Examples	
Domain	**Example**
Time	Semiconductor switch, Circulator
Frequency	Filter (e.g. diplexer)
Polarization	Ortho-Mode Transducer (OMT)
Spatial	Discrete transmit/receive antenna

Table 1-1: Examples of multiplexed domains and components

On the "digital" side of the frontend, is a transceiver or modem. Almost always built in a silicon process, it is responsible for preparing the digital data for analog transmission, and extracting it digitally from an analog reception. Interfacing may be standardized or proprietary. The modem may also integrate additional functionality, including the frontend itself or higher OSI-layers on a single chip or packaged module.

The (analog) radio frontend parts are built in a variety of technologies, often including non-silicon materials depending on their function and performance requirements.

RF frontends have constraints, both regulatory and commercial. Regulatory demands ensure that the frontend is fit for purpose and does not cause disruption to other users or systems. Commercial needs are more ambiguous, measured by cost, market availability, incumbency and performance.

There is not a one-size-fits-all frontend architecture. Presented with a specification, different engineers or teams even within the same organization will present different solutions, with their own cost and performance balances. Where cost and performance are differentiators in the competitive race, the optimum architecture needs to be considered on a case-by-case basis.

Digital modulation schemes have almost completely replaced analog. Adaptive modulation (and coding) schemes are increasingly used to continuously fine-tune the data format sent through a communication link.

This document presents higher performance frontend concepts. This goal is to enable the reader to:

- quickly understand and appraise Linearization techniques and options.
- identify best methods, and optimize or innovate their own solutions, appropriate to their own case.

1.2 Digital Predistortion & RF Power Amp Paradigm

Linearization is a much larger topic than just digital predistortion (DPD) of radio frequency power amplifiers (RFPA) in transmitters.

It is not obligatory for a frontend to be part of a transmitter nor to include any RF amplifier, in order for linearization to be helpful. DPD is not the only method of linearization.

Indeed, there are many cases where frontend linearization would be helpful, but DPD is not appropriate or optimum.

- The most obvious example is in a receiver, where the input is an already modulated RF signal, accompanied often by a whole raft of unwanted interfering signals. The interferers eat away at the dynamic range of the receiver, until the signal can be digitized and filtered with relative precision.
- In some transmit applications, there might not be access to a digital baseband, or a digitizing feedback path is not practical. For example, ADC (analog digital converters) might be too expensive, consume too much power, or not even available at the required sample rate, bandwidth or resolution.
- There might be frequency conversions in the frontend whose presence might push the cost-effort paradigm too far, to effectively implement the feedback receiver.

The latter points would appear to be quite relevant for 5G Frontends.

1.3 Reader's Guide

In Chapter 2, the subject matter of linearity is introduced, highlighting types of distortions and proposing a classification system for linearization schemes.

The hard limiter is introduced in Chapter 3. In almost all cases, it represents the best possible transfer characteristic and often is used as the case in limit to understand the robustness and performance of communication systems.

The classic intercept point method for designing a frontend cascade is appraised in Chapter 4. Typical mixer performance, as used in transmitters, repeaters and receivers, is contrasted with that of the hard limiter.

In Chapter 5, the hard limiter is compared with a representative TWTA (a type of mmWave frontend amplifier) and stimulated by a representative signal (256-APSK). The TWTA is then modified with different linearization schemes from the literature and the potential improvements are documented.

At the time of writing there is no real consensus on critical 5G parameters including signal bandwidth, amplifier model or even operating frequency. Hence, models and modulations are drawn from an adjacent mmWave industry.

Chapter 6 considers the special case of transmitters with multiple inputs. In transmitters of this type, the signal does not follow the conventional single path. Rather various components of the signal are processed separately before a final construction takes place usually before the antenna. Generally speaking, these components should be efficiently generated.

2 Linearity and Linearization

2.1 Distortion Introduction

There are different types of distortions and causes. They are created by all components (including supposedly passive) and exist in all parts of the link; transmit, repeat and receive.

Types and causes of distortion might be classified as:

- Linear distortion
  - Typically introduced by filters or frequency selective elements.
  - Cause complex gain variations across a range of frequencies.
- Non-linear distortion
  - Generally caused by semiconductors (including diodes and amplifiers)
  - At junctions between dissimilar materials (known as PIM)
  - Cause complex gain variations at different drive levels.
- Memory effects
  - Variations in complex gain over time, temperature, or in different channels or envelope frequencies.
- Noise
  - Sourced by all components
  - Causes random complex gain variation

The levels of each of these distortions may be modified by linearization, compared to the reference (i.e. backed-off into linear range) solution.

Linear distortion reduction, also called equalization, is used in all communication systems. It is performed long-term, in bulk (across multiple symbols or data packets) and in the digital baseband. It may for example, be calculated by analysis of deviation of the received input from a known training sequence in the signal

While equalization improves, or in many cases makes possible, certain communication schemes, it does not reduce non-linear distortion. In fact, equalizer performance is reduced by non-linear distortion. A more comprehensive study of the topic of equalization is beyond the scope of this document.

Linearization (of non-linear distortions) can improve equalizer performance by reducing complex gain variations in the time and amplitude domains, aiding extraction of the underlying channel frequency response. Linearization, could also intrinsically perform equalization itself.

2.2 Linearization Classifications

There are many linearization methods in the literature. To help to identify the strengths and weaknesses of the different methods, it is beneficial to classify them. Classification should aid in identification of the best technique, or techniques, for each application.

Using more than one technique is potentially of interest because combined techniques can address different deficiencies. One example of multiple techniques being used, hybrid feedback and feedforward, is given in (1). A simplified example of which will be presented in this document.

The benchmark performance is the open-loop frontend, operating with sufficient back off. No linearization is used. It relies on the intrinsic linearity of the components to be good enough. The performance cannot be made significantly better than the competitor, if access to components is assumed the same.

At the other extreme, a linearized system could be developed with multiple linearization schemes. It might utilize test equipment in-the-loop for monitoring distortions, arbitrarily sophisticated control software driving different linearization implementations.

An optimal solution lies between those limits.

Firstly, linearization may be classified depending on whether the linearizing signal is:

- Predicted/Synthesized or
- Measured/Extracted

And secondly, whether that linearizing signal is applied:

- Pre-, or prior to the distortion source
- Post-, either at or after the distortion source

These orthogonal classifications are summarized in Table 2-1. These categories may also be further divided.

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

Table 2-1: Classification of Linearization methods and examples

To illustrate these basic classifications, some general features of the different classes are given as follows:

- Predicted schemes have correction capabilities limited by the accuracy of their prediction. They have the potential to completely eliminate distortion.

- Measured Pre-source schemes cannot completely eliminate distortion. Distortion is needed for them to work. But, they do offer designable levels of correction.
- Pre-source schemes typically apply correction at a point which is lower in signal level, and are usually power efficient.
- Post-source prediction schemes can provide wideband correction capability.
  - Composition Schemes, in which linearity is constructed from multiple signal processing paths, are addressed separately in Chapter 6 - Multiple Path Tx Frontends.
  - Examples include Doherty, Outphasing/Chireix and Envelope Tracking (ET)

Adopting a linearized design is a significant challenge. It is relatively easy to simulate a scheme (as this document shows), or to build a one-off manually optimized scheme in the laboratory. Converting that into a stable self-adaptive scheme, suitable for the field, is more challenging. It is the barrier-to-entry that creates the opportunity to differentiate.

Simple schemes for adapting Linearization with for example, a single radio input, might extract operating frequency and/or temperature to adjust linearization parameters using a look-up table (LUT).

More complex adaptation schemes might include digitization or demodulation of signals at various nodes in the frontend. These signals may be processed; compared with expected or known patterns. The resultant may then be used to modify parameters.

Developing an adaptation scheme should be done with careful choice of data retrieval points. Some parameters might vary considerably through the frontend chain (e.g. signal envelope statistics).

Finally, it is important to consider DfX issues (Design for Assembly, Test, Manufacture, Repair, etc.). For example, performing a production-time temperature sweep for calibration might not scale appropriately to higher manufacturing volumes. But, measuring the actual temperature at production-time could potentially be used with design-time temperature trend characterization to yield better DfM.

3 The Hard Limiter

The hard limiter is a perfectly linear, or linearized component. It is often used as a model to understand the best possible linearity performance (2), to define communication standards. The hard limiter may be graphically described as in Fig. 3-1 and qualitatively as:

- No AM-PM distortion
- No noise, no memory effects, no dispersion, no delay, etc.
- AM-AM in two discrete regions of operation
  - Constant gain (linear)
  - Constant output level (saturation)

The hard limiter exchanges a reduction of peak-to-average power ratio (PAPR) for increased distortion. Lower PAPR is usually advantageous because it increases the average output level at which a system can operate with the required linearity.

In transmitters, this higher output level usually also translates into higher energy efficacy. In receivers, this means higher dynamic range.

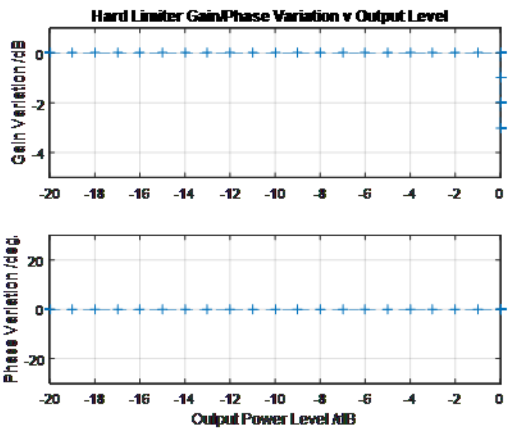

Fig. 3-1: The hard limiter's AM-AM and AM-PM characteristics

The common gain compression metrics, including P-1dB, P-3dB and Psat, which relate to the rate of change of output level with respect to input drive, are all equal.

The model of the hard limiter will be used in this document to compare and contrast the best possible performance for linearity against other frontends.

4 Third Order Intercept

4.1 IP3 Background

Historically, frontend design best practices have been developed using third order intercept points (IP3 or TOI), two-tone third-order intermodulation distortion (IM3) and P-1dB (one dB gain compression) as figures of merit.

Spreadsheets and calculators to assure linearity were widely developed, estimating IP3 and the resultant IM3 in a frontend cascade. Critical frontend building blocks like mixers and amplifiers, especially for receiver applications, were (and still are) bought and sold according to their IP3.

4.2 Frontend Mixer Example

An example linearity characteristic of a mixer is given in (3). It is suggested that a ratio of between 10dB (for high frequency) and 15dB (for low frequency) exists between IP3 and P-1dB. For a 1dB change in the absolute level of each of the two tones, there will be a 3dB change in the absolute level of the IM3. The relative change in IM3 level is 2dB for each 1dB change in input or output power.

Extracted data from (3) is given in Table 4-1 and the stated conversion loss is 7dB.

Example Mixer IM3 Characteristics (3)	
Output Level (per tone)	**IM3 Level (dBc)**
-17	-52
-22	-72
-27	-92

Table 4-1: Typical mixer characteristic data extracted from (3)

The following assumptions and calculations are made:

- 15dB ratio between P-1dB and IP3 (input P-1dB = 1dBm per tone)
- The output P-1dB level is therefore -6dBm per tone (1dBm - 7dB conversion loss)

It follows that a -52dBc IM3 can be achieved with two tones whose input level per tone is -10dBm and output level per tone is -17dBm. This corresponds to an output level back-off of 11dB, relative to the saturated level.

