New Methods for HD Radio™ Crest Factor Reduction and Pre-Correction

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ABSTRACT - *The generation and amplification of the hybrid HD Radio waveform presents unique challenges due to the inherently high peak-to-average ratio of the signals and complex system of intermodulation products any system non-linearities produce. In order to create and amplify these signals cleanly and efficiently, it is necessary to employ crest factor reduction and distortion pre-correction techniques. The authors will discuss a new implementations of Hybrid Crest Factor Reduction, Adaptive Non-Linear Pre-Correction, and Modulation Error Ratio calculation techniques as they apply to maximizing HD Radio transmitter power utilization and efficiency.*

The 4th generation HD Radio system jointly developed by GatesAir and iBiquity Digital Corporation employs new digital modulator hardware architecture and digital signal processing techniques to improve HD Radio efficiency and transmitter power utilization.

The authors will define the challenges and discuss state-of-the-art developments providing real-world examples showing improved performance and power utilization.

Intermodulation

Intermodulation distortion (IMD) occurs during the mixing of signals containing two or more different frequencies in a system with nonlinearities. The intermodulation between each frequency component will form additional signals at frequencies that are not just at harmonic frequencies (integer multiples) of either, but also at the sum and difference frequencies of the original frequencies and at multiples of those sum and difference frequencies. Intermodulation is caused by the non-linear behavior of the signal processing and amplification being used.

Crest Factor and 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. In other words, crest factor indicates how extreme the peaks are in a waveform. A crest factor of 1.0 indicates a constant envelope with no peaks, such as direct current or a CW RF signal such as the familiar analog FM signal. A crest factor greater than 1.0 indicates amplitude peaks, for example sound waves tend to have high crest factors. Crest Factor is defined as the peak amplitude of the waveform divided by the RMS value of the waveform [1]:

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

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 [1]:

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

As a power ratio, it is normally expressed in decibels (dB). When expressed in decibels, crest factor and PAPR are equivalent, due to the way decibels are calculated for power ratios vs amplitude ratios. For these discussions, we can use the terms interchangeably. The term PAPR will be used for Peak-to-Average Power Ratio and CFR will be used to discuss Crest Factor Reduction

HYBRID HD RADIO CREST FACTOR

The biggest challenge with amplifying orthogonal frequency-division multiplexed (OFDM) waveforms used for HD Radio and all other digital radio formats is their high crest factor. OFDM modulates vectors of information symbols in parallel over a large number of individual orthogonally-spaced subcarriers. An OFDM signal includes multiple subcarriers modulated at different equally spaced frequencies, which are orthogonal (90 degrees) to each other. The Hybrid FM+HD Radio broadcasting system uses up to 534 OFDM subcarriers to transmit the digital signal. Statistically, with this number of subcarriers, there will occasionally be very high amplitude peaks due to vector summation of the multiple carriers. Using the de-facto standard Power Complementary Cumulative Distribution Function (CCDF) of .01% of-the-time distribution, the peaks of the HD-only OFDM waveform are 10-12 dB above the average power. This approaches the CCDF of Gaussian noise.

Because of these peaks, the power amplifiers used in the transmitters need to operate within their linear range with large power back-offs to minimize peak distortion. Peak distortion caused by non-linearity introduces intermodulation noise interference to the subcarrier modulation, and causes out-of-band emissions. Without crest factor reduction, the power amplifiers will need to be grossly oversized, inefficient and expensive.

Crest Factor Reduction

Modulation techniques that have higher order modulation constellations can transmit more bits per second than those with lower order modulation constellations. Higher order modulation constellations with higher data payloads are more sensitive to noise from undesired intermodulation products. The linear RF amplifier’s peak power capability has a direct effect on the data capacity of the signal.

- 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 as shown in Figure 1 .
- The average power of the signal is the peak output power divided by the crest factor.

The reduction in crest factor results in a system that can either transmit more bits per second with the same hardware, or transmit the same bits per second with lower-power, less expensive hardware and lower power consumption. Many crest factor reduction techniques (CFR) have been proposed and deployed for OFDM.

