TECHNIQUES FOR PREDICTING NONLINEAR DISTORTION EFFECTS IN KA-BAND UPLINK GATEWAYS

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Abstract

In order to achieve optimum service availability, Ka-band gateways must deliver very large effective isotropic radiated power (EIRP) per signal. For most signal types, and for all multicarrier uplinks, uplink power is limited by distortion in the final amplifier. Such distortion may be defined by a number of metrics, including adjacent-channel power ratio (ACPR), noise power ratio (NPR), and two-tone intermodulation distortion (IMD). Accurate methods for predicting the effects of distortion are critical for sizing the gateway antenna/amplifier hardware and for planning service quality.

This paper reviews the method of distortion simulation using complex envelope transformation by the AM-AM and AM-PM transfer functions. Provided that the quasi-static approximation holds, as is normally the case for traveling wave tube (TWT) amplifiers, these transfer functions fully characterize the device, and thus the simulation technique provides accurate predictions of all distortion properties, including two-tone intermodulation, noise power ratio, and single- or multicarrier modulated signal distortion. By combining the transfer functions, the effects of cascaded stages (such as upconverter-amplifier or linearizer-amplifier combinations) can be computed.

The transfer functions can be measured using swept-power vector network analysis or with the spectral-null pulse technique, which also allows upconverters and amplifiers with limited continuous power to be characterized. The functions may also be generated by circuit-level simulation, or more practically, by a parameterized behavioral model. In this paper, we describe a model that allows computation of the sensitivity of distortion metrics (such as NPR and two-tone IMD) to variations in device parameters (such as peak AM-PM and gain compression knee sharpness).

The paper also presents examples of how the relationships between various distortion metrics depend on the shapes of the AM-AM and AM-PM transfer functions. Theoretical limits on linearizer performance are derived, and practical methods for testing the validity of the quasi-static assumption are described.

1. Introduction

Because rain loss is dominant and Ka-band antennas and high-power amplifiers (HPAs) are expensive, most Ka-band gateway uplink link budgets demand better precision in approaching the limits of HPA performance than can be achieved using traditional rules of thumb or closed-form approximations. On the other hand, physics-based or circuit-level models for solid-state power amplifiers (SSPAs) and linearized traveling wave tube amplifiers (LTWTAs) are not often available or practical for earth station system design. A "black box" behavioral model is desirable, one which can accept characterization data readily measurable, and which supports simulation of multiple modulated signals.

With respect to signals of a given bandwidth and power range, the nonlinear distortion in any device can be broadly placed in one of three categories:

(a) *Static distortion* is characterized by an instantaneous input-output voltage transfer curve. Example: an op-amp voltage clipper operating at audio frequencies. There can be compression or expansion of a carrier's amplitude, but there can be no carrier phase shift.

(b) *Dynamic distortion* is characterized by distortion behavior that varies with time on a time scale and magnitude that is significant with respect to the signal bandwidth and its power. Narrowband examples include feedback linearization, thermal time constants, and bias network response that have time response on the same order as the bandwidth of the signal. Full characterization is exceedingly complex.

(c) *Quasi-static distortion* is defined by a gain and phase shift of a modulated carrier that depends only on the instantaneous input level and does not depend on time. The quasi-static assumption is a good approximation for devices that have wider bandwidth than the signal of interest, and that do not have an inherent or inadvertent memory effect. TWTs best exemplify quasi-static distortion, even in saturation, but most SSPAs and mixers found in gateway uplink applications meet the criteria reasonably well.

The quasi-static behavioral model meets the criteria of simple characterization (simply the well-known AM-AM and AM-PM transfer curves) and straightforward simulation (conversion at each instant of the complex input envelope to the output envelope, via the transfer functions).