Example Mixer IM3 Characteristics (3), Normalized	
Output Level (Average, back off from P-1dB)	**IM3 Level (dBc)**
-11	-52
-16	-72
-21	-92

Table 4-2: Normalized mixer output IM3 versus output level back off from P-1dB.

The plot of the IM3 versus average output level is shown in Fig. 4-1. The IM3 in the real operating range (below P-1dB = Psat = 0dB) is separated from the virtual or extrapolated range. At -11dB, the IM3 level is -52dBc. At the nominal +15dB intercept point, the IM3 is 0dB.

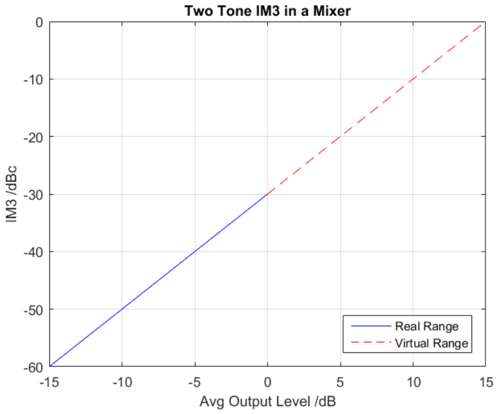

Fig. 4-1: Typical mixer two-tone third order intermodulation (IM3) from (3)

4.3 Hard Limiter TOI

The response of a hard limiter to a two-tone signal, and the resultant third order intermodulation can be calculated. That response is shown in Fig. 4-2.

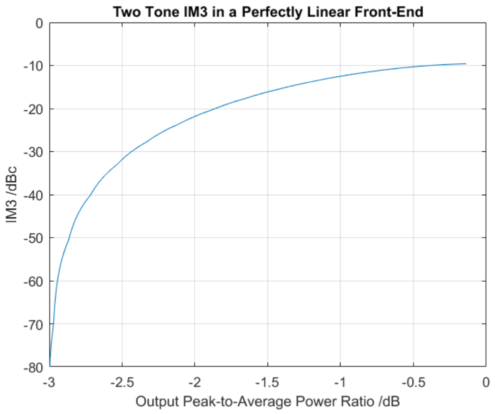

Fig. 4-2: Two-tone third-order intermodulation distortion (with 3dB source PAPR) versus output PAPR in a perfect frontend

The PAPR of a clean two-tone signal is 3dB. If the system is perfectly linear, then the PAPR is preserved. Both input and output PAPR is 3dB.

The IM3 levels of -52dBc, -72dBc and -92dBc in the previous section may all be supported at an average operating level that is not more than 3dB lower than the Psat level.

In the case of the -52dBc requirement therefore, a mixer has been specified that is 8dB higher rated (larger, more power hungry) than would be required in a linearized system. For -72dBc and -92dBc distortion, the difference in rating between the intercept point driven design and the linearized design is higher still.

In Fig. 4-3, the plot of output and IM3 levels versus input level of the off-the-shelf mixer from (3) is replicated (in red).

The plot is augmented with:

- An assumed P-1dB of -6dBm.
- The IM3 level from a linearized mixer.
- An extrapolation of IM3 from the backed off levels, to show the impact on TOI.

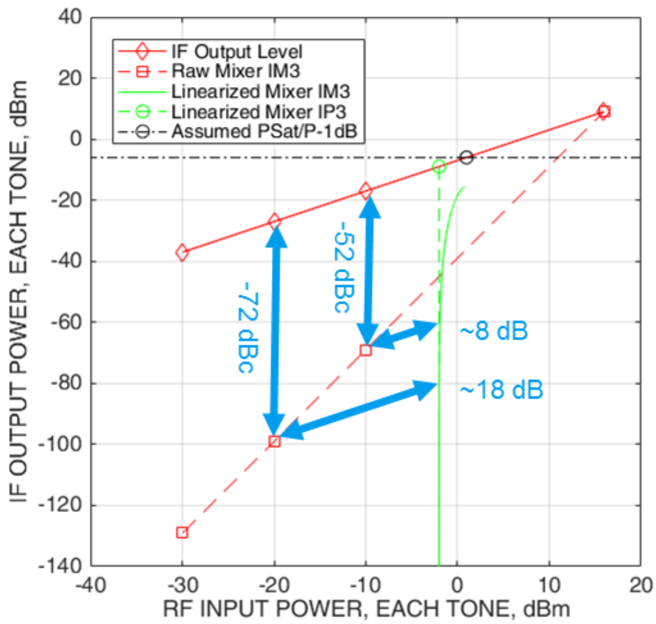

Fig. 4-3: Off-the-shelf Mixer and Linearized Mixer, IM3 and OIP3

In the event that the mixer achieves its full linearity potential, then it will exhibit an IP3 level approaching 3dB lower than its Psat. Contrary to the industry rule-of-thumb, the most linear mixer would actually have very low IP3 figures.

The Linearized Mixer IM3 curve (in green) represents a physical limit. Measurement of the off-the-shelf mixer IM3 (in red dashed) at higher drive levels would show values that approach or asymptote towards, but would not intersect or cross, the Linearized curve.

4.4 Conclusions

Frontend components are non-linear and the ubiquitous mixer is no exception. Controlling non-linearity can, even in the case of a mixer, offer significant improvements in performance and implementation.

Mixers are frequently used in receivers and receiver linearity is increasingly important with higher order modulation schemes employed in crowded spectrum. The mixer is often used in a receive chain before any real filtering of interfering signals is performed. As such, it is offered little protection from strong or multiple interfering signals that erode dynamic range.

In a perfectly linear or linearized system, signal statistics (including PAPR) are preserved. In reality, some degradation of signal integrity is allowed. Understanding the allowable degradation is critical to developing an optimum frontend. Usually, optimal performance is achieved when the frontend approaches a hard limiter response and PAPR is minimized.

The TOI-as-FOM approach to designing a frontend line-up can result in a design that is safe, but susceptible to disruption from smaller, lower power consumption, lower cost linearized equivalents.

Even when the two-tone CW signal is replaced with something representative (e.g. digitally modulated), the basic principles presented here still hold.

- An "intercept point" driven frontend design requires that each component is sufficiently redundant, i.e. over-sized and under-utilized, to achieve the net performance
- A "linearized" frontend enables components to be operated much closer to their limits, resulting in a smaller, lower cost, lower power consumption solution.

5 RF Amplifier Linearization

To further illustrate the power of Linearization, an example is made using the TWTA model documented in (2). Although the characteristic is derived from a pure amplifier subsystem, similar (gain compression plus phase distortion with increasing drive) characteristics would be representative of a more complete frontend, including for example, a mixer or upconverter.

The process used to illustrate the advantages of linearization in this chapter is as follows:

1. Build a modulated test signal (256-APSK).
2. Import the TWTA reference transfer characteristics (AM-AM and AM-PM).
3. Create linearized variants of the reference TWTA, by simulation.
4. Play the test signal through the variants.
5. Compare and contrast the results.

5.1 The Test Signal

The test signal to be used, is 256-APSK from DVB-S2X (2). The constellation is shown in Fig. 5-1.

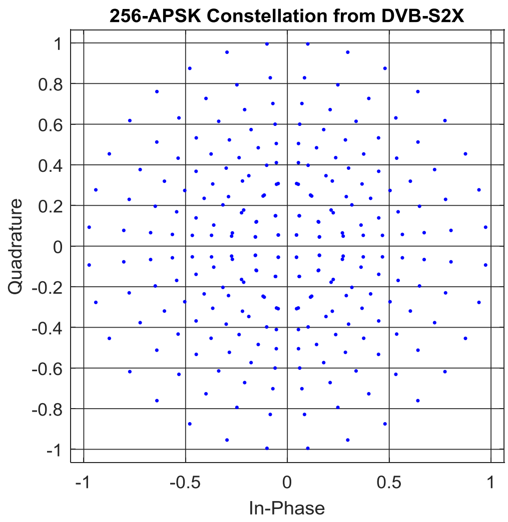

Fig. 5-1: The constellation plot of 256-APSK from DVB-S2X.

The test signal was constructed with roll-off factor 0,05. Generally speaking, this is an exceptionally low roll-off constant, spreading out the signal in the amplitude domain (increasing peak to average ratio) whilst offering a sharp roll-off of the occupied band in the frequency domain.

That modulator output spectrum is plotted in Fig. 5-2.

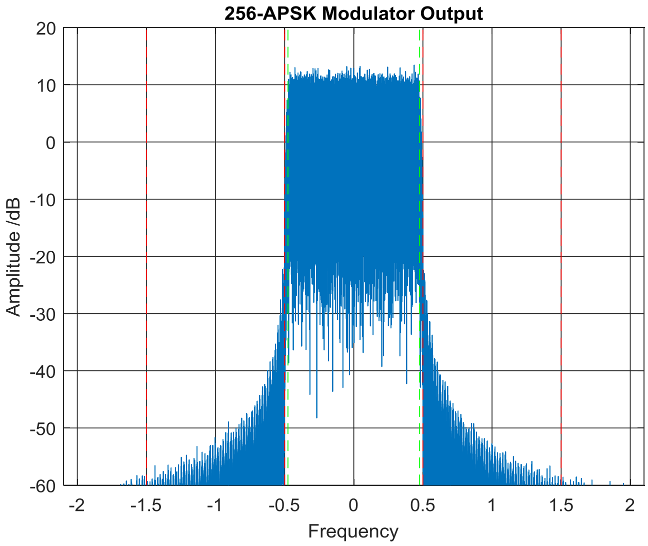

Fig. 5-2: Spectrum of the clean 256-APSK signal with 0,05 roll-off factor

The clean waveform statistics and sample waveform are presented in Fig. 5-3.

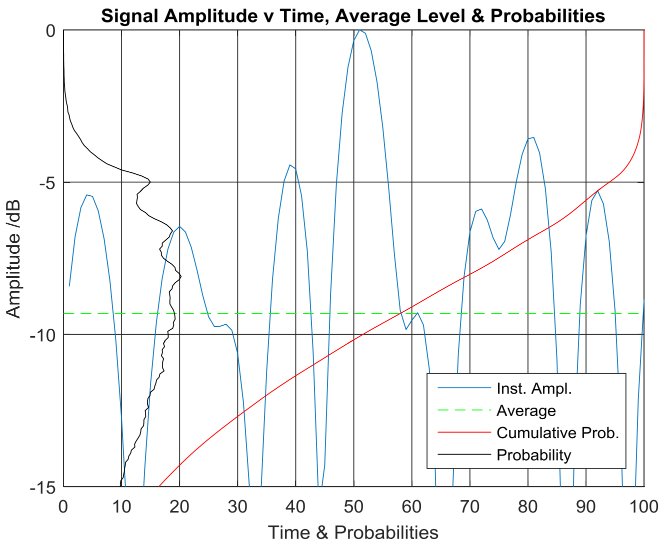

Fig. 5-3: Extracted time domain amplitude and bulk signal statistics for the 256-APSK signal

The signal presents a PAPR (peak to average power ratio) of between 9dB and 10dB at the modulator output. The cumulative probability shows that the signal spends (only) 50% of its time above 10dB power back-off and 5% of its time above 5dB power back-off.

