

All About Traveling Wave Tube Amplifiers (TWTA)

Traveling Wave Tube Amplifiers are widely used in satellite applications to provide signal power amplification at high frequencies. Solid State Amplifiers (SSPA) used mostly at S-band also exhibit performance characteristics similar to TWTAs. Therefore, this discussion applies to both SSPA and TWTAs.

TWTAs provide highly efficient power amplification at high microwave frequencies but have troublesome side effects associated with their performance. Like a bitter but effective medicine, we live with these side effects because there are no other viable options for signal amplification in space that offer similar efficiencies.

Who makes TWTAs

There are three main manufacturers of TWTAs. They are

- Hughes
- AEG/Thomson
- NEC

Hughes specializes in the development of C and Ku-band tubes, whereas the French company Thomson has tended towards Ka band. Thomson and the German company AEG have recently merged although they still maintain two different foundries and have somewhat different technologies for their TWTAs. NEC is a much smaller player than the first two. NEC makes TWTAs in S to V band and their tubes have flown mostly on Japanese programs such as COMET, ETS, and N-Star.

In 1997, Hughes sold app. 620 units, AEG 800 units, and Thomson 500 units of TWTAs. With the AEG and Thomson merger, they now have about two-thirds of the market.

Each dual-radiation cooled TWTA costs app. \$280K and a typical satellite requires approximately \$10 million dollars worth of TWTAs.

There is more choice when it comes to linearizers, a device used to mitigate the non-linearity of TWTAs. Hughes has been working with HFC (their sister company) to develop linearizers. Loral has used numerous different vendors such as NARDA, Bosch, Alcatel, and NEC, and has also developed in-house linearizers. Linearizer adds app. \$25K to \$100K per TWTA to the cost of a satellite. It is estimated that currently app. 40% of the systems use linearized TWTAs as opposed to non-linearized.

How we specify the power characteristics of a TWTA

The most common methods in which TWTAs are specified are

1. Peak Power
2. P_{in} vs. P_{out} or AM/AM Transfer and AM/PM Conversion curves
3. Input Back-off (IBO) vs. Output back-off (OBO)
4. Gain

In addition to the power characteristics of TWTAs, the measure of non-linearity of the TWTAs is commonly specified by the following Figures of Merit:

1. C/3IM
2. NPR
3. 1 dB Compression Point

1. Peak Power

TWTAs are most often referred by their peak power. The amount of peak power that can be delivered today are inversely proportional to the frequency band.

Table I - TWTA provide a range of powers in many frequency bands

Frequency	Power, watts	Comment
S-band	50-150	
C-band	15-150	
Ku-band	15-150	Growth to 200 watts
Ka-band	20-100	Growth to 150 watts

2. AM/AM Transfer and AM/PM Conversion curves

In addition to peak power, a range of power-in vs. power-out characteristics are also provided. The power-in vs. power-out curves for TWTAs are also called AM/AM transfer curves. Fig. 1 shows a typical power-in vs. power-out characteristic of a Ku band TWTA.

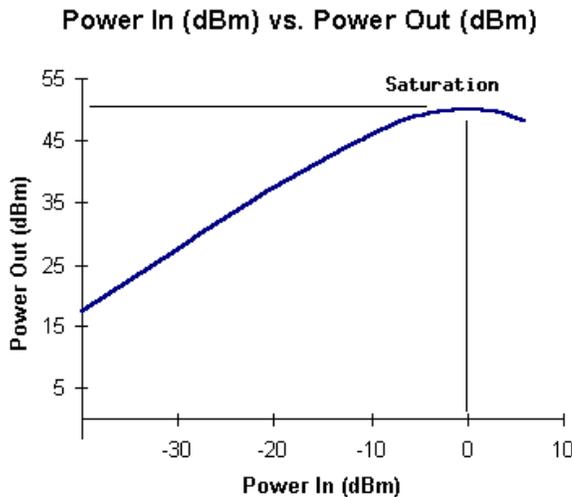


Figure 1 - Typical Input Power vs. Output Power of a TWTA

The Fig. 1 above shows that as input power is increased, beyond a certain region of linearity, the output power begins to decline. At a point called saturation, any further increase in input power produces no further increase in output power. Equate this to dialing the volume knob on your stereo which is really a kind of non-linear amplifier. The volume at first increases but as we get close to the stop of the knob (you may have to be a teenager to experience this fully), the output does not increase much and a great deal of noise can now be heard in the music. This is saturation.

The peak power is seen at the highest point of the curve. In dBs, 100 watts corresponds to 20 dBw = . Most TWTA data is given in dBm instead of dBw. 20 dBw is 50 dBm (1 dBw is equal to 30 dBm and 0 dBm is equal to 1 milliwatt.)

Similarly for a 200 Watt TWTA, we would compute its power in dBm as

$$= 10 \log(200) + 30 = 53 \text{ dBm}$$

We can see that the saturation power for the TWTA in Fig. 1 is 53 dBm. So this TWTA must have a peak power of 200 Watts. The x-axis in Fig. 1 is the input drive level power. It is also given in dBms.

Most TWTAs are designed to saturate at an input level of 0 dBm. Channel amplifiers are often used in front of the TWTA to ensure that the drive level of the TWTA is does not vary a great deal and is fixed either at 0 dBm or at some other pre-determined back-off.

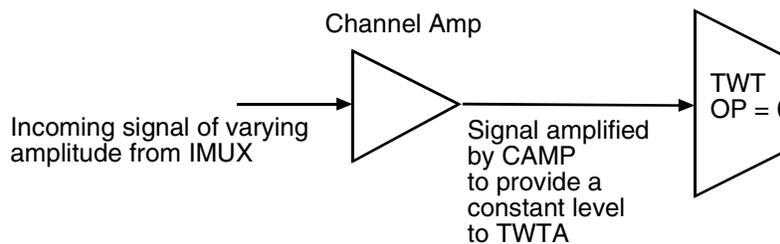


Figure 2 - TWTA being fed a level-adjusted signal so it can operate at a fixed operating point (OBO)

The place on the AM/AM transfer curve where the TWTA is nominally being operated is called its operating point or back-off. We can talk about both Input Back-off (IBO) and Output Back-off (OBO), although generally satellite operators talk in terms of Output Back-off only. This is because the operator is concerned about total maximum power being generated out of the transponder.

Ideally we want to operate the TWTA at saturation because here we get the most power out of the TWTA. But we find that the non-linear behavior of the tube causes significant signal distortion at saturation, so we back off from this desired optimum. The real optimum which is a function of number of carriers, data type, access method, etc. is determined individually for each transponder. The determination of a back-off point for a transponder is not an exact science and requires the balancing of many of these conflicting needs.

Individual carrier's must be coordinated so they do not swamp each other and a fixed output power is being delivered out of the satellite. Typically because of this, stringent limits are placed on the signal variability of each carrier going into a transponder.

A particular OBO applies only to one particular transponder. A transponder on the satellite may be carrying many carriers and hence will have a different OBO than another transponder on the same satellite carrying just one carrier. Traffic changes on a transponder would also necessitate changing the OBO. The range of OBO values however, does not vary a great deal, say from .5 dB for a single carrier, to about 5 dB for a multi-carrier system.

