Very-Sharp Filter Enhanced Compensation in ATSC 1.0 & ATSC 3.0

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Abstract – *The purpose of this paper is to present the requirements of adjacent channel filtering/combining in both ATSC 1.0 and ATSC 3.0 that will likely affect many DTV transmitter sites after the FCC repack process. We will take a closer look at the latest state-of-the-art RF Mask filter designed by Dielectric. Then, new Digital Linear Pre-correction techniques, especially designed by TeamCast to compensate such "Very-Sharp Tuned" filters, will be explained. Finally, a comprehensive report and test results performed by Comark, TeamCast and Dielectric will conclude this presentation.*

INDEX TERMS—ATSC, VERY-SHARP TUNED FILTER, DISTORTIONS, PRECORRECTION, MER

Introduction

When the 8-VSB standard was developed, a DTV emission mask was defined that ensured minimal interference with neighboring analog and digital broadcasts. These recommendations were adopted in the FCC Fifth Report and Order, as the FCC DTV Emission Mask in 1998. The FCC emission mask was defined to replicate the response of a seven section Chebyshev band pass filter. Most filters deployed for UHF broadcast are either six or eight pole filter designs that closely follow this response.

It should be noted that out-of-band emissions close to the channel edge (i.e. RF shoulders) rely primarily on the RF amplifier's design and performance in conjunction with the DTV exciter's ability to "pre-correct" for amplifier non-linear distortions. This is true with transmitter amplifiers designed for ATSC 1.0 (8VSB) and ATSC 3.0 (OFDM).

If the standard DTV emission mask is met, minimal interference will be seen on adjacent channel allocations that are of comparable power. However, the FCC places the burden on stations to ensure that interference does not take place with all services, including communication systems of disparagingly different power levels such as land-mobile two-way radio services. For each transmission site deployed in the US, RF filter manufacturers like Dielectric designed and provided optimized and dedicated FCC channel RF mask filters for both the standard mask and high rejection applications.

Due to the sensitivity to group delay and amplitude variations of 8VSB signal characteristics, the RF channel filter distortions must be compensated for. The complexity of the pre-correction algorithm depends on the amount of distortion that needs to be compensated for, which is closely related to the sharpness of the mask filter response. For broadcast channel allocations that are adjacent to land-mobile or other low power sensitive licensed services (such as channels D14 and D17), standard RF mask filter and exciter technology is not sufficient; more complex and advanced systems must be utilized.

We are on the cusp of substantial changes in the US terrestrial broadcast market. The FCC repack, combined with the desire to transition to ATSC 3.0 has a wide range of implications on the DTV transmitter infrastructure. With the current FCC repack resulting in substantially reduced spectrum available for over-the-air broadcast television, it is expected that digital adjacent channel cases will become more of a requirement to accommodate all US broadcasters.

Consequently it is foreseen that more complex and "Very-Sharp Tuned" filters will be required in the repack. Such new channel RF filters should be designed for both ATSC 1.0 (8VSB) and for future ATSC 3.0 transmission (OFDM). Note that ODFM based transmission systems have much higher peak to average power requirements when compared to 8VSB. ATSC 3.0 also occupies additional bandwidth. Accordingly, the linear pre-correction algorithm implemented within the DTV exciter must be capable of pre-correcting such "Very-Sharp Tuned" filters in order to achieve the best RF signal performance in terms of RF shoulder levels as well as MER figures.

RF Mask Filter Designs

At a DTV transmitter site, a channel filter (RF mask filter) is installed at the output of the DTV transmitter. The filter is responsible for filtering the out-of-band interference to the upper and lower adjacent RF channels and is therefore used to comply with the specific FCC emission mask.

