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Advances in AM Modulation Techniques to Improve Digital Transmission of HD Radio and DRM

ABSTRACT

Modern digital transmission standards (HD Radio, DRM) demand higher performance from transmitter equipment to ensure effective transmission of the digital signal. These digital signals use vector modulated techniques (Envelope Elimination and Restoration), which require the envelope and phase components of the digital signal to be accurately combined within the transmitter to produce the correct digital spectrum. To ensure consistent and reliable reception, the transmitter must have highly linear and matched transmission paths for both the envelope (magnitude) and RF (phase) signals.

Recent technologies breathe new life into familiar modulation schemes such as PDM. These advancements allow wider bandwidth transmissions and higher modulation levels, while maintaining a consistent time and amplitude response to minimize effects of the EE&R vector modulation technique on the digital broadcast.

In this paper we will discuss such advancements and show how they improve the performance of the complete digital AM transmission system. We will also show how many of the techniques extend the performance of basic analogue broadcasts.

INTRODUCTION

The two main requirements on any transmitter are to deliver a clean signal at the desired output power and with as high efficiency as possible. Creating a clean signal spectrum for HD radio and DRM while simultaneously getting high efficiency, is problematic. Traditionally, one was forced to trade off between linearity and efficiency, or try to compensate for the distortion caused by the transmitter.

The increased availability and the ever lowering cost of DSP has made it interesting to see to what extent Digital Signal Processing technology can be used to correct for distortion in the transmitter. The goal is to use high efficiency transmitters and to correct for the distortion with DSP in the low level stages, this way achieving the dual goals of high efficiency and low distortion. Correcting for transmitter distortion is not trivial. We believe the best approach is to have a thorough understanding about what happens in the transmitter and then figure out the correct structure based on this. There are techniques that bypass this step and simply look at the input and outputs. For example: Neural networks and Volterra series based methods. In our experience, pre-distorters based on these techniques still need too much processing power to be economical.

Although we started with an efficient transmitter and linearized it with pre-distortion, there is an interaction between pre-distortion and the transmitter. Some types of distortion are more easily corrected by changing the transmitter design. These changes might make the transmitter more non-linear but easier to correct for. The designer will have to add pre-distortion techniques to his repertoire, but this cannot be taken in isolation. It must be part of the system architecture design process.

This paper covers the design of an advanced PDM transmitter including how we chose to correct the different types of distortion that are present in the modulator and power amplifiers. The paper is organized by an introduction: ”Why PDM modulation?”, “Basic PDM techniques” and “The Vector modulation signal using EER". This is followed by a description of the practical problems in the section: "Advanced PDM techniques." explaining the chosen correction techniques, and presentation of various measurements.

Why PDM modulation?

Losses in a transistor occur only when there is simultaneous voltage and current passing through the device. A typical example is a class "A" amplifier. Using the transistor as a switch can minimize the losses exhibited in a classical linear amplifier. Since there is no current through the device when it is OFF, the loss is zero. Similarly, when the device is ON (saturated), the voltage drop across the drain to source is practically zero, resulting in no power dissipation. In practice, there will be some loss due to the finite on-resistance. During the switching time, both the current and voltage are non-zero. It follows that the losses will increase with switching frequency. This technique is often referred to as a switching amplifier.

To achieve the goal of high efficiency, some type of switching transmitter is probably the best choice.

BASIC PDM TECHNIQUE

Pulse duration modulation (PDM), also known as pulse width modulation (PWM), has been known for several decades. It is the primary method of choice for high efficiency modulation such as Amplitude Modulation of Medium Wave transmitters and high efficiency switching power supplies. The rectangular waveform is applied to a low-pass filter that allows only the low frequency component to appear on the load device. The rectangular pulse width is changed to produce the desired output signal, as illustrated in Figure 1.