The signal and its statistics will be modified as it passes through various frontend components, including amplifiers.

5.2 Transmitter Performance Requirements

The DVB-S2X reference provides a coarse statement regarding the linearity requirements, which apparently vary by satellite operator:

- "… limit the spectrum regrowth spill-over power at -30 dB" (2)

That -30dBc spectral regrowth requirement is used to avoid disruption to other users. To guarantee this figure, a margin needs to be put in place. This would depend on the industrialization solution. A typical margin might be 5dBc ACLR or 1dB power back off from the output level at which -30dBc is achieved.

Meeting the statutory linearity requirements, does not necessarily mean sufficient linearity to complete the communication link, as this study will show.

This study uses the following spectrum regrowth definition. Assuming a root-raised cosine filter roll-off of β:

- The frequency spacing between channels is 1
- The bandwidth used for calculating channel powers is smaller, 1/(1+ β)
- The spectral regrowth is the ratio of the intentional channel power to the maximum level calculated in the adjacent regrowth channels

Fig. 5-2 shows the occupied and adjacent channels.

The 256-APSK signal was played through a hard limiter and its behavior observed at different drive levels in Fig. 5-4. The demodulated constellation plots are captured through a perfect receiver.

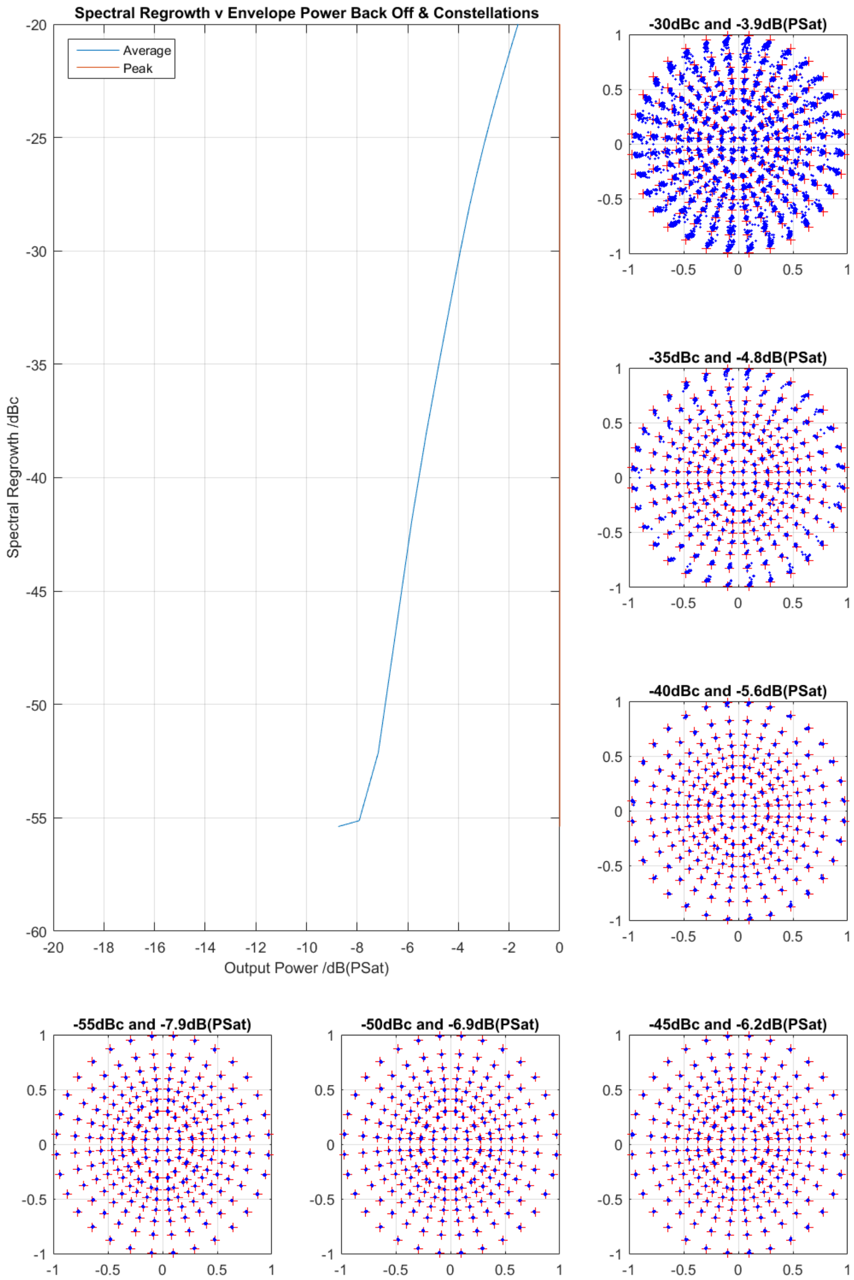

Fig. 5-4: Drive level sweep for 256-APSK through the hard limiter

From the modulator noise floor at around -55dBc to -20dBc the average and peak envelope levels are plotted. The peak envelope level is constant at 0dB, because the hard limiter is always saturated.

The average power curve in blue, represents an important theoretical limit:

- It shows the minimum PAPR required to support a given spectral regrowth.
  - The minimum PAPR, in this plot, is the x-axis difference between the average and peak curves, at a constant Spectral Regrowth.

- The -30dBc level requires a minimum 4dB PAPR, e.g.:
  - For a device with a normalized 0dB saturation level, the maximum average device output level that can be supported is -4dB.
  - The -30dBc level can potentially be supported in a frontend with up to 5dB or 6dB of gain compression.

Spectral Regrowth is an averaged and scalar quantity. It is a blunt indicator of linearity. It does not describe the nature of the distortion (e.g. the contributions of AM-AM and AM-PM). It is also difficult to understand how much distortion is in-band, on top of the carrier.

The demodulated constellation, shown at 5dB spectral regrowth intervals is more informative. A tendency of the constellation points to spread towards the center indicates AM-AM, spreading in radial fashion about the origin indicates AM-PM. As demodulated points smear and spread out, then the demodulated signal incur higher rates of bit error due to wrong demodulator decisions.

5.3 Reference Amplifier Frontend

The reference PA model for the frontend used in this study is a TWTA. The TWTA has been widely used in mmWave applications for many years having been invented in 1933.

Although arguably exhibiting relatively high levels of distortion, it does represent a valid starting point, offering a public-domain model taken from (2).

That extracted AM-AM and AM-PM curves of the TWTA are shown in Fig. 5-5.

The reference TWTA includes a distortion contribution from AM-PM, unlike the hard limiter. AM-AM is also non-zero at drive levels below 0dB (relative to the saturated level). Therefore, peak envelope levels no longer have to reach 0dB to create non-linear distortion.

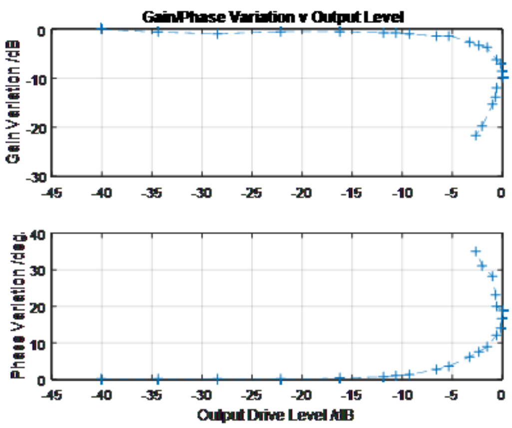

Fig. 5-5: AM-AM and AM-PM characteristics of the TWTA in (2)

Also of note is that the model is:

- non-dispersive
    - it is assumed to have the same response regardless of operating radio frequency or envelope frequency
- noise-free
    - the channel model does not add any noise to the signal
- memory-free
    - the transfer characteristic is a function only of the present input amplitude
    - it is not a function of previous conditions

These limitations are important because the model represents a best case. Adding dispersion, noise and memory effects will only degrade performance.

For this linearization study, the distortion model may be complemented with a statement of energy efficacy. The class A characteristic is assumed. The two relevant features of a class A radio are:

- constant energy consumption, regardless of drive level
- maximum theoretical efficiency of 50%, coinciding with maximum output level

The constant power consumption means that the calculation of efficiency and power dissipation are trivial.

5.4 Black's Feedforward

The reference TWTA will now be linearized using the Feedforward technique. The original feed-forward patent was granted to H.S. Black (4).

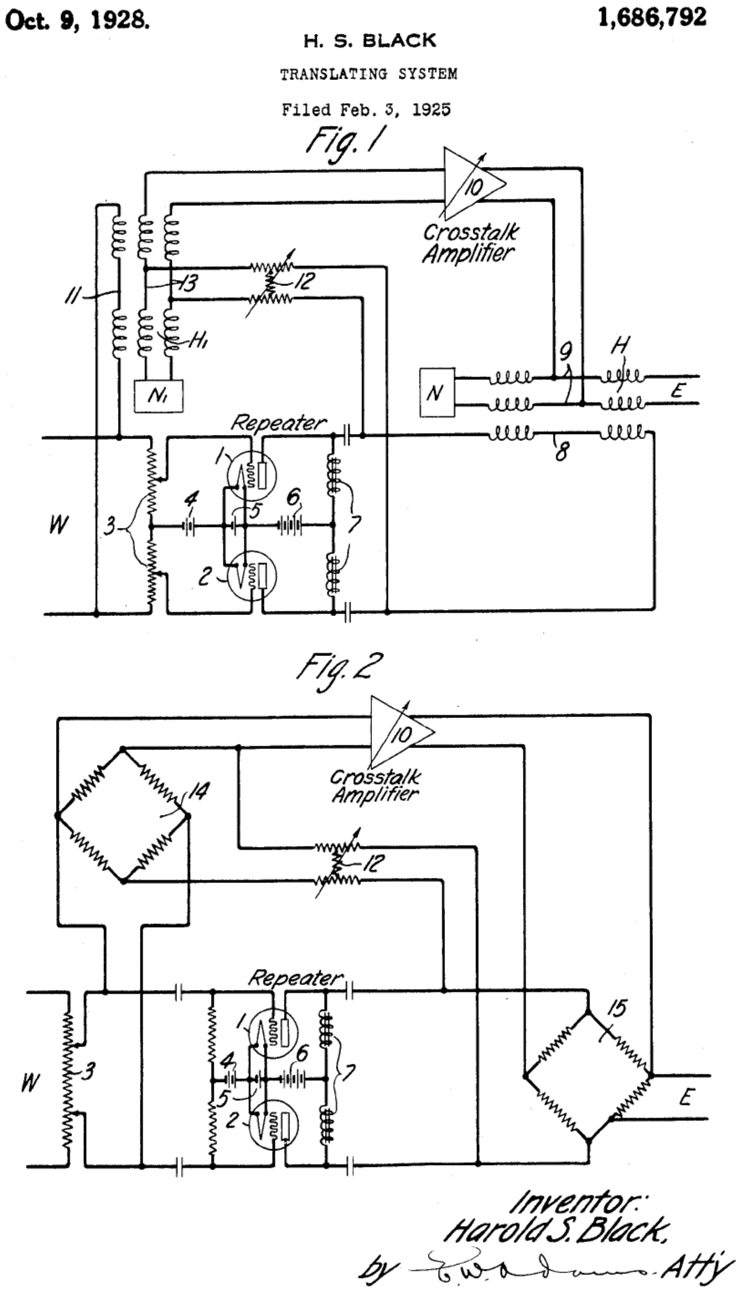

Fig. 5-6: Black's Feedforward patent front page

The feedforward scheme is made of two loops. A first loop for bulk, coarse, amplification and extracting a distortion signal. In practice that distortion also includes noise and memory effects. Then, a second loop amplifies the distortion signal so that it can be used to directly cancel the error from the first loop.