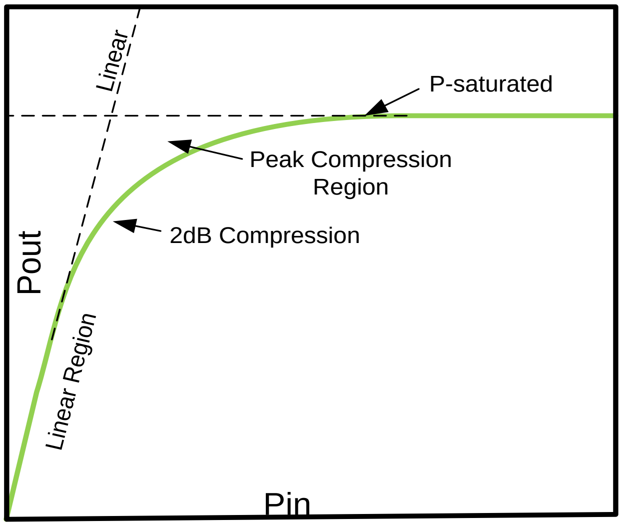


FIGURE 1: NON -LINEAR OPERATION OF A TYPICAL RF AMPLIFIER

PAR1 Crest Factor Reduction

PAR1 as it has been dubbed, was the original CFR technique implemented by iBiquity in the Gen1 HD Radio broadcast Architecture. Under the PAR1 reduction algorithm the OFDM signal alone is modestly clipped and filtered once, yielding an HD-only PAR of around 8dB. This conservative approach was relatively simple to accomplish within the limited signal processing hardware resource available at the time, generated little clipping noise as seen in Figure 2 and with minimal impact on the data carrier’s Bit Error Rate (BER).

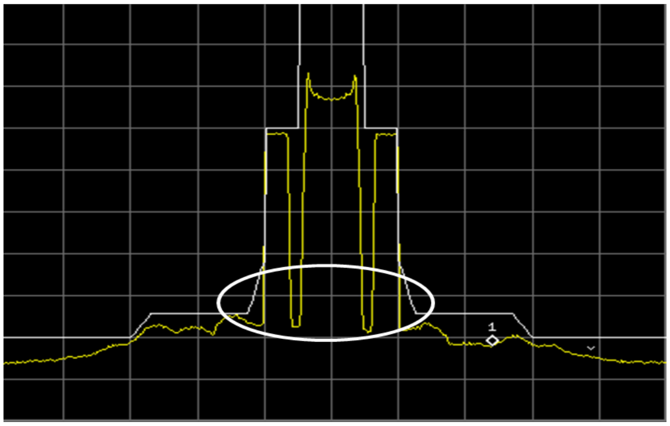


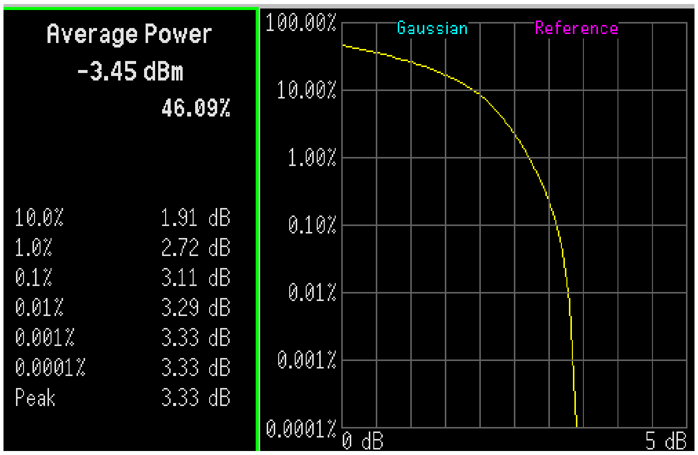
FIGURE 2: PAR 1 – NOTICE THE FM AND IBOC SIDEBANDS GO ALL THE WAY DOWN TO THE NOISE FLOOR.

When combined with analog FM at -10dBc (10%) injection ratio the .01% CCDF is 3.98 dB with total peak power of 4.28 dB. This means that a 2.5kW linear amplifier is needed to produce 1kW of FM+HD at -10 dBc.

PAR2 Hybrid Crest Factor Reduction

Par2 Hybrid Crest Factor Reduction (HCFR) is a new technique developed by iBiquity and GatesAir in the 4th Generation HD Radio Architecture.

