TRANSMISSION CHALLENGES AND SOLUTIONS FOR ALL-DIGITAL AM IBOC

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ABSTRACT

Recent tests have been performed by the NAB to assess the viability of the all-digital AM IBOC mode, MA3. Hybrid AM transmission using MA1 has been commonplace for several years now, but the all-digital mode presents some unique challenges. The peak to average power ratio of the signal increases significantly compared to a station broadcasting an analog AM or hybrid signal, requiring either a reduction in power or some form of peak control. A typical hybrid transmitter installation would have the transmitter optimized for analog AM performance, but a different set of criteria are required for the all-digital signal to optimize spectral performance and MER.

This paper will present an analysis of the MA3 signal and spectral mask, along with the implications for passing it successfully through both current and past generation AM transmitters. Suggested power levels for a given transmitter will be reviewed, along with how these could be increased by reducing the amount of power in the AM carrier. Finally, an innovative signal conditioning technique that reduces the envelope and phase frequency content will be presented, allowing the operator to choose a trade-off between MER and spectral performance into difficult loads.

1 INTRODUCTION

There has been renewed interest in the all-digital IBOC signal recently, with a few on-air tests occurring within the past year. The all-digital signal potentially offers the advantage of much greater coverage compared to existing AM stations at similar power levels, whether it is compared against analog or hybrid. There is the potential to either cover a wider audience, or to reduce power levels and operating costs while serving the same markets. The recent adoption of modulation dependent carrier level (MDCL) control in the United States would indicate that there is considerable interest in saving power to lower costs. This paper will examine some of the challenges that are placed upon the transmitter to broadcast this signal, and explore some possible solutions.

All of the results in this paper were obtained using a Nautel NX50 50 kW AM transmitter. The IBOC signals were supplied by an Exporter+ and Exgine combination into the transmitter using a digital I/Q interface.

2 ORGANIZATION OF ALL-DIGITAL SIGNAL

The all-digital AM In-Band On Channel (IBOC) signal is a logical re-organization of the hybrid AM IBOC waveform that simulcasts the analog program along with the digitally encoded audio on HD-1. The hybrid waveform is termed the MA1 mode, while the all-digital waveform is termed the MA3 mode; both are fully specified in [1].

MA1 is comprised of 3 blocks of orthogonal frequency division multiplexed (OFDM) carriers around the AM carrier; the primary, secondary and tertiary carriers each with their own power levels as shown in Figure 1. The levels are reduced closer to the AM carrier such as to minimize bleed through from the digital carriers into the analog AM transmission. Each block contains 25 individual carriers separated by 181.7 Hz, with a total of 156 carriers including the reference carriers. The higher primary carriers are 64-QAM (Quadrature Amplitude Modulation) modulated and the secondary carriers are 16-QAM modulated. An example of 64-QAM used in MA3 is shown in Figure 2. Tertiary carriers are reduced to QPSK (quadrature phase shift keying) modulation where the information is carried in the phase of the carriers such as not to interfere with the AM signal content in the same space. With a symbol duration of 5.8 ms, this produces a raw data rate of around 92 kbps, which after forward error correction (FEC) leaves a throughput rate of 36.8 kbps broken into a 20.2 kbps P1 logical channel (primary carriers) and a 16.2 kbps P3 logical channel (secondary and tertiary carriers).

P1 carries the core audio information that entirely contains the audio signal content on its own. P3 contains enhanced audio information that provides better audio definition to the P1 core audio stream. With good signal reception, a high quality audio stream is delivered to the listener, while in marginal conditions the receiver can operate on the P1 core audio stream alone. This has led to an IBOC signal configuration where select stations opted to mute the secondary and tertiary carriers in favor of their analog AM signal, reducing self-interference for