The basic feedforward is typically effective at reducing out-of-band distortion (which is typically of a very low magnitude) and memory effects. In some applications, it may also have a noise benefit, removing noise added by the amplifier but adding (ideally less) noise from other sources.

As a post-correction type of technique, it typically incurs power losses at its output. As this example will show, that does not mean an overall reduction in performance.

To illustrate the basic feed-forward performance a harmonic balance simulation is performed as per Fig. 5-7.

Note that the reference TWTA in this case is split into two equal, half-sized TWTAs. All other components shown are passive and assumed linear.

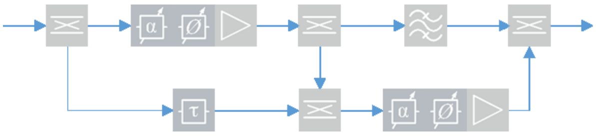

Fig. 5-7: An example feedforward schematic for the linearization of the reference TWTA

Other circuit components of note in this theoretical exercise are:

- 1dB loss assumed for delay line of the second loop Another 3dB change due to the final summation coupler

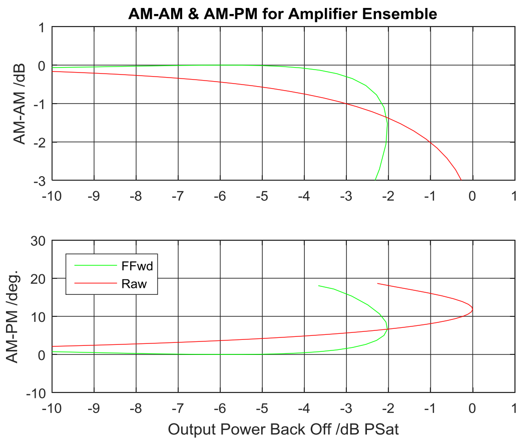

Fig. 5-8: Comparison of the feedforward and reference TWTA characteristics

An inspection of the AM-AM and AM-PM curves in Fig. 5-8 suggests:

- a significant reduction in saturated output level (circa 2dB) has been incurred, primarily because of the loss of the second loop's delay line and coupler.
- despite this, linearity and linear output level are improved
  - the AM-xM characteristics cross over at that 2dB output level back-off scenario

Two similarly-sized and equally non-linear amplifier components have been combined using only passive components and with significant losses. However, the resultant linearity has improved, and is better than any of the components on its own.

There are many more degrees of freedom to feed-forward design. This is especially true regarding the relative size of the two amplifiers and the combining coupler. This example represents merely one point in the solution continuum.

5.5 Black's Feedback

The reference TWTA will now be linearized using negative feedback. The negative feedback amplifier patent was granted to H.S. Black in (5)

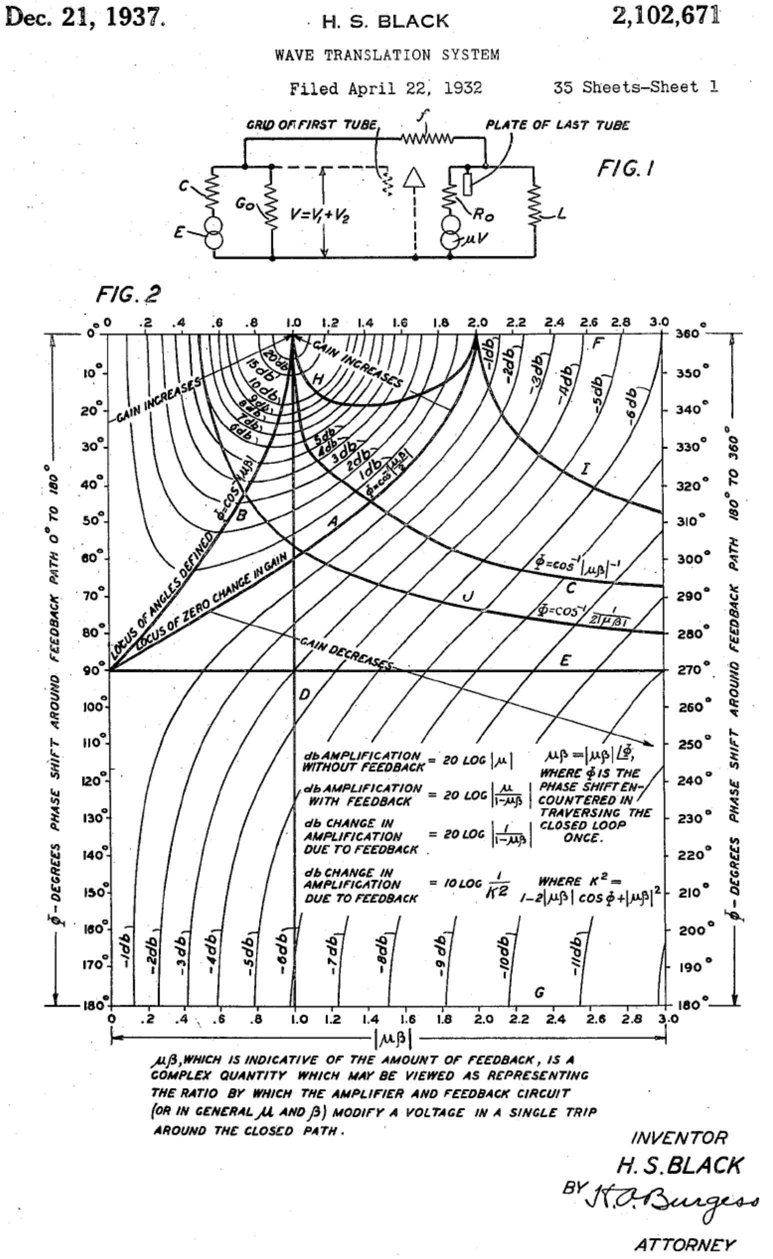

Fig. 5-9: Front page from Black's feedback patent

Output of the forward system comprises both wanted signal and distortion components. Some of the distortions are predictable, some not (e.g. noise). A sample of that output signal is fed back to the input. It is then subtracted from a later, incident, input signal.

That new input, comprising the new input signal along with a sample of the fed-back earlier signal, some distortion and some noise.

Critically, the forward amplifying path creates distortion from the new signal. Part of that new distortion is cancelled by the inverted distortion that was fed back. The result of one pass around the feedback loop is:

- A decrease in distortion, but not complete cancellation
- More noise:
  - The noise fed back from the output to the input is random and cannot be predicted.
  - That noise is amplified and further added to by another pass through the amplifier.
- Decrease in overall gain
  - Although the amplifier gain itself did not change, the feedback signal causes a reduction in the signal level at the amplifier input.

This transient process now repeats, infinitely but diminishing. Contributions from previous inputs asymptote, as they pass around the loop successively experiencing loop attenuation. The resultant feedback system gain, distortion and noise tend towards finite values.

The greater the delay around the feedback loop, the greater the difference between the sampled distortion and actual distortion. The result is degraded correction, especially with increasing bandwidth.

Although applied as direct RF feedback to an amplifier in this example, other forms of feedback are possible and can linearize larger parts of a frontend, including frequency converting sections. Other forms of feedback include Cartesian (6) and Polar (7).

Feedback techniques are especially effective at correcting in-band, or narrow-band, distortion and improving industriability (reducing variation). These benefits are derived at the expense of decreased gain, stability and increased noise.

For the purpose of this study, a direct RF feedback loop shall be installed around the reference TWTA, see Fig. 5-10.

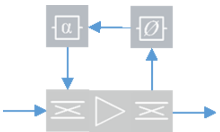

Fig. 5-10: An example direct RF feedback schematic for linearization of the reference TWTA

In this specific case, the direct feedback signal is sampled and reinserted using directional couplers.

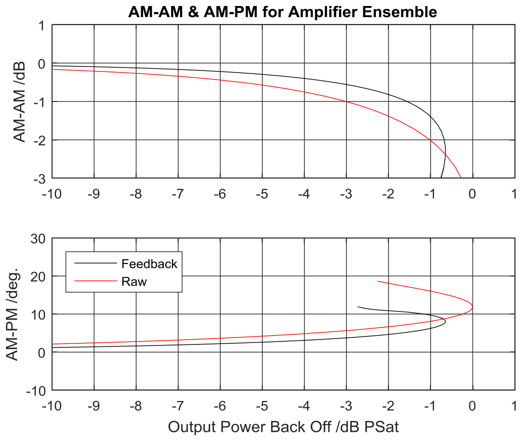

Fig. 5-11: Comparison of the feedback and the reference TWTA characteristic

The output sampling coupler causes a reduction in the saturated output level available, manifest in the maximum x-values achieved in Fig. 5-11. However, distortion (i.e. deviation from y=0) is reduced over a wide dynamic range.

The amount of feedback used is a design variable. A greater amount of feedback results in greater linearity at the expense of noise, gain and stability.

5.6 McMillan's Hybrid

The feedback and feedforward amplifiers are now integrated into a hybrid system.

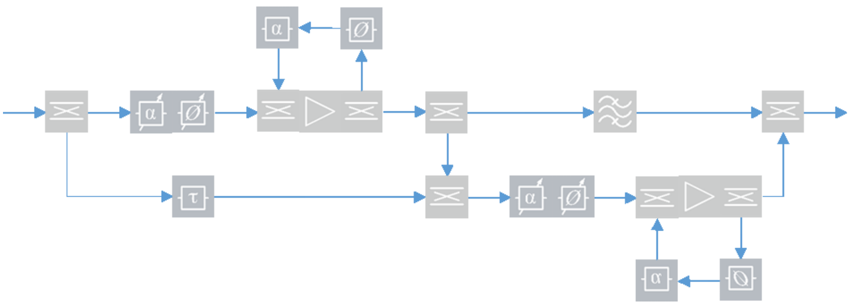

Fig. 5-12: Implementation of hybrid feedback and feedforward linearization

Potentially complementary behaviors of feedback and feedforward were leveraged in (1). Quoting directly from the patent:

"The first amplifier may be regarded as the main signal amplifier, and the second as an auxiliary or secondary amplifier the wave input and wave output of which consist largely of distortion products and other spurious effects derived from the output of the main amplifier. The spurious effects translated through the secondary amplifier are combined in approximately cancelling relation with those appearing in the output of the main amplifier thus leaving the amplified signal that is delivered to the load relatively free of such effects. The secondary amplifier itself adds but little to such residue of spurious effects as may appear in the output of the system for it is only lightly loaded and such effects as it does introduce are substantially reduced by feedback"