2. Complex Modulation

Any arbitrary waveform s(t) may be represented by:

$$s(t) = \mathbf{m}(t) \cdot \cos(\omega_0 t)$$

where $\mathbf{m}(t)$ is complex and represents the modulation vector at time t. (Note: **bold** notation indicates a complex value.) The Cartesian representation of $\mathbf{m}(t) = I(t) + jQ(t)$ is less convenient than the polar representation, i.e., the instantaneous magnitude and phase:

$$v(t) = |\mathbf{m}(t)| ; \quad P(t) = |\mathbf{m}(t)|^2 / Z_0 ;$$
$$\theta(t) = \angle \mathbf{m}(t)$$

For example, consider a two-tone test signal illustrated in Fig. 1.

$$s(t) = a\cos[\omega_0 t] + a\cos[(\omega_0 + \omega_s)t]$$
$$= \mathbf{m}(t) \cdot \cos(\omega_0 t)$$

Note the peak power is 3 dB above the average power (dashed line), and the waveform has a pulse-like behavior over a wide dynamic range.

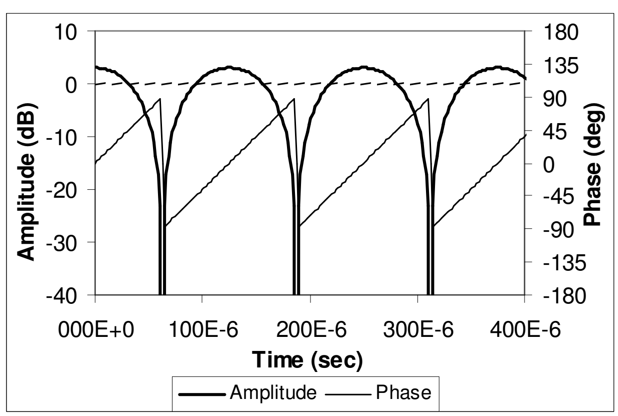

Fig. 1 Complex envelope of a two-tone test signal.

3. Simulation of Quasi-static Distortion

Under the quasi-static approximation, the complex envelope $\mathbf{m_o}(t)$ at the output of the device at time t depends only on the transfer function and the input envelope $\mathbf{m_i}(t)$, according to the following relationships:

$$20 \log|\mathbf{m_o}(t)| = P_o(t) = A\{P_i(t)\} \qquad \text{and} \qquad \angle\mathbf{m_o}(t) = \angle\mathbf{m_i}(t) + \phi\{P_i\}$$

where
$A\{P_i\}$ = power input-to-output transfer function (AM-AM curve)
$\phi\{P_i\}$ = phase input-to-output transfer function (AM-PM curve)

For example, a typical TWTA has transfer function curves shown in Fig. 2 (solid line).

Simulation of the output signal is done with the lookup table method, i.e.

a. Generate $\mathbf{m_i}(t)$ for the stimulus signal of interest
b. For each time point t, find the input power $P_i(t)$, then look up or interpolate the transfer curves to find the output power and phase shift at that time, and compute $\mathbf{m_o}(t)$.
c. For spectral analysis, perform an FFT. Note that for stimulus signals with random content (such as NPR and QPSK) the simulation normally must be repeated, and the output power spectrum averaged, on the order of 200 to 1000 times.

Simulation software packages such as Agilent ADS and AWR VSS include this capability. For the examples shown here, however, Matlab code was written.

Cascades of nonlinear devices can be simulated by mapping the output power of the first device to the input power of the second device. Fig. 2 shows an example of a predistorter that, if ideally configured, exactly compensates for the nonlinear behavior of the above TWTA up to its saturation point. If perfectly compensated, the LTWTA thus behaves as an ideal limiter. If the compensation is imperfect, the behavior of the LTWTA may be simulated using the actual composite transfer function.

4. Generalized 12-parameter HPA Model

To aid in the study of distortion sensitivity to amplifier properties, a model is proposed which permits an empirical fit of common TWTA and SSPA transfer curve shapes to a 12-term parametric model, illustrated in Fig. 3.