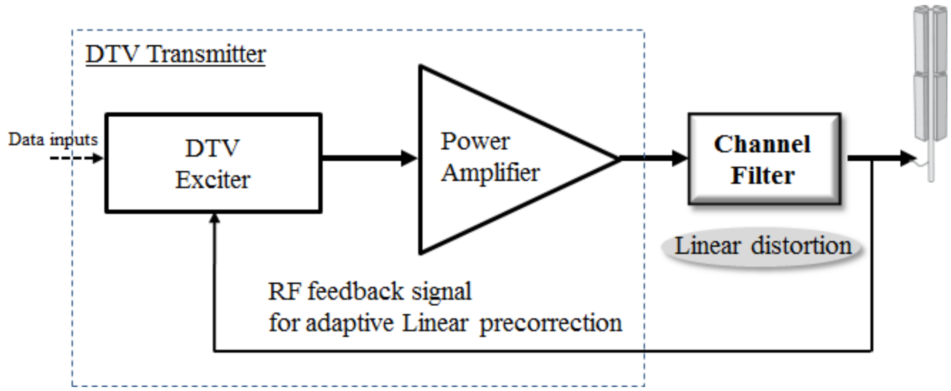

FIGURE 1: LINEAR PRECORRECTION BLOCK DIAGRAM.

Filters deployed for UHF broadcast to meet FCC emission requirements are either 6-pole, 8-pole, or some variation similar thereof to the rejection and delay responses illustrated in Figure 2. The sharper 8-pole filter is used to further reduce transmitter Inter Modulation Distortion (IMD) or for adjacent channel combining. Transmitter precorrection required to compensate for the linear amplitude and delay distortions created by these filter responses is routine for the current ATSC 1.0 standard [1].