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 for improved power amplifier utilization. [2] 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. [3]



```
Average Power
  -3.45 dBm
     46.09%

10.0%       1.91 dB
1.0%        2.72 dB
0.1%        3.11 dB
0.01%       3.29 dB
0.001%      3.33 dB
0.0001%     3.33 dB
Peak        3.33 dB
```

FIGURE 3: .01% CCDF OF 3.11 DB RESULTING FROM EIGHT ITERATIONS OF PAR2 CFR

Extensive testing has shown that eight iterations of crest factor reduction produces the best trade-offs of peak reduction, distortion and resource utilization with an MP1 -10 dBc FM+HD peak-to-average power ratio of around 3dB as can be seen in Figure 3.

PAR 2 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 which is below the receive threshold signal-to-noise decision point as can be seen in Figure 4.

It also includes equalization within the PAR reduction algorithm 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. [3] All of these improvements are performed within the PAR correction iterations instead of after the PAR algorithm which results in peak re-growth.

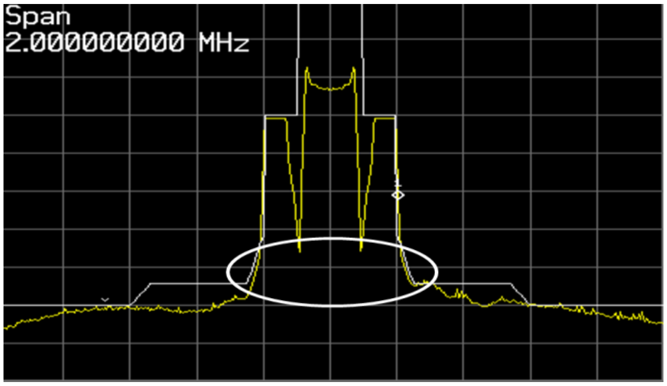


Figure 4: PAR 2 – The noise from the clipping distortion is constrained to lie within the predetermined spectral mask and below the useful MER threshold

PAR2 Hybrid Crest Factor Reduction & MER

Modulation Error Ratio (MER) is a measurement standard used to quantify the digital signal quality of a digital radio transmitter and is the standard measurement of the digital Signal-to-Noise Ratio in most digital transmission systems including HD Radio. Modulation error ratio is equal to the ratio of the root mean square (RMS) power of the reference vector to the power of the error. It is defined in dB as: [4]

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

Where P_{error} is the RMS power of the error vector, and P_{signal} is the RMS power of the ideal transmitted signal. The higher the MER, the better the signal to noise ratio and thus the ability of the receiver to decode the data stream. Figure 5 shows a QPSK constellation with no added noise yielding low MER.

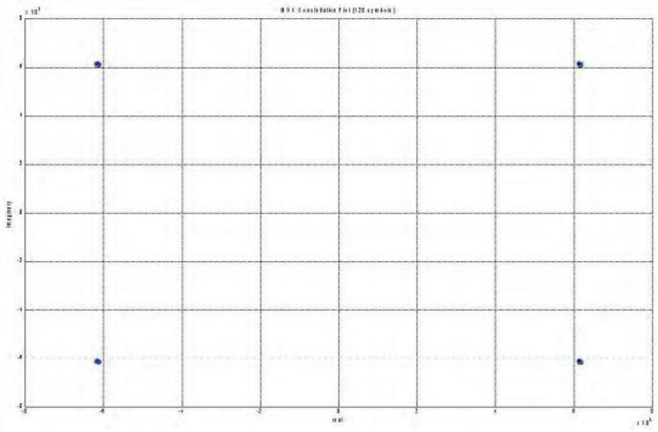


Figure 5: Simple, Robust QPSK Constellation with CFR Disabled and NO Added Noise [5]

Received MER is degraded by the intermodulation noise products caused by peak clipping of the CFR and by the propagation induced channel noise.

With the original PAR1 CFR and its conservative processing there is little to no impact on the MER. As can be seen in Figure 6, the noise products are well below the level of the digital carriers.

