IMPROVED SPECTRAL COMPLIANCE FOR FM HD RADIO USING DIGITAL ADAPTIVE PRE-CORRECTION

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ABSTRACT

HD Radio™ implementation has introduced a great deal of discussion about spectral re-growth problems when digital carriers intermodulate with the primary FM carrier, causing spurious emissions on adjacent channels. Pre-correction systems may be implemented to mitigate the effects of transmitter system non-linearity giving rise to the out-of-band emissions.

Conventional fixed pre-correction techniques have not provided a sufficient solution to ensure spectral integrity in a changing environment. Changes in VSWR, an adjustment in the output power of the transmitter, a change in amplifier temperature, or aging and failures of RF amplifiers can result in serious transgressions of the HD Radio mask and interference with other stations.

This paper presents theory and measured performance of digital adaptive pre-correction under unstable environmental conditions. Comparison is made between fixed pre-correction curves and adaptive pre-correction under typical conditions at broadcast sites.

BACKGROUND

The trend in the broadcast industry is now toward digital communications standards. The iBiquity FM HD Radio system employs a digital modulation technology known as Orthogonal Frequency Division Multiplexing (OFDM). This modern communications technique provides both excellent bandwidth efficiency and high tolerance to the multi-path fading environment common in urban settings.

All HD Radio systems going on the air today are "hybrid" systems, which means the transmitted signal consists of both an analog FM modulated portion and a digitally modulated OFDM. The digitally modulated portion consists of many QPSK modulated OFDM carriers spaced 363 Hz apart. The carrier spacing and carrier symbol rate are such that they are orthogonal, i.e. they do not interfere with each other. In the basic hybrid mode the "main" OFDM spectrum contains 382 carriers from approximately 130 kHz to 200 kHz, both above and below the channel center frequency.

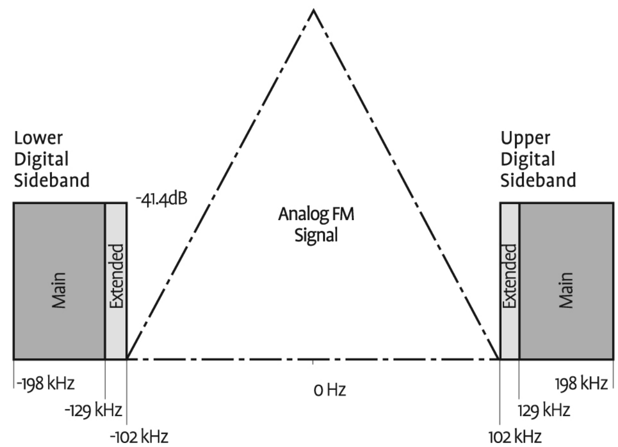

Figure 1 Hybrid FM HD Radio Spectrum

In the extended hybrid modes the spectrum contains up to 534 carriers from approximately 100 kHz to 200 kHz, both above and below the channel center frequency (Figure 1).

With the introduction of OFDM, transmitter designs have had to evolve due to a new requirement: linearity. Traditional FM transmitters operated highly non-linear class C amplifiers. This was acceptable due to the constant envelope nature of the FM signal. The OFDM envelope has large scale variations due to the changing constructive and destructive interference of the individual RF carriers.

While the answer to the linearity problem lies in part in the design of the amplifiers themselves, correction techniques are also required in a practical implementation.

LINEARITY AND THE EFFECT ON SPECTRUM:

Interference is one of the most significant potential problems when working with the HD Radio FM system. The signal broadcast by any transmitter may be broadly categorized into two classes: intentional and unintentional emissions. Intentional emissions include the FM signal and the OFDM signal. Unintentional emissions include RF harmonics, spurious emissions and noise. While some interference problems may have been caused by intentional emissions, the focus of this paper is on the mitigation of unintentional emissions due to amplifier non-linearity. All real amplifiers deviate to some degree from the ideal requirement that the gain is independent of input voltage. Generally, gain is reduced as input levels increase toward amplifier saturation (Figure 2). This is referred to as AM-AM distortion. AM-AM distortion may be described by a function that relates the magnitude of the instantaneous gain to the instantaneous input magnitude.