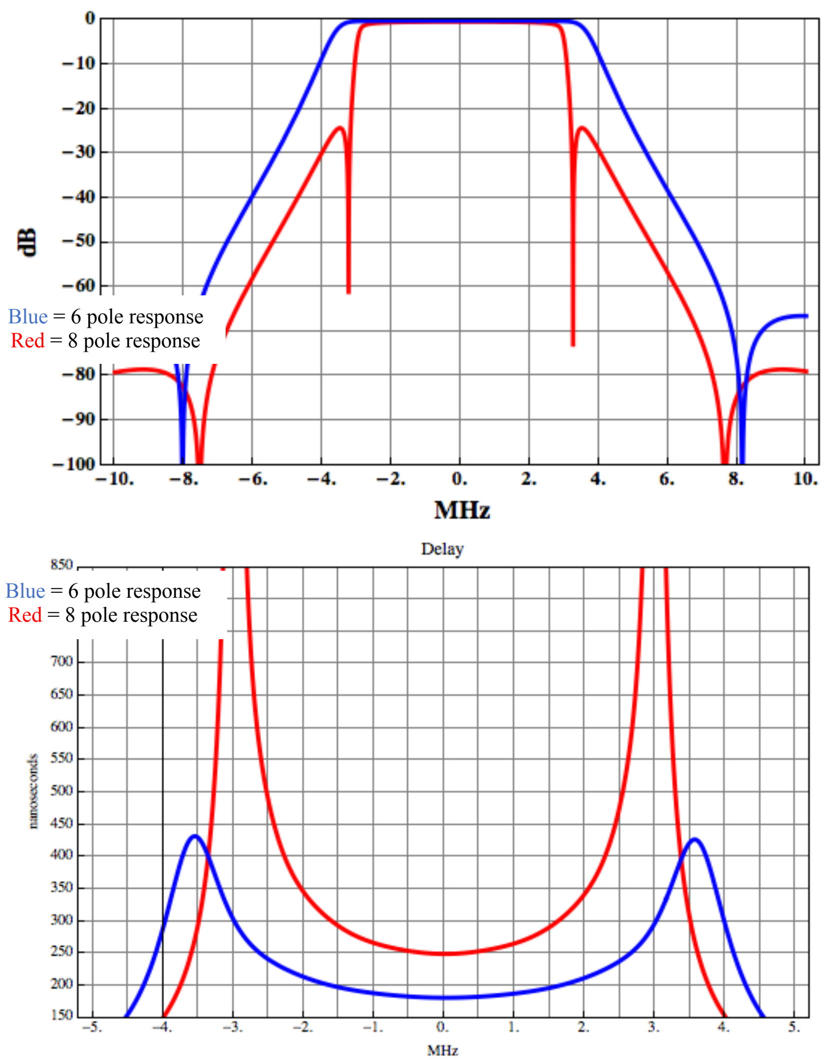

FIGURE 2: TYPICAL ATSC 1.0 6- AND 8-POLE MASK FILTER RESPONSE

Passband delay variation in Figure 2 is a function of filter order and required channel edge attenuation. The 8-pole filter provides greater rejection close to channel edge, resulting in greater mid-band delay and delay variation in the passband. Since the signal spends more time in the filter at passband edges, insertion loss is higher too. Loss variation is not plotted because it depends on the filter cavity size, or Q. In general, smaller filters with lower Q have higher mid-band loss resulting in greater passband loss variation. Filter mid-band loss, L_o, is found from the cavity Q and filter transfer function H(f) parameters as referenced in Cohn [2]. Filter loss can be plotted using the formula shown below and is a function of the mid-band loss multiplied by the ratio of the delay at the frequency of interest, $\tau(f)$, to the delay at mid-band, τ_o.

$$\mathbf{Loss[f] = -20\ Log\ [H(f) - L_o\ \tau(f)/\tau_o\ ]\ dB}$$

High power filters using waveguide cavities, ATSC 1.0 loss variation is approximately .06dB and .29dB for the 6 and 8-pole responses respectively.

I. ATSC 1.0 vs. ATSC 3.0

Up until now, licensed DTV transmitters in the US use ATSC 1.0 with an 8-VSB digital modulation scheme. The DTV industry is on the cusp of releasing a new digital television standard called ATSC 3.0. The ATSC 3.0 standard is an OFDM type modulation that has a peak to average ratio or crest factor that is approximately 9-10dB (compared to 6.5-7dB for ATSC 1.0). DTV transmitter amplifiers can only produce so much RF power. The higher peak to average power (PAPR) of ATSC 3.0 will result in higher IMD if the PA is not designed to handle the extra peak power.

Precorrection techniques are used to improve signal performance including shoulder levels; however there is a limit on a particular amplifiers ability to produce power with acceptable RF shoulders. It should also be noted that the RF shoulder performance is indicative of the in band signal to noise performance of the DTV transmitter system. DTV transmitters that are "pushed" harder (i.e. have poor shoulder performance) and rely on sharp tuned filters to meet the FCC spectral mask will have lower MER performance in ATSC 1.0 and will have to be derated substantially (TPO back off) when switching to ATSC 3.0.

Another important aspect of ATSC 3.0 is the occupied bandwidth. ATSC 1.0 has an occupied bandwidth of 5.38MHz; ATSC 3.0 is 5.84MHz [3] as specified in the Physical Layer Protocol standard A/322. This 8.4% increase in occupied bandwidth allows for higher data throughput but it also has implications to the RF mask filter system. If a particular ATSC 3.0 DTV station operates on adjacent RF channel or through a channel combiner into a shared broadband antenna, the occupied bandwidth needs to be considered.

The last difference worth mentioning between ATSC 1.0 and ATSC 3.0 is the receiver sensitivity to Group Delay variation. In ATSC 3.0, the OFDM based signal includes a large number of carrier pilots that are dedicated to ease the channel equalization at the receiver site. The fact that those pilots are spread over the channel spectrum makes the receiving condition much less sensitive to any Group Delay variation unlike as with ATSC 1.0. This explains that the majority of existing OFDM networks (DVB-T, DVB-T2, ISDB-T...) seldom use Linear Precorrection to compensate regular RF channel mask filters.