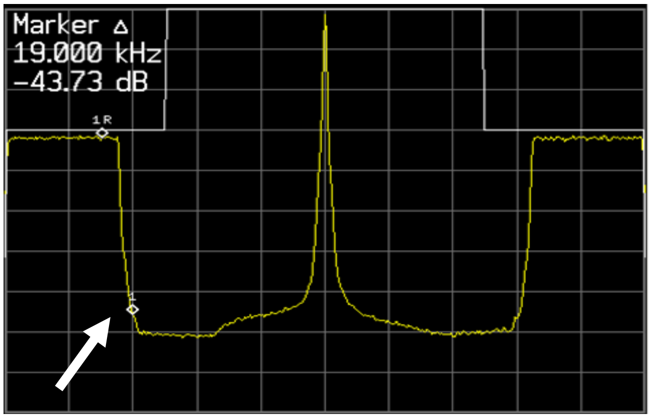


Figure 6: PAR1 Clipping Noise Products 44dB below digital carriers yielding approximately 44dB MER

With PAR2 CFR consideration was given to effects of added clipping noise to the MER where the noise products are permitted to rise much higher as shown in Figure 7. Here we see that the noise is only 14.7 dB below the digital carriers.

The NRSC 5 FM hybrid HD Radio transmission specification requires that the average MER measured at the RF output of the transmission system be a minimum of 14 dB. [5] Informal testing has shown that full data recovery is reliably accomplished with a received MER of 11dB and the absolute failure point is about 7dB MER. Some margin needs to be maintained to account for the difference between the transmitted MER and worst case received MER due to the additional noise encountered through propagation and reception channel noise.

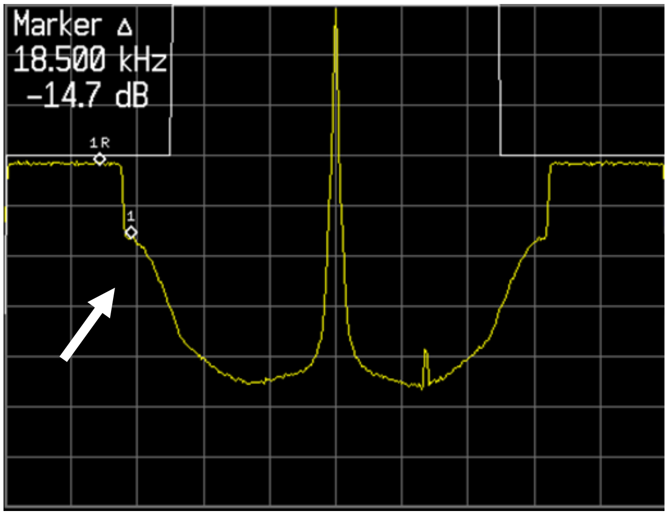


FIGURE 7: PAR2 IMPOSES SIGNIFICANTLY HIGHER CLIPPING NOISE CONSTRAINED BELOW A PREDETERMINED MASK

PAR2 HCFR takes advantage of a technique whereby the clipping noise is pushed “away from the decision point” as shown in Figure 8. [3]

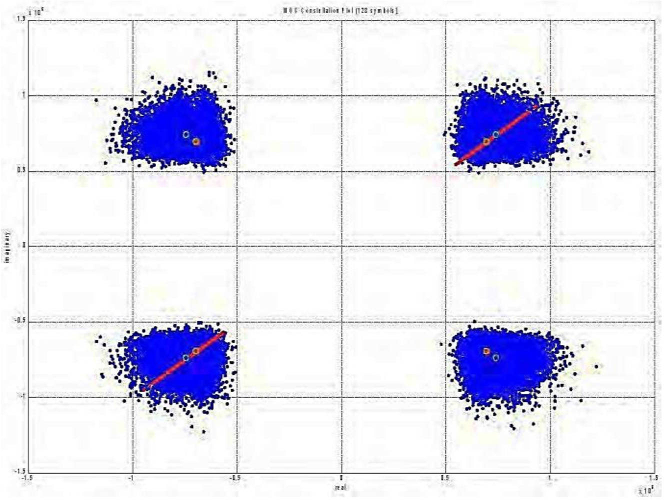


FIGURE 8: IBOC CONSTELLATION WITH CFR ENABLED AND NO ADDED NOISE. CLIPPING NOISE PUSHED AWAY FROM THE DECISION POINT. [4]

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 (Figure 9) or disabled (Figure 10). [4]