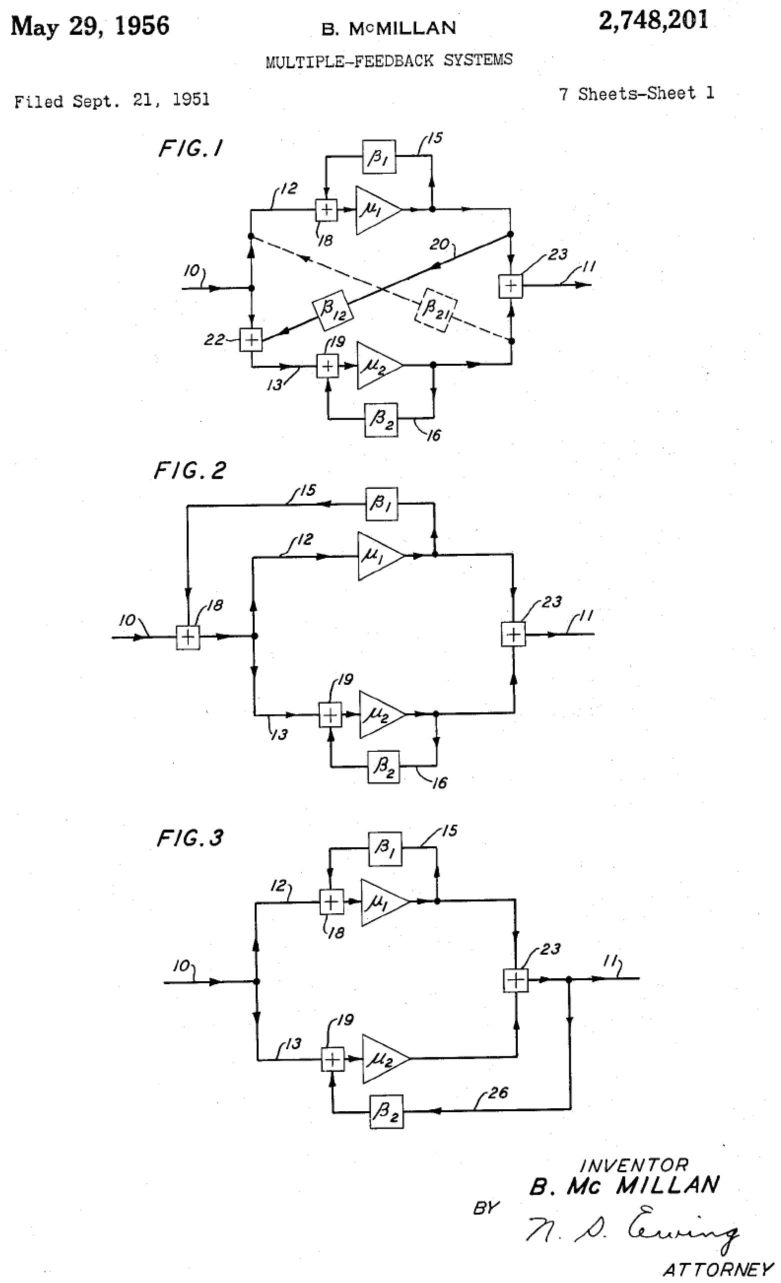

Fig. 5-13: Front page from McMillan's hybrid feedforward-feedback patent

In the simulation environment, the two reference TWTA of the earlier feedforward experiment are replaced by two feedback TWTA. The gain and phase of the feedforward loops are adjusted to optimize the changes in transfer characteristics of those TWTA.

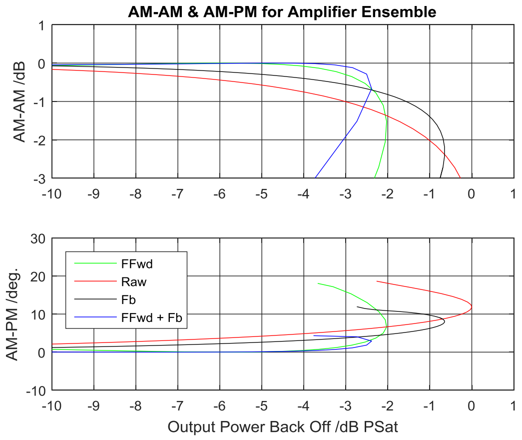

Fig. 5-14: Ensemble of feedback, feedforward, reference and hybrid TWTA characteristics

This hybrid combination of feedback and feedforward yields a hybrid of performance improvements (Fig. 5-14). Despite even greater losses from the combined schemes, the resultant linearity is again better than either feedforward or feedback on its own.

AM-AM and AM-PM (i.e. deviations from y=0) levels are lower, and kept lower, up to a higher absolute output level (x value). This, in spite of a further reduction in the maximum possible, or saturated, output level.

5.7 Performance with Modulated Signals

Each of the linearized variants are now excited with a modulated signal, 256-APSK from the DVB-S2X standard, instead of CW stimulus as in the previous sections.

Firstly, the reference TWTA case is power swept. The ACLR is plotted with increasing drive in Fig. 5-15.

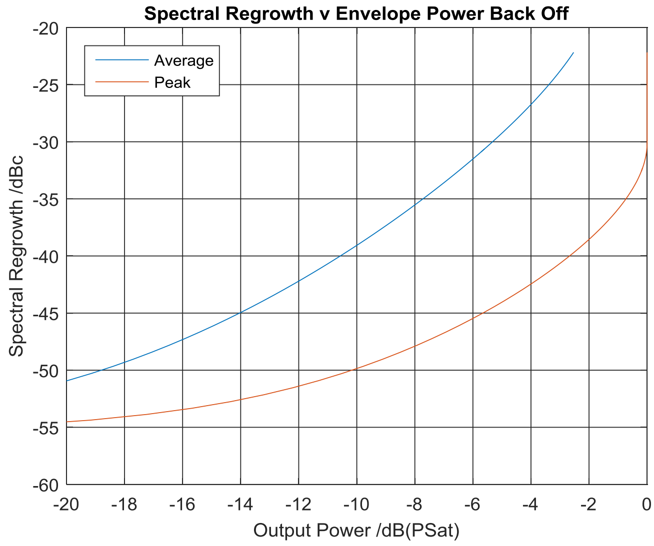

Fig. 5-15: Spectral regrowth versus output level for the reference TWTA, without linearization, showing average and peak envelope amplitudes

At the -35dBc target, the typical output level is 7.7dB backed off from the saturated output level. That corresponds to an average power of 17% of the saturated. For a 1kW TWTA therefore, the average output power would have to be limited to 170W.

It is not until the ACLR reaches -30dBc that the peak envelope output level has saturated and the TWTA is fully utilized. Therefore, operating at -35dBc without linearization, the TWTA is not using all of its resource.

Now that regulatory demands are met, attention turns to the intended link quality. The -35dBc TWTA output signal may be demodulated with a perfect receiver

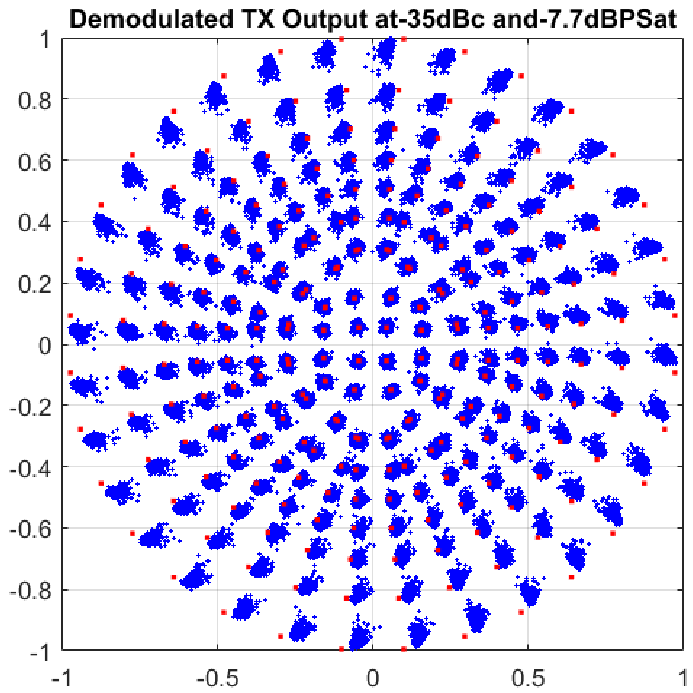

Fig. 5-16: Demodulated 256-APSK for the reference TWTA operating at -35dBc spectral regrowth

Significant dispersion of the symbols can already be subjectively observed in Fig. 5-16, especially smearing between inner constellation points. In practice, additional degradation of the signal in the link would result from repeater and receiver impairments.

Demodulation of the signal at other linearity levels, in 5dBc spectral regrowth steps, demonstrates the trend in Fig. 5-17.

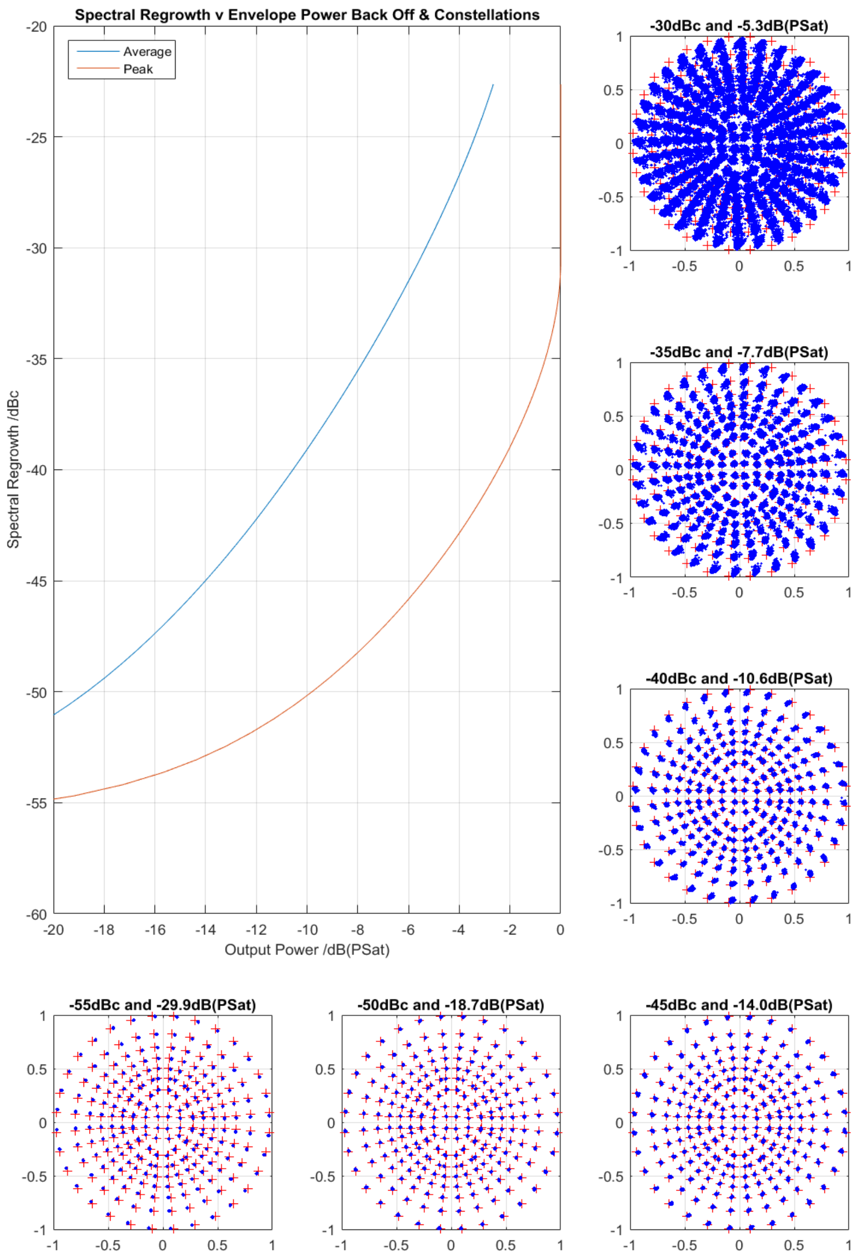

Fig. 5-17: Swept drive level showing average and peak envelope levels and demodulated constellations at 5dB increments in spectral regrowth for the reference TWTA

A more comprehensive study, including the effects of the repeater and receiver, might suggest that an ACLR level better than -40dBc or even -45dBc needs to be used. That would correspond to output of 90W or just 40W for the 1kW TWTA.

