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NPR AND INTERMODULATION DISTORTION MODELLING OF TRAVELLING-WAVE TUBE AMPLIFIER OF TELECOMMUNICATION SPACECRAFT

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ABSTRACT

Communication satellite RF technologies are in a dynamic course which are being developed swiftly today. Interest in the design and production of payload systems which claim more capacity demanding multi-carrier operation, which can meet variable throughput requirements during orbital lifetime, is expanding. The purpose of this study is to examine the conceptual wideband multi-carrier intermodulation performance and noise power ratio (NPR) test performance estimation of the satellite repeater system with modeling and simulation measurements through MATLAB SIMULINK. The obtained results from the simulations are in line and in correlation with the predetermined subsystem specifications and telecommunication satellite project requirements.

Keywords: ***Behavioral modelling, Travelling-wave Tube, microwave amplifier, power amplifier tests, Simulink***

INTRODUCTION

Nonlinearity of an amplifier system is one of the key performance merits and requirements of the communication satellite transponder in order to perform its operation with linear input-output transfer characteristics to be able to neglect channel impairments like inter-symbol and in-band channel interference from adjacent carriers. There are numerous performance aspects which are related with and caused by these nonlinearities such as intermodulation interference and adjacent channel interference which lead to undesirable power consumption and dissipation and power inefficiencies [Liang, 1999]. The most challenging issue for TWT design is to operate as close as possible around saturation point for power output and efficiency whilst having very less nonlinear effects such as intermodulation distortion (IMD) [Carter, 2001]. Several test methods exist to be performed in the design and manufacturing phase of repeater equipments in order to verify the transponder nonlinearities and interference caused by intermodulation distortion which must be below the required system level values and verify the noise power added to the wanted signal in the transmission chain.

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One of these methods is a 2-tone harmonic balance experiment which is the test of multi-carrier continuous waveform (CW) insertion into the transponder where at least 2 carriers with same power level are amplified through the output section of repeater subsystem and the output spectrum is measured in terms of intermodulation levels before the injected stimulus signal is propagated through output multiplexer (OMUX). The second approach is the noise power ratio (NPR) test which a white Gaussian noise is generated to fit the amplifier bandwidth and then notched with a filter in the center frequency in order to observe and measure the noise level increment inside this notched channel bandwidth after the amplification through the repeater output section. For the following sections of this paper, several methods for modelling TWT's and verification of such nonlinearities are discussed as; TWTA modelling and model verification, NPR testing and simulation, intermodulation distortion testing and validation considering an equipment level TWT of telecommunication payload.

TRANSPONDER NONLINEARITY & TEST METHODS

TWTA Modelling

Travelling-wave tube amplifier (TWTA) is an amplification unit in a communication satellite which amplifies the input signals coming from uplink channels from several micro or miliwatts through the repeater RF transmission line up to several hundreds of watts. It is essential that the TWTA is sufficient to supply the required output power with low intermodulation and thermal noise [Saabe, 2015]. TWTA units onboard telecommunication spacecraft are in a compact form factor defined as microwave power module (MPM). MPM has three main sub-modules; electric power conditioner (EPC) which supplies the required anode voltage for one or two TWTs and regulates the power distribution among units, channel amplifier or driver (CAMP) which drives the input signal to TWT with several modes (fixed gain (FGM) or automatic level control (ALC) modes) and a TWT. In this paper, channel amplification section where digital pre-distortion lineariser with feedback loop to reduce the intermodulation distortion effect, providing amplitude and phase expansion to compensate phase nonlinearities and amplitude mismatch implemented digitally on FPGA level is not modeled to gather individual power transfer model, NPR and intermodulation performance of TWT since any nonlinear device before TWT (downconverter, receiver, channel amplifier etc.) will introduce additional noise and cause the TWT input signal SNR to decrease [McMorrow & Yates, 1994].

The nonlinearity functions of of TWT's used in this research are modelled with the Saleh Model [Saleh, 1981] which is a memoryless power amplifier model and usually well suited for modelling TWT's rather than Rapp or Ghorbani's nonlinear amplifier models, which develop significantly better results for Gallium Arsenide (GaAs) and Gallium Nitride (GaN) high-electron-mobility transistor (HEMT) solid state power amplifiers (SSPAs). As indicated by Saleh, the input (x(t)) and output signal (y(t)) power functions can be written in terms of carrier frequency (ω_0), modulated envelope (r(t)) and phase (Ψ(t)), such amplifier transfer trajectories obtained are modeled with several coefficents with a curve fitting algorithm. Input and output functions are written in terms of frequency, amplitude and phase which are time dependent as given in equations below:

$$\boldsymbol{x(t) = r(t)cos[\omega_0 t + \Psi(t)]} \tag{1}$$

$$\boldsymbol{y(t) = A[r(t)]\, cos\{\omega_0 t + \Psi(t) + \phi[r(t)]\}} \tag{2}$$

where A(r) is the odd function of r and $\boldsymbol{\phi}$ is the even function of r(t). Generalized formulation of Saleh model (which is z(r)) is computed according to the procedure described here where z(r) and r are memoryless TWT's input and output envelopes.