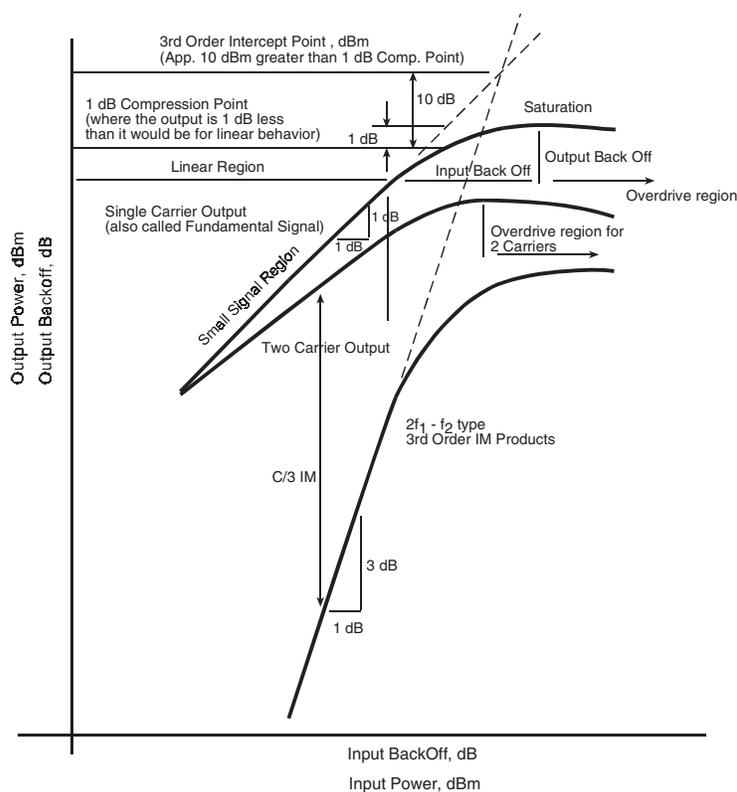


Figure 3 - Common TWTA Operating Parameters

Let's look at some of the other parameters of a TWTA. These are shown in complicated looking Fig. of 3. The linear range is called the small signal region, and the region beyond the saturation point is called the overdrive region. The overdrive capability of a tube is a region over which most (although not all) of the saturation power can be maintained with increasing input power. Satellite applications, however, rarely operate in the overdrive region.

The characteristic response curves in Fig. 1 and Fig. 3 are always for a single carrier going through the TWTA. The top-most curve of Fig. 3 is obtained by putting a single tone of known amplitude through the tube and measuring the amplitude of the output. Since the data is given for carriers which are tones of single frequency, it does not reflect the behavior of a modulated signal. A 100 Watt TWTA will not always produce 100 Watts at saturation if a modulated signal is put through it. A realistic number is about .5 dB less or about 90 Watts.

To complicate matters further, very often there is more than one carrier present. The AM/AM transfer curve tells us nothing of what will happen for a case with more than one carrier. How much power would we get out of the tube then? Is it more or is it less, and if so how much less than the single carrier case.

The knowledge of how a tube will behave in the presence of more than one carrier is very important, and the manufacturers provide us with two carrier power-in vs. power-out curves. In Fig. 3, you can see this curve just below the one carrier case. We can see that at saturation the two-carrier case does not provide the full output power but something about 1.5 dB less or for a 100 Watt TWTA, delivering only about 70 Watts. What a huge loss! What happened to the rest of the energy? We will attempt to answer this question later.

AM/PM Conversion or the Phase performance

In addition to the AM/AM transfer curves, manufacturers also provide phase shift properties. A phase shift is imparted to the signal depending on the drive level. In the small signal region, the phase shift is so small as to be negligible. As we increase the level, the phase shift increases up to about 50 degrees. A typical phase shift vs. Input Back Off curve is shown below.

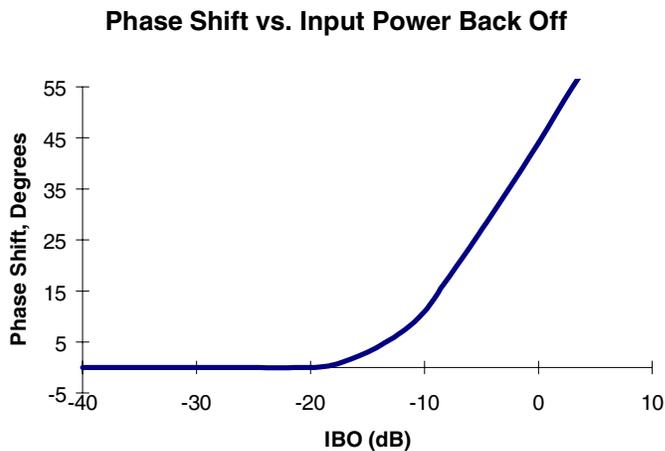


Figure 4 - Phase Shift, Degrees vs. IBO, dB

The phase shift curve is also called the AM/PM conversion curve. This phase shift is an additional cause of degradation. The phase shift that occurs as a result of the amplitude non-linearity has smaller effect on the over all link. The impact of this phase shift is about .6 dB degradation vs. as much as 2.5 dB degradation of the Eb/N0 due to the amplitude effects.

A TWTA that had a smaller phase shift at saturation by 10 degrees would provide us with app. 0.1 dB better performance.

Why worry about phase?

Why is phase important anyway? Here is a brief demonstration of how phase shift distorts the signal. In Fig. 5 we show an almost-square wave made from just three frequencies. The phase values

are all assumed to be zero.

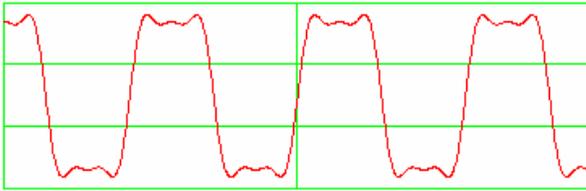


Figure 5 - A fairly decent looking square wave consisting of just 3 frequencies

Now let's change the phase slightly for each frequency, representing the frequency-selective phase shift property of a TWTA and we see how distorted the output signal in Fig. 6 has become. And this without any noise or amplitude distortion at all!

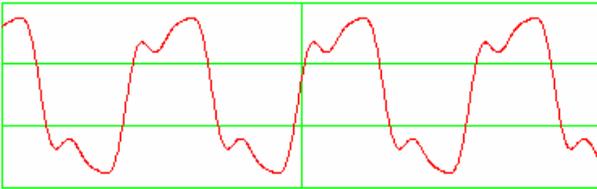


Figure 6 - Effect of phase shift on the simple square wave, not so decent anymore.

Although the above example is instructive as to the effects of phase distortion, we have to recognize that phase shift caused by the TWTA is lesser of the two evils. Most of the degradation comes from the amplitude non-linearity effects of the TWTA. If the envelope of the signal (its outline) is fairly constant, then the TWTA amplitude gremlins are likely to go hungry but if the envelope fluctuates, they have a feast.

To get around this envelope effect, phase modulation is used to some advantage in satellite communications. But even phase modulated signals such as QPSK have some amplitude variation and suffer degradation. A QPSK signal goes through 180 degree phase shift at each bit change and this sudden "collapsing" of the signal to zero, stresses the dynamic range of the TWTA and results in signal distortion. The offset QPSK signal has "less" envelope fluctuation because the phase shifts are limited to 90 degrees and because of this we conclude that offset QPSK signal suffers less distortion. And this is indeed so. We would always prefer O-QPSK if it were not for the cost of the receivers.

2. IBO/OBO

The Power-in vs. Power-out curve of a TWTA is often normalized to output power. Instead of talking of actual power-out in Watts or dBms (as we did in Fig. 1 with $P_{out} = 200$ watts), we normalize the curve so that it produces 0 dB at saturation. This type of curve is called the Input Back-off (IBO) vs. Output Back-off (OBO) curve.

We convert the AM/AM transfer curve to IBO/OBO by the following relationships.