In which case, the situation for the TWTA frontend is as follows:

- Forced to operate at this more stringent linearity level, the peak envelope level is only utilizing 30-60% of the TWTA resource.
- Worse still, the system requires a 2kW power supply for the 1kW TWTA.

For the **feedback variant**, the situation is improved as in Fig. 5-18.

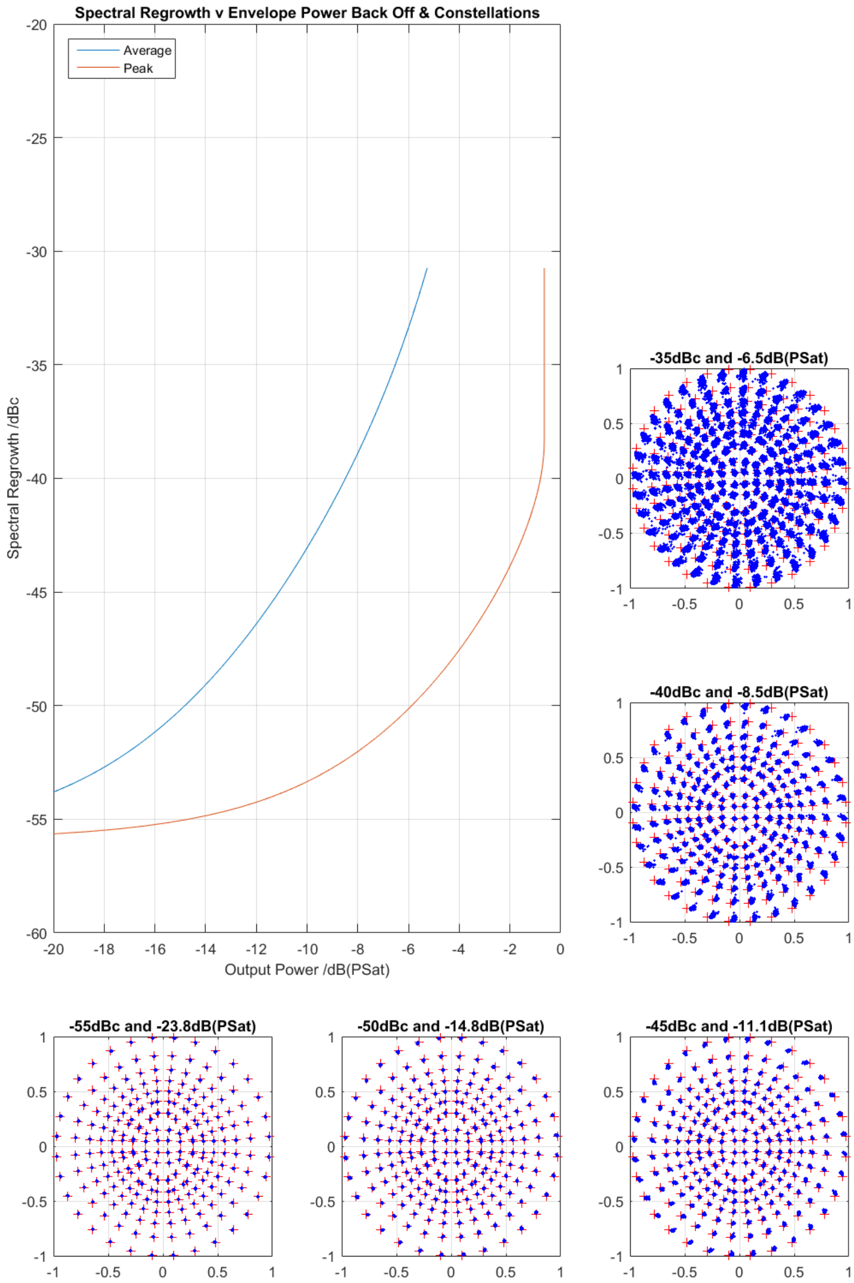

Fig. 5-18: Swept drive level showing average and peak envelope levels and demodulated constellations at 5dB increments in spectral regrowth for the feedback TWTA

Linear output of the transmitter is such that for a -40dBC or 45dBc ACLR target, the corresponding output levels increase up to the range of 141W and 76W, respectively.

It is important to note that this improvement in utilization is at the expense of saturated output power, which has now been reduced to by 14% from 1kW to 861W. But despite this drop in Psat, the peak envelope power - the utilization - has actually bettered.

Ahead of evaluating the other linearized cases, it is worth summarizing the following has been achieved:

- Higher average output power
- Higher peak output power level
- Reduced Psat

Linearization has demonstrated that there is no unilateral proportionality between saturated output power level and useable or linear output level.

Perhaps counter-intuitively, adding loss to the output does not necessarily result in lower system output.

The **feedforward**-linearized solution offers a slightly different set of improvements compared to feedback. In this specific embodiment, the 1kW single TWTA is replaced by two 500W subsystems.

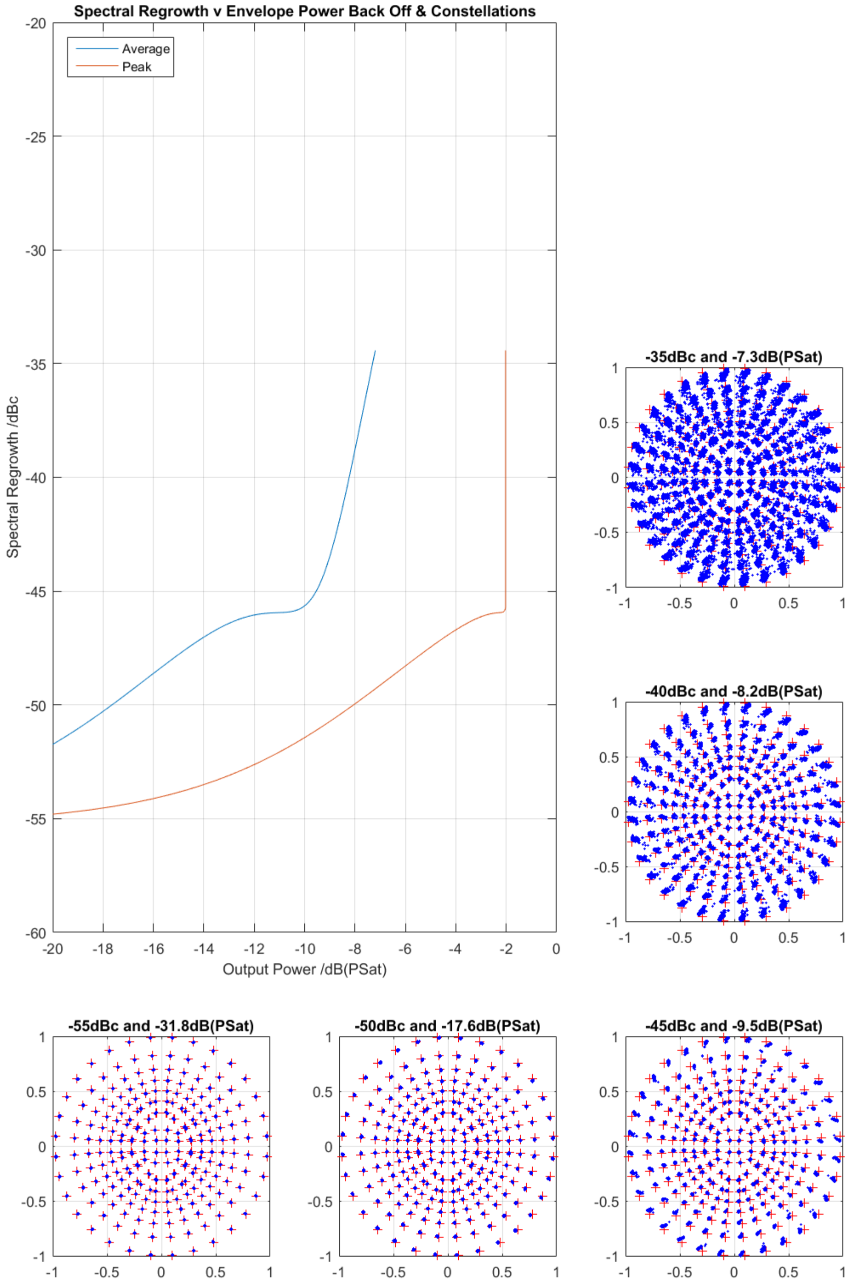

Fig. 5-19: Swept drive level showing average and peak envelope levels and demodulated constellations at 5dB increments in spectral regrowth for the feedforward TWTA

Again, the output power levels associated with -45dBc and -40dBc spectral regrowth are greatly increased over the reference case. They are shown in Fig. 5-19 to be 110W and 148W, respectively.

The saturated output power has decreased from 1kW to 628W.