The AM-AM gain function is based on a rotated hyperbola; the foldover is a variable-power term added after the designated saturation point. A Gaussian-shaped gain "bump" may be added. The AM-PM function is exponential, with variable power in order to control squareness. The 12 parameters may be adjusted to fit practical Ka-band TWTAs and SSPAs very closely.

By comparison with the well-known Saleh model [1], this model allows more degrees of freedom in the shape, width, and height of the AM-PM curve, more control of the sharpness and foldover behavior of the AM-AM curve, and allows for an increase in gain prior to the onset of compression (gain expansion), which is common in SSPAs. On the other hand, the model does not lend itself to analytic computation of distortion metrics, and so is useful only for numerical simulation.

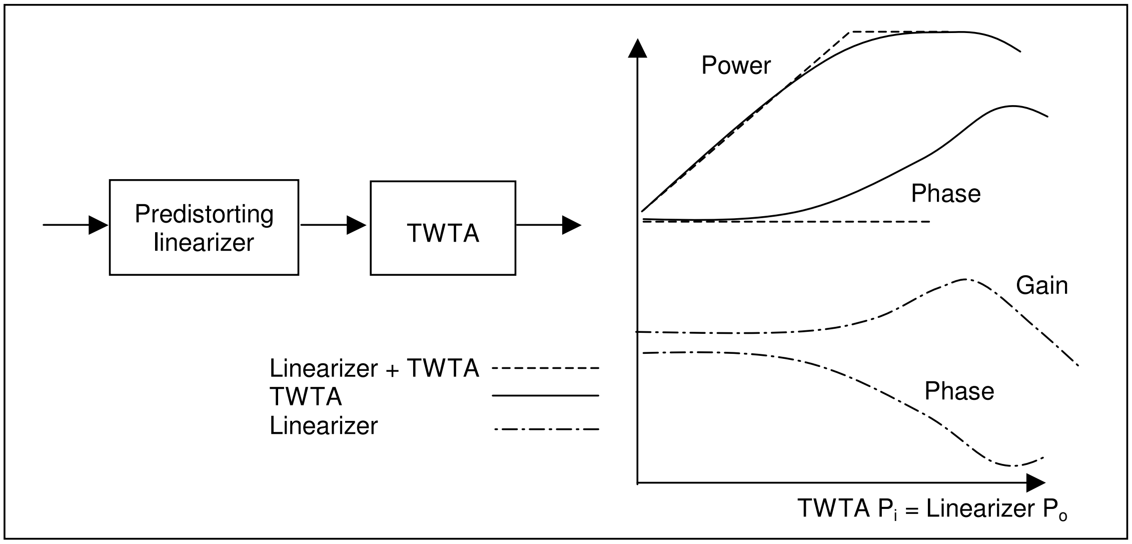

Fig. 2 Typical TWTA transfer curve and the effect of a cascade of nonlinear devices

