



New Methods for HD Radio Crest Factor Reduction and Pre-correction

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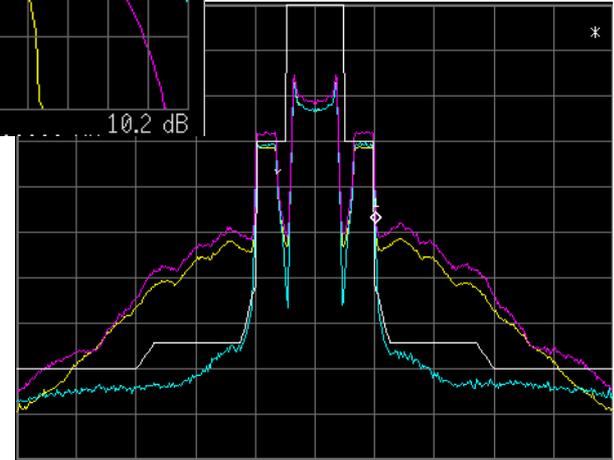
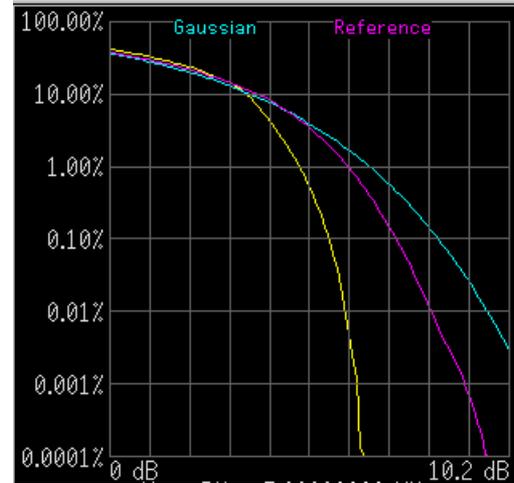
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Crest Factor and Intermodulation Distortion

The biggest challenge in amplifying orthogonal frequency-division multiplexed (OFDM) waveforms used for HD Radio and all other digital radio formats is:

- a) High Crest Factor of multiple carriers.
- b) Intermodulation products of multiple carriers



Crest Factor vs. Peak-Average Power Ratio



- Crest factor is a measure of a waveform, such as alternating current, sound or complex RF waveform, showing the ratio of peak values to the average value.
- Crest Factor is defined as the peak amplitude of the waveform divided by the RMS value of the waveform
- The peak-to-average power ratio (PAPR) is the peak amplitude squared (giving the peak power) divided by the RMS value squared (giving the average power). It is the square of the crest factor

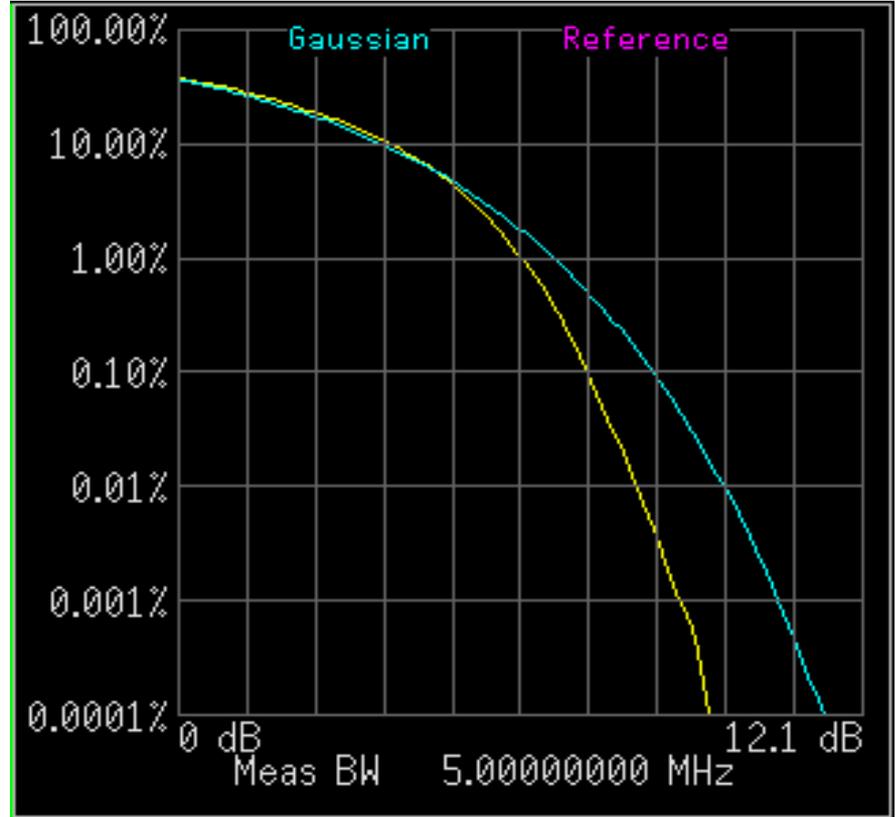
$$C = \frac{|x|_{\text{peak}}}{x_{\text{rms}}}$$

$$PAPR = \frac{|x|_{\text{peak}}^2}{x_{\text{rms}}^2} = C^2$$

- As a power ratio, PAPR is normally expressed in decibels (dB).
- When expressed in decibels, Crest Factor and PAPR are equivalent

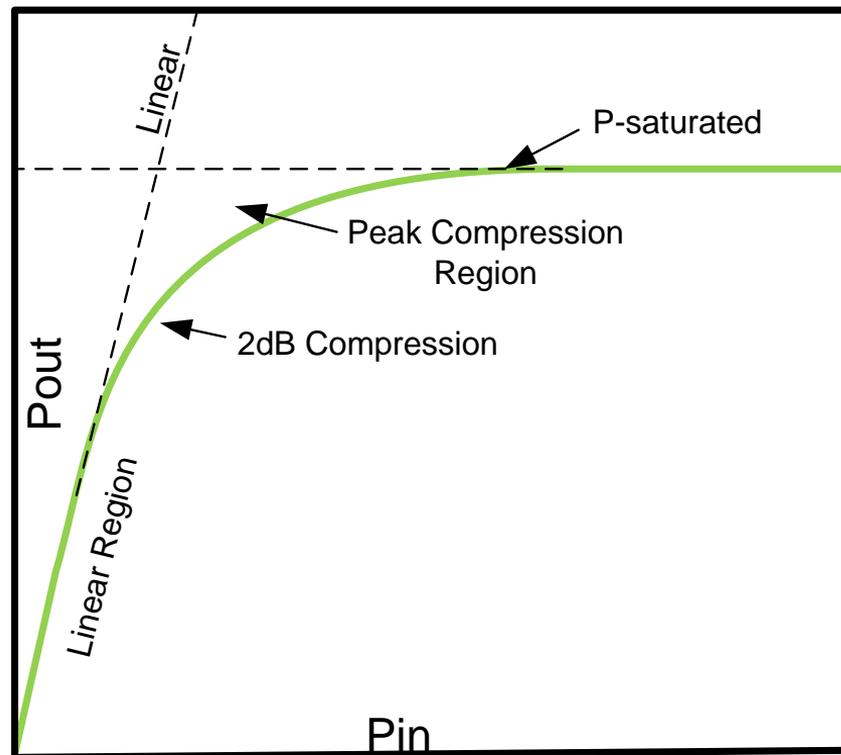
Peak Distribution

- The Hybrid HD Radio™ system uses up to 534 Orthogonal Frequency Division Multiplexed (OFDM) subcarriers modulated at equally spaced frequencies and 90 degrees to one another.
- Statistically, with this number of orthogonally opposed subcarriers, there can and will occasionally be very high amplitude peaks due to vector summation of the carriers.
- In a CCDF .01% distribution, these peaks are 10-12 dB above average power.
- This approaches the distribution figure of Gaussian noise