II. Adjacent Channel Combiners/Filters

Loss and delay variation of the 8-pole filter response in Figure 2 increases more with the 5.84MHz occupied bandwidth of ATSC 3.0 (with maximum number of carriers). Existing 8-pole or greater filters used for adjacent channel combining will likely be too narrow for ATSC 3.0. Constant impedance combining modules (or directional filter designs) will require redesign for ATSC 3.0. Due to the wider occupied bandwidth of ATSC 3.0 and resulting reduction in guard band between channels, filters will have to be tuned wider in bandwidth with elevated VSWR to achieve the required rejection over the smaller guard band. For example, if multiple adjacent channels are combined, 8-pole CIF (or directional) modules are cascaded to form the channel combiner layout in Figure 3.

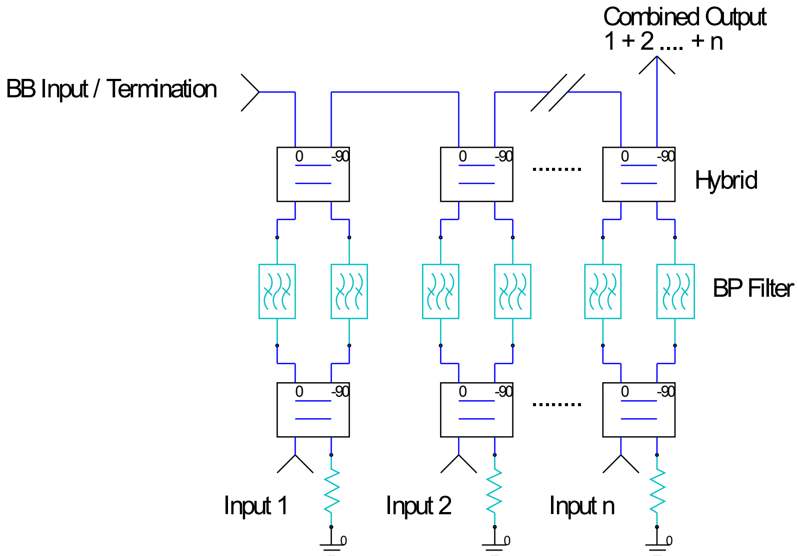

FIGURE 3: CIF COMBINER FOR ADJACENT CHANNELS

With the highest channel being the last module in line (closest to the antenna), the filter amplitude and delay response of adjacent ATSC 1.0 channels is illustrated in Figure 4 and ATSC 3.0 in Figure 5. Note the asymmetric amplitude and delay on the lower adjacent due to the requirement of entering the broadband port of the last module, and, the excessive passband variation on the ATSC 3.0 combiner due to reduced guard band between adjacent channels. A summary of amplitude and delay variation for ATSC 1.0 and 3.0 combiner modules is shown in Table 1 for high Q waveguide cavities. Loss variation is exacerbated using smaller filters with lower Q.

	Adjacent CH Combiner Response	
	ATSC 1.0	**ATSC 3.0**
Insertion Loss		
Max. (dB)	0.6	3.3
Variation (dB)	0.4	3.0
Group Delay		
Max. (ns)	1100	2900
Variation (ns)	800	2600