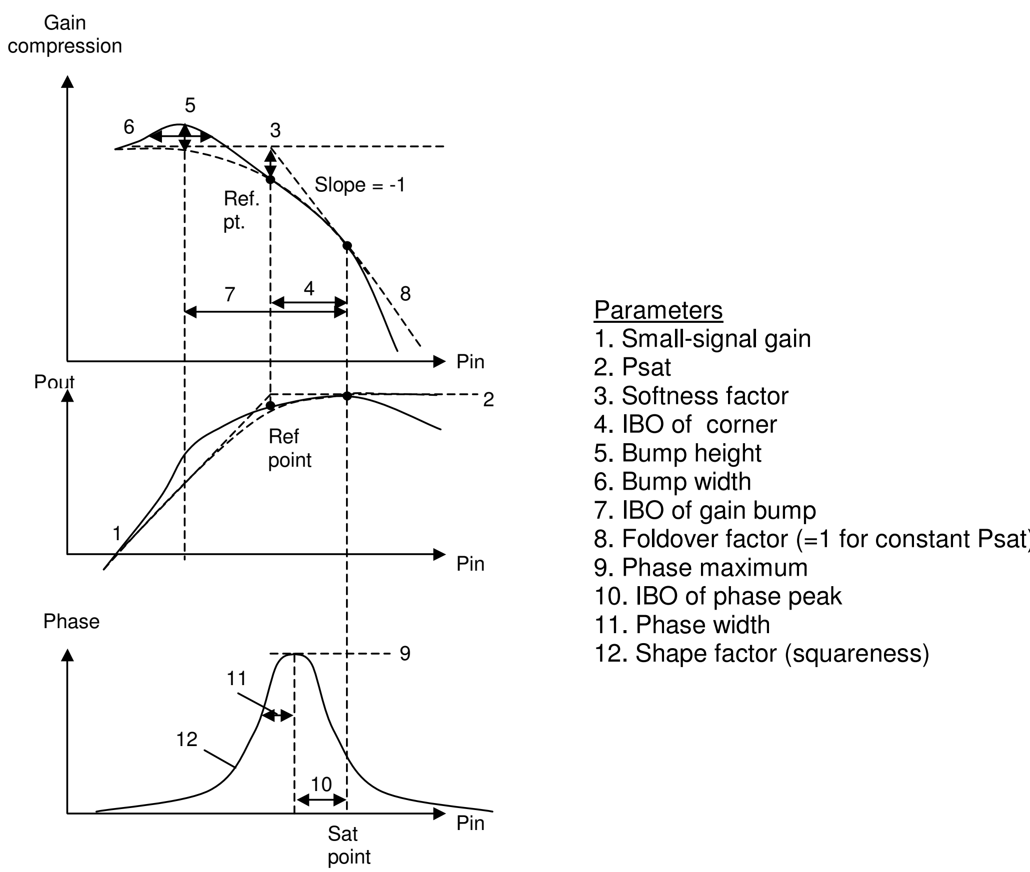

Fig. 3 Generalized 12-parameter HPA model

5. Distortion Metrics and Inter-relationships

Alone, the transfer functions may be analyzed for CW metrics such as P_{1dB}, P_{sat}, and AM-PM. Metrics such as two-tone 3rd-order IMD or carrier-to-IMD ratio (C-I), noise power ratio (NPR), and adjacent-channel power ratio (ACPR) presume specific stimuli, as summarized in the following table:

Stimulus	Directly measurable distortion metrics
CW	P_{1dB}; P_{sat}; AM-PM (slope and absolute)
2-tone	C-I (IMD); IP_3; two-tone aggregate output power
NPR waveform	NPR; noise aggregate output power
Modulated carrier	ACPR; EVM; signal output power

The NPR waveform is defined as band-limited white Gaussian noise with a notch in the center of the spectrum. Intermodulation distortion fills in the notch. The corresponding NPR metric equals the power spectral density in the notch compared with that adjacent to the notch. The NPR waveform may be closely approximated by a large number of equal-power carriers with random phases [2], but care must be taken either to use a very large number of carriers or to average the NPR result over many runs. Although the instantaneous signal power is more likely to be near the mean power, excursions occur to arbitrarily large and small levels.

The NPR waveform thus exercises the transfer curves over their complete ranges, as opposed to the two-tone waveform, which has power excursions no higher than 3 dB above the mean. Therefore a universal relationship between NPR and two-tone IMD *cannot exist*.

If simplifying assumptions about the nature of the distortion are made, however, (e.g. that it is well described by a 3rd-order polynomial), relationships between these metrics may be derived, such as NPR vs. multi-tone IMD [3] [4].

Nevertheless, the 3rd-order assumption is not a good approximation in the compression and saturation regions [5]. Therefore, if transfer function characterization data is available (and the quasi-static approximation is valid), numerical simulation will be more accurate, and furthermore, can predict *any* distortion metric due to *any* stimulus waveform.