$$\boldsymbol{z(r) = \frac{\alpha r^n}{(1+\beta r^2)^\nu}} \tag{3}$$

Where n is defined as 1 for amplitude modulation (AM/AM) transfer and 2 for phase modulation (AM/PM) transfer for output envelope z(r), v is 1 or 2 (can be either non-integer values for the best curve fitting trial). “n” can also be selected as 3 for quadrature amplitude transfer. Then it is obtained that the general formulation of amplitude and phase transfer curves related to modulated input signal envelope “r(t)” are;

$$A\big(r(t)\big) = \frac{\alpha_A r(t)}{\big(1+\beta_A r^2(t)\big)} \tag{4}$$

$$\phi\big(r(t)\big) = \frac{\alpha_\phi r^2(t)}{\big(1+\beta_\phi r^2(t)\big)} \tag{5}$$

The A is a function which represent amplitude deviations of output signal and ϕ is a function which represents phase deviations of the output signal which is mostly distorted owing to transponder multicarrier nonlinear operational behaviour leading to intermodulation interference close to saturation point. The solution of coefficents α_A, β_A, α_ϕ, β_ϕ are found as outputs of minimum mean-square error curve fitting process. Considering the fact that z_i & r_i are measurement duos for input signal envelope and output signal, with n = 1 for AM/AM and n =2 for AM/PM coefficents α & β in the equations are found as given in the equation 7 & 8. below.

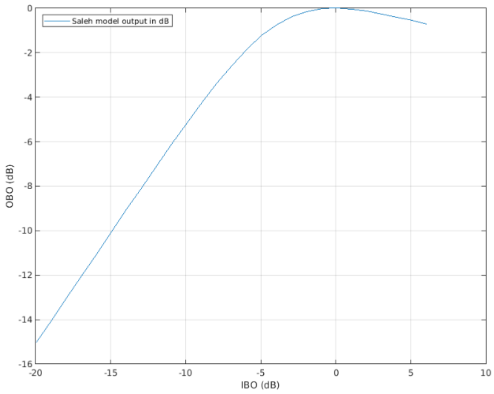
$$w_i = \left(\frac{z_i}{r_i^n}\right)^{-\frac{1}{v}}, i = 1, 2, \dots, m \tag{6}$$

$$\alpha = \left\{\frac{\left(\sum r_i^2\right)^2 - m\sum r_i^4}{\left(\sum r_i^2\right)\left(\sum w_i r_i^2\right) - \left(\sum r_i^4\right)\left(\sum w_i\right)}\right\}^v \tag{7}$$

$$\beta = \frac{\left(\sum r_i^2\right)\left(\sum w_i\right) - m\sum w_i r_i^2}{\left(\sum r_i^2\right)\left(\sum w_i r_i^2\right) - \left(\sum r_i^4\right)\left(\sum w_i\right)} \tag{8}$$

After implementing the modelling approach described previously, obtained α_A, β_A, α_ϕ & β_ϕ coefficents of the TWT under test are converged to 1.76, 0.68, 2.36, 0,41 with v = 0.5911 respectively. Resulting root mean squared error analyse between the measurement and modeled TWT AM/AM curve is 0.015 which is equal to 0.2606 W of average output power error in signal amplitude envelope. In Matlab Simulink simulation domain, corresponding TWT is modeled with 28 dB noise figure which is distributed as white noise with an input power scaling of 15 dB and output power scaling of 30 dB respectively. This procedure with nearly the same results can be obtained with an alternative approach such as implementing the hyperbolic tangent technique with linear gain of 57.654 dB with third order input intercept point (IIP3) of around “-1” dBm where the desired fundamental (first order terms having a slope 1:1) tone and 3rd order interception (TOI) line (3rd order intermodulation terms having a slope 3:1) cross each other around -1 dBm input power at driver (channel amplifier) output or TWT SMA coaxial input. TOI is generally used as figure of merit for harmonics or IMD testing, the higher it is the slower the TWT saturates.

First the TWTA model characteristic transfer curves are generated with the Simulink RF modelling by defining an amplifier with the obtained Saleh model coefficents. TWT’s under test which are modeled have around 57.5 dB small signal gain, 56.5 dB gain at 1 dB compression point and have approximately 51 dB gain at saturation point. The TWTs can supply 157 Watts or 51.967 dBm at saturation point in Ku frequency band. After the TWT AM/AM transfer curve is modeled with Saleh modelling approach and converted into Simulink environment, it is simulated with corresponding driver power levels and then extracted the power transfer as given in the TWTA AM/AM transfer curves Figure 2 below, where complementary cumulative distribution function (CCDF) analyse results gave average power of 51.98 dBm at saturation point with 6572544 of sample count. Resultant modeled TWT has 57.61 dB small signal gain, have 56.6 dB gain at 1 dB compression,have 50.194 dB gain at saturation and can deliver 155 W of RF output power to OMUX at saturation which is equal to 51.905 dBm.