TABLE 1: ATSC 1.0 AND ATSC 3.0 ADJACENT CHANNEL COMBINER LOSS AND DELAY SUMMARY

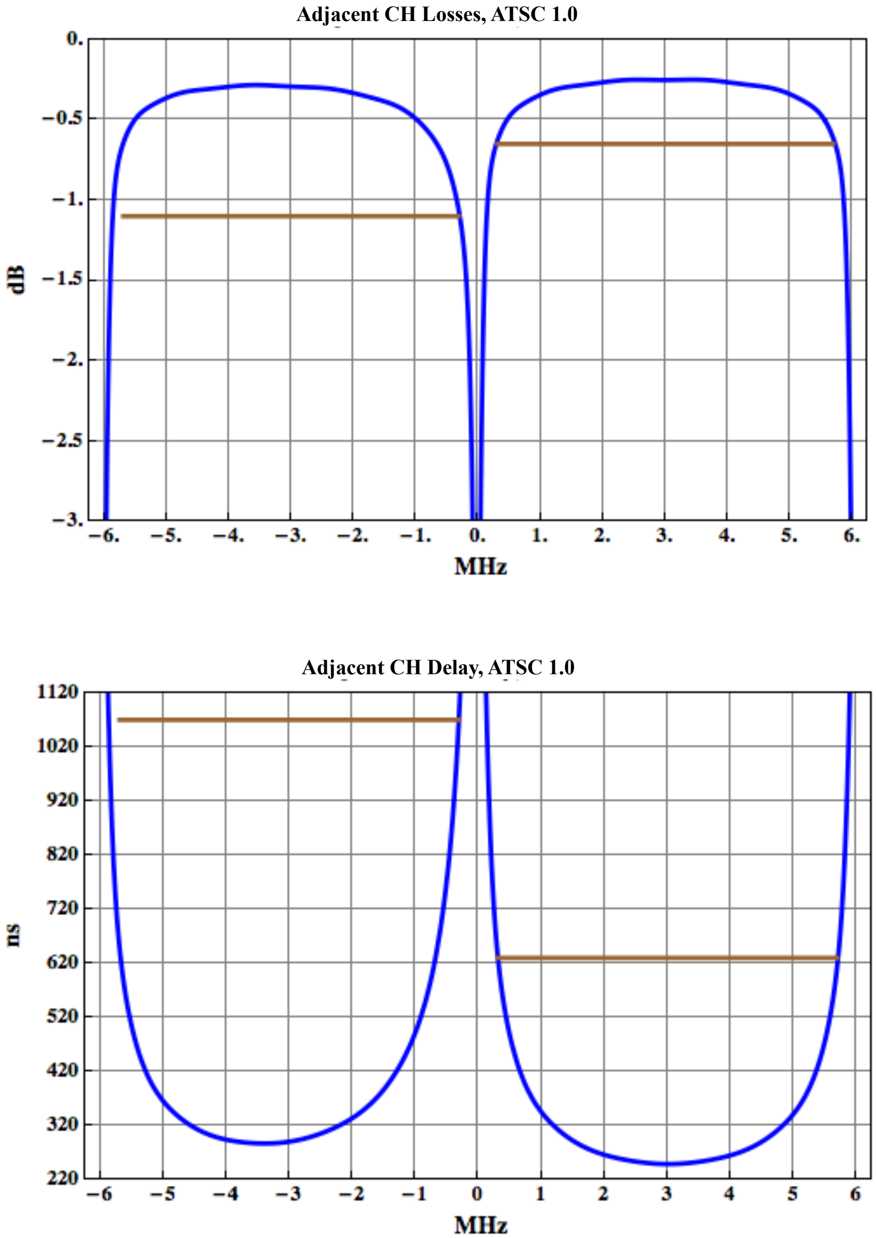

FIGURE 4: ATSC 1.0 LOSS AND DELAY VARIATION FOR ADJACENT CHANNEL COMBINER

Note that in Figures 4 and 5 the **Blue** traces indicate the pass band response of the adjacent transmitter inputs to the RF channel combiner. The **Brown** lines indicate the passband response relative to 5.38MHz signal bandwidth (ATSC 1.0) in Figure 4 and 5.84MHz signal bandwidth (ATSC 3.0) in Figure 5.