$$\left|\frac{V_o}{V_i}\right| = g_m(|V_i|) \qquad \text{(Eq 1)}$$

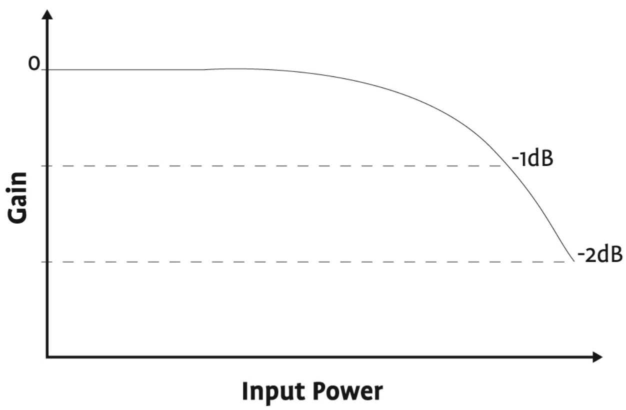

Figure 2 – AM-AM Characteristic

Alternately, the AM-AM characteristic can be modeled by a Taylor series expansion relating the instantaneous input voltage magnitude to the instantaneous output voltage magnitude. Both equation 1 and 2 may accurately represent the AM-AM characteristic of a typical amplifier.

$$|V_o| = a_1|V_i| + a_3|V_i|^3 + a_5|V_i|^5 \ldots a_n|V_i|^n \qquad \text{(Eq 2)}$$

The first term of the expansion is the linear term. The coefficient a_1 is the small signal gain of the amplifier. For an ideal amplifier, all higher order coefficients would be zero. Even order terms of the Taylor series are often not used as they cannot produce any distortion terms in the band of the fundamental RF term. The effect of this non-linear model can be illustrated by driving this function with a two tone input signal.

$$V_i = \cos(w_1 t) + \cos(w_2 t) \qquad \text{(Eq 3)}$$

The response of the Taylor series model to a two tone input signal can be determined by expanding and using trigonometric identities. In addition to fundamental and harmonics of the input tones, distortion products are produced. Third order intermodulation products, IM3, result from the third order term of the Taylor series.

IM3 occurs in the spectrum at the following frequencies:

$$\cos(2*w_1 - w_2) \qquad \cos(2*w_2 - w_1)$$

The fifth order term of the Taylor series produces fifth order intermodulation products, IM5, that occur at these frequencies:

$$\cos(3*w_1 - 2*w_2) \qquad \cos(3*w_2 - 2*w_1)$$

Note that the higher order terms of the Taylor series also contribute to the lower order intermodulation products. In this case, the IM3 products also have a contribution from the fifth order polynomial term expansion. Figure 3 shows the two tones, IM3 and IM5 distortion products.

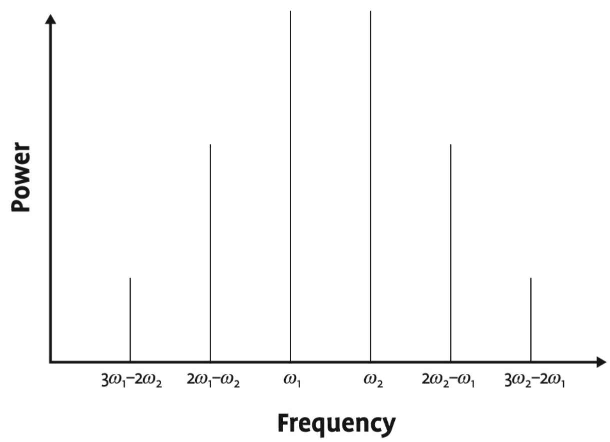

Figure 3 Output of Fifth Order Model with Two Tone Input

The non-linear response of amplifiers may be measured using a network analyzer by doing what is referred to as a power sweep. In this type of measurement, the amplifier is characterized using a single RF input tone of varying voltage. As the voltage is stepped over a wide range, the output of the amplifier is measured. If the output voltage magnitude is divided by the input voltage magnitude, a gain characteristic describing the amplifier AM-AM distortion is determined. For example, the fifth order Taylor series would have the following gain characteristic.