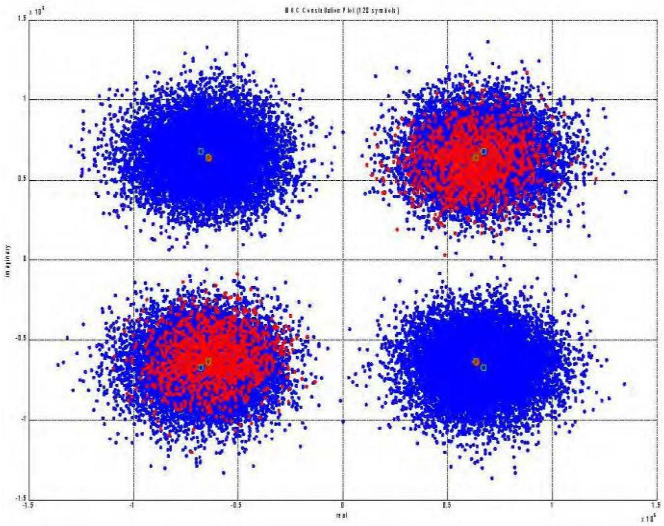


FIGURE 9: IBOC CONSTELLATION WITH CFR REDUCTION ENABLED AND CD/NO OF 64 DB-HZ [4]

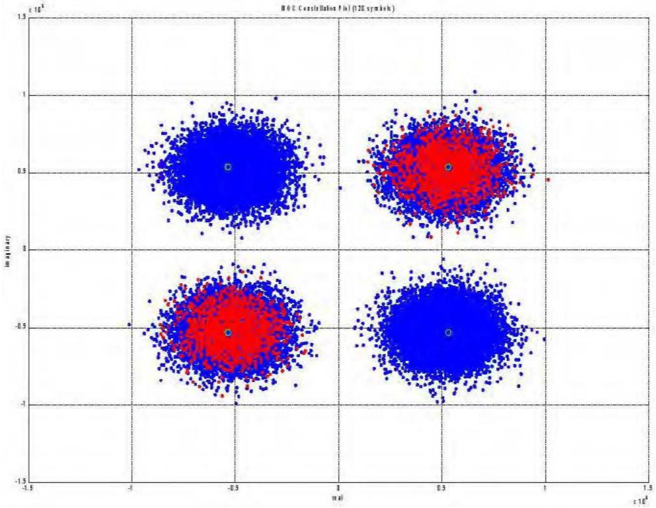


FIGURE 10: IBOC CONSTELLATION WITH CFR DISABLED AND CD/NO = 64 DB-HZ [4]

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 [4] as seen Table 1.

Here the difference in received MER between CFR enabled in Figure 11 and CFR disabled in Figure 12 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. [4]

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

TABLE 1: MER VALUES AND RECEIVER PERFORMANCE [4]

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. [4]

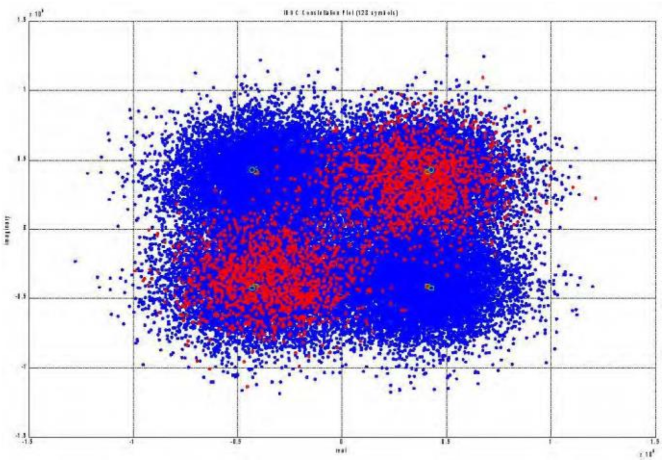


FIGURE 11: IBOC CONSTELLATION WITH CFR ENABLED AND CD/NO = 56 DB-HZ [4]