IBO/OBO curve shape is exactly the same as the original AM/AM transfer curve given to us by the manufacturer except for the scaling. Now we interpret the x-axis not as a power-in reading but as “dBs less than what it would take to cause saturation”. The y-axis is read as “dBs less than output power that could be obtained at saturation”. A 3 dB OBO would mean that a 100 Watt TWTA is producing only 50 Watts.

The IBO vs. OBO format is often used instead for specification of non-linear performance such as for C/3IM, NPR etc. and is also used in analysis and simulation. The normalization makes it possible to compare various tubes even though they may have different output powers.

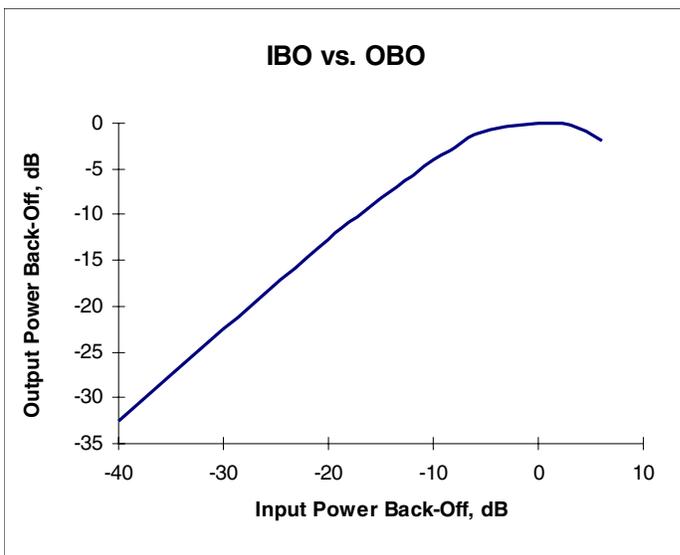


Figure 7 - Typical IBO vs. OBO curve for a TWTA

OBO is also used to specify the operating point of a transponder.

The specific relationship between IBO and OBO varies somewhat for each TWT. The following table gives a typical set of values. Note for example that it takes 10 dB Input Back-off to get a 4 dB Output Back-off.

IBO	OBO
-20.00	-13.3
-18.00	-11.1
-15.00	-8.2
-12.00	-5.6
-9	-2.6
-6	-1.2
-3	-.3
0	0

In the following Figure, we show several tubes on one chart.

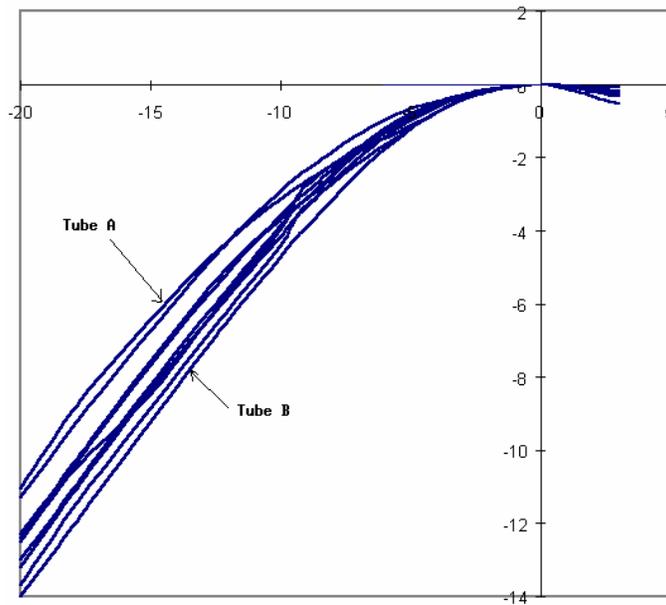


Figure 8 - Comparing TWTAs

3. Gain

When talking about Gain of a TWTA, it is the small signal or the linear gain that we are referring to. The linear gain of the tube is given by

A typical TWTA has a gain of 50 dB. The Fig. 9 below shows a typical gain curve.

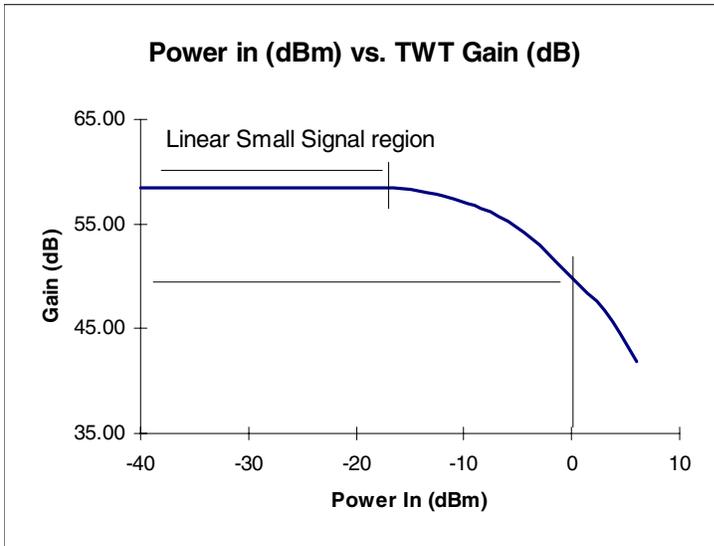


Figure 9 - Typical Gain Curve of a TWTA

The gain of this tube is constant up to a drive level of -17 dBm. From -40 dBm to -17 dBm input drive level, the gain is 58 dB independent of the input power. We can calculate the output power by just adding this gain to the input power. In this constant-gain region, the TWTA acts like a linear gain amplifier.

The maximum power output at -17 dBm input power is only 11 dBw (or 12.5 watts). This is not acceptable, particularly as the TWTA is advertised to deliver 100 Watts of output power. So we move further up (actually down) the gain curve. The gain now begins to decline and at input power level of 0 dBm, the gain is only 50 dB as opposed to 58 dB in the linear region. But since the output power is now 100 watts (= 0 dBm + 50 dB = 50 dBm = 20 dBw = 100 Watts) we accept this gain hit. We don't much care about the gain as it is the total output power we want.

We typically like to see a flat gain in the band of interest but this is not the case with TWTAs. The gain in the region near saturation is any thing but flat. This causes problems.

Why TWTAs behave the way they do?

Now a little Math.....

The Traveling-Wave non-linear behavior can be modeled with a power series, so that each term represents a contribution of higher order effects.

$$V_{out} = k_0 + k_1 V_{in} + k_2 V_{in}^2 + k_3 V_{in}^3 + k_4 V_{in}^5 + \dots$$

Most models are simplified by ignoring all terms beyond the third or fifth order since only the second and third-order distortions are significant. Second order effects are not very important in communications.

$$V_{out} = k_0 + k_1 V_{in} + k_2 V_{in}^2 + k_3 V_{in}^3 \quad 1$$

Let's take a carrier of the form

$$V_{in} = A \cos \omega t$$

and put it through the non-linearity specified by Eq 1. We get

$$V_{out} = \underbrace{(k_0 + k_2 A^2 / 2)}_{\text{DC Component}} + \underbrace{(k_1 A + 3k_3 A^3 / 4)}_{\text{Fundamental}} \cos \omega t + \underbrace{(k_2 A^2 / 2)}_{\text{2nd Order harmonic}} c \quad \underbrace{\quad}_{\text{3rd Order harmon}}$$

We can see that the effect of the non-linearity is to produce an attenuated fundamental and second order products which steal power away from the fundamental. The equation by itself is not very helpful because we do not know what the coefficients are but it does allow us to see what happens to these terms relative to each other.