Peak Distortion

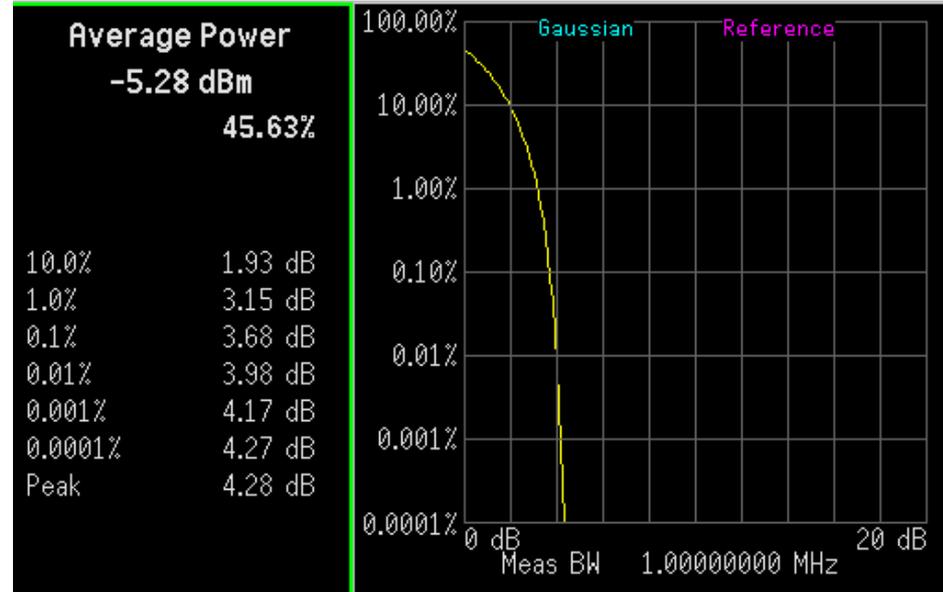
- Because of these peaks, linear power amplifiers used in the transmitters need to operate with large power back-offs to minimize peak distortion.
- Any given linear amplifier has some "peak output power"—some maximum possible instantaneous peak amplitude it can support and still stay in the linear range
- Peak distortion caused by non-linearity introduces noise to the subcarrier modulation, exacerbating intermodulation distortion products and generating out-of-band emissions.
- Without further crest factor reduction, amplifiers would be expensive and inefficient.



PAR1 Peak Reduction



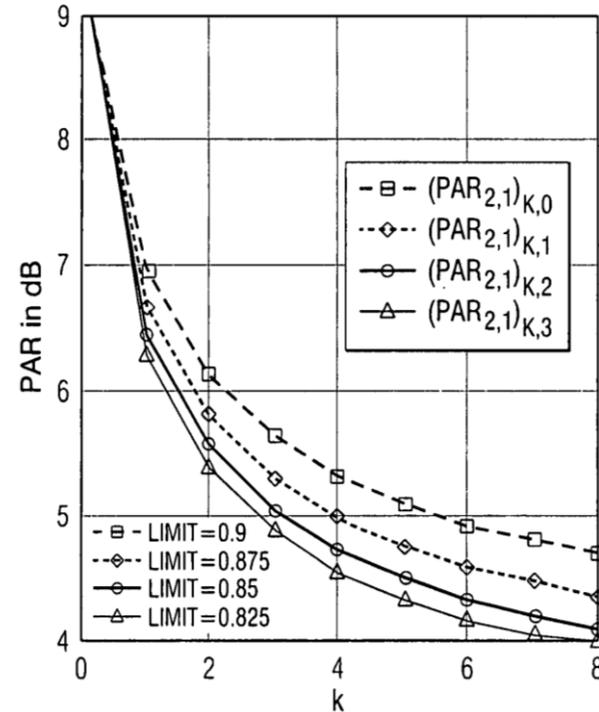
- Under the “original” iBiquity PAR1 peak reduction algorithm the OFDM signal alone is modestly clipped and filtered once, yielding an HD-only PAR of around 8dB
- When combined with analog FM at -10dBc (10%) injection ratio the .01% distribution crest factor is 3.98 dB with total peak power of 4.28 dB.
- Almost 2.75kW of linear amplification is needed to produce 1kW of FM+HD at -10.



PAR2 / Hybrid Crest Factor Reduction



- PAR2 / HCFR uses a predictive summation of the peak magnitude of both the analog FM and digital waveform to calculate a resulting peak vector and apply multiple iterations of demodulation, intelligent clipping, restoration and re-modulation of the input signal vectors.
- While the first iteration produces the most dramatic reduction to a PAPR of around 8dB, each subsequent iteration further reduces the PAPR a bit more at a rate of diminishing returns
- Eight iterations of crest factor reduction produces the best trade-offs of peak reduction, distortion, MER and resource utilization.

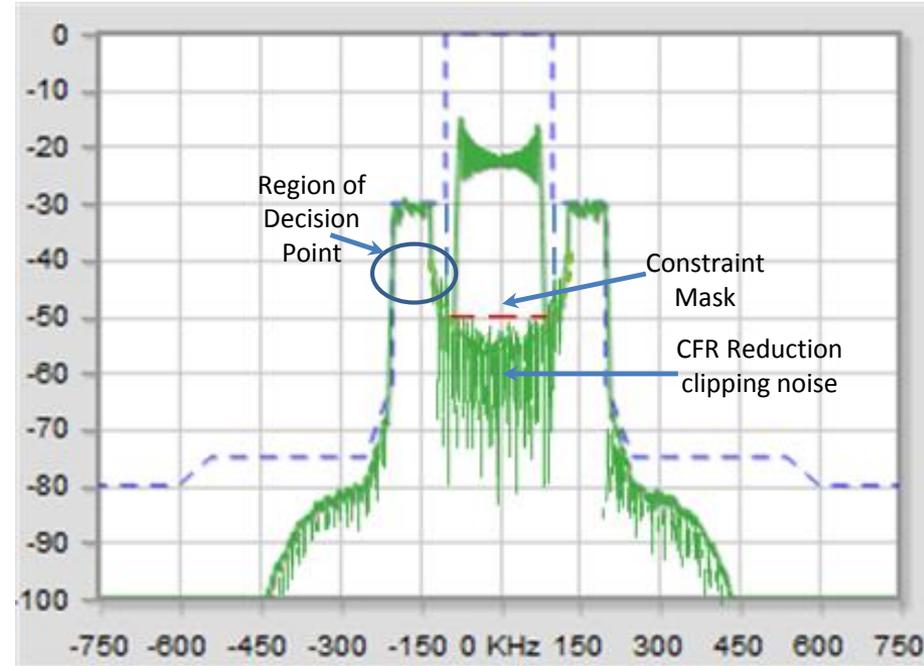


Graph showing simulated average PAR results for PAR2/HCFR reduction algorithm for HD Radio™ FM Hybrid mode MP1 over a range of constraint values (limits between 0.825 and 0.9)

PAR2 / Hybrid Crest Factor Reduction

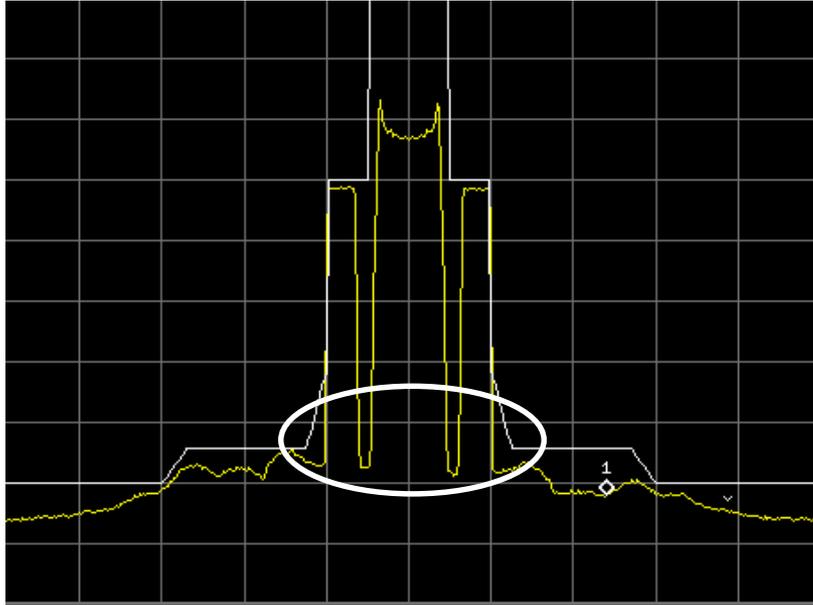


- PAR2 / HCFR offers improved performance for reducing the PAR while controlling undesirable out-of-band emissions.
- Within each iteration, the distortion is constrained to a maximum threshold value whereby the out-of-band spectral components lie within a predetermined spectral mask, below the receive threshold signal-to-noise decision point.
- PAR2/HCFR also includes equalization to compensate for the effects of linear distortion and nonlinear signal compression caused by amplification as well as AM/PM conversion below the peaks of the PAR-reduced signal.
- All of these improvements are performed within the PAR correction iterations instead of after the PAR algorithm which results in peak re-growth.