6. Analysis Examples

The following examples illustrate the usefulness of the lookup-table simulation method, in conjunction with the quasi-static approximation, in gaining an understanding of fundamental behaviors of power amplifiers such as are used in Ka-band gateways.

(a) Distortion metrics in an ideal limiter or LTWTA.

An ideal limiter serves as the limit case for an amplifier perfectly linearized by a predistorter. It is defined in CW mode as having constant gain up to the saturation power, then constant power; phase shift is zero at all power levels. As Fig. 4 (left side) illustrates, the modulation on the two-tone, NPR, and QPSK waveforms causes saturated power to be less than that of a CW signal.

The distortion metrics NPR, two-tone C-I, and ACPR for these same input power levels are shown in the right side of Fig. 4. Note that when the backoff is greater than 3 dB, the two-tone waveform peaks do not reach the limiter's corner (refer to Fig. 1), and hence there is no distortion (i.e., infinite C-I). A QPSK waveform also has a finite peak-to-average power ratio, and thus the onset of distortion is similarly abrupt. By comparison, the NPR waveform, being essentially a noise envelope, has a gradual and continuous increase in distortion as its level increases.

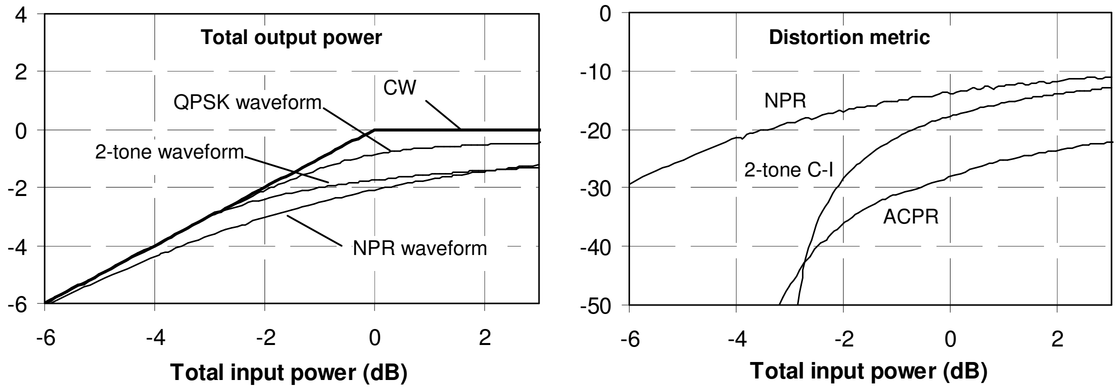

Fig. 4 Pin-Pout (left) and distortion behavior (right) of an ideal limiter

(b) Relationship between NPR and two-tone IMD

Although NPR is a very useful predictor of the intermodulation noise generated by multiple non-coherent modulated carriers (such as would be common in gateway uplinks), it is quite difficult to measure accurately or quickly. Two-tone IMD measurement, by comparison, is accurate and straightforward. It would be desirable, therefore, if two-tone C-I results could predict NPR. By hypothesizing the transfer functions of a variety of amplifier types and tolerance limits, the quasi-static method can be used to explore the relationship between C-I and NPR over a range of power backoffs.

Fig. 5 illustrates the result of simulations of two-tone C-I vs. NPR, for the same aggregate power level (input or output), of (i) and ideal limiter, (ii) a typical Ka-band 120 W TWTA, (iii) the same TWTA with an ideal predistorting linearizer but interstage gain incorrect by +3 dB and –3 dB, (iv) the same TWTA with the AM-PM curve scaled by +20% and –20%, (v) the same TWTA with the AM-AM compression "knee" made sharper and softer, and (vi) a typical 10 W Ka-band SSPA. Note that a trend emerges but the prediction accuracy is limited.