$$Gain(|V_i|) = \frac{|V_o|}{|V_i|} = a_1 + a_3|V_i|^2 + a_5|V_i|^4 \qquad \text{(Eq 4)}$$

Additionally the network analyzer will tell us that the phase measured between the input and output of the amplifiers was not constant during the power sweep. This phase characteristic is called AM-PM distortion (Figure 4).

(Eq 5)

$$Phase\left(\frac{V_o}{V_i}\right) = g_\phi(|V_i|)$$

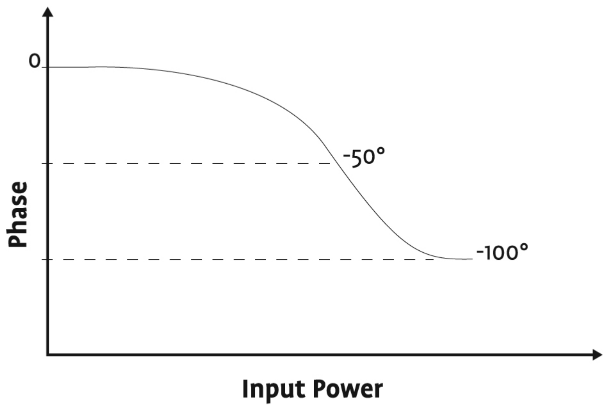

Figure 4 AM-PM Characteristic

Using the functions g_m and $g_Ø$ representing the AM-AM and AM-PM distortions, the relationship of the input voltage to the output voltage is shown.

$$V_o = V_i g(|V_i|) = V_i g_m(|V_i|) e^{j g_\phi(|V_i|)} \quad \text{(Eq 6)}$$

Equation 6 is useful because it suggests the amplifier characteristic is essentially a complex valued gain defined solely by the input signal magnitude. The amplifier complex gain is also defined by the AM-AM and AM-PM distortions that may be measured and tabulated by a network analyzer.

As was described by the two tone analysis shown above, the amplifier non-linearity will introduce distortion to the signal if not corrected for. Figure 5 shows the output spectrum for a typical FM amplifier operating with the HD Radio signal.

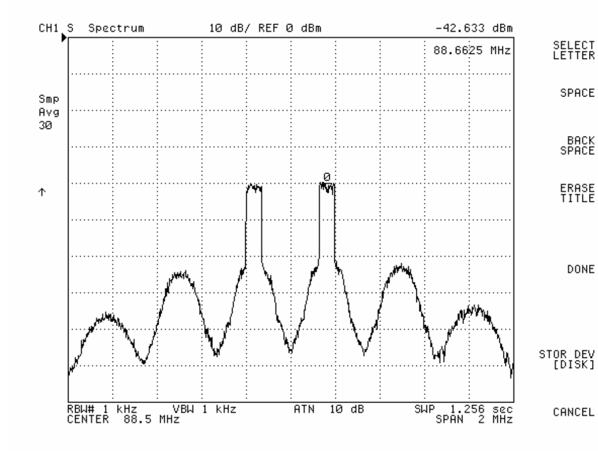

Figure 5 Un-Corrected Amplifier Spectrum

This signal contains the upper and lower OFDM sidebands that inter-modulate in a similar manner as the two tone test described above. The IM3 and IM5 products can be clearly seen. In addition the carriers of the individual OFDM sidebands intermodulate causing skirts.

The IM products are unintentional emissions from the transmitter that may cause several undesirable effects if they are not controlled:

- Out of band interference with adjacent Broadcast channels
- In band interference with your HD Radio OFDM signal
- In band interference with your FM signal

Out of band interference can happen when the transmitter output contains signals in another broadcast channel. The acceptable out of band emissions levels are currently governed by an emissions mask proposed by iBiquity (Figure 6).