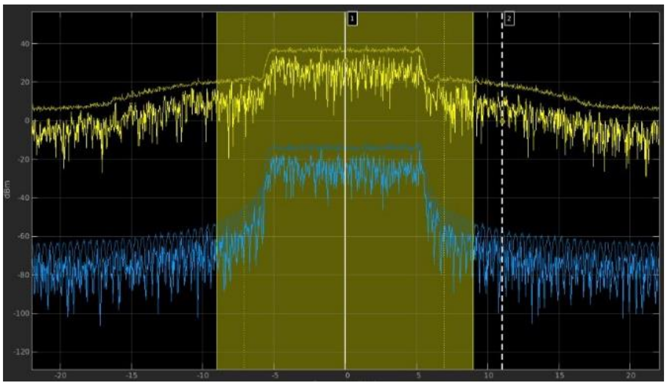


Figure 1: TWTA Saleh model output power modeling results for AM/AM transfer with respect to input back-off (IBO) [dB] (left) and saturated output spectrum of modeled TWTA (right).

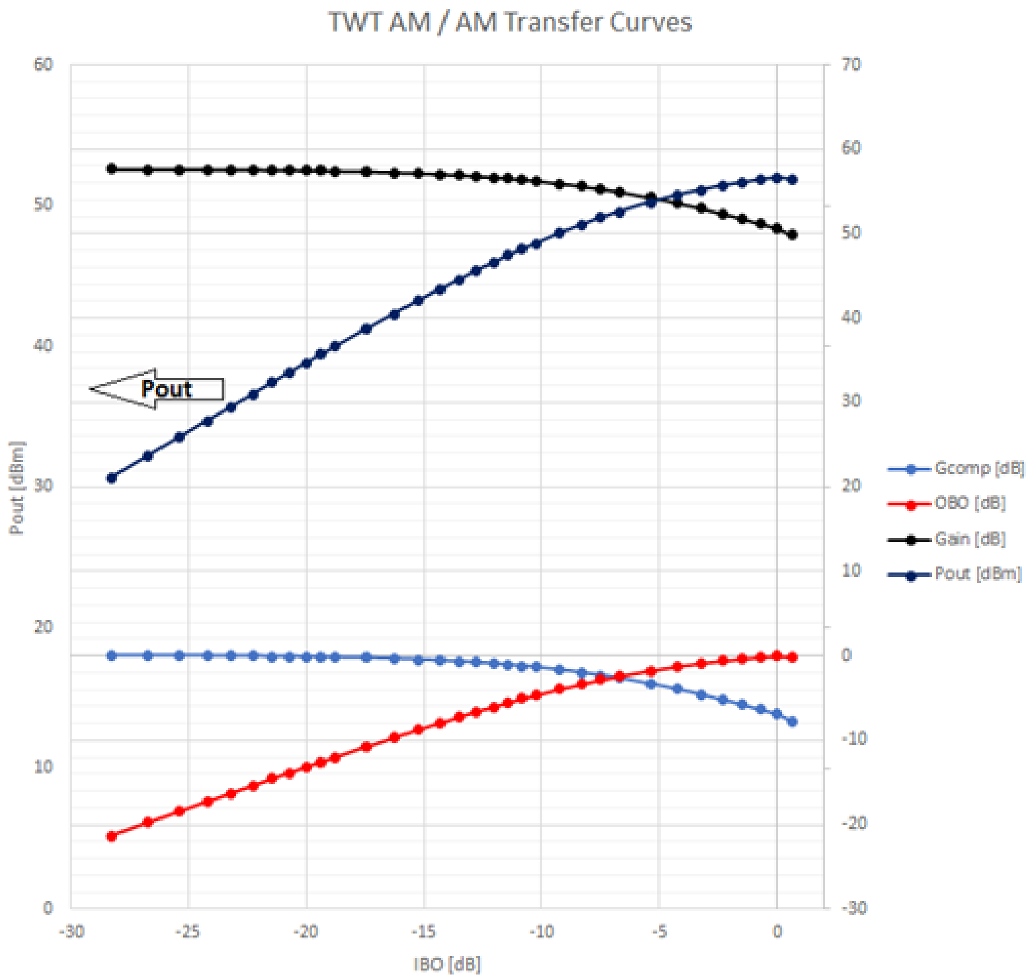


Figure 2: Behavioral model of Simulink modeled TWTA drived with a QPSK modulated carrier AM/AM power and gain transfer curve results with respect to input back-off level (horizontal axis), gain [dB] (black), OBO [dB] (red), gain compression [dB] (blue), output power [dBm] (dark blue) curves from small signal until saturation.