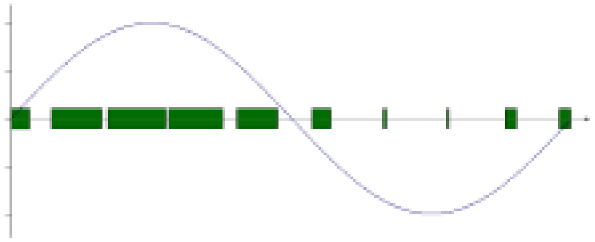

Figure 1. PDM modulated sine wave

Pulse width modulation inherently produces some distortion of the modulating signal even if the modulator produces perfectly timed pulses. Although the length of the pulses is proportional to the signal amplitude, the modulation scheme is actually non-linear. The distortion inherent in PDM modulation will decrease with switching frequency and modulation amplitude. A simple spectral plot is shown in the signal below. The desired signal is recovered at the load through a low-pass filter network. Those spurious products that fall inside the pass band of the modulator filter will appear in the load as intermodulation distortion.

The distortion primarily depends on the centering of the pulses. For example, the center of the pulses should all occur at the same time for minimum distortion. Figure 3 shows the distortion as a function of amplitude of the modulating tone. Note how the amplitude slightly drops as the level increases and how the harmonics increase. Also note that the distortion is rather low so that one can say that PDM modulation is "almost" linear. The relative amplitude in Figure 3 is the amplitude relative to the maximum allowable input.

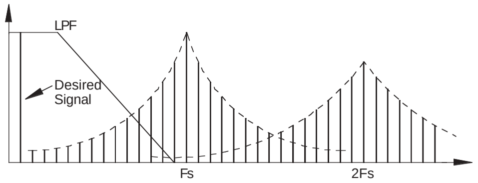

Figure 2. Spectrum of the modulating signal

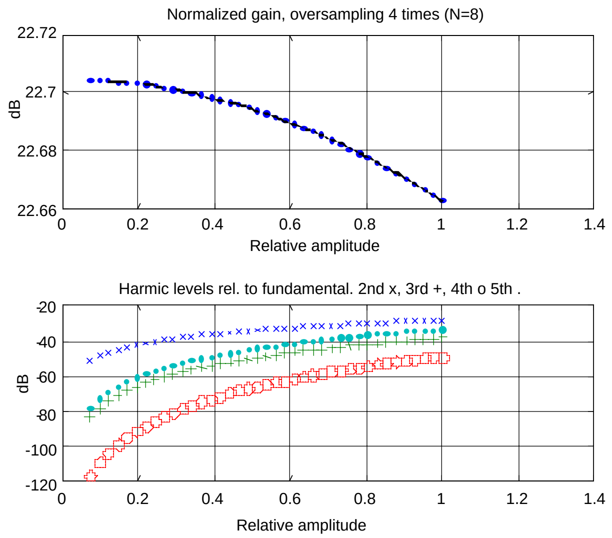

Figure 3. Over sampling 4 times N=8. Gain change of 0.05 dB

The distortion also depends on the frequency of the modulating signal. In Figure 3, the harmonic levels shown in the (3) curves refer to the harmonics of the modulating tone, not the harmonics of the PDM clock frequency. The complete PDM signal will have modulated harmonics at multiples of the PDM clock frequency as shown in Figure 2. These harmonic spectra are fairly wide and will, to some extent, bleed into the base band spectra causing additional distortion.

POLYPHASE PDM SYSTEM

In a polyphase system, there are several PDM modulators that are phase offset from each other. This will help by suppressing harmonics of the PDM clock frequency and reduce the distortion associated with the harmonics, but it will not completely eliminate the distortion on the modulating/fundamental signal as shown in Figure 4. In order to have good PDM harmonic suppression, the phase and amplitude responses of the PDM filter need to be precisely constant. In practice, this is seldom achieved, resulting in extra distortion.

The most important choice in the design of a PDM system is the switching frequency, the higher the better, since this will minimize distortion on the modulating signal and will also put the harmonics of the PDM switching frequency far away from the desired modulation component. A polyphase PDM system will eliminate the first harmonic spectrum of the PDM clock frequency, which provides some possible tradeoffs between the number of phases vs. PDM switching frequency. In practice, the switching frequency will be limited by the transistor switching times and the associated loss in efficiency.