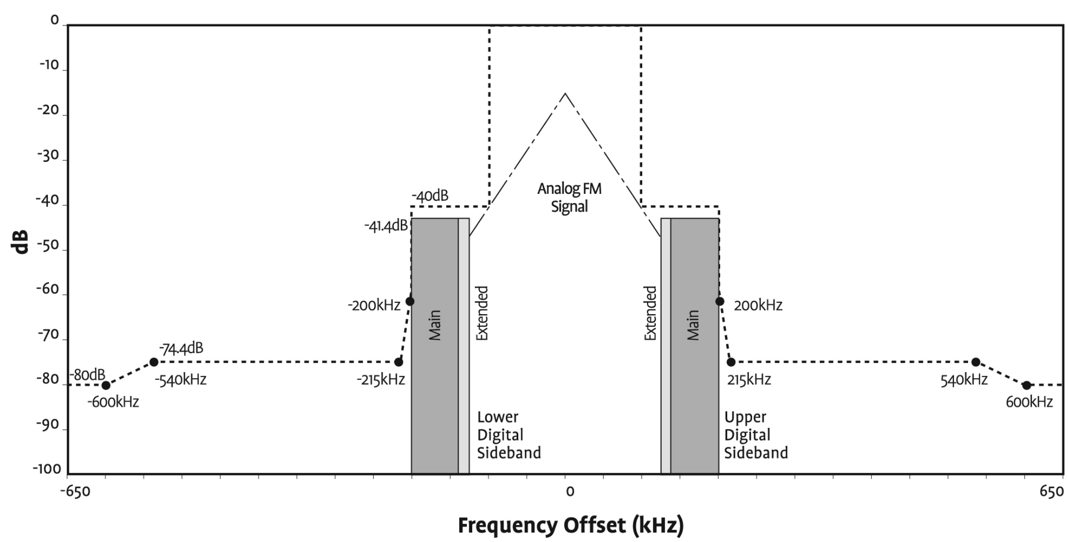

Figure 6 Proposed HD Radio Emissions Mask

In band interference with the digital signal occurs when the unintentional emissions interfere with the OFDM carriers at the receiver. This is generally less of a concern because the QPSK modulated carriers are very robust and relatively tolerant of noise and interference. It is very unlikely that any transmitter linear enough to meet the proposed emissions mask will have a negative effect on the OFDM signal to noise ratio at the receiver.

In band interference with the FM Signal may also occur. This may be more significant as the analog signal can be degraded by lower levels of emissions than the digital signal. The problem worsens if the unintentional emissions are close to the center frequency where the FM receiver is most sensitive. Because the FM system is analog, this interference could be perceived as noise or hiss when using analog receivers. Extended hybrid operation may exacerbate this situation as the additional OFDM carriers and their local IM products are closer to the FM carrier.

SOLUTIONS TO THE SPECTRUM PROBLEM:

The amplifier linearity may be improved for HD Radio operation by changing the class of operation from class C to A/B or even class A. This generally has the effect of improving the amplifier characteristic at low levels at the expense of efficiency. Highly linear operation may be obtained in this way by increasing the amplifier bias currents and reducing the peak output power. Typically a 3 dB improvement in IM3 products is obtained for a 1 dB reduction in output power. Unfortunately, this cannot be the complete solution due to the increased number of amplifiers required.

Other industries before broadcast radio have been coping with the linearity problem for some time. Many techniques for improving amplifier linearity have been investigated including feed forward, feedback and cartesian loop to name a few. The technique employed by Nautel and other HD Radio transmitter manufacturers is known as pre-distortion or pre-correction. Pre-correction is the preferred technique for Nautel because of its high performance, stability, low cost and low impact on the transmitter design itself.

PRE-CORRECTION:

Pre-Correction can be defined as placing a complementary non-linear system at the input of the Amplifier stages such that the overall system is linear (Figure 7). Because the pre-correction system is at the amplifier input, small signal techniques may be used making this a more practical solution.