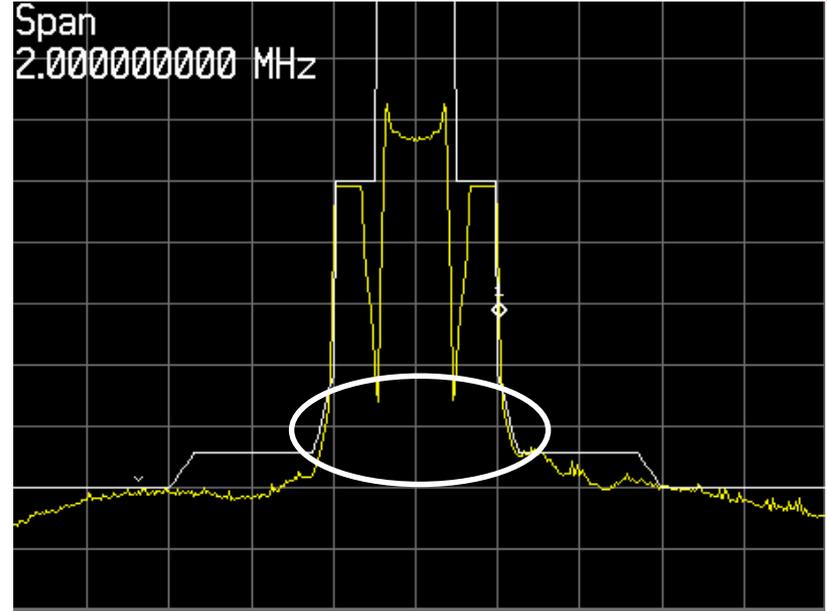


Actual plot from a G4 Engine equipped Flexiva Exciter's spectrum analyzer showing (enhanced) the constrained out-of-band noise and generated by the PAR2 reduction

PAR2 / Hybrid Crest Factor Reduction & MER

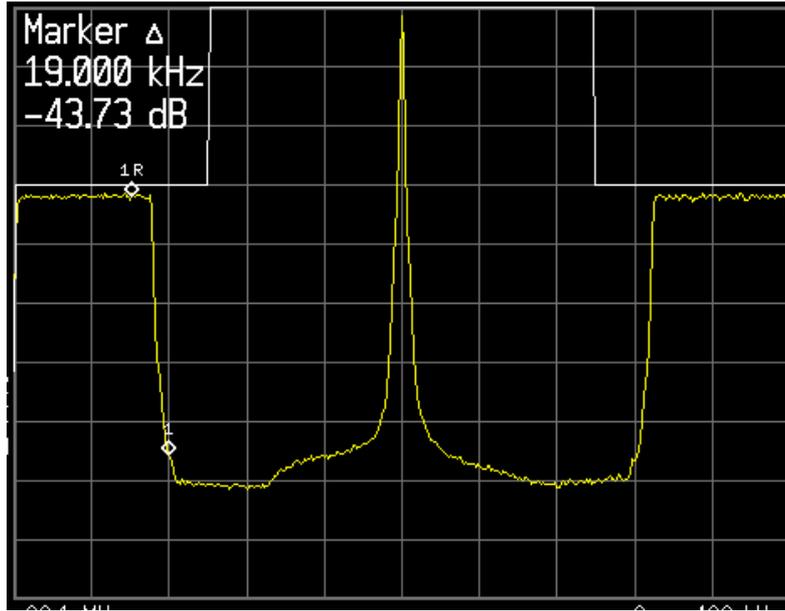


PAR 1 – Notice the FM and sidebands go down to the noise floor.

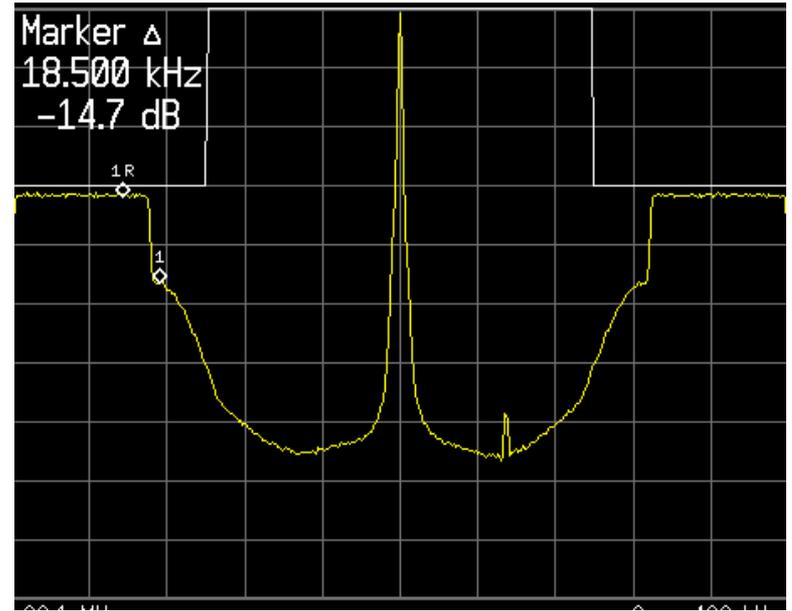


PAR 2 – The noise from the clipping distortion is directed and constrained to lie within the predetermined spectral mask and **below the useful MER threshold**

PAR2 / Hybrid Crest Factor Reduction & MER



PAR1 MER ~ 44 dBc



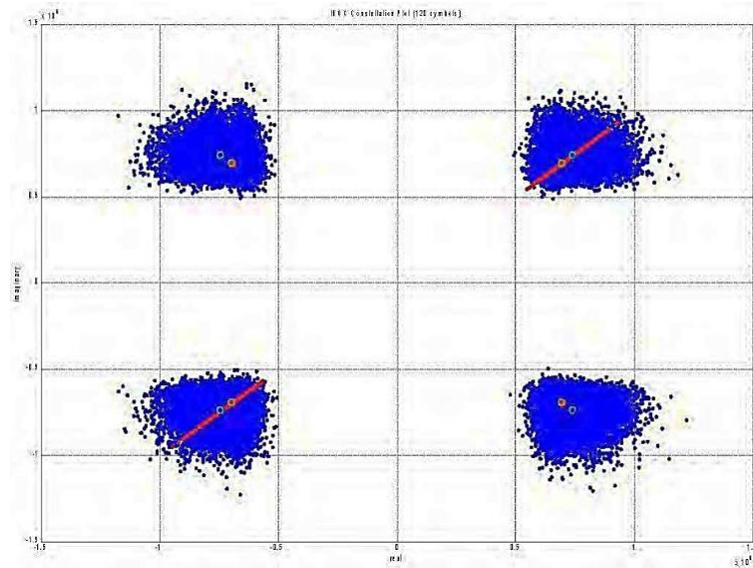
PAR2 MER ~ 15 dBc

Modulation Error Ratio (MER) is the measurement of the Digital signal-to-noise ratio.
MER is degraded by the intermodulation noise products caused by peak clipping of the CFR

$$\text{MER(dB)} = 10 \log_{10} \left(\frac{P_{\text{signal}}}{P_{\text{error}}} \right)$$