Besides these theoretical distortions, there are also several other ways that distortion gets into the system through a non-ideal implementation. For example, the pulses themselves can be distorted. This is very noticeable if the duty cycle is short and the load current is minimal, therefore distorting the output rectangular signal by giving the pulses a “tail” on the decay side of the pulse. In addition, power supply ripple and dynamic load variation will also contribute to signal distortion.

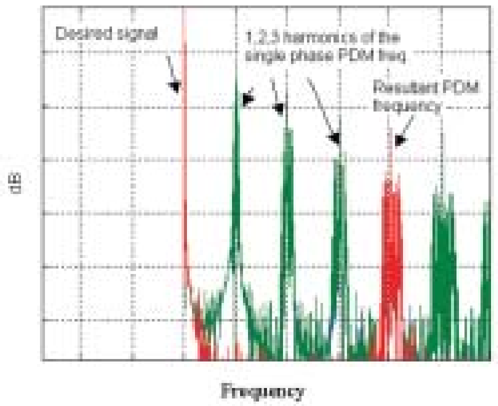

Figure 4. Polyphase PDM using four phases

GENERATING A VECTOR MODULATION SIGNAL

Using Envelope Elimination and Restoration (EE&R)

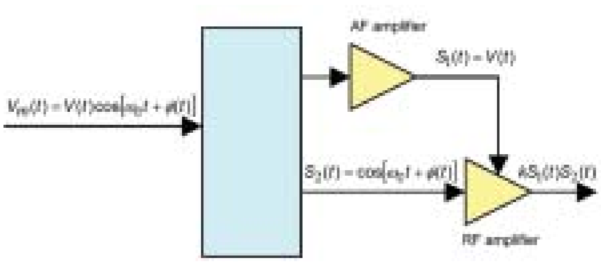

Figure5. EE&R block diagram

Most modern AM transmitters consist of both an envelope modulator and a final output RF switching power amplifier. These two circuits operate independently in a conventional AM transmitter.

The digital signal is typically modulated using OFDM (Orthogonal Frequency Division Multiplex). OFDM is a parallel modulation scheme in which the data stream modulates a large number of sub carriers that are transmitted simultaneously. The digital signal is a vector signal and can be represented in polar coordinates having both magnitude and phase information. In a traditional mono AM transmitter, the relationship between the phase of the carrier and the envelop is irrelevant, but for OFDM signals, the relationship is crucial.

Figure 5 shows a block diagram splitting an input vector signal into an envelope and a phase component known as Envelope Elimination and Restoration, (EE&R). The envelope signal is amplified using a high efficiency PDM modulator cascaded with an RF switching power amplifier (ie: High efficiency full-bridge class D amplifier).

The AM HD Radio transmitter receives individual phase and magnitude inputs from the AM HD Radio exciter. The outputs are then combined into a vector modulated signal to the external broadcast antenna system.

ADVANCED PDM MODULATION

The EE&R technique requires a linear AM transmitter having a constant group delay and flat frequency response in both the envelope and RF channels for minimum intermodulation distortion (IMD) product.

There are a number of potential sources of IMD in a EE&R type transmitter which affect digital radio transmission. They are:

1. Bandwidth of the pulse width modulator.
2. Pulse width modulator distortion.
3. Bandwidth limiting of the amplitude and phase signals.
4. Differential delay between the envelope and phase signals.
5. AM to AM distortion in the modulator, power amplifier, and combiner.
6. AM to PM distortion in the final power amplifier stage.
7. RF phase reversal at low envelope levels.

By overcoming these distortion sources, we have created a new advanced AM modulation technique which provides significant performance improvements over existing PDM transmitters in the present market place. The rest of this section will focus on the discussion of the hardware and Digital Signal

Processing (DSP) advancements and show how they improve the performance of the complete digital AM transmission system. Digital modulation schemes, as well as, conventional analogue broadcasting will benefit from these improvements.