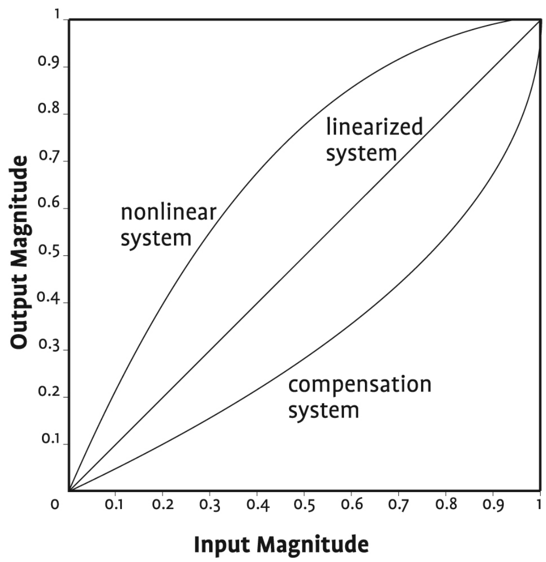

Figure 7 Complementary Gain Curves - Pre-Correction Principle

Mathematically, a non-linear amplifier characteristic $g(x)$ may be corrected for with a complementary characteristic $h(x)$ such that $g(h(x)) = Gx$ where G is the constant linear gain resulting from the cascade of the two systems. For this to be true, $G\,h(x) = g^{-1}(x)$.