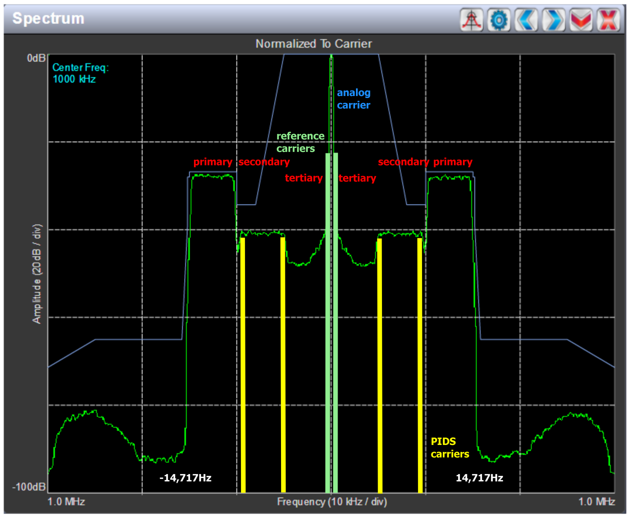

Figure 1: Spectrum of the MA1 signal.

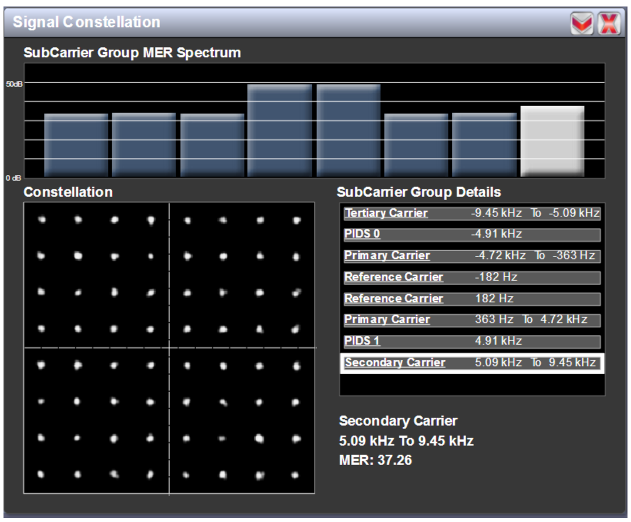

Figure 2: Constellation and MER display for the secondary carrier group in MA3 mode.

analog listeners. This is called the reduced bandwidth mode (RBM) since the digital bandwidth is reduced by the 16.2 kbps in the P3 partitions.

MA3 is a reorganization of MA1 for all-digital operation, as can be seen in Figure 3. The primary carriers have been relocated to replace the analog signal entirely and are increased by 15 dB in power. The secondary carriers have moved to the upper sideband and the tertiary carriers moved to the lower sideband both are increased in power to -30 dBc. The overall broadcast signal bandwidth is reduced from around 30 kHz to under 19 kHz, with a total of 102 carriers. The same P1 and P3 channel organization is maintained with a modest increase in P3 channel capacity to 20.2 kbps. Both P1 and P3 continue to operate in core and enhanced mode. Just like in MA1 mode, the secondary and tertiary carriers can be disabled in a RBM configuration. Along with a reduction in bit rate, this provides a low bandwidth signal configuration only occupying 10 kHz of bandwidth.

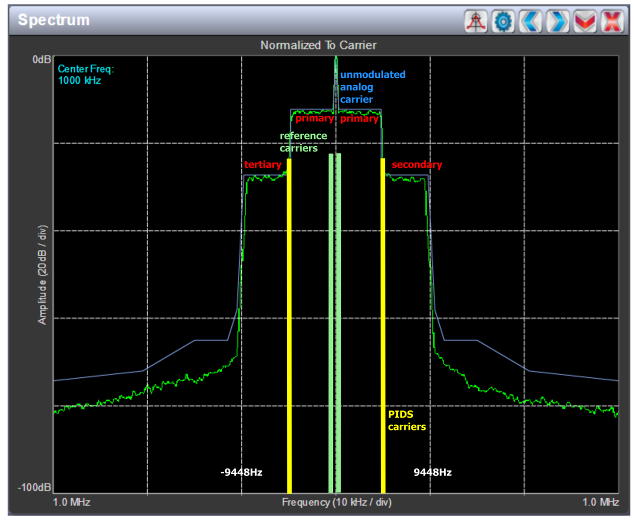

Figure 3: Spectrum of the MA3 signal.