As shown in Figure 1, typical PDM switching frequencies (Fs) used today in AM audio frequency modulators are approximately 60 to 70 kHz. This limits the practical filter bandwidth to 1/3 Fs (or 20 kHz). This is insufficient for good digital radio transmission using the EE&R technique. Harris' new advanced PDM transmitter uses an average PDM switching frequency of 175 kHz and has an audio bandwidth of greater than 50 kHz. To achieve a high switching frequency while maintaining low pulse width distortion, an improved PDM modulator using a push-pull transistor arrangement with a shoot through elimination resistor circuit is employed (known as tail-biter circuit), see Figure 6 below. This circuit switches transistors Q1 and Q2 that are operating in a true push-pull mode without the need for any dead time between the transistors Q1 and Q2. A small value resistor R1 is added to limit the shoot through current if both transistors Q1 and Q2 are turned ON momentary at the same time. R1 has negligible effect on the overall efficiency of the modulator. This push-pull modulator is especially beneficial when the pulse width duty cycle is small. Q2 increases the turn-off speed of Q1 by providing a return path for the commutating current in L1. In addition, using this push-pull switch arrangement reduces the sensitivity to load changes.

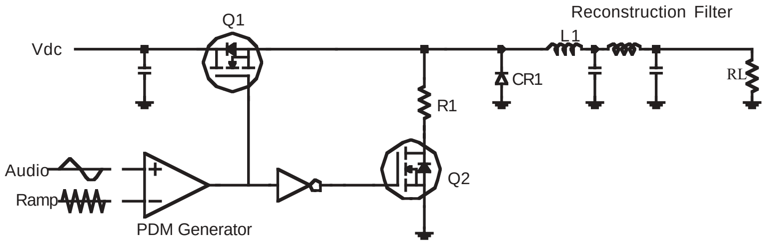

Figure 6. Advanced PDM modulator simplified diagram

Conventional PDM modulation shows a substantial amount of distortion from the input rectangular pulse with respect to the output PDM pulse depicted in Figure 7. The turn-off delay is extended and creates a tail effect. Significant improvement can be seen in Figure 8 using the APDM (Advanced Pulse Duration Modulation) modulator with the new "tail-biter" technique (Patents Pending). The circuit diagram is shown in Figure 6.

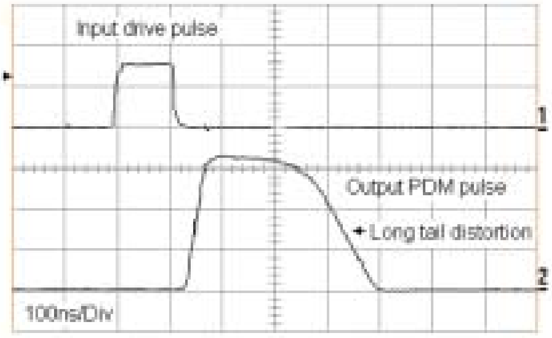

Figure 7 Conventional PDM modulator waveforms

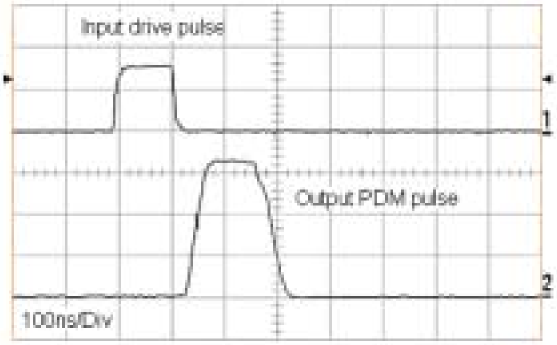

Figure 8. Advanced PDM modulator waveforms

The output PDM pulse is now following the input drive pulse much more closely, even at very short duty cycles. There is still a small amount of error due to practical component drive speed, propagation delay, etc. Further improvement using DSP will be described in the following section and is used to reduce the residual AM-AM distortion.

Proper timing alignment of $S_1(t)$ and $S_2(t)$ is also critical to recreate the accurate vector signals. Besides having a wider bandwidth reconstruction filter, it is important to maintain a constant group delay in the filter pass band to allow the envelope and phase reconstruction to properly align for accurate reproduction of the digital vector modulated input signals. This is of course, not a problem when transmitting analogue AM with no phase modulation.