PAR2 and MER

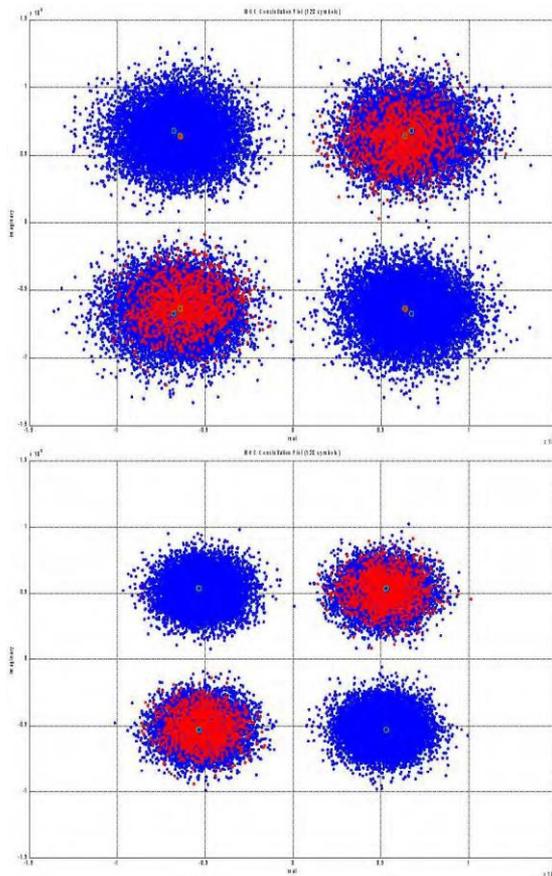
- PAR2 HCFR takes advantage of a technique whereby the clipping noise is pushed “away from the decision point”



IBOC Constellation with CFR Enabled and no Added Noise. Clipping noise pushed away from the decision point

PAR2 and MER

- As propagation/reception channel noise is added into the signal, the noise quickly dominates over the CFR induced constellation noise before bit errors become apparent.
- With channel noise at 64 dB-Hz where no bit errors are detected, the constellations start to look quite similar whether CFR is enabled or not



CFR Enabled
Cd/No of 64 dB-Hz

CFR Disabled
Cd/No = 64 dB-Hz

PAR2 and MER

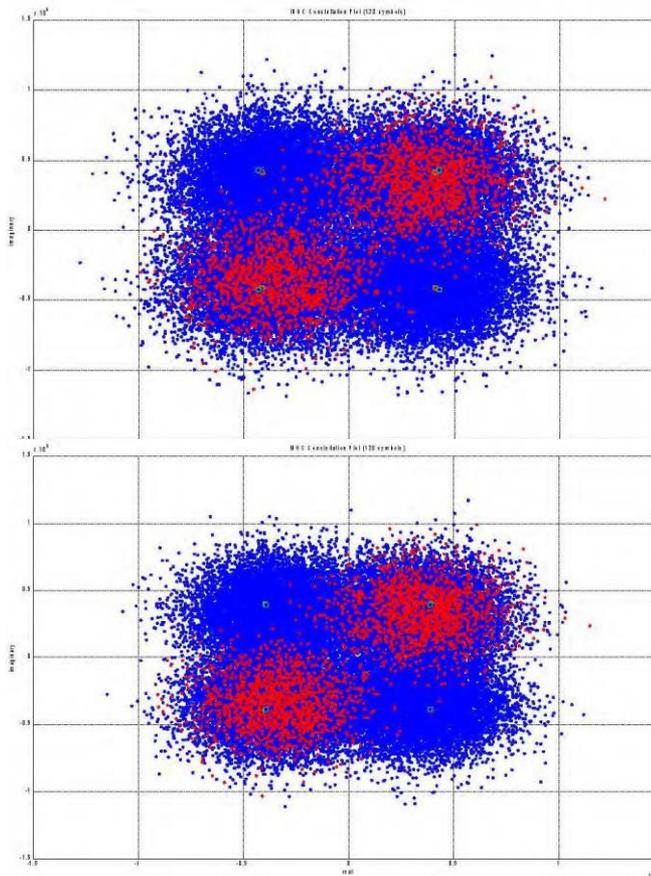


- The difference in received MER with CFR enabled vs. disabled quickly diminishes with increased channel noise.
- Received bit errors are just beginning to occur around Cd/No of 56 dB-Hz where the BER is still around 10^{-7} , or almost error free and about 2dB above the blend threshold

CFR On/Off	CD/No dB-Hz	Avg MER dB @ Rcvr	BER
ON	56	6.0	1.10E-07
OFF		5.5	5.70E-08
OFF	64	12.8	0
ON		11.2	0
OFF	No Noise	88.6	0
ON		18.0	0

PAR2 and MER

- With Cd/No of 56 dB-Hz, the CFR-disabled signal begins showing bit errors at an MER of 6.0 dB. The “no noise” CFR-induced MER of 18.0 dB provides a large margin before reception failure of the digital signal
- The difference in received MER between CFR enabled and CFR disabled is only 0.5 dB.
- **As long as the CFR induced constellation noise is sufficiently below the MER of the CFR-disabled signal with added noise, the impact of the CFR-induced noise will be minimal to the received signal**



CFR Enabled
Cd/No = 56 dB-Hz

CFR Disabled
Cd/No = 56 dB-Hz

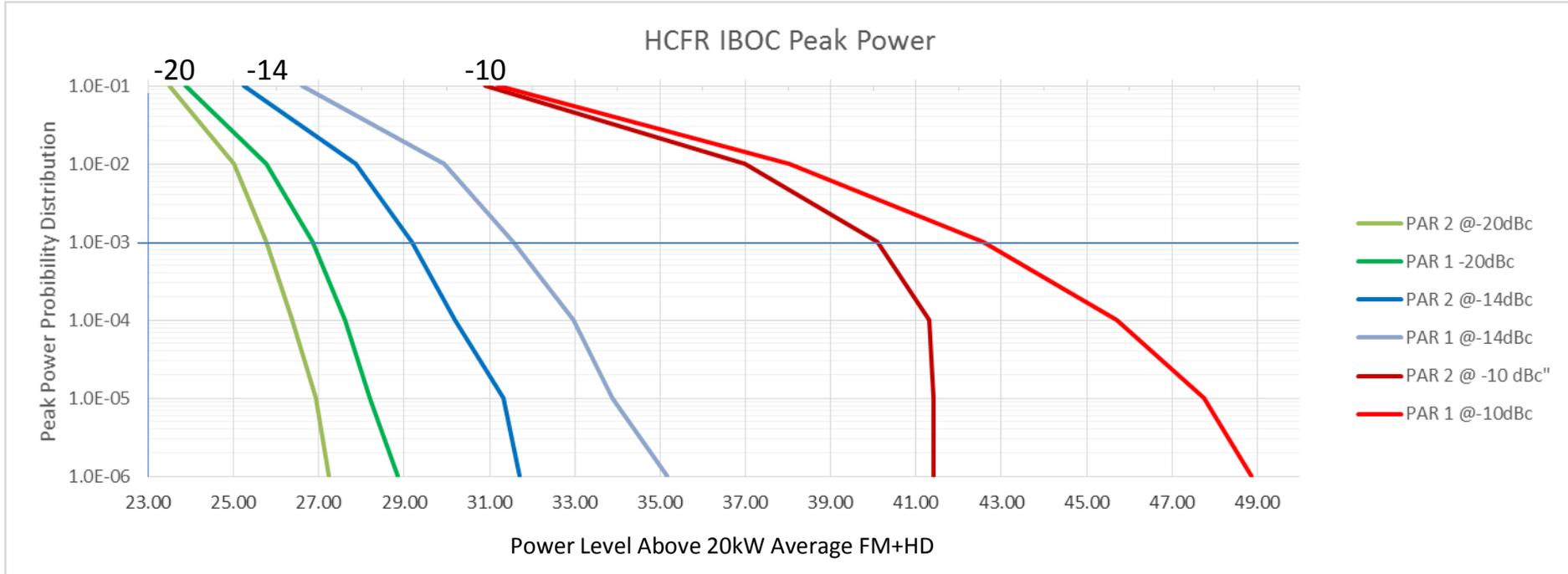
PAR2 Results



- When combined in a 10dBc (10%) ratio with the analog FM waveform, the resulting .01% distribution crest factor of 3.45dB is a .53dB (or ~11%) improvement over PAR 1.
- This means that now, a 2.4 kW linear amplifier can produce 1 kW of FM+HD at -10.
 - (909W FM + 91W HD)
- **REMEMBER:** PAR1 Required a 2.75kW amplifier!
 - That is a 12% improvement in power utilization from PAR reduction alone!