Noise Power Ratio (NPR) Test

Noise power ratio (NPR) is a concept which helps to assess system performance under full spectrum of traffic load and unwanted interferer signals, generally defined as a spectral analysis to determine systems spurious-free dynamic range [Agilent Technologies, 2000]. NPR of an power amplifier of satellite transponder is validated injecting a specific waveform by generating a noise, filtering in bandpass then filtering with notch filter in the center of useful channel bandwidth. Then the same approach is conducted as employed like other repeater performance tests, the input power of NPR stimulus is gradually increased and the power difference levels between the notched center frequency and in the useful bandwidth is measured with spectrum analyzer. The key point in the NPR test is the notch filter attenuation must be at least 50 dB to achieve high notch depth in the power spectral density for measurement granularity. Also the notch width must be considered between 1% – 10% of the transponder useful bandwidth. However, the determination of the notch width of the band-stop filter has trade-off in terms of signal state when it is wide, ambiguity of noise power due to small number of tones inside the notched bandwidth when it is narrower [Mallet, 2002]. The configuration of the test set-up is given in the Figure 3 below. Typical NPR multicarrier satellite systems operation requirement can be defined as 20 dBc.

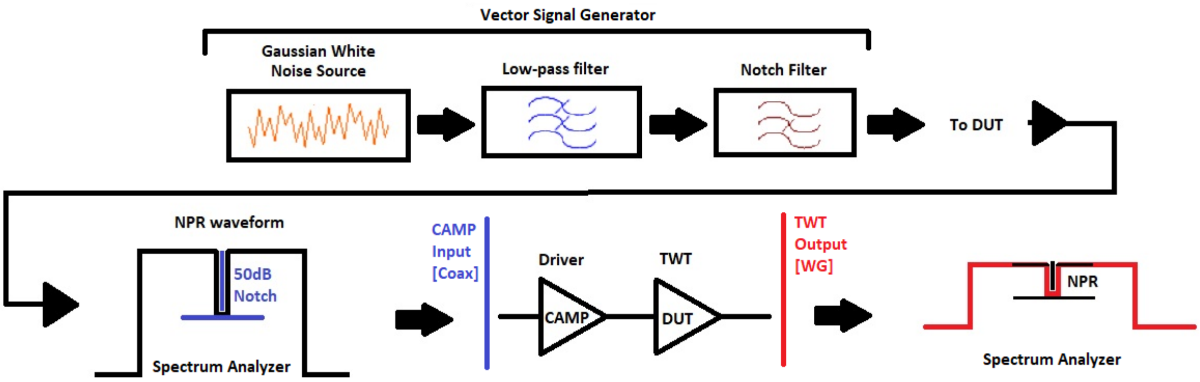


Figure 3: NPR measurement approach, input test signal generation, spectrum before TWT, driver – channel amplifier, device under test – TWT configuration and measured output signal spectrum after nonlinear amplification.

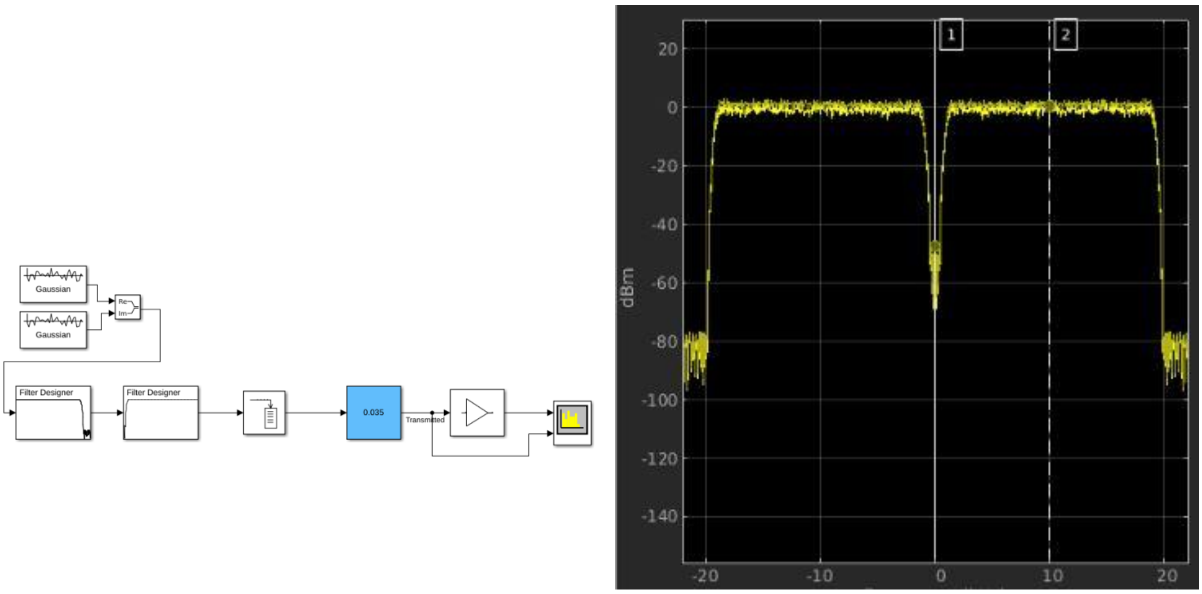


Figure 4: TWTA NPR test set-up prepared in Simulink (left) and digital TWTA NPR test stimuli with at least 50 dB notch depth and 1% notch bandwidth (right), y axis is input signal power level and x is frequency of input test stimuli.