Splitting the signal into phase and envelope components generally results in the two components occupying a larger bandwidth than that of the original I and Q signals. In theory, the envelope and phase components can have nearly infinite bandwidth. Any practical design must allow for envelope and phase signals that have 5-10 times the bandwidth of the corresponding I and Q components. How much more bandwidth is needed, will depend on how much distortion that can be tolerated on the final signal. In addition, the higher bandwidth on the envelope signal will require a PDM clock frequency that is sufficiently high. This, in turn, can cause other problems for the PDM modulator. For a higher PDM switching frequency, the “tail-biter” circuit is a must to ensure a good output pulse, since any small pulse width distortion will be a larger percentage of the total pulse width.

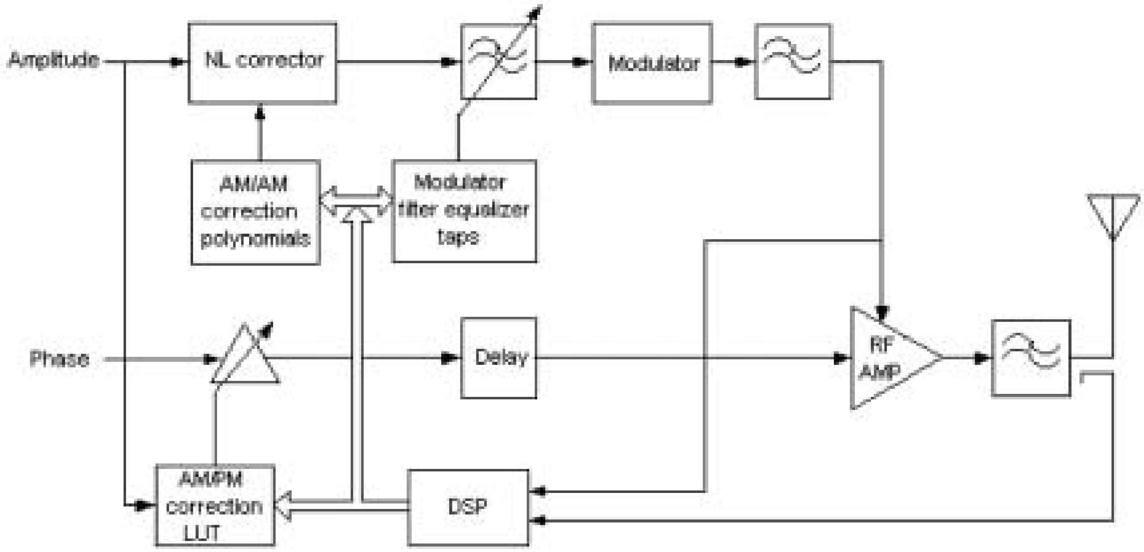

Figure 9 Simplified ADPM system block diagram

Keeping the phase and envelope signals pristine is of little use if they are misaligned in time or amplitude when combined into the composite RF waveform at the output of the transmitter. Hence, knowing the difference in delay between the phase and envelope is crucial. To complicate matters, the delay tends to vary with changes in the output filter and antenna load impedance. Consequently, estimating and correcting for the delay is a task ideally suited for a DSP.

APDM transmitter using advanced correction

As stated previously, there are numerous sources of non-linearities in a high efficiency PDM transmitter, which, if not corrected, can produce less than optimal spectral performance and higher BER (Bit Error Rate). Non-linear effects of the modulator, power amplifier, and RF combiner can all contribute to the spectral degradation if left uncorrected.

Advancements in DSP technology and advanced PDM modulation coupled with an innovative RF design have lead to a cost effective solution in achieving a highly linear PDM transmitter. The simplified system block diagram in Figure 9 depicts correction circuits used to linearize a new generation of APDM transmitters (Patents Pending). Implementation of a NL (non-linear) AM/AM Corrector, Modulator Filter Equalizer, and NL AM/PM Corrector using the new advanced PDM technology can dramatically reduce IMD distortion as shown in Figure 10 and Figure 11 below. These graphs were taken on a 5KW DAX transmitter passing an HD Radio hybrid signal.

AM/AM corrector

The NL AM/AM corrector works on a pre-distortion principal. The linearization technique applies the inverse of the amplitude distortion in the transmitter to the input envelope. A DSP is used to calculate the inverse using samples collected from the input envelope and the output RF envelope. The resulting inverse is a polynomial equation implemented in real-time by dedicated hardware or by the DSP.