We can see that if we double the amplitude of the input signal, no matter what these coefficients, the amplitude of the 3rd order fundamental increases by 9 dB. There is a 3 dB to 1 dB relationship between the 3rd product and the fundamental and this is widely observed and documented. We plotted these products in Fig. 4 and note that they have a slope of 3 to 1 against the fundamental.

Let's take a look at the effect of this behavior on a signal in the time domain and in the frequency domain.

Fig. 10a shows a baseband binary signal. This signal is then wave-shaped as shown in Fig. 10b. Compare the signal in 10b to the signal in 10c which is the same signal through the TWTA. The distortion you see includes both the amplitude and the phase distortions.

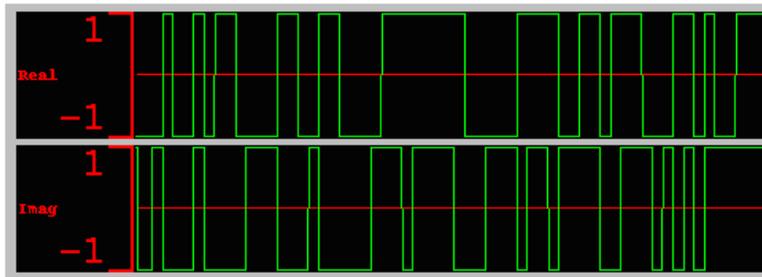


Figure 10a - Binary Signal

(You may to print to see all the details in the figures.)

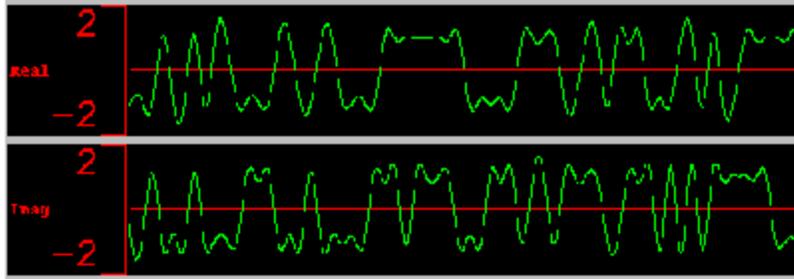


Figure 10b - Same signal through a Root-raised cosine filter that shaped the square waves. (This is not considered distortion.)

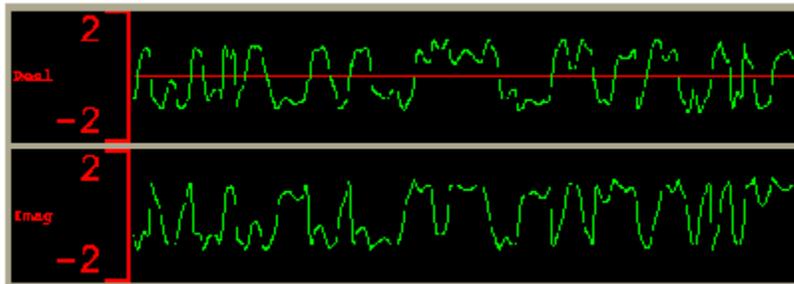


Figure 10c- Same signal through the TWTAs, distorted both in phase and amplitude.

We can qualitatively see the effect of this signal distortion by looking at the before and after spectrum of this signal in Fig. 11a and 11b.

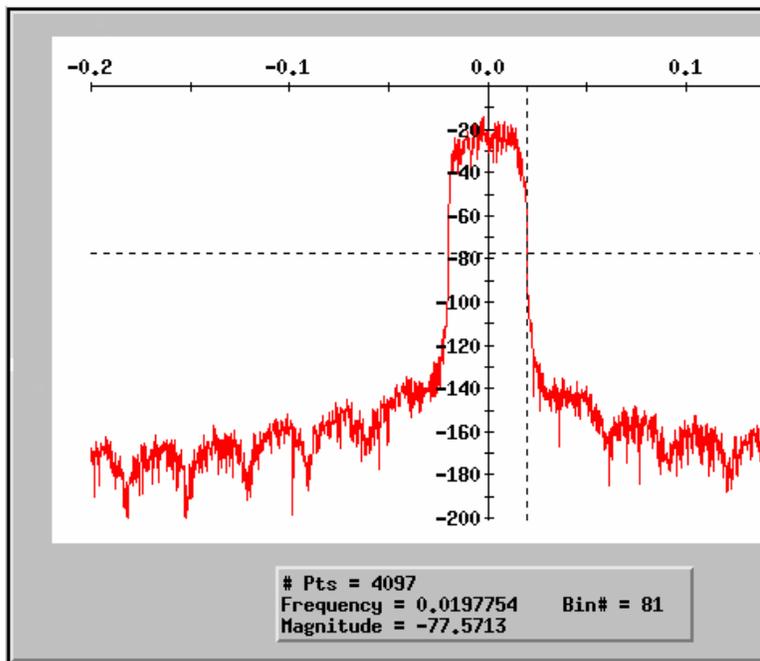


Figure 11a - Spectrum of incoming signal (Most all of the energy is confined in-band)

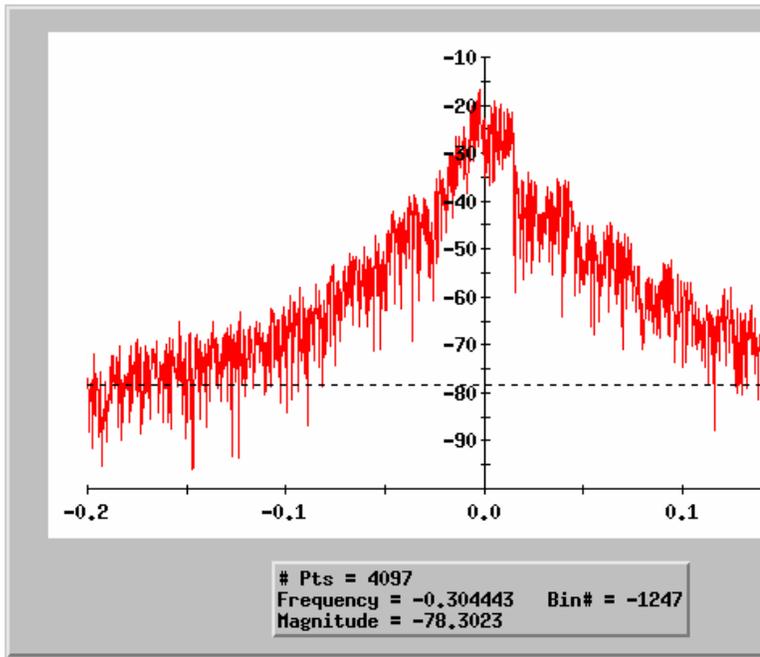


Figure 11b - Spectrum of signal post TWTA (at OBO = 0)
 Note that the signal energy has spilled into adjacent bands which have come up.