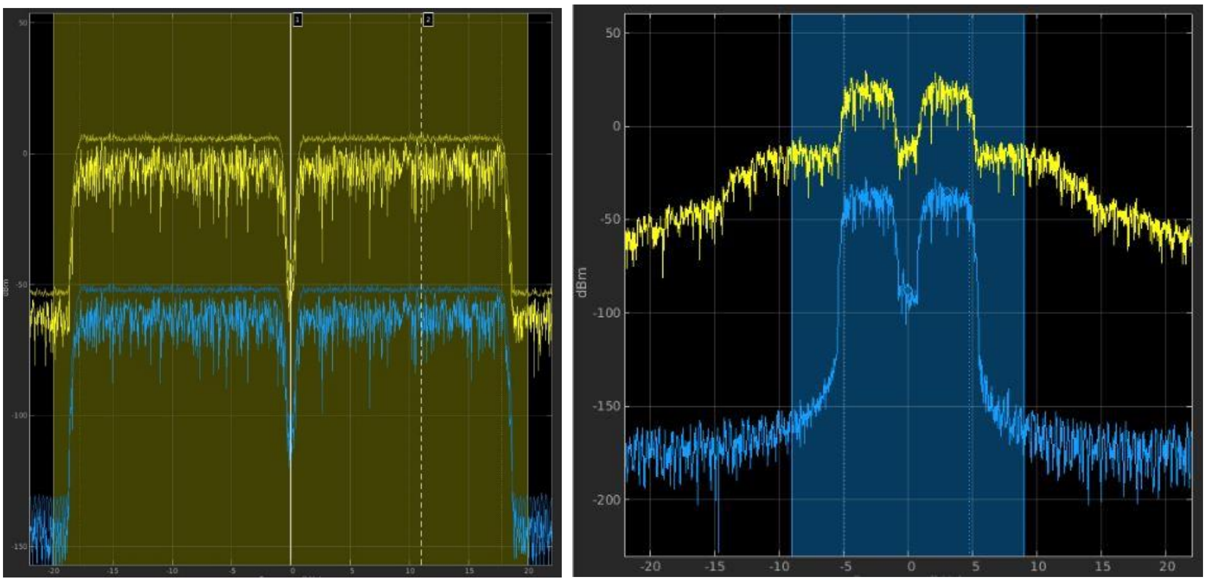


Figure 5: TWTA NPR test input stimuli (blue) and signal NPR response at output of DUT (yellow), measurement at small signal (linear) starting region (left), NPR test response spectrum at output of DUT (right) with 20% notch width (right), y axis is input & output signal power level and x is frequency.

Intermodulation (C/I3) Test

Intermodulation and noise can always be generated with an active power transmission system operating with multi-carriers. IMD has origins around nonlinearities in electronics. Such devices generate harmonics which are multiples of input signals in frequency domain, moreover, intermodulation interference is the key result of these harmonics. It is essential that before the testing of the transponder system it is a must to verify the transmission elements individually. Therefore, it is needed to clarify the nonlinearity performance of TWT for this subject. First thing to consider for the TWT nonlinearity is the intermodulation products. The test for intermodulation products is conducted with two separate tones where the spectral power densities of both tones are raised with same increments. At several test points the output spectrum of the test setup is saved with an analyzer and compared the levels of intermodulation to the useful tones which is as described in Figure 6 below.

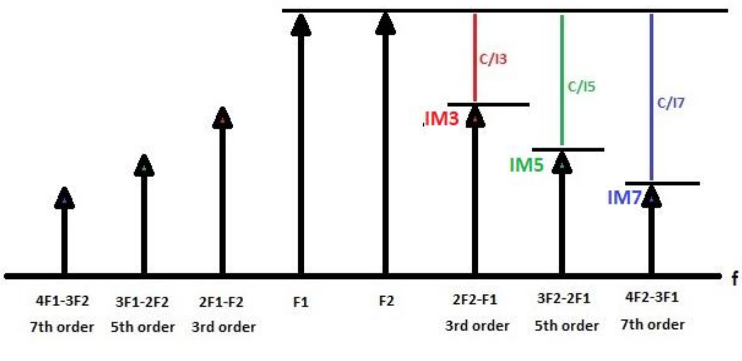


Figure 6: 2-Tone intermodulation harmonic balance output spectrum in a typical channel bandwidth, intermodulation orders and power of carrier to intermodulation level (C/I3 – C/I5 – C/I7) representation.

The most distinctive intermodulation product in terms of power is the 3rd order intermodulation which is the closest one to these two tones. Generally 5th and 7th order intermodulation products are negligible in terms of power; however, they are also considered as intermodulation which contributes to the overall nonlinearity of the amplification system. Number of tones may be increased at the input to check higher order intermodulation products As a side note, NPR test is more relevant when considering multi-carrier operation (typically 6 or more carriers share the same TWTA), however the amplitude linearity validation or intermodulation test (C/I3) is compliant to verify all the conditions and multi-carrier amplification scenarios.