Since the logical channel organization is similar to MA1, on-air bit rates remain comparable. It is likely not the addition of audio and data services that will drive adoption of MA3, but rather the improved IBOC coverage resulting from the IBOC carrier power increase and improved signal robustness.

3 PEAK AND AVERAGE POWER IMPLICATIONS

As noted in the previous section, the all-digital waveform consists of a large analog carrier surrounded by OFDM carriers. The default specification for the MA3 signal calls for the primary carriers to be at -15 dBc and for the secondary and tertiary carriers to be at -30 dBc. This waveform has some interesting properties that differ from both a standard analog broadcast and a typical OFDM broadcast. In this configuration, approximately 38% of the transmitted power is allocated to the analog carrier. This gives the receiver something to lock onto, and should help to improve the transmitter spectral performance. Unfortunately, this energy doesn't carry any information and reduces the potential peak digital power out of the transmitter. There has been some discussion about reducing the level of this carrier, since even dropping it by a few dB would provide significant power savings.

It should be noted that it is more appropriate to consider the power level of the station referenced to the total power from the transmitter, rather than the carrier power. In hybrid AM mode, an AM station would typically maintain the carrier power level that it would have before implementing IBOC. This would not work for a conversion to all-digital, since this would imply that for a

50 kW transmitter it would need to deliver over 130 kW RMS. The typical AM transmitter is rated for an RMS power corresponding to 100% tone modulation, or 150% of the carrier power level. With the example of the 50 kW transmitter, that would imply that it should be rated for a maximum RMS power level of 75 kW. This turns out to be an overly optimistic estimate of the power that can be achieved from the transmitter. Despite the headroom built into the power amplifiers to allow AM operation, the peak power of the digital signal dictates the achievable power level.

Modern AM transmitters are designed to be able to handle at least 125% positive peak modulation when broadcasting AM. In many cases, such as with the NX, the transmitter is tuned to allow 140% positive peaks. This implies that the headroom beyond the rated carrier power level of the transmitter is 7.6 dB and this is the peak to average power ratio that the transmitter can sustain without clipping when operating at an equivalent RMS power level. Coincidentally, this is approximately the limit as to where the MA3 signal can be clipped and still meet the spectral mask, assuming no other transmitter nonlinearity. In reality, any transmitter will have difficulty sustaining this power level and meeting the current spectral mask without a method for reducing the spectral impact of clipping peaks.

4 REDUCING THE ANALOG CARRIER

One point of discussion for the MA3 signal is how much power should be devoted to the analog carrier. The carrier serves a few purposes.

- The receiver can use the carrier to obtain a perfect frequency and phase lock to the incoming signal.
- The receiver automatic gain control can use the carrier to set the appropriate signal level.
- The carrier may make the signal easier to transmit while meeting the spectral mask.

There is an open question as to what carrier level is required to meet the first two purposes. With a number of receivers already in the field, the transmitted signal should be kept compatible if the all-digital standard is to succeed. It may be possible to reduce the carrier by 3 or even 6 dB and maintain compatibility with receivers, since finer equalization and level control uses reference cells within the OFDM signal.

As for making the signal easier to transmit, this may be a false assumption. In Figure 4, the complementary cumulative distribution function (CCDF) of the signal was plotted with the original carrier level, with a 6 dB reduction, and with no carrier at all. Removing the analog carrier entirely increases the absolute peaks relative to the RMS by 0.8 dB, but it reduces the overall power out of the transmitter by approximately 2.1 dB. This means that for a peak-limited transmitter, the overall coverage (which is largely governed by the power in the digital carriers) could be increased by approximately 1.3 dB due to the removal of the analog carrier. For the first two reasons stated above, some carrier level is required, so the same analysis can be done for a 6 dB reduced carrier. In this case, comparing against the standard signal, the power from the transmitter is reduced by about 1.5 dB, and the peaks are similarly increased by 0.5 dB. This corresponds to a 1 dB increase in the overall coverage, which is worth considering if that carrier level would be sufficient.