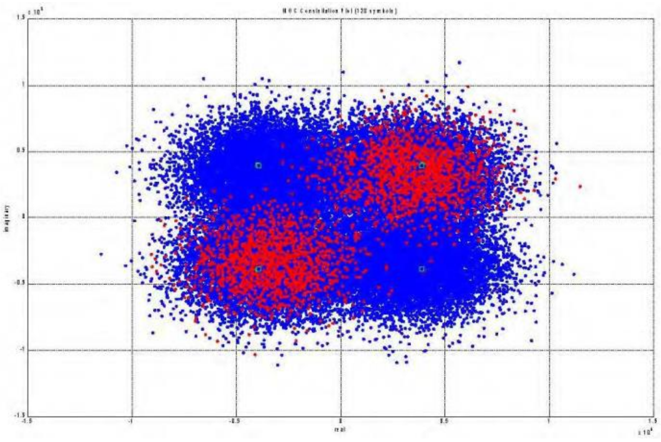
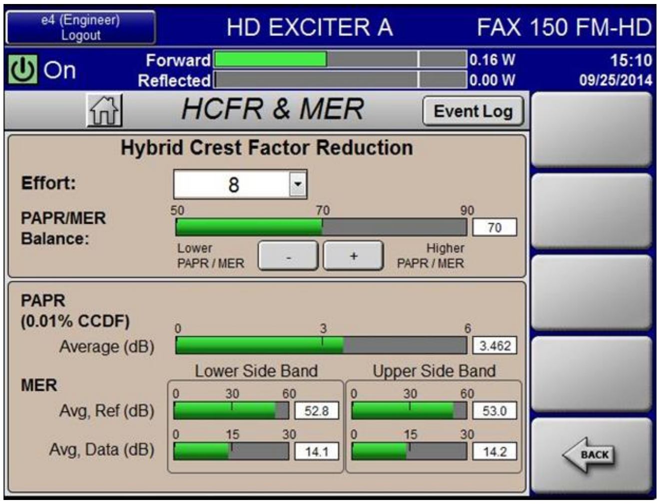


FIGURE 12: IBOC CONSTELLATION WITH CFR DISABLED AND CD/NO = 56 DB-HZ [4]

HCFR and MER Controls in the G4 Exgine

The G4 Exgine graphical user interface (GUI) shown in Figure 13 employs parameters that allow the user to adjust the trade-offs between CFR and MER. The aggressiveness by which the application of these controls are applied would be dependent mainly on the headroom available in the power amplifier system.

- An “Effort” control determines the number of constrained “clip/filter/restore” iterations between 1 and 8. Lower settings provide less aggressive clipping and thus higher PAPR.
- The “PAPR/MER Balance” controls the constraint of peak reduction noise toward the decision point and hence the transmission system induced MER created by the clipping distortion.
- Direct measurements of the .01% peak/average cumulative power distribution and the resulting MER values for both the data and reference subcarriers are displayed in real-time as adjustments are made.



Forward 0.16 W

Reflected 0.00 W

15:10

09/25/2014

Effort: 8

PAPR/MER Balance: 70

PAPR (0.01% CCDF) Average (dB) 3.462

MER

	Lower Side Band	Upper Side Band
Avg, Ref (dB)	52.8	53.0
Avg, Data (dB)	14.1	14.2

FIGURE 13: HCFR CONTROLS, PAPR AND MER DISPLAYS ALLOW QUALITY MONITORING AND “FINE-TUNING” OF THE CREST FACTOR REDUCTION VS. MER

At -10dBc FM+HD Radio carrier injection, the range of adjustment can provide PAPR as low as 2.99dB with 12dB of MER to as high as 4.48dB PAPR and 24dB of MER. At its most aggressive, that is 1dB or 26% more power than was available from PAR1.

NON-LINEAR PRE-CORRECTION

AM to AM non-linearities cause the RF power amplifier’s output amplitude to not exactly track the input amplitude creating intermodulation products seen in Figure 14.

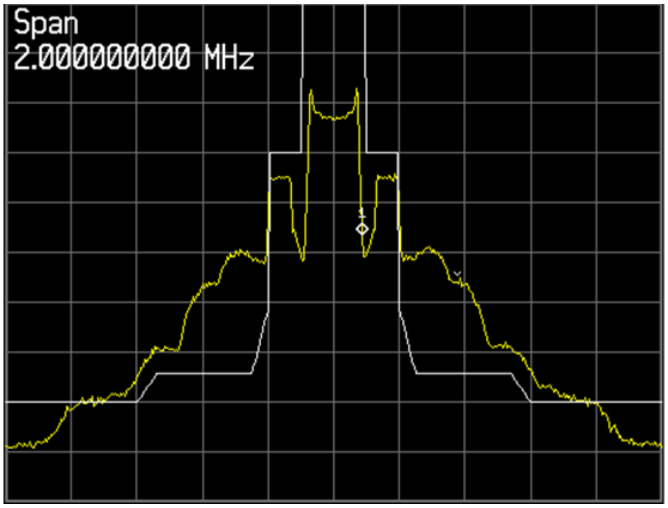


FIGURE 14: UNCORRECTED SPECTRAL PLOT OF FM+HD SIGNAL AT -10 DBC THROUGH AN AMPLIFIER APPROACHING SATURATION

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 as can be seen in Figure 15.