SIMULATION RESULTS

Simulation results and obtained analyse outputs are presented and visualized in this section. The TWTA equipment level requirement curves for NPR and IMD are plotted with red colour on the output result graphs for better comparison. For NPR testing and validation, we introduce three notch width on the same bandwidth: 20% (in fact it is a poor measurement case for wideband NPR), 5% & 1% with same notch depth constant as 50 dB. As seen from the Figure 8, the worst NPR result case is observed for 1% notch width as it is anticipated since closer the carriers higher the NPR. Test results are obtained as the power level difference from the amplitude levels of the output signal and power level inside the notch in the center. Before -15 dB IBO level, the operation is assumed to be linear and noise levels increase with the increment in input power level. After this input level (around -14 dBm), the signal nonlinearities at the output spectrum are observed and the noise levels increase nonlinearly with steady increase of the input power. Distinctively sharp, steep and continuous decrease of the NPR is observed at this level until saturation status is achieved. Simulation results never crossed the specification during the measurement as it is seen from Figure 8.

For intermodulation modelling of TWT, it is two-tone continuous wave signal injection at the input and the tones which are separated with 40 MHz apart from each other at 12.1 GHz center frequency, which is the center of the middle Ku band. Measurments for the results are obtained for 3rd, 5th and 7th order intermodulation products from the output spectrum. Test results are analyzed with peak marker injection to output spectrum, then taking difference of the IMD product levels from the maximum fundamental tone levels at F_1 & F_2 which are at 12.08 and 12.12 GHz. The output spectrum of the intermodulation distortion products for assesment and obtained simulation results can be seen from the Figure 9, 10 & 11 respectively. Output spectrum power fundamental tone and intermodulation product levels can be seen from Figure 9 (left) and carrier to intermodulation level from Figure 9 (right). Simulation results never crossed the specification during the measurement for IMD case as well as NPR simulation. The curve on the right is calculated from the left by subtraction of corresponding intermodulation level from the fundamental tone level. The third order intercept point (IP3) is computed as 60.65 dB for average and 57.43 dB at saturation.

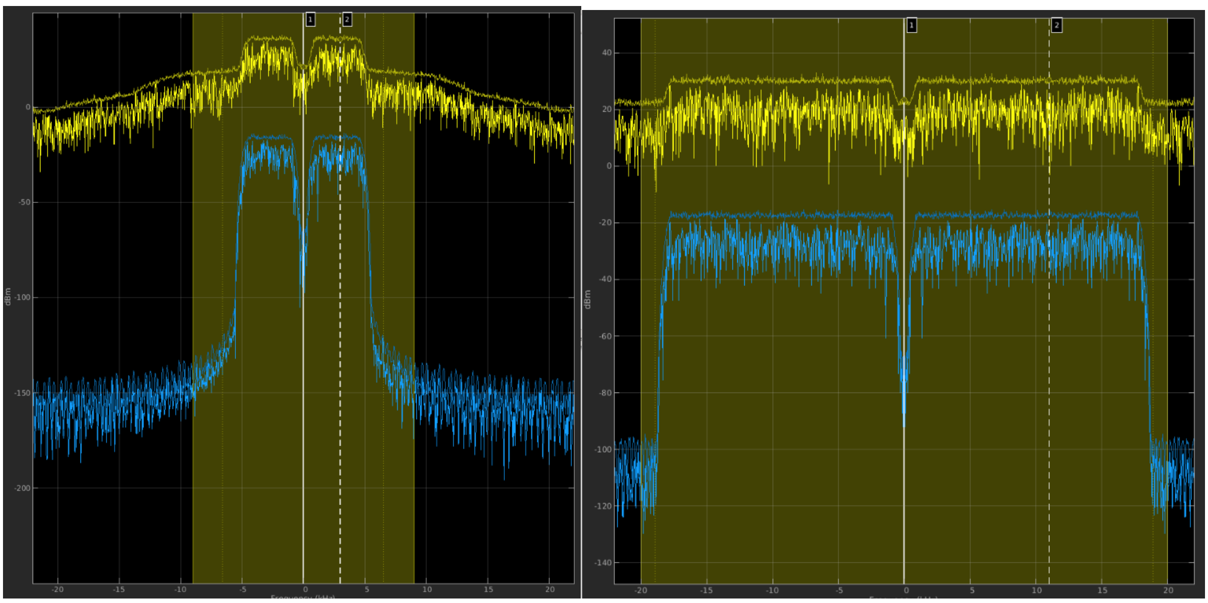


Figure 7: NPR stimulus at 1 dB IBO with 5% notch width and output spectrum (left), NPR stimulus at 1 dB overdrive with 1% notch width and output spectrum (right), y axis is input & output signal power level and x is frequency.