Peak Power Requirements PAR1 vs. PAR2



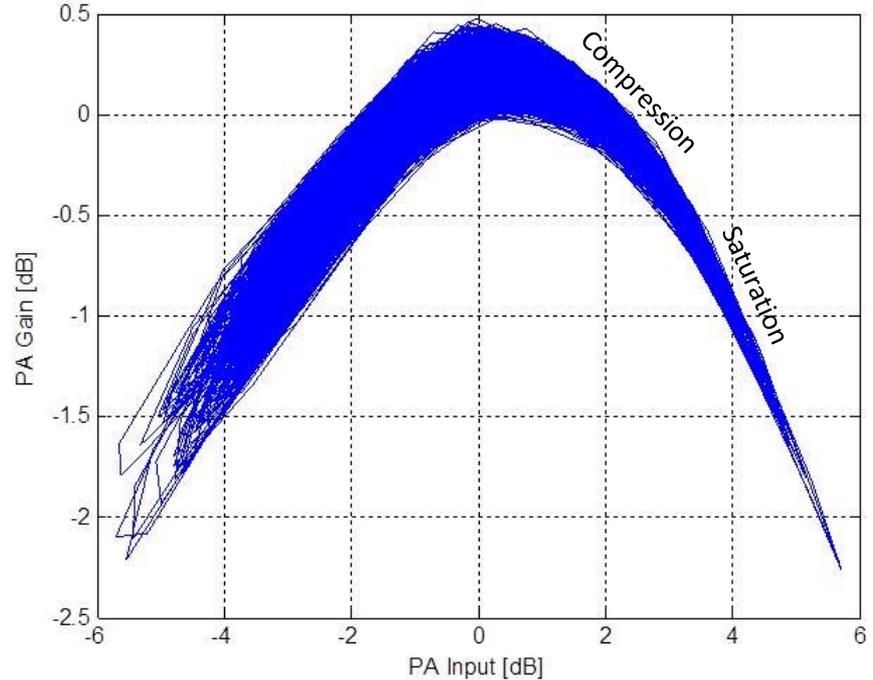
Causes of Non-Linear Distortion



AM to AM Distortion

AM to AM non-linearities cause the RF power amplifier's output amplitude to not exactly track the input amplitude.

Typically these non-linearities occur near the peak output power of the amplifier where saturation effects cause the output response to flatten as the input continues to increase



Power amplifier nonlinear gain

Causes of Non-Linear Distortion



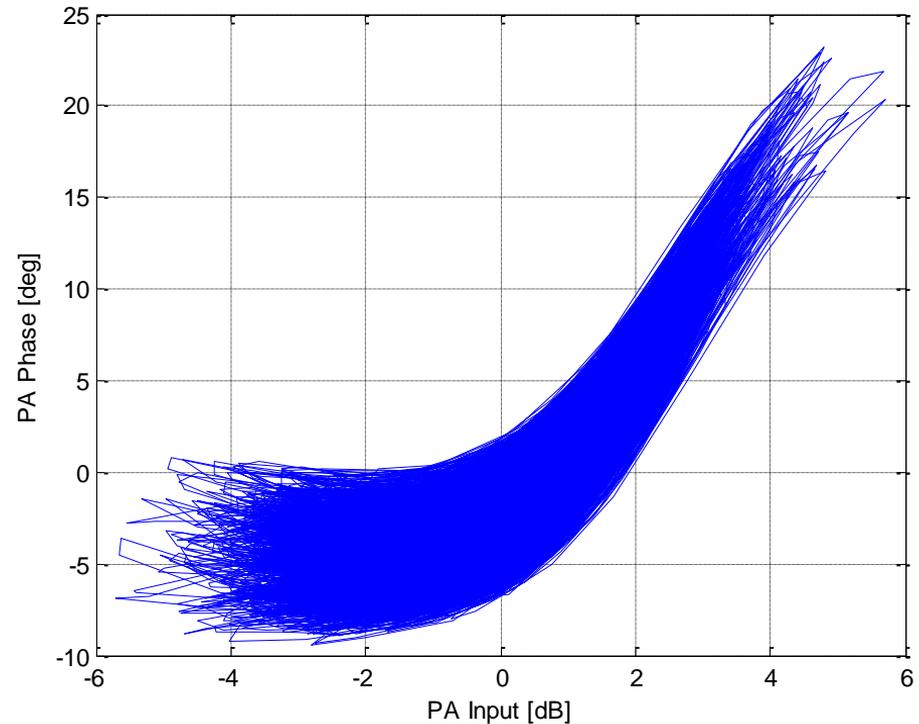
AM to PM Distortion

AM to PM non-linearities cause the RF power amplifier's output RF phase to not track the input phase. The amplifier acts like a phase modulator as the power output varies to follow the input signal.

Memory-Full Behavior

All RF amplifiers also have some temporal memory effects that make the shape of the non-linearities change over time with changing modulation data states.

The memory effects can be seen in as a blurring of the gain and phase traces.