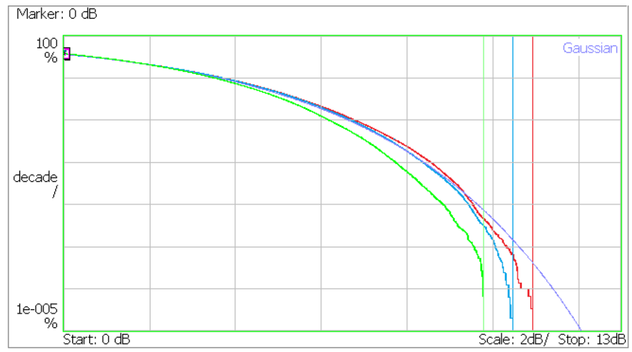

Figure 4: CCDF of the MA3 signal as specified (green), with a 6 dB reduction on the carrier (blue), and with no carrier (red). This plot shows the probability of exceeding a given peak level, as referenced to the signal RMS power.

It is true that with a typical AM transmitter architecture that amplifies the envelope and RF drive signals separately, there is usually some benefit to having a DC component to the envelope since it helps reduce the high frequency content. In this case, the added carrier provides very little benefit because it simply isn't large enough compared to the OFDM carriers. Increasing the level of the carrier to help with spectral issues is impractical, so the transmitter must essentially be linear enough to pass a signal that has no carrier at all. If the transmitter already has that linearity requirement placed upon it, meeting the spectral mask should be possible at any of the carriers levels discussed here. When the discussed signals were experimentally passed through an NX transmitter, there were several dB of clearance from the mask at all points, with only minor differences in performance.

5 MEASURING POWER

It should be noted that measuring power with the MA3 signal must be done differently than with an analog AM signal. The typical AM site uses a current probe and averaging meter to determine the carrier power, since by averaging the envelope voltage the effect of modulation can be removed. This technique no longer works as expected once the OFDM signal is introduced. The value obtained by that type of measurement will not be equal to either the carrier or the RMS power out of the transmitter. To illustrate the point, Table 1 lists the readings that would be obtained for three different signals. The AM modulation used for the analog case is the same as that on the MA1 signal. The averaging meter works well for analog mode, results in a slight error for MA1, and gives an error of almost 20% when using it for MA3. The error would only increase if the analog carrier were reduced. When in MA3 mode the NX is configured to use the RMS power for monitoring, protection, and power control, while MA1 mode is referenced to AM carrier power as for standard AM broadcasting. This can be observed in Figure 5, which shows an NX50 operating in MA3.

Signal	Carrier	RMS	Averaging meter
Analog AM	1	1.05	1
MA1 with Analog	1	1.11	1.02
MA3	1	2.62	2.11

Table 1: Carrier, RMS, and averaging power meter readings in various modes, each referenced to the analog carrier in that mode.

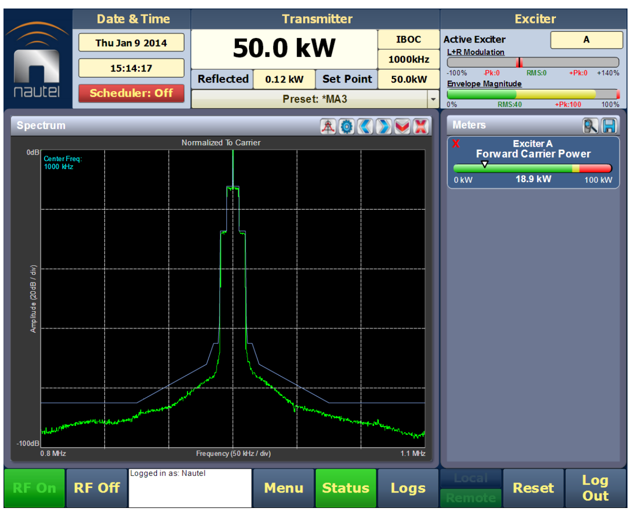

Figure 5: The MA3 signal passing through an NX50 transmitter. Note that the power level displayed in the top banner is RMS, while the sidebar shows the actual carrier power.