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. This caused by changes in the RF power transistor’s output capacitance over the dynamic range of the signal as shown in Figure 16.

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 Figure 15 and Figure 16 as a blurring of the gain and phase traces. This is known as “memory-full” behavior.

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.

Application of Non-Linear Pre-Correction

The power amplifier's nonlinear gain and phase are mathematically observed and characterized in real-time with the actual OFDM HD Radio waveform in a manner similar to that shown in Figure 15 and Figure 16. 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.

The average gain of the PA is normalized to 0 dB by a linear scaling of the PA output. The remaining non-constant gain is due to the non-linearity of the LD-MOSFET PA. The PA input amplitude on the x-axis is normalized to the average input power. Note that the envelope of a hybrid FM+HD does not reach zero magnitude because of the presence of the dominant constant magnitude FM carrier.

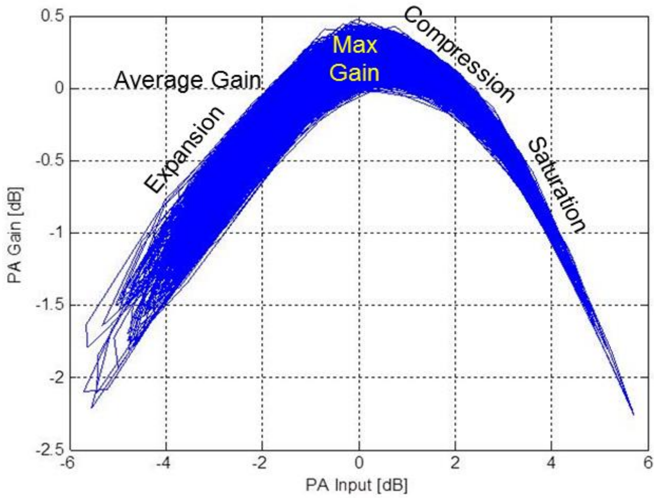


FIGURE 15: THE POWER AMPLIFIER'S NONLINEAR GAIN AS OBSERVED WITH THE IBOC+FM WAVEFORM

It can be observed in Figure 15 that 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. To compensate for this compression, peak-stretching is applied to the digital peaks that lie within the compression region of the power amplifiers.

The amplitude linearity distortion (AM-AM) becomes more pronounced near the amplifier's saturation point; and so by minimizing its effects we can effectively increase the amplifiers output level and by controlling the distortion to the reference level selected.

Similarly, in Figure 16, the PA introduces phase distortion in the saturation region, i.e. the phase of the PA output signal envelope depends on the signal amplitude.

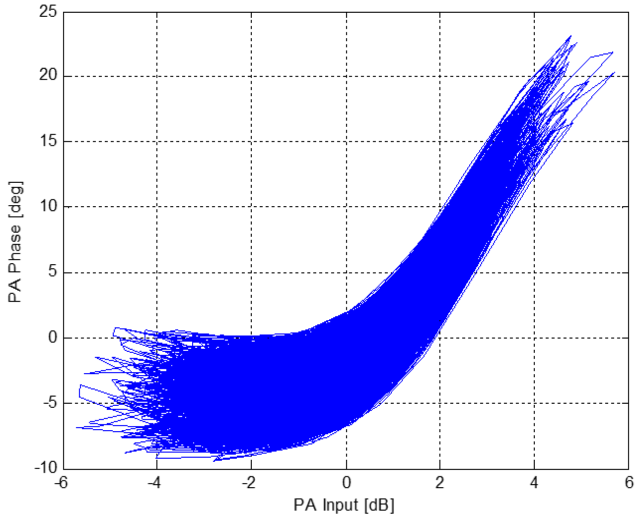


FIGURE 16: PA INTRODUCES PHASE DISTORTION IN THE SATURATION REGION

The phase non-linearity (AM-PM) distortion causes spectral re-growth; and so by minimizing both types of distortion, the hybrid signal from the amplifier can be made to fit the NRSC spectral mask requirements.