The application of feedforward-type linearization has simultaneously:

- decreased Psat requirement by 2dB

- increased useable output level by at least the same amount

Finally, the **McMillan Hybrid** version. It exhibits, in Fig. 5-20, the combined output losses of the feedback and feedforward, and the saturated output power is reduced to 578W from 1kW. But now, a figure of -50dBc spectral regrowth can be supported at 107W

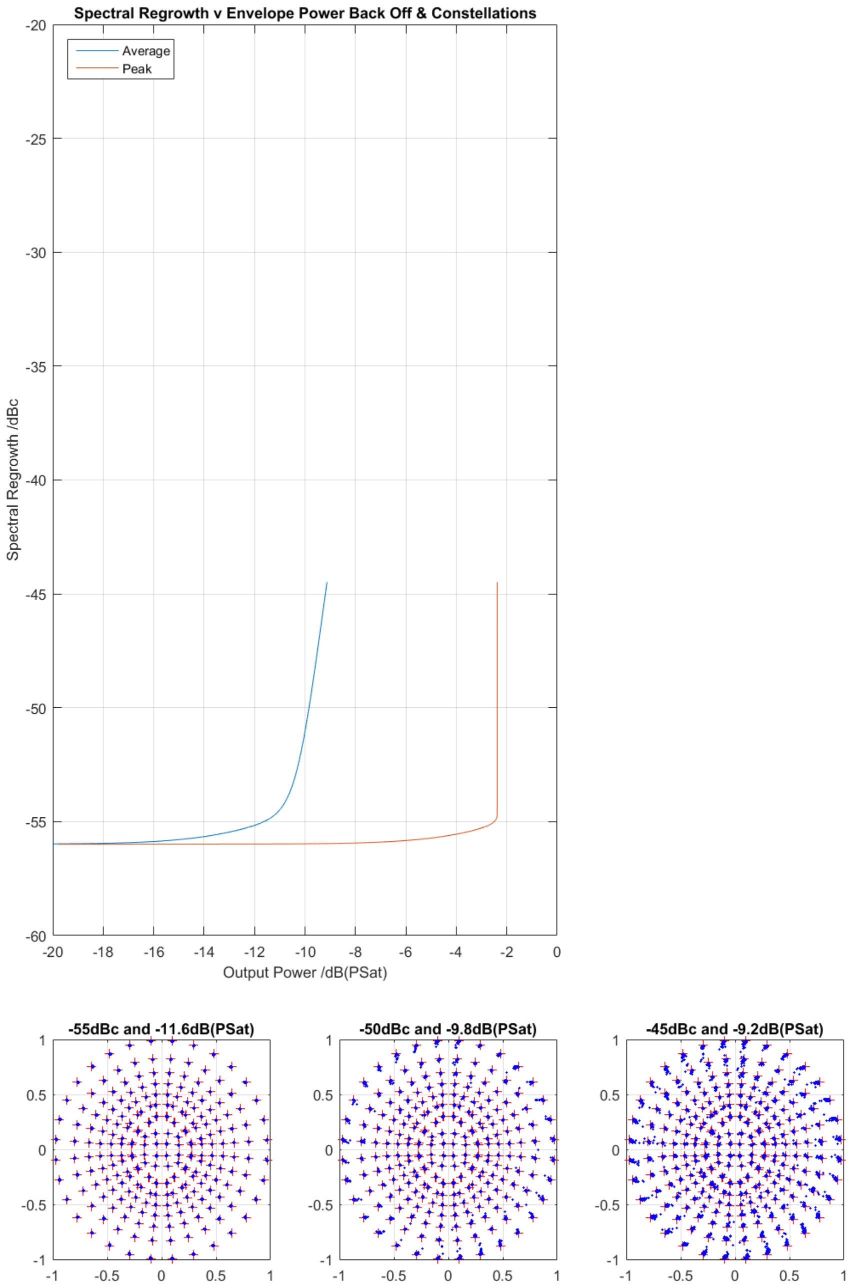

Fig. 5-20: Swept drive level showing average and peak envelope levels and demodulated constellations at 5dB increments in spectral regrowth for the hybrid feedback/feedforward TWTA

A performance summary of the variants presented is in Table 5-1.

Linearized TWTA Variant 256-APSK Performance					
Parameter	**Reference**	**Feedback**	**Feedforward**	**Hybrid**	**Hard Limiter**
Saturated Power (W) (using 1kW TWTA total)	1000	861	628	578	1000
Useful Output Power (W) at:					
-40dBc	90	141	148	141	278
-45dBc	40	76	110	124	237
-50dBc	13	31	18	107	203

Table 5-1: Summary of performance of the reference, linearized and hard limiter TWTA under 256-APSK excitation

The 1kW TWTA, operating class A, with a theoretical maximum efficiency of 50% needs a constant 2000W power to operate.

Using this approximation, it is now possible to compare and contrast the impacts of alternative systems with a given output power level and linearity constraint as exhibited by the reference TWTA. These are shown in Table 5-2.

Alternative TWTA Implementations for 256-APSK					
Parameter	**Reference**	**Feedback**	**Feedforward**	**Hybrid**	**Hard Limiter**
Scaled for -40dBc and 90W					
TWTA Size Required	1000	638	608	638	323
Power Wasted	1910	1186	1126	1186	556
Scaled for -45dBc and 40W					
TWTA Size Required	1000	526	364	323	169
Power Wasted	1960	1013	687	605	298
Scaled for -50dBc and 13W					
TWTA Size Required	1000	419	722	121	64
Power Wasted	1987	826	1431	230	115

Table 5-2: Optimized and linearized example alternatives to the meet performance of the reference TWTA

To reiterate the effect of the Linearized radio chain on the signal, consider the specific -45dBc/40W case. In Fig. 5-21, the feedforward output is illustrated alongside the clean modulator output.

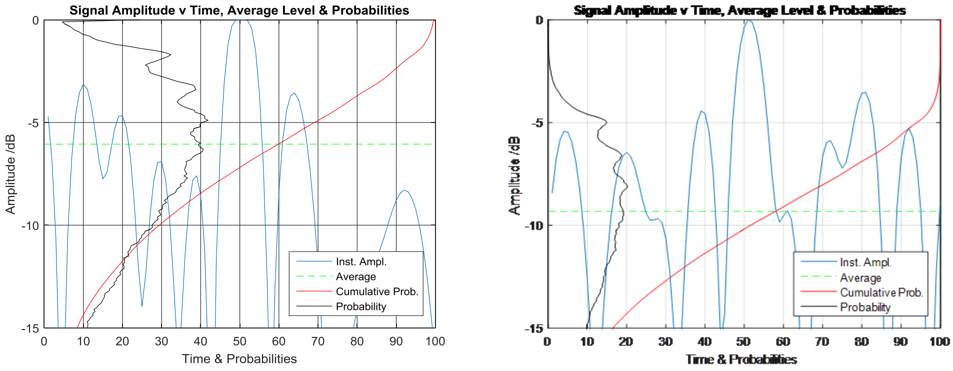

Fig. 5-21: Amplitude and key statistics for the -45dBc/40W signal using the feedforward embodiment (left), alongside the clean modulator output (right)

- The probability characteristic is shunted upwards in relative amplitude, in the feedforward case. In this feedforward, the instantaneous envelope amplitude is at levels lower than 5dB for 70% of the time, compared with 95% for the clean modulator output.
- As a result, PAPR has been reduced from more than 9dB (at the modulator output) to approximately 6dB (at the TWTA output)
- Envelope amplitudes approaching the 0dB saturated level are heavily compressed or clipped in the feedforward case, compared with the cleanly modulated case.
  - This compression manifests itself as an increase, a spike, in the envelope probability density function
  - This compression forces an increase in the rate-of-change of envelope amplitude, speeding up the signal, causing spectral regrowth.

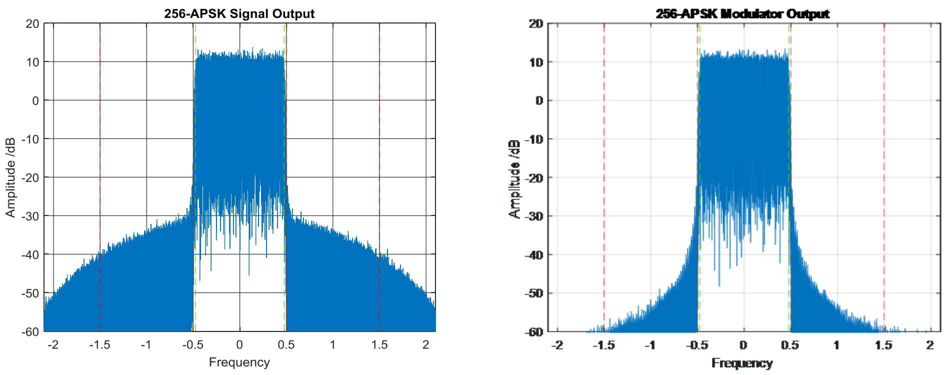

Fig. 5-22: Spectrum output of the feedforward TWTA operating at -45dBc (left) alongside the modulator output (right)

The TWTA output spectrum is plotted at -45dBc/40W for the feedforward, alongside the modulator output in Fig. 5-22. Clear increases in the amplitude of out-of-band frequencies (distortion affecting other users in the system) can clearly be seen, whilst the in-band distortion level increase cannot easily be seen in the spectrum plot. In-band distortions (affecting the user) are more discernible in the constellation plots, for example.

5.8 Conclusions

The following generalized observations are noted:

- A classification system for linearization techniques has been presented:
  - Understanding the general advantages of each of the classes in relation to the particular application can help identify which class, or classes, offer the best cost-performance compromise.
- Linearization is relevant for most transmit, repeat and receive equipment:
  - Each presents its own set of limitations, challenges and opportunities for disruption.
  - Each position in the communication link (transmit, repeat, receive) offers different access to different resources
- Linearization can liberate performance and add value to the frontend:
  - Unfortunately, there is no silver bullet solution because of the sheer diversity in frontend applications and realizations.
  - For example, Frontend solutions that are appropriate for Microwave Backhaul Receivers, LTE Infrastructure Repeaters, Satellite Communication BUCs, Optical Fiber Modulators or indeed, precision Test & Measurement are not likely to be the same.
  - Perfect Linearization (i.e. hard limiter with clipping avoidance) is not optimal in many cases. PAPR should be traded for Distortion.

Relating directly to the cases presented, the following conclusions are drawn, and may also be of relevance to other cases:

- In the simplified TWTA/256-APSK scenario, four implementation variants of the same TWTA power were shown to have quite different performance:
  - Only passive components are added to differentiate the solutions.
  - In the case of Black's feedforward and its derivatives, the signal is decomposed to multiple amplifiers. The resultant characteristic is significantly more linear than either of the individual amplifiers.
- Significant energy consumption impacts are noted:
  - The scenarios presented generate 27% to 90% less heat for a given output level and signal fidelity when Linearization is used.
- Significant equipment cost savings could also be made:
  - The big-ticket bill of materials for a 40W/-45dBc solution built using a reference 1kW TWTA compared to the feedforward variant example solution might look something like Table 5-3

-45dBc/40W 256-APSK Bill of Materials: Reference versus Feedforward		
Material	**Reference**	**Feedforward**
TWTA	1 x 1000W	2 x 190W
Power Supply Size	2000W	780W
Cooling Capacity	1960W	740W
Radio Components	No additional	Passive, including couplers, filters, etc.
Management & Control	No additional	Linearization Adaptation

Table 5-3: Example key component bill of materials for a 40W/-45dBc 256-APSK TWTA solution

- An almost perfectly linearized system is probably not economical in this case. There is significant value to be gained in allowing a controlled degradation of PAPR.

6 Multiple Path Tx Frontends

Frontends used in high performance transmitters may take advantage of multiple channels to improve linearity and energy efficiency. Compared to the building blocks used, the overall transmitter performance can be significantly improved.

A characteristic of these multi-path schemes is that the desired signal is synthesized at the output, using predictive post-correction, from efficiently generated components. Residual or created distortions from these schemes may be further reduced using supplementary linearization schemes.

This multi-path architecture typically offers higher energy efficiency possibilities than would ordinarily be the case with the conventional single-path quasi-linear alternative.

In (8), the range of multi-path transmitters is condensed into three categories:

- Doherty PA (9)
  - Two or more RF PA source currents into a Doherty combiner.
  - The combiner/load transforms these currents into powers which are, when considered independently, grossly non-linear.
  - The sum of these two (or more) grossly non-linear power contributions is, in fact, linear.

- Outphasing/Chireix (10)
  - Two (or more) sources are operated at equal and high output levels.
  - The phase difference between their contributions is varied, according to the desired output level (in-phase contributions result in constructive combining, out-of-phase resulting in an output null).
  - Chireix differs only by its output design and might be preferred at higher frequencies. A treatment of both Outphasing and Chireix techniques are given in (11).