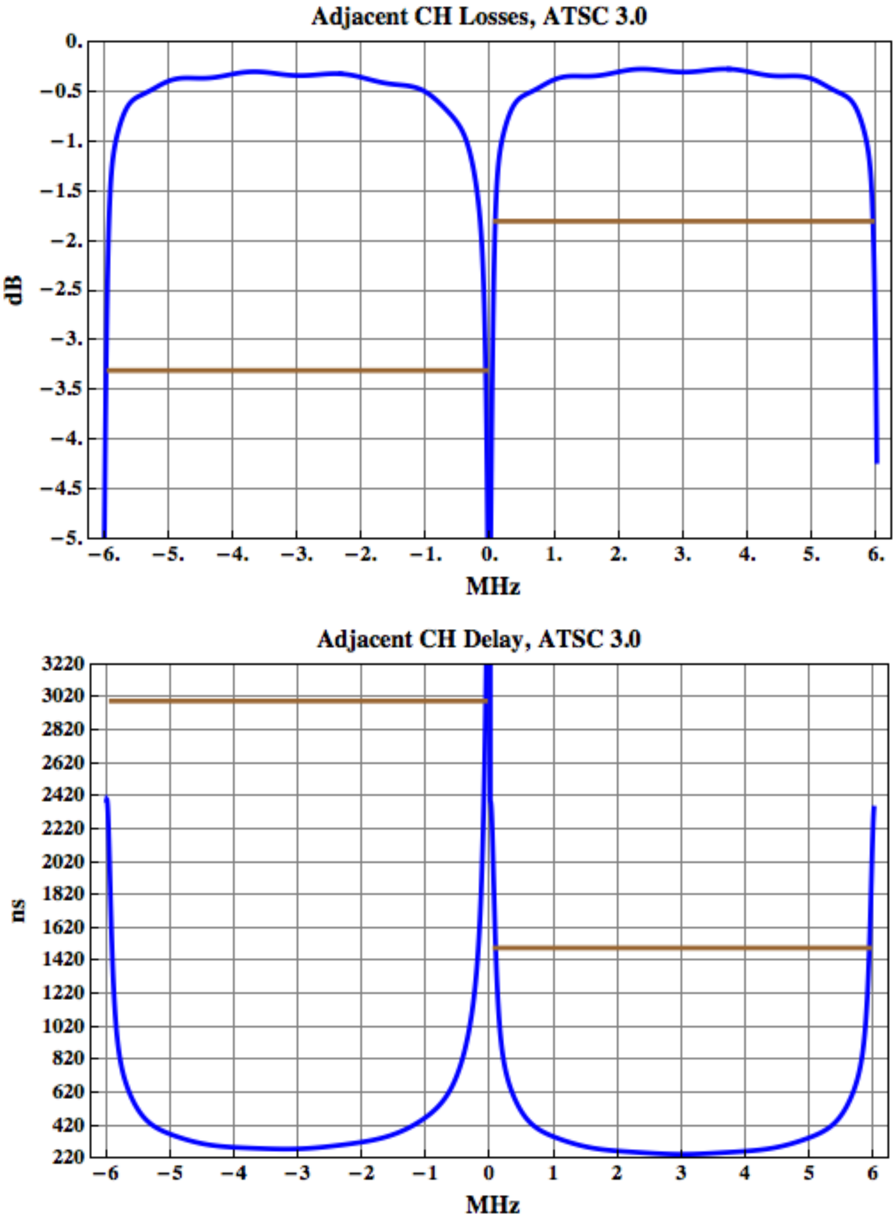

FIGURE 5: ATSC 3.0 LOSS AND DELAY VARIATION FOR ADJACENT CHANNEL COMBINER

III. Very-Sharp Tuned Filter Design

Higher order filters used to attenuate unwanted signals for land mobile or other low-power sensitive licensed services that occupy adjacent channel spectrum can exhibit significantly higher delay and loss variation. For example, the 12-pole filter response illustrated in Figure 6 might be used on DTV channel 14 or 17 to protect a lower adjacent land mobile operator. Multiple transmission zeros are placed very close to channel edge to provide 50dB of attenuation. Attenuation this close to channel edge results in significant amplitude and delay variation in the ATSC 1.0 occupied bandwidth. Even with high Q waveguide cavities, amplitude variation of 1.1dB and delay variation 1.5 μsec make ATSC 1.0 transmitter corrections a challenge. Elevated filter bandwidth and VSWR will also be required for similar ATSC 3.0 applications.