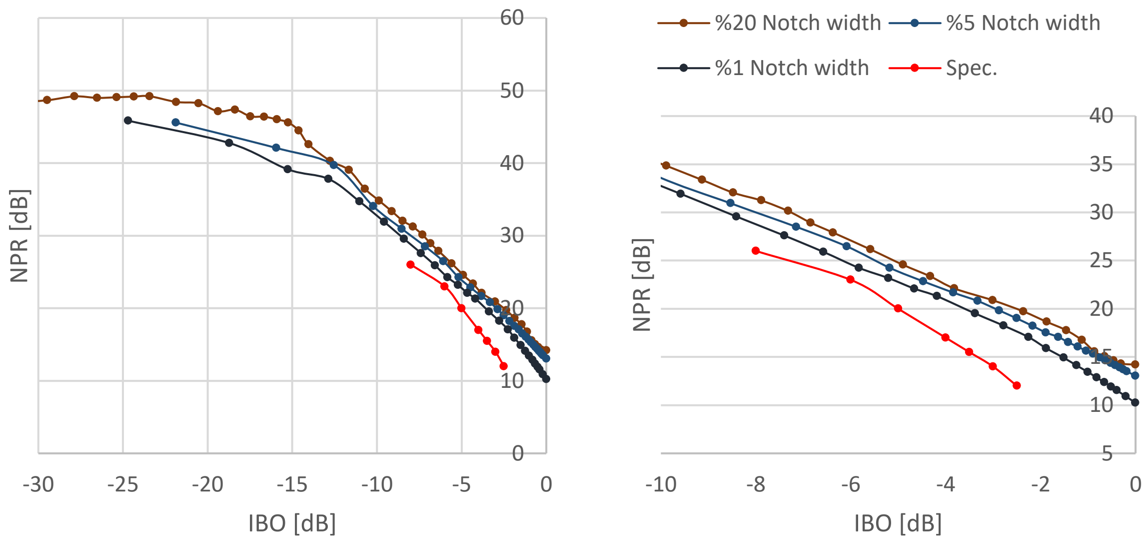


Figure 8: TWTA NPR simulation results for several notch widths vs. IBO [dB] with respect to specified requirement, for small and large signal measurement case (left) & for large signal measurement case (right).

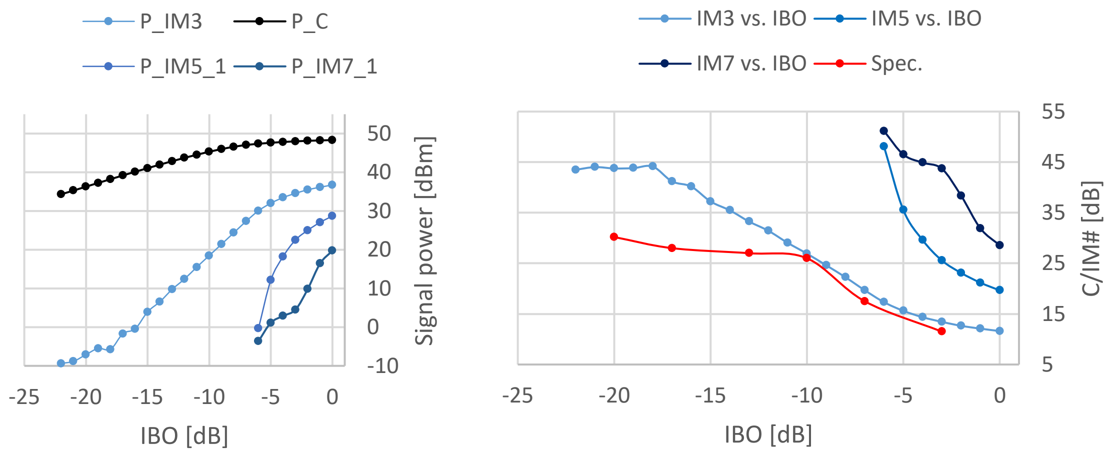


Figure 9: Intermodulation simulation IMD power levels from output spectrum analyse results of TWTA with respect to input back-off level, carrier power of one of the tones and intermodulation power (left), Carrier-to-Intermodulation (C/IM) ratio [dB] (right).