6 TRANSMITTER NONLINEARITY CORRECTION

The transmitter would not have any difficulty with meeting the spectral mask if it were not for some inherent nonlinearities in the amplification. There are four principal sources of spectral regrowth:

1. Amplitude nonlinearity, otherwise known as AM-AM distortion
2. Incidental phase modulation caused by envelope variation, also know as AM-PM distortion
3. Frequency response on the envelope path (or phase path)
4. Peak clipping in the power amplifier

Most AM transmitters are designed using some form of envelope elimination and restoration (EER) amplifier. The principle in this architecture is that the envelope voltage is developed using nonlinear amplification and is mixed with the RF drive in the final stage power amplifier to produce the desired waveform. The main advantage of this type of transmitter over linear amplification is efficiency. The downside can be that the magnitude and phase signals that are passed through the amplifier have much wider bandwidth than the RF signal for all cases except analog AM. The resulting envelope spectrum can be observed in Figure 6. Note that the original 20 kHz bandwidth on the RF signal has been expanded to 100 kHz on the magnitude; similarly, there is an expansion to 150 kHz on the phase. If the amplifier is not capable of passing these signals without significant distortion, then the transmitter will have difficulty with the spectral mask. Some of these concepts were discussed in a previous paper[2] with respect to the MA1 signal.

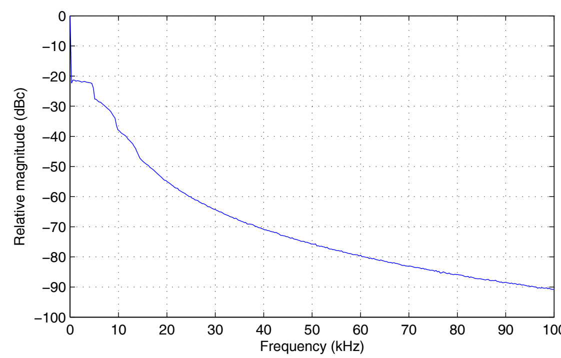

Figure 6: MA3 magnitude spectrum.

7 AM-AM CORRECTION

The amplifiers in the transmitter will tend to have some degree of amplitude distortion. The distortion is typically low enough that it does not cause issue with analog transmission, but it benefits from being corrected for better audio specifications as well as digital transmission. The actual mechanism for applying this type of correction in the NX transmitter is by digitally applying a look-up table (LUT) to the magnitude signal before generating the pulse duration modulation (PDM) signals for the amplifiers. It is adapted by comparing the desired signal against the measured output voltage of the transmitter, after appropriate delay-matching and filtering. The correction that would usually be applied on a transmitter is accomplished with a 1 kHz tone, and assumes that the amplitude distortion is relatively constant with frequency. This simplification holds true at low frequency, but as the frequency increases the response of the modulator filter comes into play.

The transmitter AM-AM correction was adapted using several different frequencies as shown in Figure 7. At 1 kHz, the modulator filter has very little response and so its impedance can be modelled as a short. As the frequency increases, the source impedance added by the modulator filter increases, and an interesting effect happens. The PA tends to behave as a lower resistance value at very low amplitudes, which then has a tendency to counteract the modulator distortion once the source impedance increases. As a result, less AM-AM correction is required at higher modulating frequencies. This implies that while the curve determined at 1 kHz, which reflects the low frequency characteristic of the amplifier, help with AM performance it is not ideal for digital, where the modulating frequencies tend to be much higher.

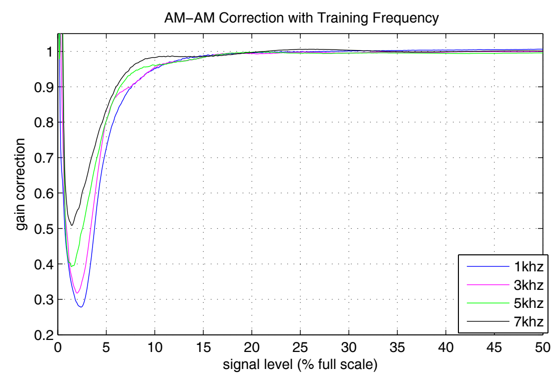

Figure 7: AM-AM correction curves at 1, 3, 5, and 7 kHz.