- Envelope Tracking
  - A quasi-linear amplifier has its auxiliary power supply modulated by an envelope source.
  - The resultant linearity is a complicated combination of the RF PA intrinsic linearity and its response to a modulated power supply.

Other multi-path studies in the literature blur the orthogonality between these categories, demonstrating hybrid schemes, for example (12), (13) and (14).

Expanding on the classification from (8), to include these and other examples of other pure and hybrid schemes yields Fig. 6-1.

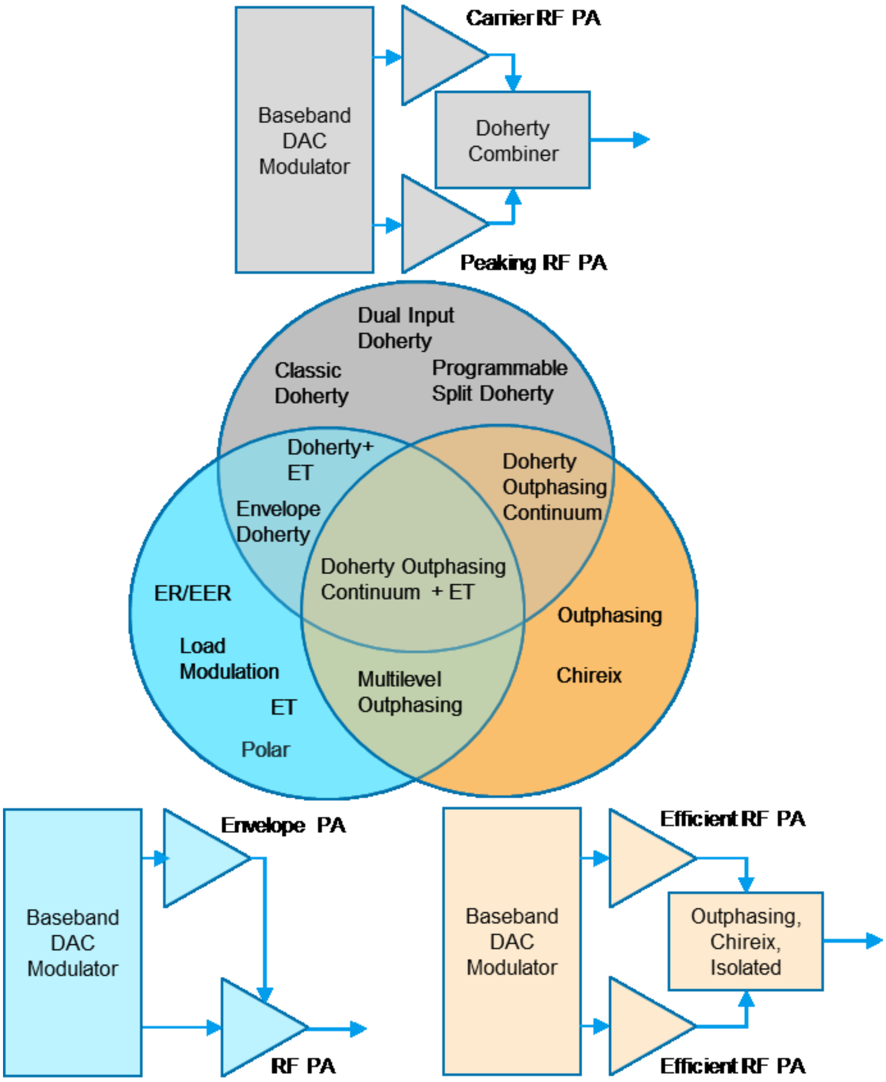

Fig. 6-1 - Extension of example multiple-input TxFE architectures, developed from (8)

Multi-path architectures open up a range of implementation options for simultaneously realizing better linearity and higher efficiency frontends.

7 References

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8 Appendices

8.1 RF Linearity Tests on a Frontend

Historically, frontends were designed and developed using two-tone CW measurement, with metrics such as IM3 and TOI (IP3). The migration of communication systems to digital modulation, means that linearity testing is frequently performed using more sophisticated signal generators and analyzers.

Often, a particular system will define specific test signals using known digital data sequences and linearity metrics will be derived from those. In addition to the simple spectral regrowth, which can be analyzed with a spectrum analyzer in amplitude-detecting frequency sweep mode, the test signals are often demodulated and decoded enabling bit-wise digital analysis.

The designer usually has access to this intermediate demodulated IQ data. Analysis of this data can be a powerful diagnostic development tool for frontend engineering.

Metrics and metrological techniques for linearity evaluation include:

- Harmonics
  - Harmonic frequencies of the intended signal are well defined and easily calculated. Measurement of harmonic levels is straightforward.
  - A spectrum analyzer scanning several narrow, specific, frequency spans is most often used to measure harmonic levels, either with CW or modulated stimulus.

- Spurious
  - Frontends may be built using a variety of architectures, often involving one or more frequency conversions.
  - Intentional oscillators, e.g. unstable amplifiers, used to drive mixers or modulators to create these frequency conversions, may generate a significant number of harmonics.
  - The mixers and modulators, driven by oscillators, will multiply the range of frequencies at which these harmonics appear. The harmonics of the oscillator (n x LO), multiplied by harmonics of the signal (n x IF or n x RF) must be checked and managed.
  - A spectrum analyzer in a broad swept frequency mode is often used to measure spurious levels and their associated frequencies.

- IMRR (Image response rejection ratio) and LO Leakage
  - In a frequency conversion stage, there will be additional representations of the wanted signal, appearing at the converter's output. The most significant of these is the image or unintended frequency.
  - The image appears regardless of whether frequency is shifted up- or down-, and whether high- or low- sided conversion is performed.

- The image may be superimposed, in part or in whole, over the intended band. In which case, there will often be further signal quality impacts (e.g. EVM).
- Normally it is not desirable for the LO (local oscillator) to appear at the mixer or the frontend output. The LO leakage will normally be measured dynamically as its level is optimized.
- A spectrum analyzer in swept frequency mode is often used to measure frequency conversion performance.

- ACxR and EVM
  - ACxR (Adjacent channel power /leakage ratio), or spectral regrowth, represents the amount of undesired signal power and distortion, appearing in frequency bands or channels, neighboring the intended frequency band or channel. Usually such signals are strongest in proximity to the carrier and diminish with increased frequency offset.
  - EVM (error vector magnitude) represents the IQ error power present on the symbols of the modulated signal. Degradation of EVM may be caused by more than just distortion. Even without symbol-by-symbol demodulation, a simple envelope EVM measurement may be made.
  - Measurements, regarding the integrity of the modulated signal, are often carried out using a Signal Analyzer to capture IQ data. This captured output IQ data may be aligned and compared directly with the input IQ data. ACxR may be calculated from the captured output IQ data.

- Psat and Output PAPR
  - As presented in this document, in order to achieve the best possible performance, it is important to ensure that (i) an envelope's peak signal level is able stimulate the frontend's Psat and, (ii) that it is done with the minimum output PAPR.
  - The Output PAPR may be calculated directly from the captured, demodulated IQ data.
  - The Psat figure is calculated as the sum of the Output PAPR, and the RMS power.
  - Psat measurement should be performed using a representative signal, rather than using a CW power/frequency sweep, to avoid inaccuracies driven by memory effects.
  - Measurement of Psat and PAPR may be performed, for example, using IQ waveforms captured on an Oscilloscope coupled with a Power Sensor.

8.2 Exemplary Linearity Test & Measurement Equipment

As discussed in 8.1, different test equipment formats are able to perform different tasks. Those task may often be performed using two different pieces of equipment, rather than one dedicated unit.

Table 8-1 presents a summary of different equipment formats and functions.

Instrument Family	Example	Description
Signal Generator		
	R&S®SMW200A	A proprietary vector signal generator with dual RF and dual Envelope outputs; enabling the development of higher performance radio frontends.
	R&S®SMBV100A	RF and Microwave Signal Generator; a single RF output source capable of modulating a stored, or real-time, waveform.
Signal and Spectrum Analyzer		
	R&S®FSW	Signal and Spectrum Analyzer; historically used to measure amplitude versus frequency. Modern analyzers offer increasingly sophisticated functionality and signal analysis.
	R&S®FS-Z	Harmonic Mixer; used to convert an RF signal down in frequency, extending the upper frequency of a spectrum or signal analyzer.
Oscilloscope		
	R&S®RTO	Digital Oscilloscope; input channels are often used to sample IQ waveforms.
Power Sensor		
	R&S®NRP	Three-path Diode Power Sensor; often used to establish the average power of a modulated waveform.
Baseband Generator		
	R&S®AFQ	Signal and I/Q Modulation Generator; used to synthesize IQ data in either digital or analog form.

Table 8-1: Example Test & Measurement equipment families and functional descriptions.

- Application dependent operating frequency range, software and hardware options, should be specified separately.
- Please ask your local representative for a suitable configuration, tailored to your requirements.

Glossary

AM-AM, AM-PM: Amplitude modulation to amplitude (phase) modulation conversion. The change in transfer amplitude (phase) of a signal that occurs when exposed to non-linear behavior.

ANT: Antenna. Used to transition transmitted signals from a conducted medium into free space and received signals vice versa.

BUC: Block up-converter. Terminology used predominantly in the satellite communications industry to describe a transmitting radio front-end which performs both a frequency up-conversion and amplification within a single functional unit.

DfX: Design for X. Encompasses a broad range of matters relating to assembly, test, adaptation, maintenance and repair of front-end hardware in the manufacturing and deployed environment.

LUT: Look up table. A method for creating an output value from one or more input values, without using an underlying formula.

mmWave: Millimeter-wave. Strictly speaking, the frequency range from 30 GHz to 300 GHz. Increasingly used to describe a more expansive frequency range, starting at 6 GHz. Used interchangeably with Microwave.

MUX: Multiplexer. In a front-end, it is used to coordinate transmission and reception.

OSI: Open systems interconnection model. A conceptual model that characterizes and standardizes the communication functions of a telecommunication or computing system without regard to their underlying internal structure and technology.

PAPR: Peak to average power ratio. For a time varying waveform, the ratio of peak power to average power.

PHY: Physical layer. The foundation of the seven layer OSI model, comprising the hardware required to create a communication link.

RRC: Root raised cosine filter. Used in communication systems to minimize inter-symbol interference. One RRC is normally used in both transmit and receive front-ends, giving a net "raised-cosine" response.

TWTA: Traveling wave tube amplifier. An amplifying device, usually used for very high frequencies and powers, built without the use of semiconductors.

Utilization: The ratio of the subsystem (e.g. amplifier) resource used, compared to its Psat.

5G: The Fifth Generation of mobile communication networks, following 4G.

Rohde & Schwarz

The Rohde & Schwarz electronics group offers innovative solutions in the following business fields: test and measurement, broadcast and media, secure communications, cybersecurity, radiomonitoring and radiolocation. Founded more than 80 years ago, this independent company has an extensive sales and service network and is present in more than 70 countries.

The electronics group is among the world market leaders in its established business fields. The company is headquartered in Munich, Germany. It also has regional headquarters in Singapore and Columbia, Maryland, USA, to manage its operations in these regions.

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Sustainable product design

- Environmental compatibility and eco-footprint
- Energy efficiency and low emissions
- Longevity and optimized total cost of ownership

Certified Quality Management
ISO 9001

Certified Environmental Management
ISO 14001

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