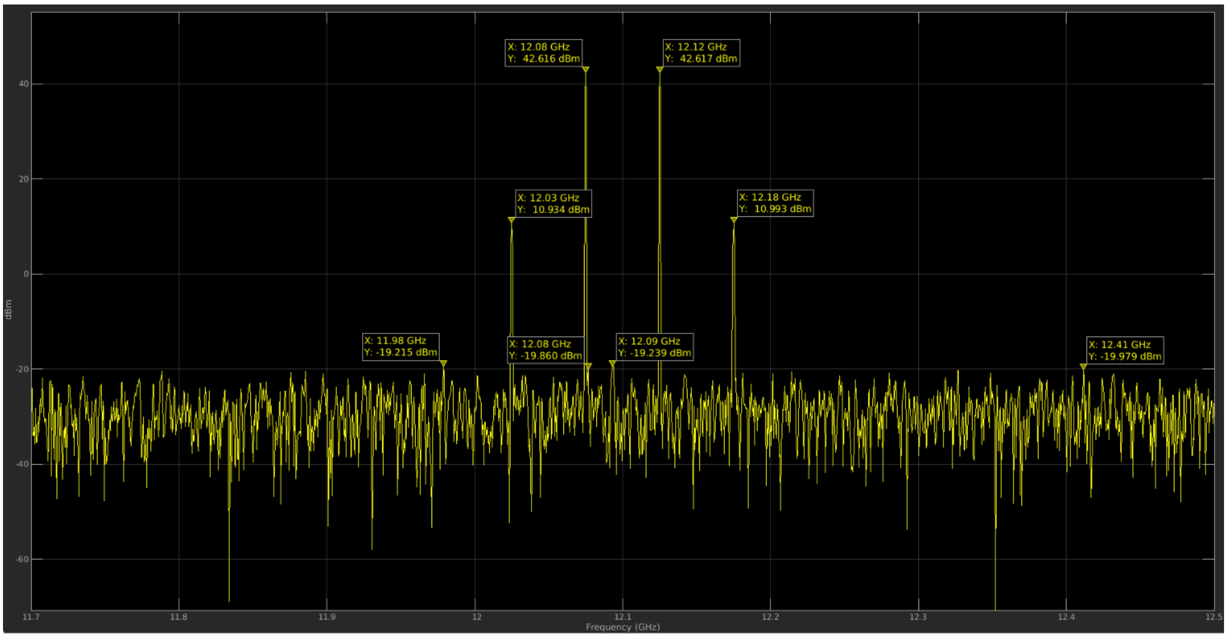


Figure 10: Wideband intermodulation products of TWTA and output spectrum at 1 dB gain compression point, y axis is signal power level and x is frequency in GHz.

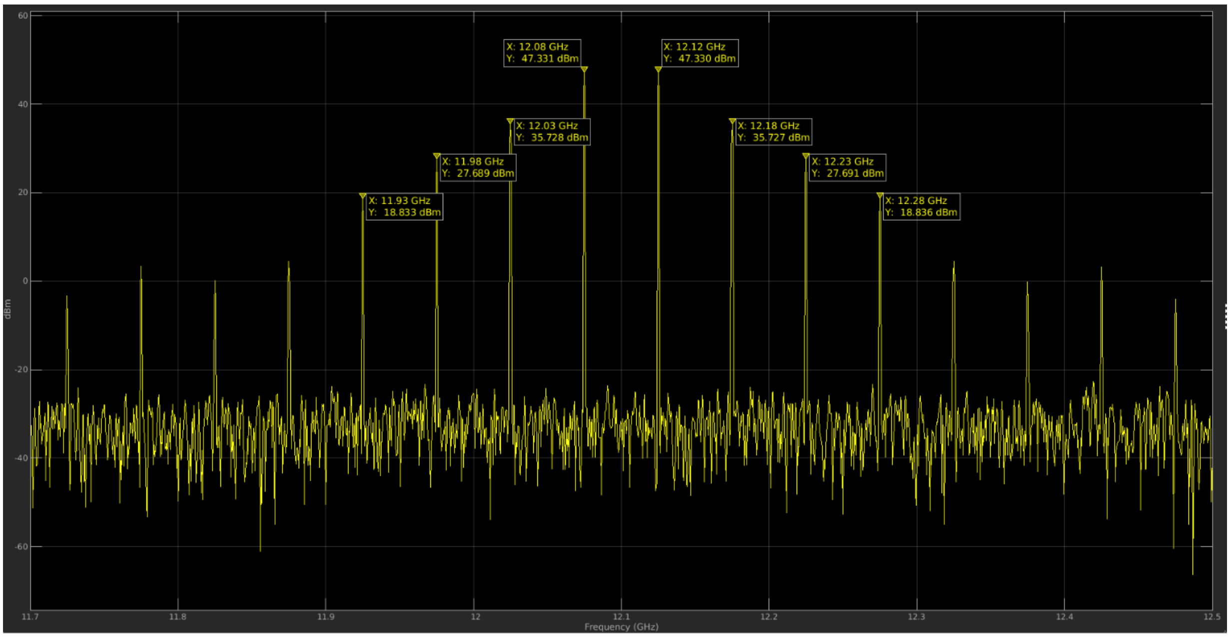


Figure 11: Wideband intermodulation products of TWTA and output spectrum at saturation point [(0, 0) dB IBO & OBO], y axis is signal power level and x is frequency in GHz.

CONCLUSION

NPR and IMD measurement techniques applied on telecommunication satellite communication module testing phases are discussed and analysed in this paper then realized with practical and rational modelling approach on Matlab Simulink environment. Models that are implemented showed good and accurate results, obtained results coincide with real test cases as well. NPR results have much lower values than IM3, IM5 & IM7 level analysis results since it is wideband spectrum stimulation technique and uses more bandwidth rather than such smaller capacity occupying 2-tone simulation approach. NPR test results could be improved and closer results can be obtained by applying a stimuli with 40 dBc notch depth to achieve higher NPR slope for a little early TWT saturation when the 50 dBc NPR stimuli results are compared to actual test results. There are still improvements and concepts to implement on the models in order to obtain higher accuracy for measurements such as application of memory effects and frequency dependent amplifier models since Saleh model is a memoryless and frequency independent amplifier model, developing a testbed tool for approximation of generic telecommunication satellite amplifier use cases. For further analysis and implementations, these obtained TWT nonlinearity models are going to be used and tested as an amplfication element for multi-port amplfier system of an high-throughput satellite transponder considering system level research and demonstrations for future projects such as flexible repeater output section.

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