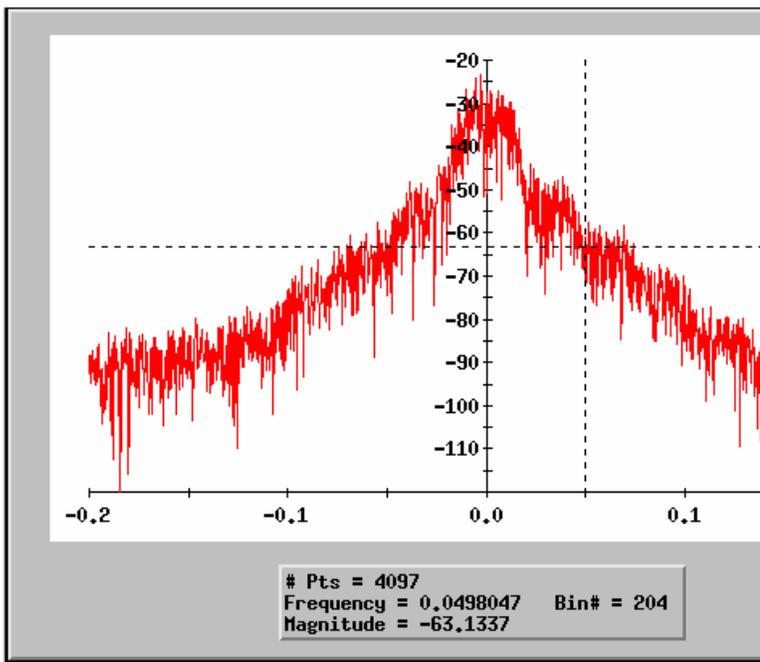


Figure 11c - Spectrum of signal post TWTA (at OBO = -2 dB)

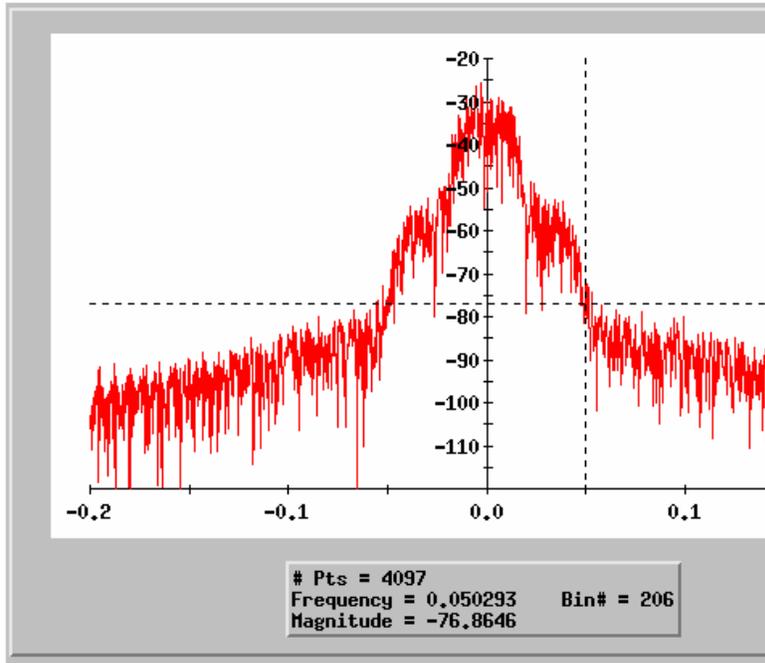


Figure11d - Spectrum of signal post TWTA (at OBO = -6 dB)

We can see in Figures 11c and d that as we reduce the input power, the TWTA backs-off into a linear range of operation. The spectrum of the two cases above shows the decreasing non-linear behavior as input drive level is decreased. (Fig. 11c is for a OBO of -2 dB and Fig. 11d is for OBO of -6 dB.) There is much less energy in the adjacent bands. Had we shown the time-domain signal for these cases, we would see that there is much less signal distortion that what we see in Fig. 10c.

Behavior with two tones

Now let's take a look at what happens mathematically if we put two tones through the TWTA instead of one. We characterized the TWTA behavior as

$$V_{out} = k_0 + k_1 V_{in} + k_2 V_{in}^2 + k_3 V_{in}^3$$

The two tone signal is described as

$$V_{in} =$$

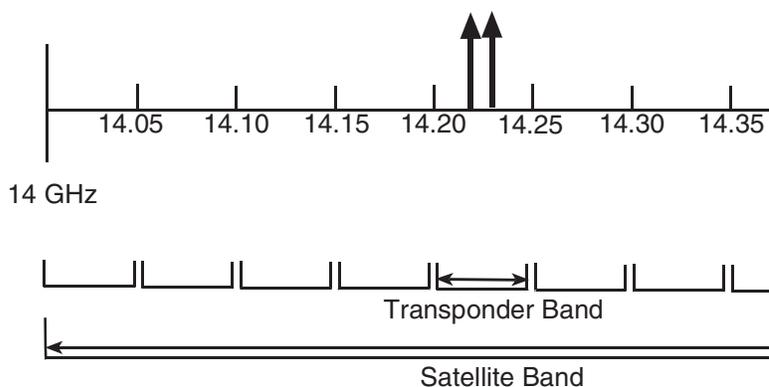
The signal is composed of two tones of the same amplitude, A. Putting this through the transformation equation above gives us many different combinations of the two original frequencies w_1 and

ω_2 . The output tones take the form of

where the order of the non-linearity is equal to $n+m$.

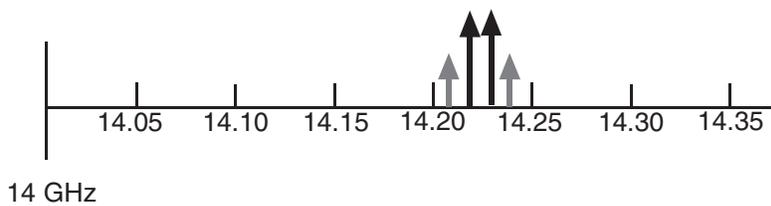
Term	Note
$= k_0 + k_2 A^2$	DC term
$+ k_1 A \cos \omega_1 t + k_1 A \cos \omega_2 t$	- the fundamental tones, 1 st order effect
$+ k_2 A^2 \cos 2\omega_1 t + k_2 A^2 \cos 2\omega_2 t$	- Harmonics at twice the original frequency due to 2 nd order effects
$+ k_2 A^2 \cos (\omega_1 + \omega_2) t$	-Sums of two frequencies due to 2 nd order effects
$+ k_2 A^2 \cos (\omega_1 - \omega_2) t$	-Differences of two frequencies due to 2 nd order effects
$+ k_3 A^3 \cos \omega_1 t + k_3 A^3 \cos \omega_2 t$	- Contribution to fundamentals due to the 3 rd order term
$+ k_3 A^3 \cos 3\omega_1 t + k_3 A^3 \cos 3\omega_2 t$	- Harmonics at three the original frequency due order effects
$+ k_3 A^3 \cos (2\omega_1 + \omega_2) t + k_3 A^3 \cos (2\omega_2 + \omega_1) t$	- Sum of the two frequencies due to 3 rd order effects
$+ k_3 A^3 \cos (2\omega_1 - \omega_2) t + k_3 A^3 \cos (2\omega_2 - \omega_1) t$	- Differences of the two frequencies due to 3 rd order effects

The above Table is a little bit confusing so let's do an example. We will look at a particular transponder inside the Ku-band frequency range for a satellite. We have picked a band of 14 GHz to 14.5 GHz. In it there are ten transponder each of 50 MHz bandwidth. In transponder number 5, we show two signals at frequencies of 14.22 and 14.23 GHz.



The table below shows the various products that results from these two signals going through the TWTA.

Non-linearity Order (n+m)	Frequency Location	Relative Amplitude	Note
1	14.22	3	In-band
1	14.23	3	In-band
2	28.44	1.5	Out-of-band
2	28.46	1.5	Out-of-band
2	28.45	1.5	Out-of-band
2	0.01	1.5	Out-of-band
3	42.66	0.3	Out-of-band
3	42.69	0.3	Out-of-band
3	42.67	1	Out-of-band
3	42.68	1	Out-of-band
3	14.21	1	In-band
3	14.24	1	In-band



We can see the products that result from the inter-modulation of the two tones, and there are only two that lie anywhere inside the band of interest. These are due to the 3rd order effects. All 2nd order effects are at twice the nominal frequency and of no effect on Ku-band at all. One term lies close to zero and this is filtered out.