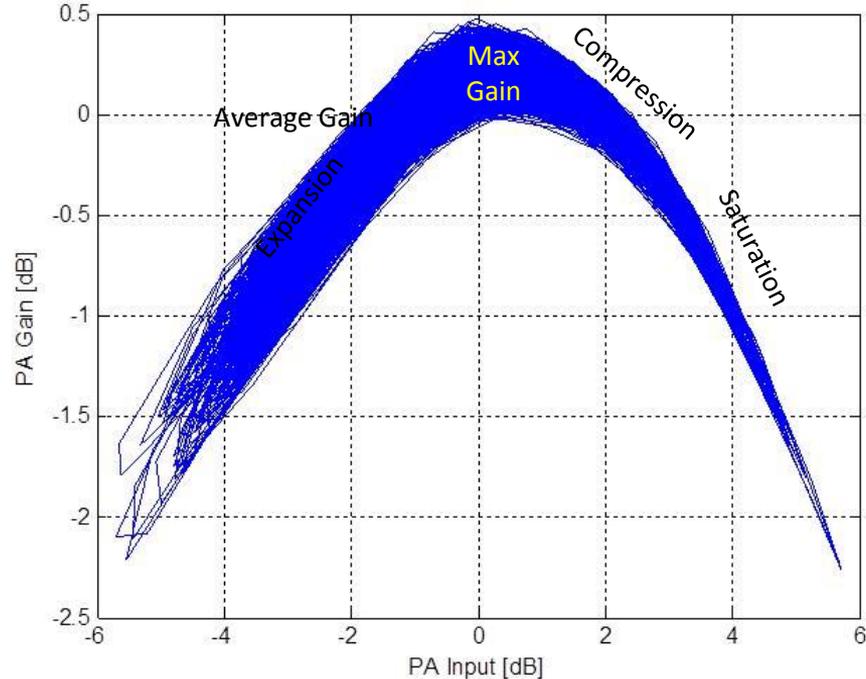


PA introduces phase distortion in the saturation region

Non-Linear Pre-Correction



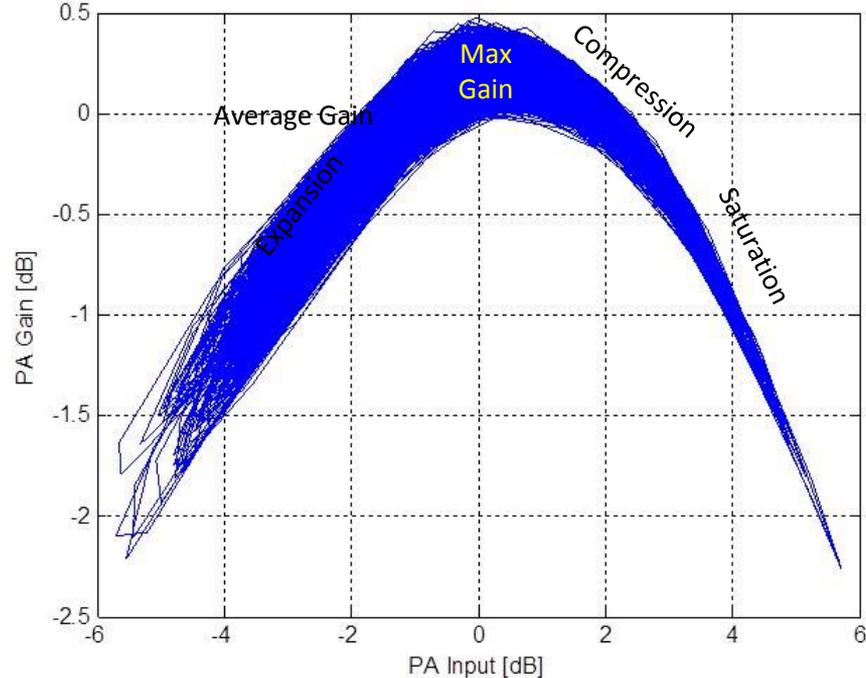
- The power amplifier's nonlinear gain is observed and characterized with the actual IBOC waveform.
- The envelope of the signal is sampled over a period of time. The PA output vs. the PA input is representative of the AM/AM and AM/PM.
- As shown here, the average gain of the PA is normalized to zero by a linear scaling of the PA output.
- The remaining non-constant gain is due to the non-linear MOSFET PA.



The power amplifier's nonlinear gain as observed with the IBOC+FM waveform

Non-Linear Pre-Correction

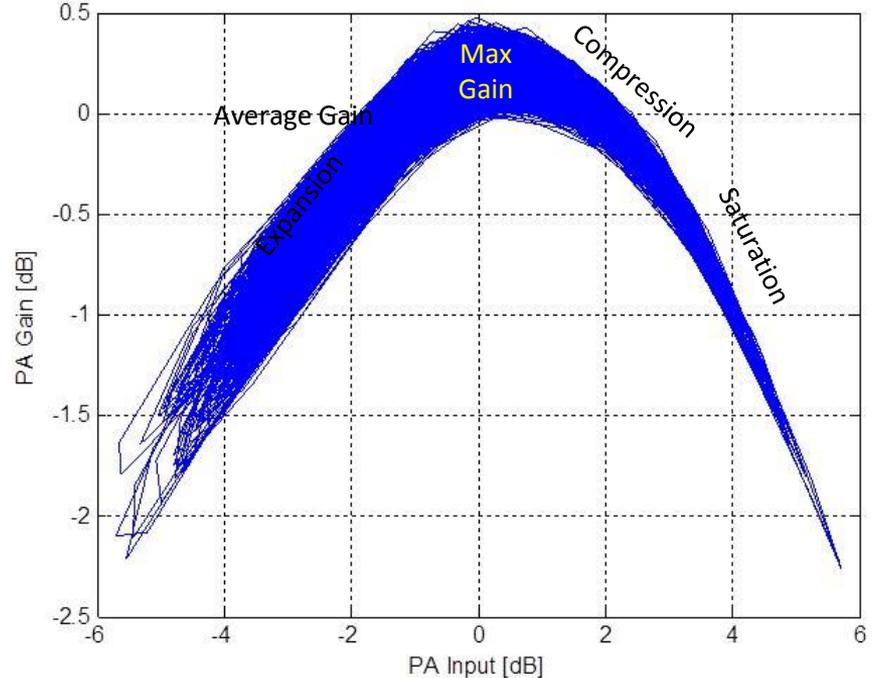
- The PA input amplitude on the x-axis is normalized to the average input power.
- The envelope of a hybrid FM+HD does not reach zero magnitude because of the dominant constant magnitude FM carrier.
- Below the point of maximum gain the amplifier exhibits compression by decreased gain.
- The gain decreases at the highest input levels corresponding to PA saturation.



The power amplifier's nonlinear gain as observed with the IBOC+FM waveform

Non-Linear Pre-Correction

- The amplitude linearity distortion (AM-AM) becomes more pronounced near the amplifier's saturation point; and so by minimizing its effects you can effectively increase the amplifiers output level and utilization (vs. a reference distortion amount).
- Peak-stretching is applied to digital peaks that lie within the compression region of the power amplifiers

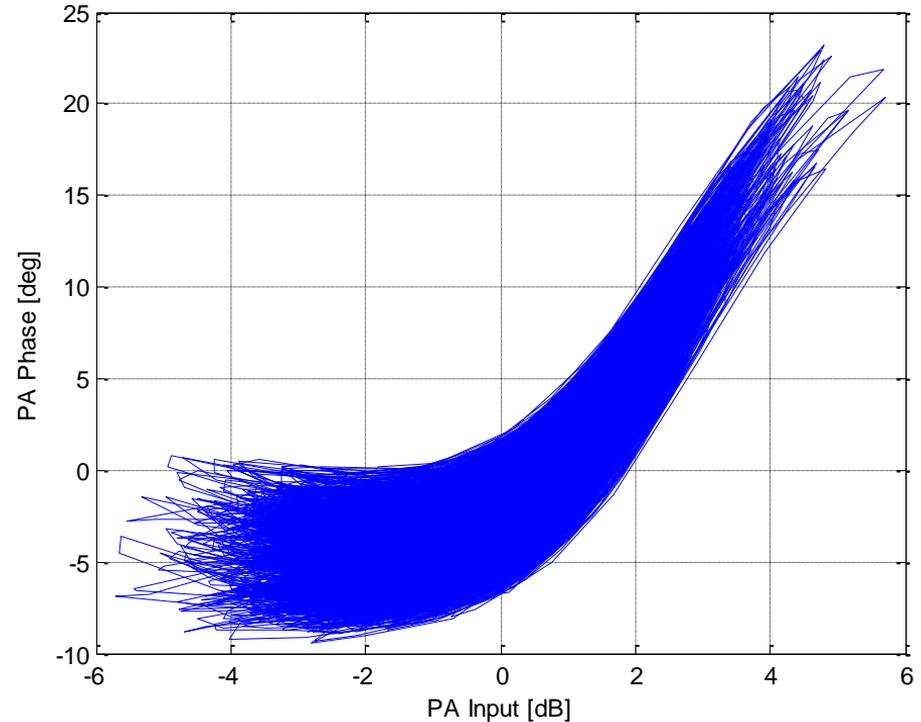


The power amplifier's nonlinear gain as observed with the IBOC+FM waveform

Non-Linear Pre-Correction



- Similarly, as shown here, the PA introduces phase distortion in the saturation region, ie. the phase of the PA output signal envelope depends on the signal amplitude.
- Non-linear pre-correction including memory-full correction is applied to reduce undesired RF gain and phase intermodulation products to meet NRSC RF mask compliance