The principal problem with running the AM-AM correction at higher frequencies, or on an actual signal, is that there tends to be a frequency response on the resultant signal due to the modulator filter. The requirement for delay matching on the desired signal vs. the measured output also becomes much stricter, since otherwise a correction update may be applied to the wrong index in the look-up table. This can cause instability in the precorrection algorithm, and will result in the transmitter emitting unwanted spectral content because of noise and poor convergence in the LUT. In order to help alleviate this issue, each update to the lookup table can be applied as a weighted average to a region of the look-up table. This has the effect of filtering the update, and helps tremendously with the stability of the algorithm. Using this technique to run the adaptation on the actual signal allows for the most appropriate correction to be used, and does not interrupt the on-air signal.

8 AM-PM CORRECTION

Another common distortion found on AM transmitters is AM-PM distortion. When this occurs, the phase shift of the RF output is dependent on the magnitude of the envelope voltage. This effect is certainly present when broadcasting in analog, and a suitable correction can be applied to remove it. A relatively simple method involves using a lookup table to find the opposite phase shift at a given amplitude and applying it to cancel the distortion. An example of such a lookup table is shown in Figure 8. It can be seen from the characteristic in the graph that the correction required is quite significant at low amplitudes, and drops off to almost nothing above the nominal carrier level.

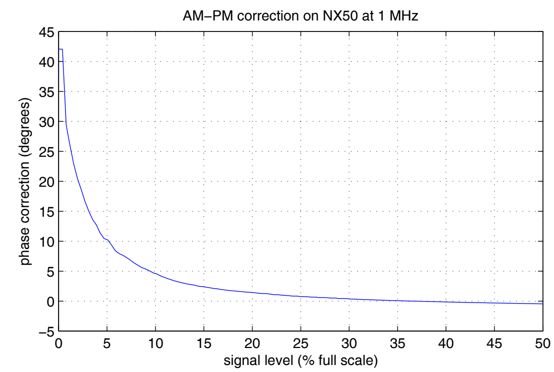

Figure 8: Example AM-PM correction curves from NX50 operating at 1 MHz, using 1 kHz training frequency.

When operating with an all-digital signal, this type of AM-PM distortion can result in poor spectral compliance if left uncorrected. This is considerably worse than if the same transmitter were transmitting analog. It may be counter intuitive, since there would obviously also be troughs on an analog signal that would result in phase modulation, but the high frequency envelope content in the troughs of a digital signal in turn causes high frequency phase modulation. This has far more of a tendency to make the transmitter exceed the spectral mask, especially at frequencies farther away from the carrier. In contrast, the incidental phase modulation of an analog transmitter tends to fall closer to the carrier and be within the spectral emissions mask.

9 ENVELOPE EQUALIZATION

In an AM transmitter using an EER architecture, with a modulator followed by a RF amplifier, there is often a bandwidth limitation on the envelope path. This is imposed by the combination of the PDM process and the reconstruction filter. The PDM frequency should be kept low to minimize AM-AM distortion and to boost the efficiency. At the same time, the modulator filter must attenuate any harmonics of the PDM that might pass through the amplifier and cause unwanted spectral emissions. These goals are at odds with the desire to keep the envelope bandwidth as wide as possible to maximize transmitter linearity.

Using a compensation filter on the magnitude signal can help extend the bandwidth by boosting those frequencies that are attenuated by the modulator reconstruction filter. This compensation filter also equalizes group delay, which is often just as if not more important than correcting for amplitude variation. The challenge often lies in finding the ideal filter for the system. On the NX series, a modified version of the least mean squares (LMS) algorithm is used to adapt the filter from the measured voltage sample.