The term “in-band” can be confusing. Does it mean within the transponder’s band or the satellite’s? Unfortunately it is used both ways.

Two related concepts

The Noise Figure is defined as

$$NoiseFigure = \frac{S / N}{S_0 / N_0} = \frac{SNR \text{ at the input}}{SNR \text{ at the output}}$$

Since all amplifiers add thermal noise to the incoming signal, the output signal-to-noise ratio will be less. So the Noise Figure of a TWTA is always greater than 1, or is always positive in dBs. The Noise Figure can also be expressed as a noise temperature (in Kelvin) as

$$\text{NoiseFigure} = 10\text{Log} \left[\frac{\text{Noise temperture in Kelvin}}{290^{\text{Deg Kelvin}}} + 1 \right]$$

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Dynamic Range

All devices have an intrinsic noise level. This is called the thermal noise of the device. The lowest signal that can be resolved above this noise level and the maximum signal level that can be produced by the device determines the dynamic range of the device. TWTA are not often characterized by dynamic range but the concept is very relevant to their operation.

We can summarize the effects of TWTAs as two fold;

1. They transfer energy into the adjacent bands, which acts as interference for the adjacent channels. These we can filter.
2. It steals energy from the fundamental and also distorts the in-band signal. There is not a whole lot that can be done about that.

All in all, a troublesome but manageable phenomenon.
How do we manage it?

1. We use a TWTA that is as linear as possible and has a small phase shift.
2. We use strong filters after the TWTA to remove the out-of-band energy so as to reduce the effect on the adjacent channels.
3. We can operate the TWTA in a non-linear region but this is not really a practical suggestion as it would be like to driving a Ferrari at 45 miles-per-hour because it gives the best gas mileage at that point.
4. We can use a linearizer.

How we specify the non-linearity of TWTAs

The TWTA manufacturers provide us with measures of the non-linearity of the TWTAs. There are three main method by which non-linearity is specified.

- 1 C/3IM
- 2 NPR
- 3 1 dB Compression Point and Intercept Points

What is C/3Im

When two carriers are put through a TWTA, we get the characteristic frequency response in the Figure below. In the first figure we see the two input tones. The second picture, which shows the

output of the TWTA, shows not only the two original tones but multiple other harmonics. Each of these harmonics are located at frequencies related to the two original frequencies. These previously-not-there tones are called intermodulation products. Third order products of () and () type which are of the highest power level and also lie close in to the band of interest are of most concern to us.

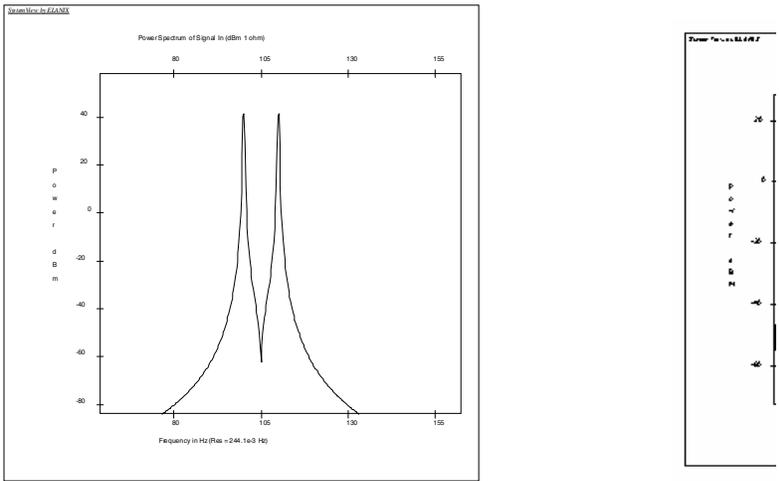


Figure 12 - Two equal carriers through a TWT, a. input signal, 2. Output signal

C/3IM is defined as the ratio of the power in one of the two main (or fundamental carriers) and the next nearest spike.

$$C / 3IM = \frac{\text{Power of one of the main carriers}}{\text{Power of the next highest 3rd order product}}$$

Figure 13 shows what happens to the total power delivered when a second carrier of exactly the same power level is added to the input of the tube. Note that the new response characteristic has shifted down and to the right. In other words, not only do we get less total output power but we also reach it at a lower drive level. The new saturation point or drive level is usually about 3 db less.

The reason why this happens is because of the birth of all those undesired inter-modulation products. Each spike has stolen power from the parent carriers.

The C/3IM is computed by putting two tones of equal power through the TWTA. The carrier output power and the power in the inter-modulation product is measured. The ratio of the carrier power to the 3rd order IM is called the C/3IM. (The third-order inter-modulation is the highest spike next to the fundamental carriers.) It nearly always takes the following shape for non-linearized TWTAs.

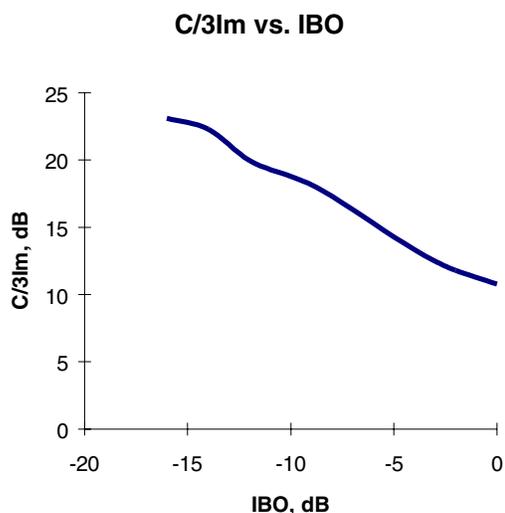


Figure 13 - C/3IM levels at various IBO

C/3IM is nearly always specified as a function of the input power back-off per carrier. So the saturation level means that both carriers are backed off by 3 dB. Typical C/3IM values start at about 9 dB at saturation. For each dB of decrease in the carrier output power, the IM level goes down by about 3 dB.

At about C/3IM level of 20 dB, we can say that the TWTA is operating nearly linear.

A typical set of C/IM values are

IBO, dB	C/3IM, dB
0	7
-3	10
-6	12
-9	15

C/I

In an associated analysis, we can extend the C/3IM analysis from two to many carriers. These pictures give an indication of what happens to the numerous signals as they go through the TWTA. As more and more carriers are added, numerous intermodulation products result. The center carriers are more effected by this and in each case are depressed (less output power).

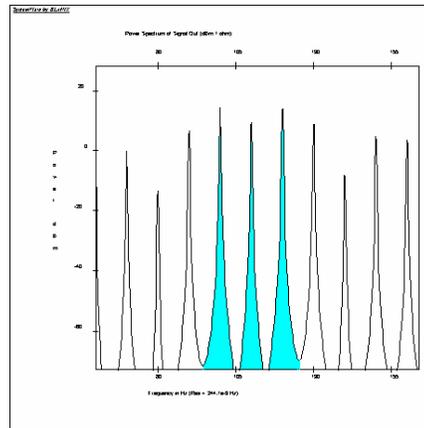
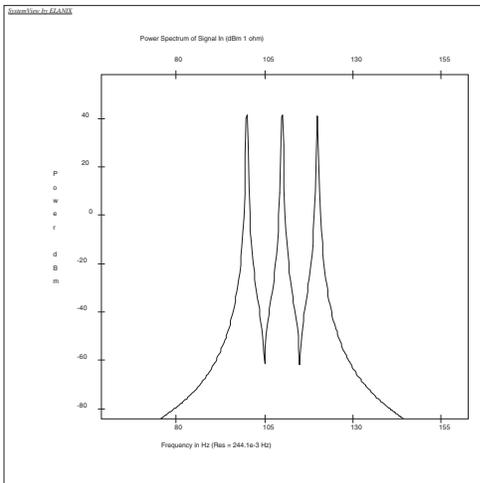


Figure 14a- Three equal carriers through a TWT, a. input signal, 2. Output signal (Note that the middle signal has been depressed.)