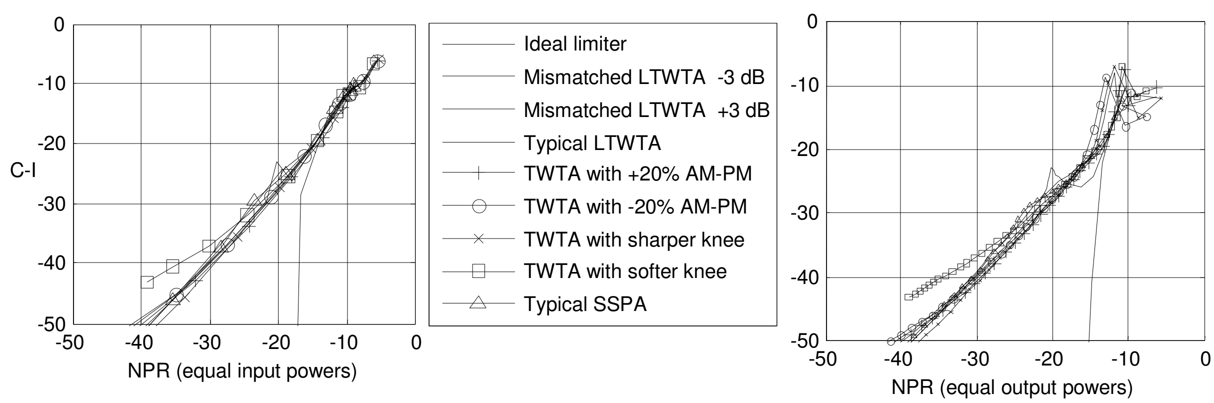

Fig. 5 NPR vs. IMD for various amplifiers at equal input (left) and output (right) powers

(c) Linearizer gain mismatch effect on NPR

Linearized TWTAs consist of a TWTA preceded by a predistorting linearizer. Each of these components has its own transfer curve variations over temperature, carrier frequency, aging, etc. If, for example, the small-signal gain of the TWTA varied over its lifetime or temperature, the linearizer would not correctly predistort the gain and phase of the TWTA and the system transfer function would not be that of an ideal limiter. Fig. 6 (left) shows such an effect, where an arbitrary 3 dB gain error is inserted between the linearizer and the TWTA.

The abrupt edges in the transfer curves of the –3 dB and +3 dB cases are artifacts of the assumption that the linearizer perfectly predistorts the TWTA at its nominal gain and limits at any powers higher than the input level that saturates the TWTA (in order to prevent the TWTA output power from reaching the post-saturation foldover region). This condition, however, is not ideal if the TWTA gain varies: if the TWTA gain is less than nominal, for example, the predistorter will limit before the TWTA reaches full power, which is obviously undesirable. In practice, linearizers do not have such sharp breakpoints, and the resultant system transfer curves are not as abrupt.

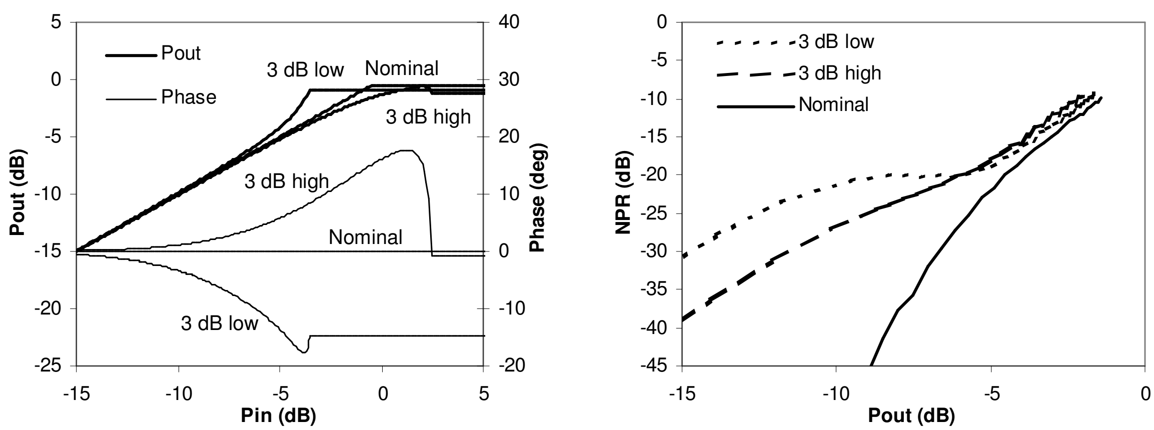

Fig. 6 Normalized transfer curves (left) and corresponding NPR (right) of an LTWTA with linearizer gain error.