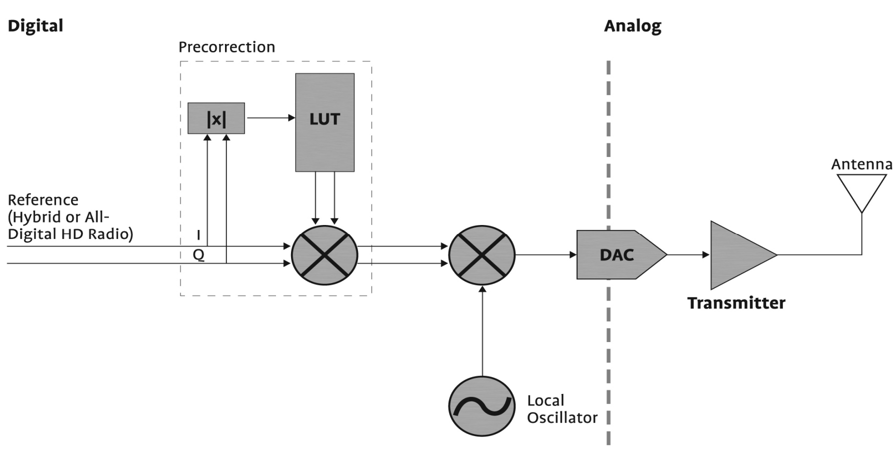

Figure 8 Fixed Digital Pre-Correction Block Diagram

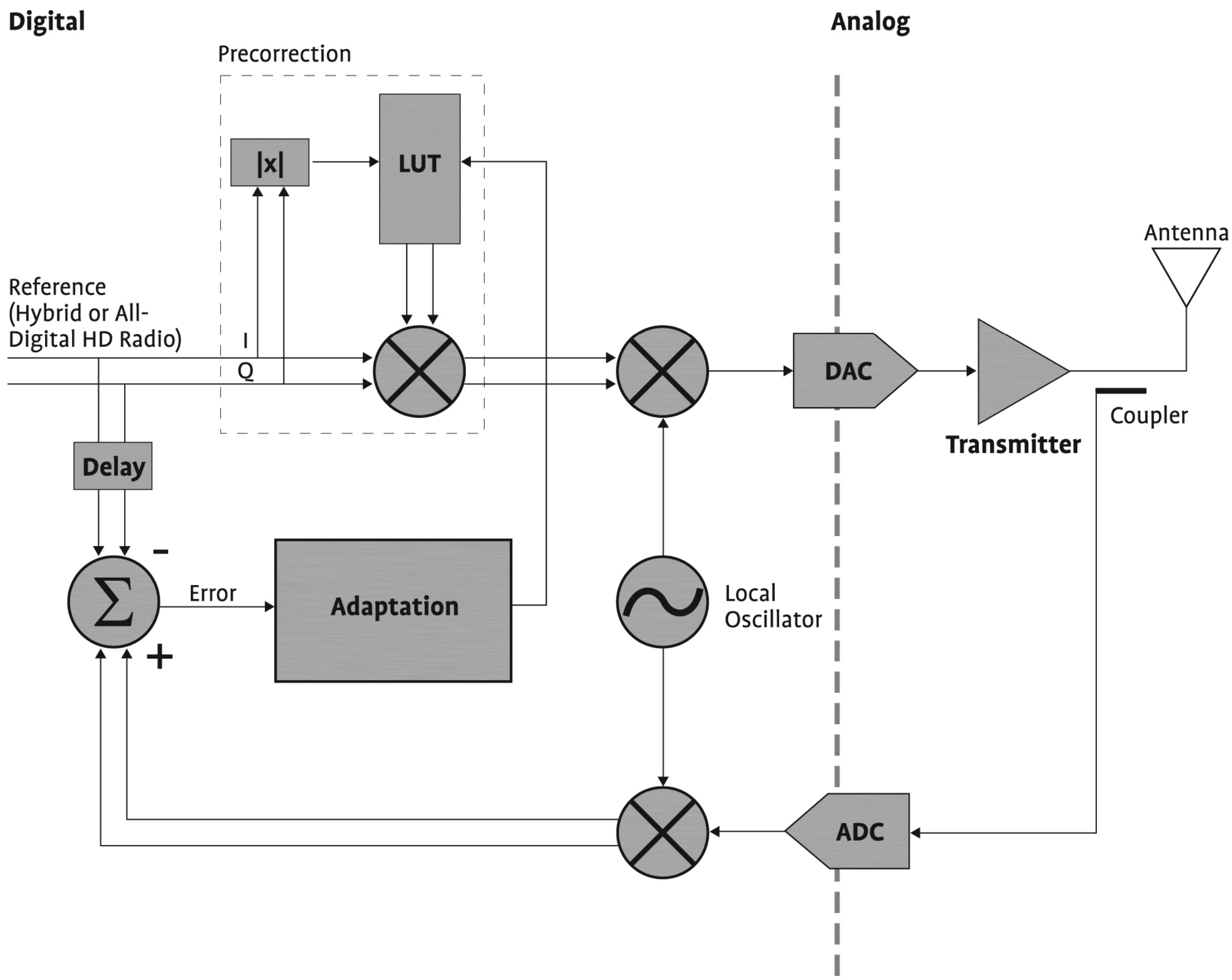

Figure 9 Adaptive Digital Pre-Correction Block Diagram

This technique may correct for both AM-AM and AM-PM distortion.

Pre-correction systems may be implemented in either the analog or digital domain. Analog pre-correction may be limited in its ability to faithfully produce the required inverse characteristic. The degree of improvement made by pre-correction is determined by how well the two non-linear characteristics are matched. When properly adjusted, digital pre-correction generally yields excellent results.

Even if careful manual matching of the pre-correction curve is done, the amplifier characteristic will generally vary over time. The causes of varying amplifier non-linearity include temperature effects (seasonal or warm-up), load impedance changes due to antenna mismatch or icing and changes in the operating frequency or power level.

ADAPTIVE PRE-CORRECTION:

Designing a system that “learns” the non-linear characteristic will mitigate the sensitivity of fixed pre-correction linearization systems. This is known as adaptive pre-correction and was first proposed in 1983 by Saleh and Salz.