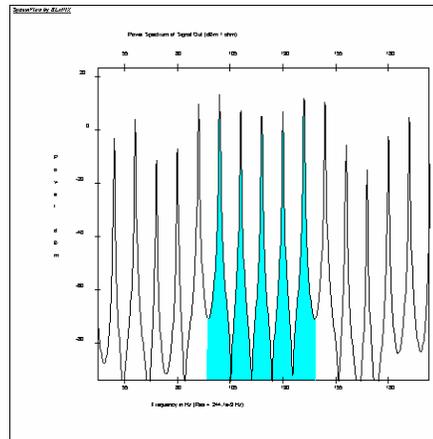
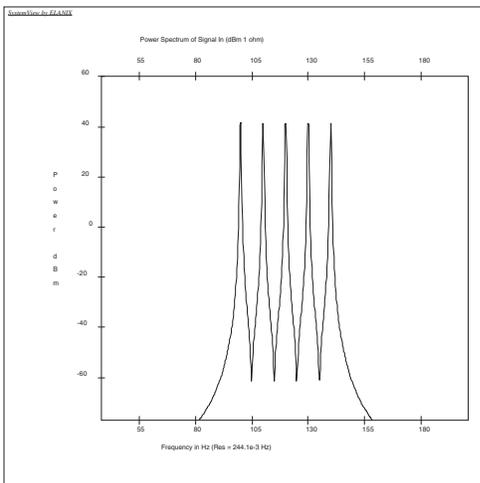


Figure 14b - Five Equal carriers through a TWT, a. input signal, 2. Output signal (Note that the middle signals are depressed.)

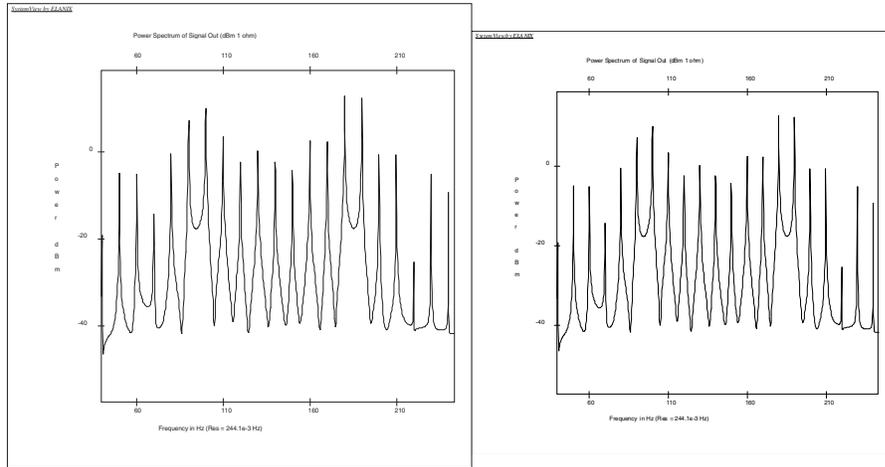


Figure 14c - Nine Equal carriers through a TWTA, a. input signal, 2. Output signal (Note that the middle signals are depressed.)

NPR

The Noise Power Ratio (NPR) is a useful Figure of Merit when we have many carriers. It shows the effect of many carriers on one particular carrier. With C/3IM we have an indication what happens at the band edge when two carriers are used. NPR on the other hand gives an indication of what happens to one of the in-band carriers when there are many others carriers present.

Noise Power Ratio (NPR) is a test of non-linearity that comes from Telephony and applies not just to TWTA but to any system level DUT. NPR can be performed on whole receivers or systems. In a typical telephone band, there are numerous line carriers. A test where one of these line carriers is left out and then noise power in the empty band is measured corresponds to the NPR. This measured noise in the target channel is a function of “leaking” into this band from other carriers. The NPR test standardizes this form of testing and is conducted as shown in Fig. 15 below.

NPR is defined as

$$NPR = \frac{\text{Power level in the noise signal}}{\text{Power level in the notch}}$$

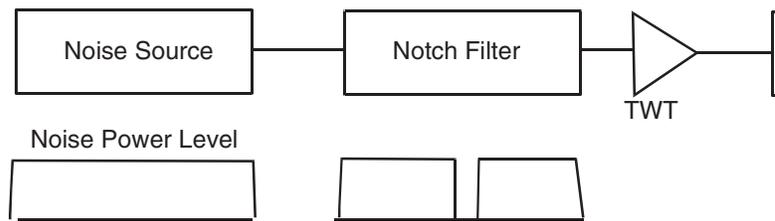


Figure 15 - NPR Test Set-up

A wide-band noise source is generated. The noise signal is then filtered by a narrow notch with as much rejection as is practically possible. Let's say that we were able to reduce the level in the notch to 40 dB below the noise power level.

Now this notched filter is put through the TWTA. The non-linear effect of the TWTA is to generate intermodulation products that tend to fill this notch. Now the new noise power in the notch is 20 dB below the noise power. NPR is then defined as the ratio between the signal input noise power and the signal notch output power.

How does NPR compare with C/3IM? This is not a really valid question because they are not equivalent. The two parameters look at different aspects of the non-linearity but it is a question that is often asked. We can say in general that NPR is always less than C/3IM, because it shows the response to many carriers vs. the two tones for the C/3IM. A behavior for one particular TWTA is shown below.

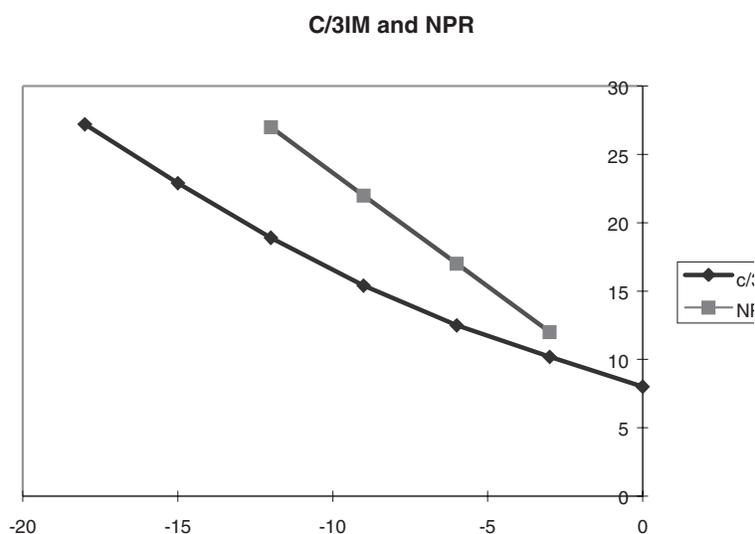


Figure 16 - Comparing C/3IM and NPR (Note error: The labels are reversed)

1 dB Compression Point

1 dB Compression point is rarely used for TWTAs as but is often used for other amplifiers such as LNAs, and sometimes for SSPAs.