The technique described here allows investigation of the sensitivity of NPR to such an internal gain error. Fig. 6 (right) shows the simulated NPR for each of the above cases. Note that the NPR performance in the < –20 dB region is substantially degraded by linearizer-to-TWTA mismatch. It should also be noted that for the same reasons that the transfer curves of practical LTWTAs would not have the discontinuities seen in Fig. 6, the NPR sensitivity to gain error may also be somewhat different than the figure indicates. In fact, this study suggests why an "ideal" linearizer might cause NPR to degrade rapidly if there is gain mismatch, whereas a more practical non-ideal linearizer without abrupt transitions could actually degrade NPR less.

(d) Amplifier combiner balance error effect on NPR

In Ka-band gateways, a common technique to achieve high EIRP is to use nominally-identical linearized TWTAs in parallel, together with quadrature phase combiners on the input and output. Imbalances in the gain or phase of the two paths will cause not only small-signal performance degradation, but will alter the nonlinear transfer functions. For example, if the two amplifiers are ideally linearized but one has a ±3 dB error in small signal gain, the AM-AM transfer functions shown in Fig. 7 will result. Note that in either case, one amplifier enters saturation before the other, creating an early breakpoint.

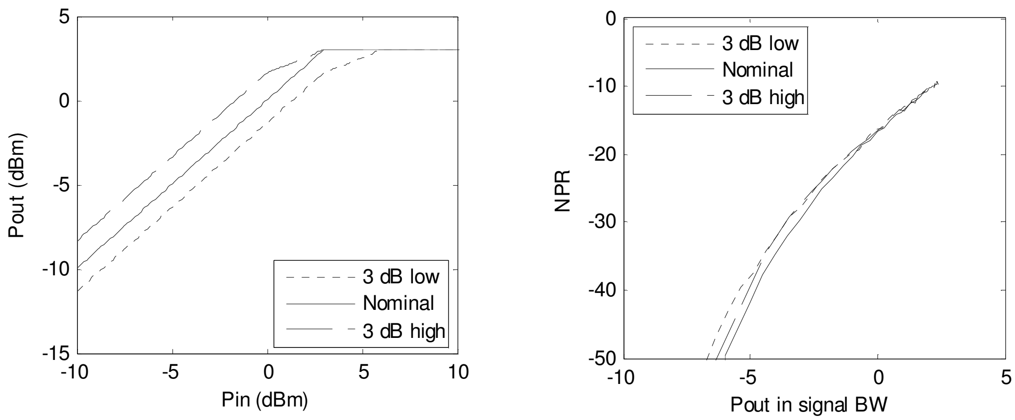

Fig. 7 Normalized transfer curves (left) and corresponding NPR (right) of phase-combined parallel LTWTAs with imperfect balance

The simulated effect on NPR of this error is shown on the right side of Fig. 7. Note that the degradation becomes non-negligible in the region when NPR is better than –20 dB. It is also interesting to note that small-signal phase error has quite a different effect than that of a small-signal gain error. Because the transfer function is a function of input power, the effect of a phase imbalance is to reduce to saturated power without creating a breakpoint. The NPR is thus degraded evenly over its entire range.