Real-Time Adaptive Non-Linear Pre-Correction

Real-Time Adaptive Non-Linear Pre-Correction (RTAC™) takes an RF output sample from the transmitter output or antenna system sample point and analyzes the waveform to characterize the gain and phase non-linearities of power amplifier shown in Figure 15 and Figure 16 compared to the original input signal

Based on that analysis, a set of algorithms is applied to the signal generation process in order to create a gain and phase pre-distorted waveform as represented by the yellow trace in Figure 17.

The resulting corrected output of the power amplifier is shown by the blue trace in Figure 17. This pre-correction process is repeated continually a regular intervals. The corrected output is displayed on the transmitters Spectrum Analyzer in Figure 18

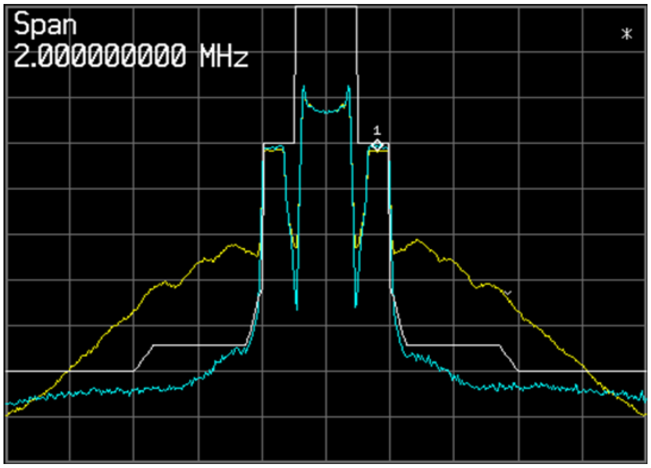
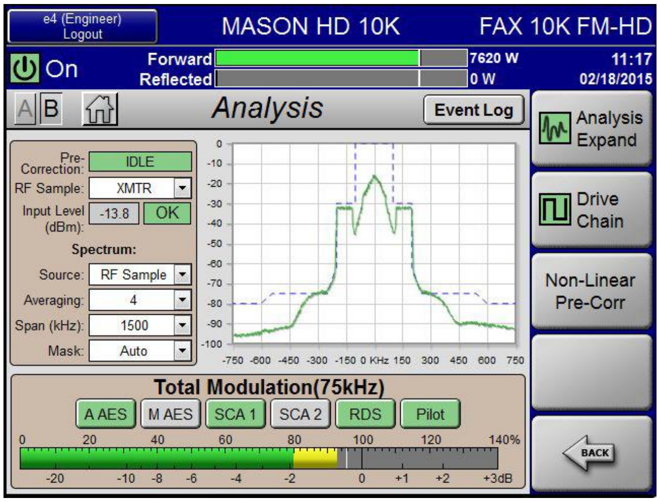


FIGURE 17: "INVERSE" GAIN AND PHASE CORRECTIONS APPLIED TO THE



Forward 7620 W
Reflected 0 W
11:17
02/18/2015

Pre-Correction: IDLE
RF Sample: XMTR
Input Level (dBm): -13.8 OK

Spectrum:
Source: RF Sample
Averaging: 4
Span (kHz): 1500
Mask: Auto

FIGURE 18: CORRECTED WAVEFORM AT TRANSMITTER OUTPUT AS SHOWN ON EXCITER'S REMOTE INTERFACE

REAL WORLD 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

TABLE 2: FLEXSTAR GEN 3 VS. FLEXIVA GEN 4 POWER AND EFFICIENCY IMPROVEMENT

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ACKNOWLEDGEMENTS

The authors would like to gratefully acknowledge the following people for their invaluable contributions to this paper:

George Cabrera, Principal RF Engineer, GatesAir

Jeff Detweiler, Executive Director, Engineering, iBiquity Digital Corporation

Dr. Brian Kroeger, Chief Scientist, iBiquity Digital Corporation

Geoffrey Mendenhall, PE, Technology Consultant, Gates Air

Ted Staros, Principal Signal Processing Engineer, GatesAir