The Nautel system is implemented completely in the digital domain (Figure 9). In the forward path, an ideal digital signal containing the HD Radio carriers and the FM signal (in the case of common amplification) is synthesized. The ideal signal is then pre-corrected using a correction curve stored in a look up table (LUT). This LUT stores a large number of discrete correction vectors. Each correction vector can correct for the amplifier gain and phase error for a given amplifier input voltage range. As the signal amplitude changes over time, many different correction vectors are used.

Still in the digital domain, the pre-corrected signal is then converted to the correct FM channel frequency and fed to a digital to analog converter (DAC). The analog signal is then fed to the transmitter for amplification.

In the reverse path, the transmitter output is sampled using a directional coupler and digitized with an analog to digital converter (ADC). The output sample is then shifted to the same frequency as the ideal reference signal at the system input. The reference signal is fed through a delay register to time align it with the sampled transmitter output signal. By subtracting the ideal signal from the actual transmitter output, an error signal is obtained. This error signal describes signal distortion at the transmitter output.

Using a recursive algorithm, the error signal is used to update the pre-correction curve stored in memory. After each iteration of the recursive algorithm, the correction vectors in the LUT converge on the ideal pre-correction solution such that distortion at the transmitter output is minimized.

Utilizing modern digital hardware, the conversion time is on the order of a few seconds, easily fast enough to correct for real world variations in the amplifier non-linear characteristic.

Adaptive Pre-Correction Limitations:

Saturation: At some point, the amplifier's output power cannot be made to increase when the input power is increased. As a result, the desired output power must be set so that the amplifier saturation point does not significantly distort the signal. For the HD Radio signal, iBiquity requires a minimum peak to average ratio of 5.5 dB at the transmitter output. For example, a 10 kW transmitter capable of 11,000 W peak power should not be driven beyond 3,100 W average digital power in a separate amplification system. If the digital power is increased significantly beyond this point, amplifier saturation may introduce unacceptable emissions outside the emissions mask.

Amplifier memory: The relatively simple adaptive pre-correction system described assumes that the amplifier is "memoryless". Amplifier memory occurs when the gain at any one instant in time is dependent not only on the current amplifier input but also on previous amplifier inputs. For signals of relatively low bandwidth, using careful amplifier design techniques, memory effects can be minimized such that the effect is not troublesome.

Comparison of Fixed and Adaptive Pre-Correction:

The following experiments were conducted to determine the improvement obtained by using an adaptive pre-correction system. In each experiment a reasonable deviation of the amplifiers operational environment was made. These changes were intended to represent the real world conditions that might be found at a typical broadcast site.

These measurements were made on a Nautel V10 operating in all-digital mode as required by the digital transmitter in a separate amplification system. The output power in every case is 3 kW and the operating frequency is 98 MHz. The spectrum analyzer was set to 1 kHz RBW and VBW, sample detection with a 30 sweep average.

Each spectrum plot shows the spectrum resulting from making a change in the operational environment with the adaptation disabled. After the initial measurement is made, the adaptation was enabled and a second measurement was made illustrating the improvement due to the adaptive pre-correction.

VSWR sensitivity:

In this experiment, a 1.5:1 VSWR was introduced by means of a short circuit stub on the transmitter output.

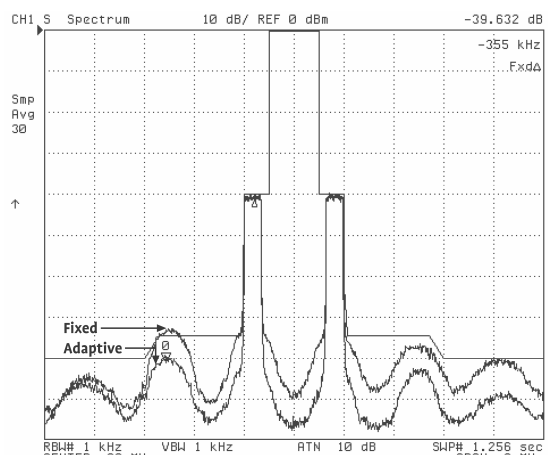

Figure 10: 1.5:1 VSWR with fixed and adaptive pre-correction

The VSWR test shows that adaptive correction achieved an improvement of 7 dB over fixed correction on the lower or worse IM3 sideband (Figure 10). Also note that the fixed pre-correction did not ensure compliance with the emissions mask with a 1.5:1 VSWR.