(e) Improvement in EIRP made by a TWTA linearizer

The fundamental objective of a linearizer is to allow higher output powers with a given level of distortion. The quasi-static method allows prediction of intermodulation noise and signal power due to an actual multicarrier input spectrum. For example, as shown in Fig. 8, a spectrum with four QPSK carriers (alpha = 0.35, raised cosine) results in about –18 dBc IMD at the central gap in a typical TWTA at an output backoff of about 5.2 dB from saturation. An ideally linearized amplifier produces similar IMD at only 1.9 dB output backoff, a 3.3 dB improvement in EIRP.

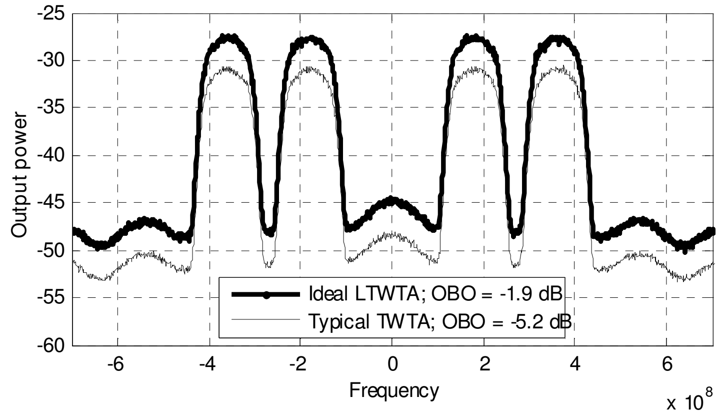

Fig. 8 Output spectrum of a TWTA with and without linearizer at equivalent output backoffs

7. Characterization Techniques and Validating the Quasi-static Assumption

Characterization of quasi-static distortion amounts to measuring the AM-AM and AM-PM transfer functions at the signal frequency of interest. Several methods are viable:

Method	Pros and cons
Vector network analyzer (VNA)	Most accurate.
	Not suitable for many frequency-converting devices.
	May burn out some devices
Pulsed VNA	Not suitable for non-coherent frequency-converting devices;
	Complex equipment setup
Spectral-null pulse (SNP) [4]	Suitable for frequency-translating devices and devices that burn out at continuous saturation levels.
	Requires arbitrary waveform generator

Validating the assumption that distortion is in fact quasi-static (memoryless) is a matter of looking for evidence of changes in the transfer functions as a function of the speed at which they are measured. Such evidence may be direct (such as pulse edge transient response) or indirect (such as a change in intermodulation product levels). One of the most straightforward and revealing methods is to examine the two-tone C-I as a function of spacing. Again referring to Fig. 1, we can see that the envelope rapidly exercises the transfer function over its entire range from zero to 3 dB over the average power. Varying the tone spacing causes the beat frequency to vary. Therefore, a change in two-tone C-I as a function of tone spacing up to the bandwidth of the signal of interest is direct evidence of memory effect on such a signal. Sometimes the effects are very pronounced, e.g., in the case of a bias network resonance. Fig. 9 illustrates the technique and an observation of a distortion memory effect using the swept two-tone method.

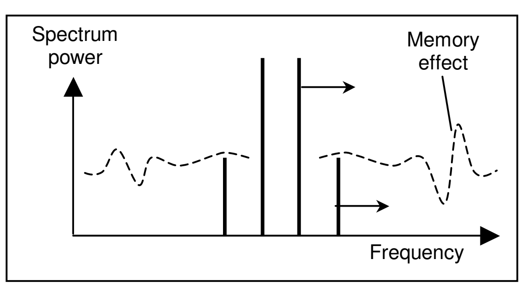

Fig. 9 Swept two-tone test

8. Conclusion

The quasi-static approximation, while not exact, is a simple and powerful basis for insight into the distortion behavior of high-power amplifiers in Ka-band uplink gateways. The proposed 12-parameter model allows rapid study of the sensitivity of performance-related distortion metrics such as NPR, multicarrier intermodulation noise, and ACPR due to tolerance variations in a single or combined amplifier, with and without linearization.

9. References

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