AM/PM corrector

Similarly, the AM/PM distortion is estimated by the DSP. Samples of the input envelope and RF phase are correlated with the sampled transmitter RF output. The time correlation allows the DSP to calculate the amount of phase distortion present at any given input amplitude. Once calculated, the phase correction signal is simply added to the input phase signal. The resulting pre-corrected phase signal is then used as the PA RF drive signal. When the pre-corrected RF drive signal passes thru the PA, a consistent RF phase delay is achieved regardless of the RF envelope.

Modulator filter linearity corrector

The envelope signal used to modulate the RF carrier suffers some linear distortion caused mainly by the modulator filter. For example, the power supply voltage applied to the RF amplifier represents the envelope signal, but due to the linear distortion of the modulator filter, the power supply signal is slightly distorted. This is corrected by estimating this distortion and sending the envelope through an inverse filter before modulating the power supply. In addition to correcting the frequency response and group delay of the modulator filter, the equalization filter ensures that the delay thru the envelope path of the transmitter remains constant. As previously stated, this is critical for EE&R transmitters to ensure that the phase and magnitude components recombine accurately for minimum intermodulation distortion products.

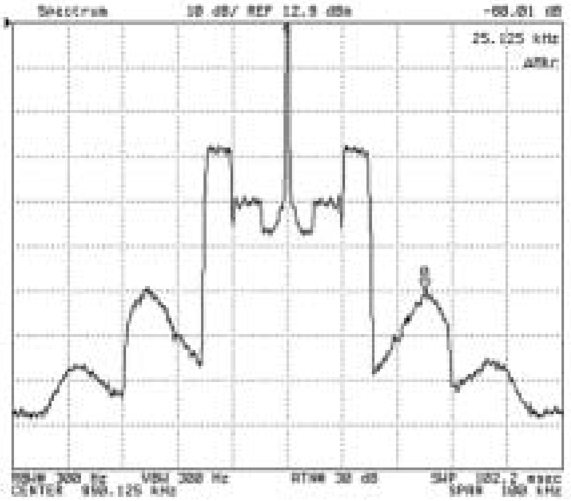

Figure 10. HD Radio output spectrum from a typical PDM transmitter

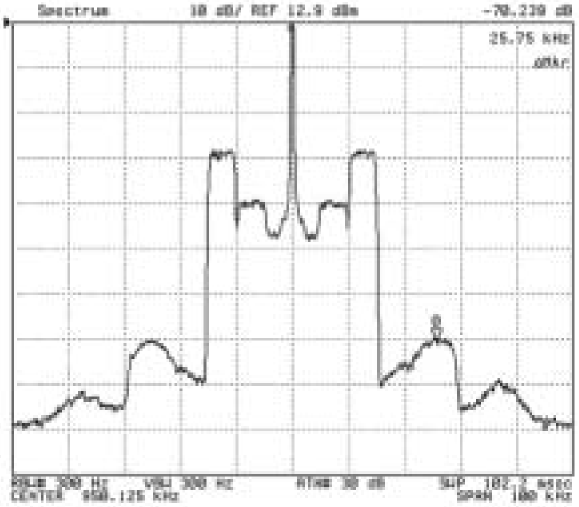

Figure 11. HD Radio output spectrum from an advanced PDM transmitter with DSP correction

DRM PERFORMANCE

DRM (Digital Radio Modiale) is a new worldwide standard for digital radio broadcast of medium wave and short wave transmissions. A major benefit of the DRM system is its ability to cope with multipath propagation (selective fading) which has been a continued source of irritation for medium wave listeners. Multipath is eliminated except in the most severe cases by employing COFDM modulation. Typically, a DRM signal has a peak to mean ratio of 10-12dB, thus an amplifier producing a signal having an average power of 1kW must have a peak power capability of 10kW. The recommendation from the "Broadcaster's Guide To DRM" suggesting that, for a 10kHz DRM signal, the audio path bandwidth needs to be 40kHz while maintaining a constant group delay.