Temperature Sensitivity:

In this test the air intake and exhaust ports were impeded until the exhaust air temperature rose by 50ºF. This was intended to simulate a change in the room temperature that might be found with seasonal variations at a site without heating or air-conditioning.

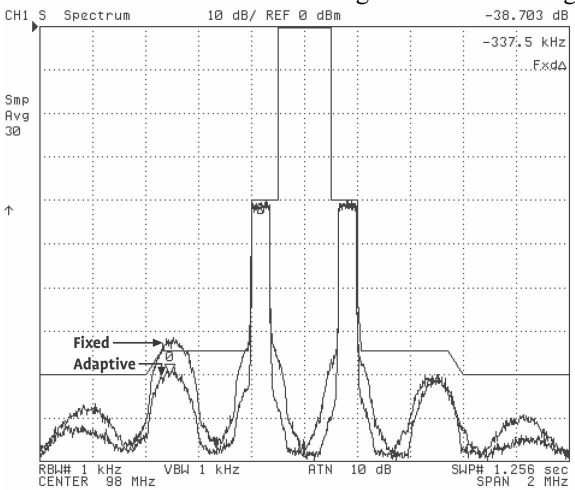

Figure 11: 29ºC Temperature Rise with Fixed and Adaptive Pre-correction

The temperature test shows that adaptive correction achieved an improvement of 8 dB over fixed correction on the lower or worse IM3 sideband (Figure 11). Also note that the fixed pre-correction did not ensure compliance with the emissions mask with a 50ºF temperature change.

Frequency Sensitivity (N+1 capability):

In this test the frequency was changed from 88 MHz to 108 MHz with fixed and adaptive pre-correction. While this test is not relevant to most stations because they always operate on a fixed frequency, it is significant in installations where there is a single backup transmitter for multiple stations.

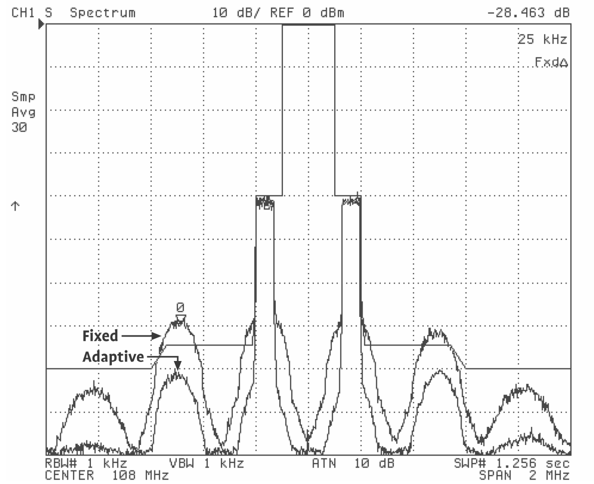

Figure 12: Frequency Change From 88 MHz to 108 MHz with Fixed and Adaptive Pre-correction

The frequency change test shows that adaptive correction achieved an improvement of 12 dB over fixed correction on the lower or worse IM3 sideband (Figure 12). Also note that the fixed pre-correction did not ensure compliance with the emissions mask with frequency change across the band.

CONCLUSIONS

Pre-correction is the accepted linearization technique used by FM HD Radio transmitter manufacturers. Pre-correction can correct for AM-AM and AM-PM characteristics that would otherwise result in unacceptable emissions.

Fixed pre-correction systems are unable to correct for the effect of a varying environment on amplifier non-linear characteristics. Experimental results show that VSWR, temperature and frequency changes typical of many broadcast sites may result in unacceptable emissions as defined by the proposed HD-Radio emissions mask. Digital adaptive pre-correction did not suffer a similar degradation. Emissions were maintained within the mask at all times.