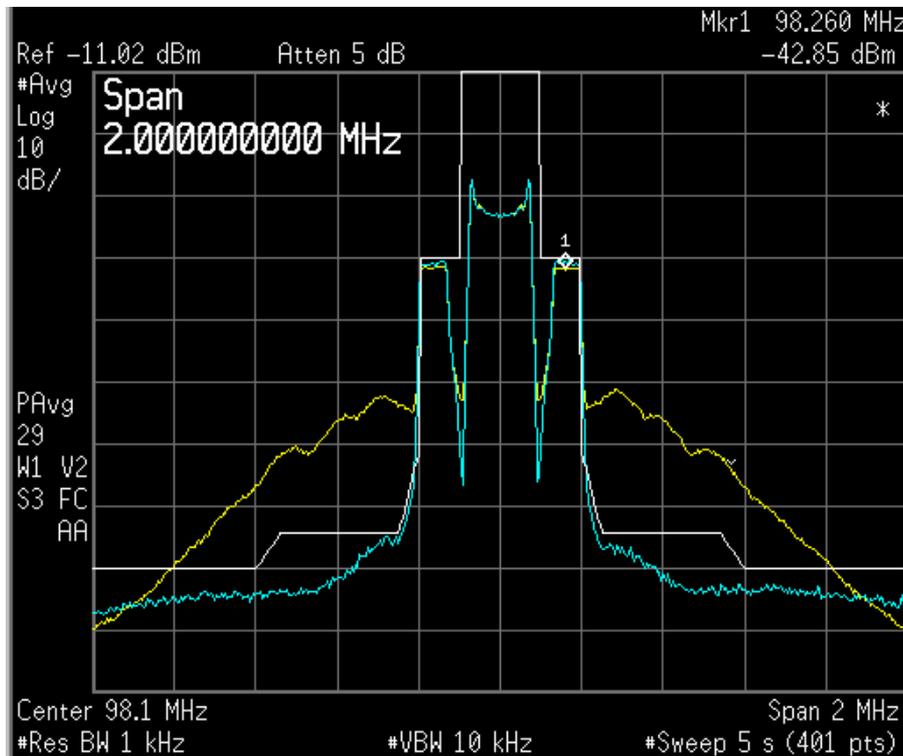


PA introduces phase distortion in the saturation region

Application of RTAC



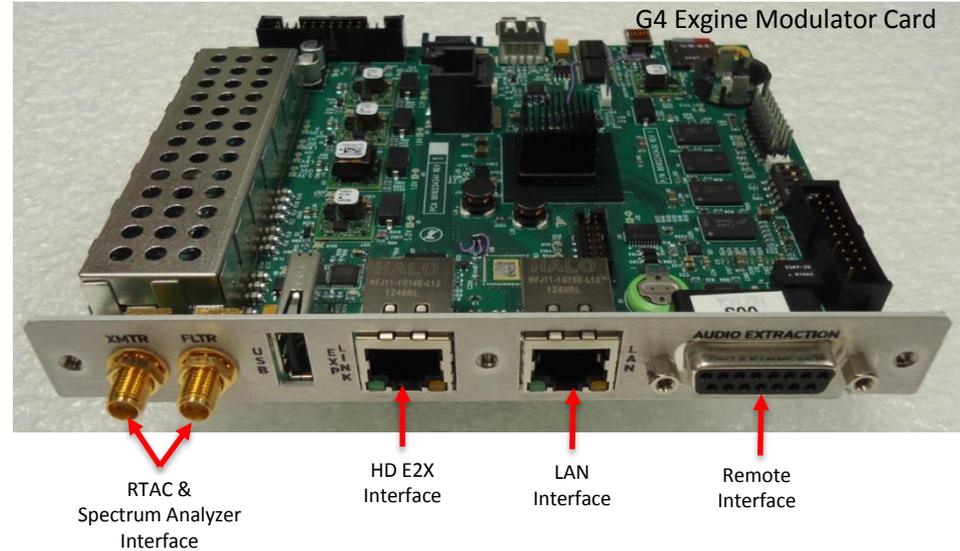
- Real-Time Adaptive Non-Linear Pre-Correction (RTAC™) takes an RF output sample from the transmitter or antenna and analyzes the waveform to characterize the gain, phase and memory-full non-linearities of the power amplifier
- Based on that analysis, a set of algorithms is applied to pre-distort the modulator's gain and phase as represented by the **yellow trace**.
- The resulting corrected output of the power amplifier is shown by the **blue trace**



G4 Engine Introduction



- The 4th generation HD Radio system developed by GatesAir and iBiquity for the Flexiva FAX digital transmitter family employs new hardware architecture and digital signal processing techniques to support the new PAR2 and RTAC algorithms.

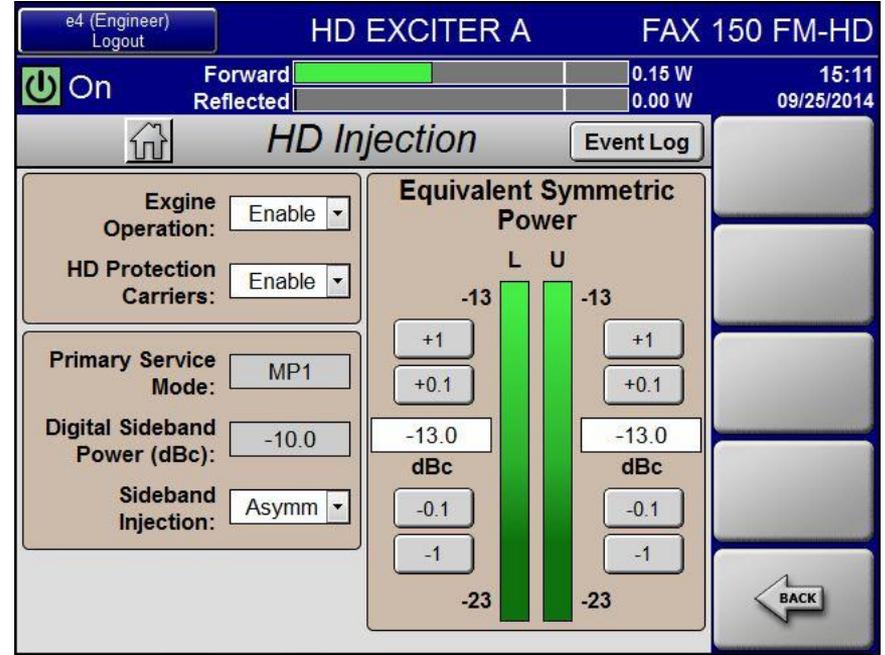


G4 Engine Equipped Flexiva FM Exciters and Transmitters

G4 Engine Controls

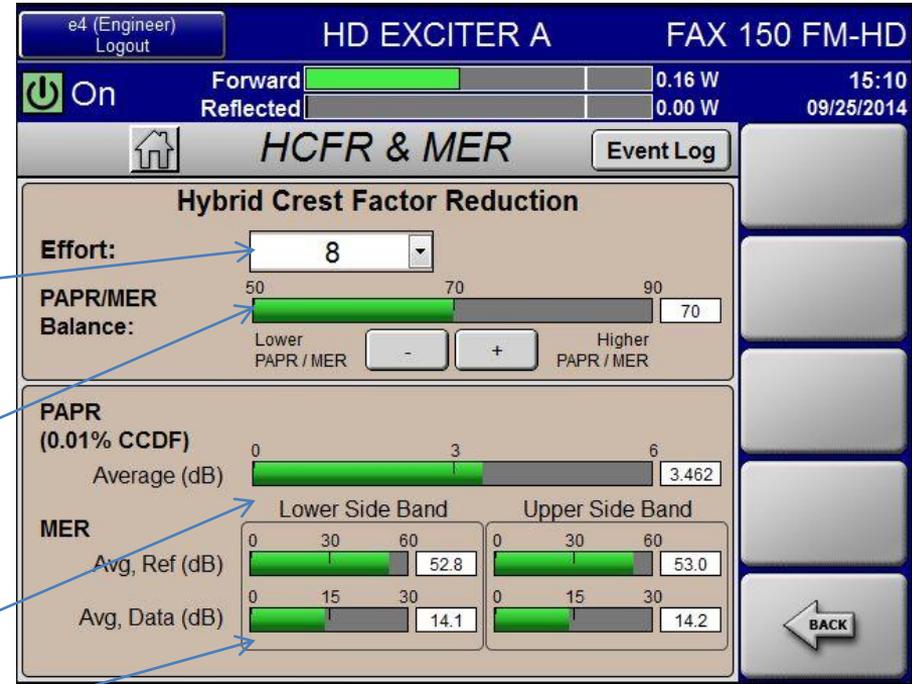


- Control of the HD signal generation within the G4 Engine is managed through the HD Injection GUI page.
- Here we can manage the sideband power, and asymmetry over a 10dB range for both the upper and lower sidebands