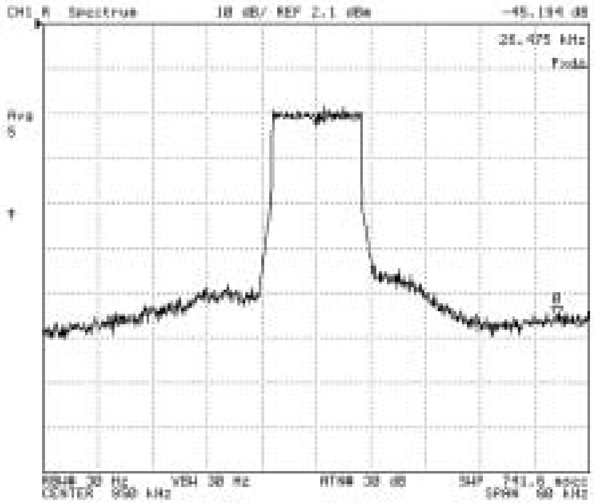

Figure 12. Typical PDM transmitter output spectrum – DRM spectrum

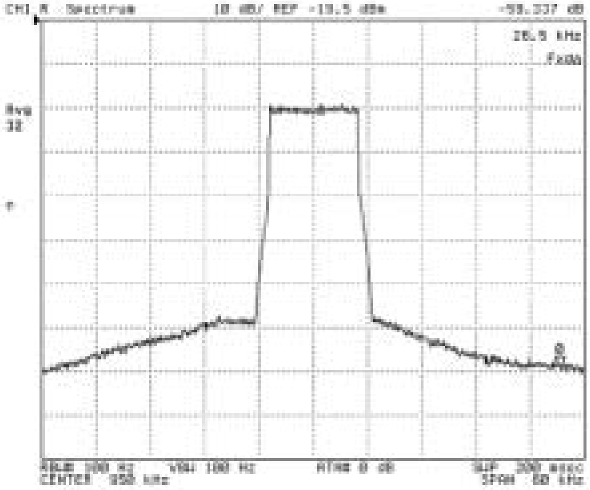

Figure 13 DAX DRM output spectrum

Figures 12 and 13 show the spectral plots comparing a conventional PDM transmitter to the DAX-5, APDM transmitter. In both cases, 2000W of DRM RF output power was generated using an experimental DRM exciter. The actual performance was somewhat limited by the prototype DRM exciter so the actual performance of the transmitter is better than that shown in Figures 12 and 13.

Figure 12 is the output spectrum of a typical PDM transmitter having an audio bandwidth of 20 kHz. While running the same test, Figure 13 has more than a 13dB shoulder improvement using the DAX-5 transmitter having a 250% wider bandwidth. Similar improvements in HD Radio performance are also illustrated in Figure 10 and Figure 11 when running a side-by-side comparison of the two technologies.

CONCLUSION

The emerging digital modulation formats for AM Medium Wave transmitters demand higher performance from transmitter equipment to ensure effective transmission of the digital signals. These signals, HD-Radio (In Band On Channel) or DRM (the worldwide standard), require more bandwidth, higher linearity, and constant group delays in the envelope and phase paths to achieve low IMD and improved spectral performance.

The addition of an adaptive DSP modulator filter equalizer ensures a constant group delay in the envelope path of the transmitter. This eliminates the need for constant tweaking of the Exciter delay adjustment to optimize recombining of the envelope and phase signals.

Using a new APDM modulator design coupled with an advanced RF power amplifier design and DSP correction, it is possible to greatly improve the performance of a traditional PDM transmitter. The APDM transmitter's excellent performance offers improved spectral results for both HD Radio and DRM while at the same time, providing very high overall transmitter efficiency at lower cost than other modulation techniques.

These transmitter advancements allow broadcasters to offer a superior signal to their audience by utilizing the latest digital technology to maintain optimal performance without constant adjustments.

REFERENCES

[1] P. B. Kensigton, ”High-linearity RF amplifier design”, Artech House, London, 2000.
[2] ETSI, “ETSI TS 101 980 V1.1.1 (2001-09), *Digital Radio Mondiale (DRM); System Specification.*” 2001.

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