One method that has been used with success to adapt the filter is simply to run the transmitter in AM mode with wide band (>70 kHz) noise as the modulation source. This has the advantage of being very simple to implement, it tends not to be affected by any other nonlinear effects, and it gives a good characterization of the modulator response since there is known frequency content. The disadvantages are that it can be affected by the RF filter response and a broadcaster could not realistically run a signal like this into the antenna, since it would cause interference with several other stations.

To optimize the transmitter for the all-digital signal, the equalization needs to be adapted with the transmitted signal, ideally into the antenna. This allows for the unique characteristics of the load to be taken into account, has the advantage of not driving the RF load at frequencies that are not of interest, and allows on-air adaptation. The challenge with using the transmitted signal is that the frequency content will not be flat for the adaptation. Using this filtering algorithm, this type of signal adapts the filter fairly well where there is significant frequency content, but not where there is less energy. This is insufficient to help with the spectral regrowth, and in many cases can make it worse than having no equalizer at all.

The envelope signal can be altered to allow adaptation by using a shaping filter to flatten the envelope frequency content. This is only used in the adaptation algorithm, not on the transmitted signal. The implementation on the NX series measures the signal going through the transmitter to dynamically design the shaping filter to use. The overall effect of this process is that the equalization filter will adapt more closely to the high-frequency regions in the trough. The same portions of the signal tend to be responsible for most spectral regrowth, so this gives the best results.

10 SIGNAL ENVELOPE CONDITIONING

An alternate approach to meeting the spectral mask requirements for MA3 is to make the signal easier to pass through the transmitter, rather than attempting to correct all nonlinearity. In a real system where the antenna may not present an ideal load, or with a previous generation transmitter not designed for the high bandwidth requirements of an all-digital signal, this may be the only way to meet the mask. The approach described in this section should be considered after all precorrection options are exhausted, since it will degrade the modulation error ratio (MER) slightly. It has been incorporated in the NX series for wide bandwidth Digital Radio Mondiale (DRM), but is equally applicable to the MA3 signal with the appropriate configuration[3]. The principle used is similar to some peak to average power ratio (PAPR) reduction schemes, where the problematic portion of the signal is modified slightly to reduce its impact. With a PAPR reduction the problem areas are peaks; with the typical AM transmitter, the most challenging portions of the signal are in the troughs, for a few reasons.

- The envelope signal has the highest frequency content in the troughs when operating with a digital signal.
- The AM-AM distortion is most pronounced at low amplitudes, and the variation with frequency means that it cannot be perfectly cancelled.
- The AM-PM distortion on the signal is largest at low amplitude where the current from the PA is low. This can typically be corrected extremely well, but errors in the other corrections will cause phase errors since the predicted amplitude would not match the voltage across the RF bridge.
- Bandwidth limitations on the antenna can translate to either increasing or decreasing impedance being presented by the RF PA with frequency. This may result in a requirement for the modulator to apply a negative voltage to the RF PA in order to achieve the desired output, which is not possible without the addition of considerable complexity to the amplifier.

There are a few essential stages to the algorithm, with several methods being possible for each step.

- Identify the problematic sections of the signal
- Flag and extend the identified sections
- Replace each section with a lower frequency transition (as measured with the magnitude and phase)
- Low pass filter the resulting signal to ensure it stays within the original RF bandwidth

The sections of the signal requiring correction can be identified by high-pass filtering the magnitude and phase signals, and looking for the output to cross a threshold. Alternatively, the magnitude signal can be examined for falling below a threshold, although this could flag sections of the signal that are not high frequency and thus have less requirement for modification. The final method that can be used is to examine the second derivative for exceeding a threshold. Regardless of how the sections of the signal are identified, the next step is to determine what to do about them.

In order for the identified sections to be modified, the first step is to extend the flagged regions of the signal in the time domain. This allows a more gradual modification to be made, reducing its spectral impact. It also serves to join together any isolated samples, and helps to create a region to be corrected. There are some additional checks performed within the implementation to ensure that a replacement region does not become too large, and that the corrections do not become too frequent; otherwise the MER might be too severely impacted.