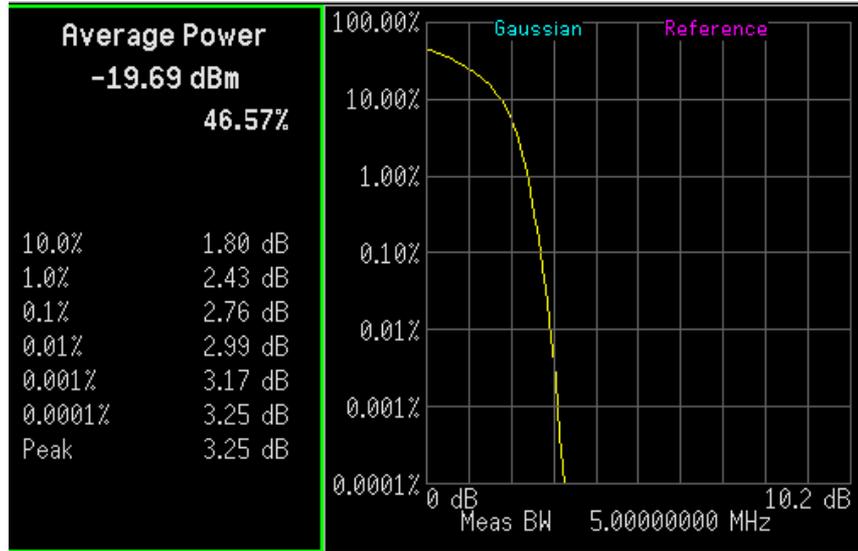


G4 Engine Controls

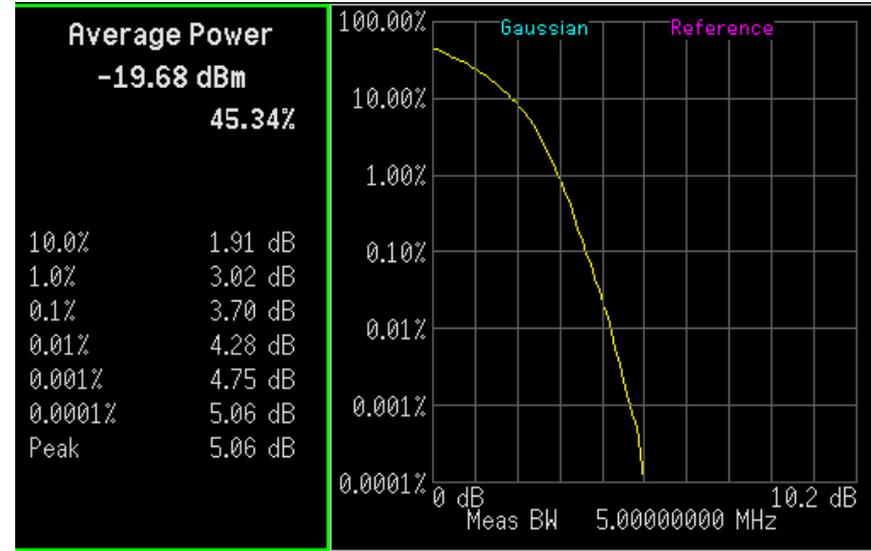
- The G4 Engine for Flexiva FM transmitters incorporates the new PAR2 Hybrid Crest Factor Reduction (HCFR) algorithms with controls and quality monitoring to “fine-tune” HD performance and TPO headroom.
- An “Effort” control determines the number of constrained “clip/filter/restore” iterations between 1 and 8.
- “PAPR/MER Balance” controls the trade-off between the constraint of peak reduction applied and the noise/distortion and hence the Modulation Error Ratio (MER) created by the clipping distortion.
- Direct measurements of the .01% peak/average distribution
- Resulting MER values of the Data and Reference carriers are displayed in real-time as adjustments are made



G4 Engine Controls



FM+HD at -10dBc
Lowest PAPR (2.99 dB)
Lowest MER (12 dB)

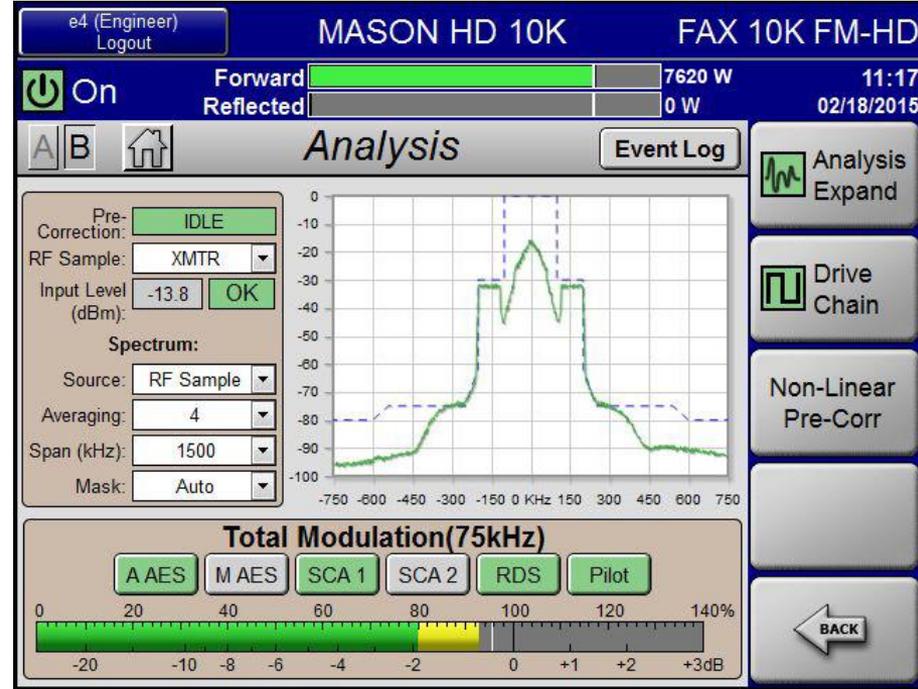


FM+HD at -10dBc
Highest PAPR (4.48 dB)
Highest MER (24 dB)

G4 Engine Controls



- The corrected output is displayed on the transmitter's Spectrum Analyzer



Corrected waveform at transmitter output as shown on Exciter's remote interface

Results



- Testing was accomplished using a Flexiva FAX10K 10kW transmitter with a Flexstar Gen3 exciter running PAR1 with original RTAC compared to a Gen4 Flexiva exciter using PAR2 with Advanced RTAC. Adjustments were made to the transmitter using RF drive and PA voltage to maximize the transmitters RF output and efficiency while maintaining a minimum of 14dB MER and 1 dB of NRSC Mask compliance headroom.
- As can be seen below, the improvement between the Gen3 and Gen4 system are negligible at -20 dBc as would be expected. Improvements become much more significant as the injection levels are increased. At -14 dBc the Gen4 .01% CCDF PAPR is nearly .3dB better, yielding 15% higher average power and a 6% improvement in overall efficiency. At -10 dBc, the PAPR is reduced by 1.2dB allowing for 32% more average power and a 12% increase in efficiency over PAR1



HD Injection	-20			-14			-10		
Exgine	GEN 3	GEN 4	DELTA	GEN 3	GEN 4	DELTA	GEN 3	GEN 4	DELTA
Total Pout W	9,950	10,100	+2%	7,500	8,630	+15%	5,515	7,260	+32%
AC-RF Efficiency	61%	62%	+1%	55%	58%	+3%	47%	59%	+12
PAPR dB .01% CCDF	1.32	1.29	-0.03	2.6	2.32	-0.28	3.98	2.79	-1.19

FLEXSTAR GEN 3 vs. FLEXIVA GEN 4 POWER AND EFFICIENCY IMPROVEMENT

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Jeff Detweiler, Executive Director, Engineering, iBiquity Digital Corporation

Dr. Brian Kroeger, Chief Scientist, iBiquity Digital Corporation

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