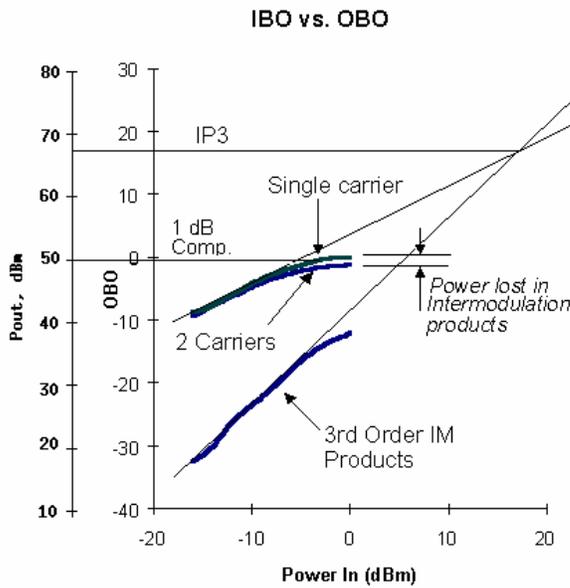


Figure 17 - 1 dB Compression Point is a measure of the non-linearity

The 1 dB compression point is that drive level where the power-out in dBm is 1 dB less than the perfectly linear case. Extend the slope of the linear part of P_{in} vs. P_{out} curve and the point on the AM/AM transfer curve where this straight line rises 1 dB above the actual P_{out} , is the 1 dB compression point. See Fig. 3.

For the case above, the 1 dB compression point for P_{out} is app. 46 dBm. The relationship is given by

$$P_{out} \text{ (at 1 dB Comp. Pt)} = P_{in} \text{ (at 1 dB Comp. Pt)} + \text{Linear Gain} - 1 \text{ dB}$$

(A Rule of Thumb: the 1 dB compression point is usually 6 dB below saturation power.)
Intercept Points

A method of specifying non-linearity that is closely tied to the 1 dB compression point method of specifying non-linearity is called the Intercept Method. The method requires the same test data as C/3IM with two tones. IM levels are measured and plotted. Then a tangent is drawn to the IM vs. IBO line. The point where this line intersects the tangent to the fundamental curve is called the 3rd order intercept.

The third Order Intercept point is generally about 10 dB or more above the 1 dB compression point.

What can we do to make TWTAs less non-linear

Most of the system components used in communications systems are considered linear. This means that the output is directly related to input. A sine wave remains a sine wave with the same phase and an impulse remains an impulse even though its amplitude may be reduced or amplified. The behavior is also constant over a given frequency range.

In addition, the output of a linear system contains only those frequencies that were transmitted and no others. Any other frequencies that may be present in the output are considered distortion, the result of non-linear behavior. (However, spurious responses that are not related to the input frequencies in any way, are usually not considered a non-linear response.)

TWTAs are notable primarily because their behavior is not linear. Since this results in spectrum distortion, mitigation of these effects is important. One method of mitigating the nonlinear behavior of a TWTA on the signals is to use a technique called pre-distortion.

In Fig. 18b, the AM/AM transfer response of a typical TWTA is shown. If we distorted the signal as shown in 18a, then the sum of the pre-distorted signal and the TWTA distortion would cancel out the TWTA non-linearity and give us a linear AM/AM transfer curve as in Fig. 18c. This is the principle of operation of a linearizer.

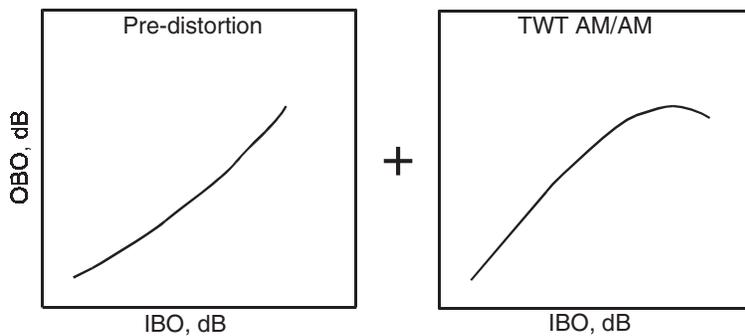


Figure 18a. Pre-Distortion, b. TWTA response, c. Sum of two is quasi-linear.

We can do the same thing to the phase rotation caused by the TWTA. The linearizer has to be matched to the characteristics of the TWTA in order to produce the maximum beneficial effects.

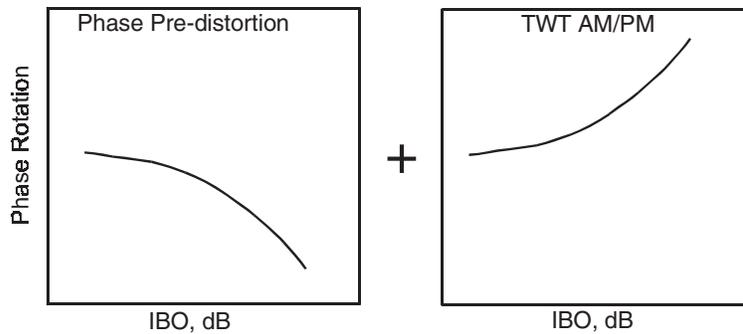


Figure 19a. Phase pre-distortion, b. TWTA Phase distortion, c. Sum of two is linear

A linearized TWTA (called LTWTA) has an expanded linearized region so we can operate closer to saturation and get smaller non-linear effects. However, we don't get something for nothing. The benefits of a linearized TWTA are not realized for all traffic configurations and in some cases the use of a linearizer is actually disadvantageous. These disadvantages come from

1. Gain distortion near peak.
2. Difficult to match or tune the linearizer so optimum performance can be obtained
3. Not suitable for all traffic types
4. Requires expenditure of additional RF power and adds weight to the system

In the figure below we see the comparison of a TWTA and LTWTA. Two behaviors are notable.

1. The linearized AM/AM transfer curve crosses the non-linearized curve not at 0 dB but slightly to the left. This says that when using a linearized TWT, maximum power is not obtained at saturation but at slightly less than that.

2. We see that the LTWTA gain (Fig. 21) has a slight hump near saturation. The maximum gain occurs at app. -3dB IBO which corresponds with the conclusion in Behavior 1. The hump introduces some non-linearities of its own which we see in the $C/3IM$ curve for a linearized TWTA. $C/3IM$ curves of LTWTAs are not nearly as regular as the non-linearized TWTA's. There are places in the operating curve of LTWTAs, where the fifth order products are higher than the third order products.

Linearized vs. Non-Linearized TWT AWAM Behavior

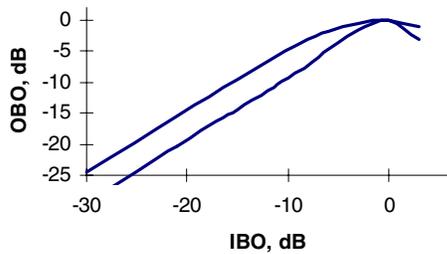


Figure 20 - IBO vs. OBO for a LTWTA vs. TWTA

Linearized vs. Non-Linearized TWT Gain Behavior

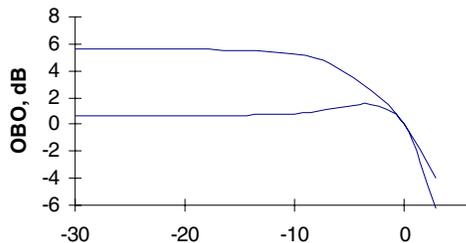


Figure 21 - Gain vs. OBO for a Linearized vs. non-linearized TWTA

The C/3IM and the NPR behavior of a LTWTA vs. the non-linearized TWTA holds some surprises. Although both the C/3IM and the NPR for the linearized tubes are better than the non-linearized tube, the pattern has some unexpected bumps. These come from points where occasionally the fifth order products rise above 3rd order products.

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