The next stage has the purpose of replacing the section of the signal with a segment that is smooth in both I and Q as well as magnitude and phase. This requires deliberate intervention to make sure the signal will not fall back to its original samples when the final low pass filter is applied. The method used here determines a new midpoint for the section being replaced, then uses cubic spline interpolation to fill in the remaining samples. The midpoint as determined in this algorithm is the mean of the magnitude and phase of the samples entering and exiting the replaced section. An example of a correction made by the algorithm can be seen in Figure 9. The signal has been moved away from zero, which was causing high frequency content on the magnitude and phase.

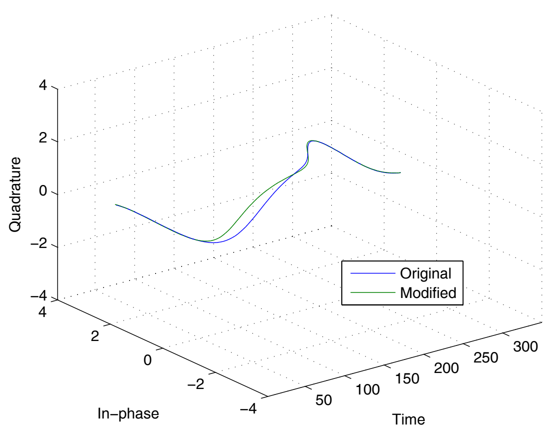

Figure 9: Example of a correction made by this algorithm. Note that the signal has been moved away from the origin, but is still smooth in the I/Q plane.

Finally, a low pass filter is applied to the signal to suppress any out of band content created during the interpolation process. The cutoff on this filter must be very aggressive in order to avoid modifying the desired signal, but it does not require a significant amount of attenuation since the signal should not have too much content to suppress.

The resulting signal has lower frequency content on the magnitude and phase signals than the original. This helps to reduce the effects of some of the possible transmitter nonlinearity described in this paper. Provided the algorithm is set in such a way that it has little impact on MER, it should have imperceptible impact on coverage, but it may help with a system needing to meet the mask. The advantage of this type of approach is that it does not require knowledge of the transmitter, and there are no RF samples required as there would be with precorrection. The downside is that it has limited ability to overcome certain transmitter issues, and may only be useful for systems that are close to, but are not quite spectrally compliant.

11 CONCLUSION

The specification for the MA3 signal might be misleading if the assumption is made that the carrier level would be the same as with MA1 or analog. Transitioning to all-digital implies that the licensed power level for a given station should be reconsidered, and coverage tests still need to be completed to determine appropriate power levels. The capabilities of the existing equipment in the field should be taken into account: many transmitters may only be capable of an RMS setpoint that is less than their current carrier power. The level of the analog carrier in the signal should be reviewed; if possible, the 6 dB reduction shown in this paper should be considered, since it makes a significant difference in both the transmitter power capability and the RMS transmitted power.

The other consideration for deploying MA3 will be the ability of the existing transmitters in the field to meet the spectral mask. Many AM stations currently struggle to meet the MA1 mask, and the MA3 mask is significantly more stringent. It is likely that many legacy transmitters will be unable to meet the mask unless it is relaxed somewhat, or they employ some of the techniques described in this paper. The NX transmitter used for these tests is not representative of many of the older systems in the field that have been retrofitted for IBOC. The envelope conditioning technique may be of benefit to some of these systems, since adding it to an existing transmitter is far less invasive than the changes required to allow precorrection.

References

[1] *HD Radio™ Air Interface Design Description - Layer 1 AM*, iBiquity Digital Corporation, http://www.nrscstandards.org/SG/NRSC-5-C/1012sf.pdf, August 23, 2011, rev. F.

[2] B. W. Walker, "Easing the Transition to AM IBOC: Tools and Techniques to Help the Broadcaster," *NAB Broadcast Engineering Conference Proceedings*, 2009.

[3] B. W. Walker, "Signal Correction for Digital Audio Broadcasting Using EER Amplifiers," Master's thesis, Dalhousie University, Dec 2006.