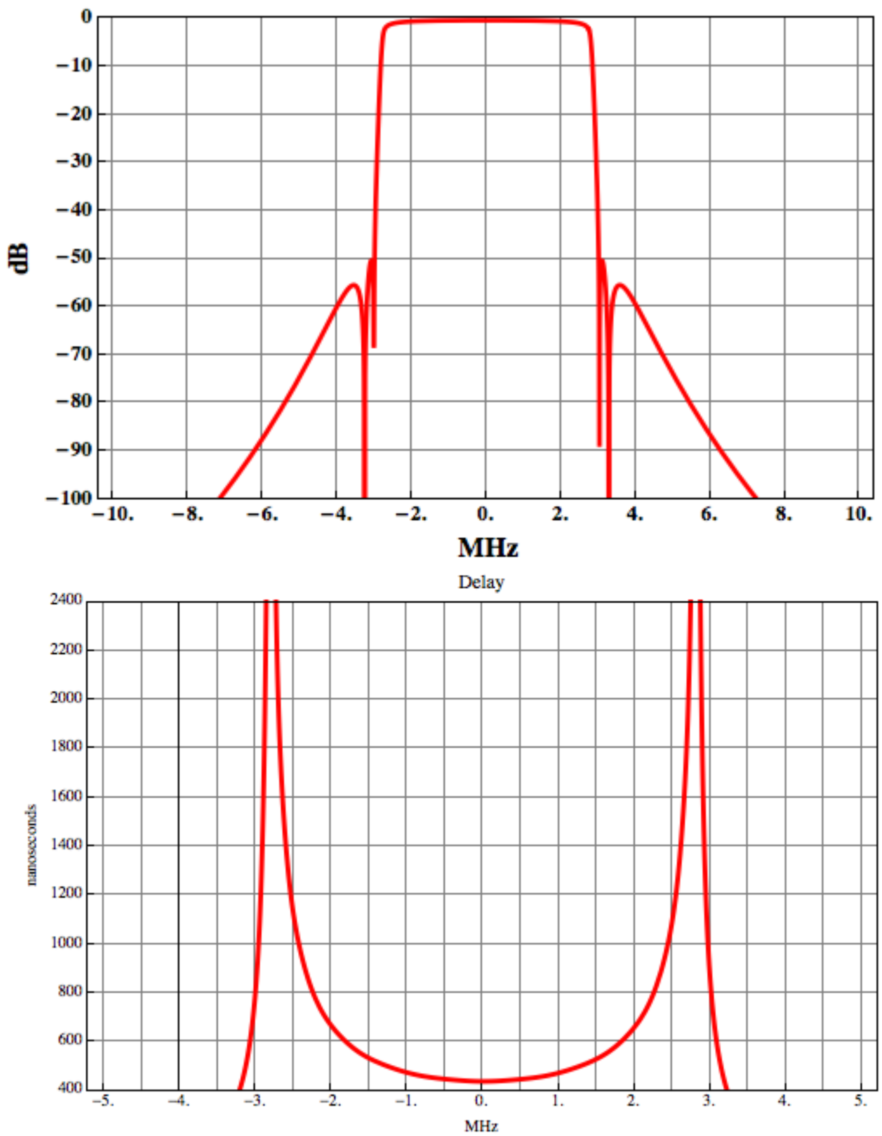

FIGURE 6: TYPICAL 12-POLE MASK FILTER RESPONSE USED FOR LAND MOBILE PROTECTION

IV. Filter Impact on ATSC 1.0 & ATSC 3.0 Signals

Elevated group delay due to high rejection requirements means the signal spends more time in the filter (hence the loss) resulting in greater stored energy at each resonator. The stored energy elevates voltage within the filter cavity and can be used to analyze filter power-handling capability [4]. Stored energy (normalized to 1nJ) for the 12-pole land mobile filter in Figure 6 is generated using *Guided Wave Technology's Filter & Coupling Matrix Synthesis* tool and is illustrated in Figure 7 (first 1MHz from lower channel edge). Note the elevated level of stored energy in the resonators 310 kHz up from lower channel edge. Resonator 6 has the highest stored energy or elevated voltage making it the weakest point for voltage breakdown.

Power handling is related to the maximum E-field threshold before breakdown, typically 2.3 x 10^6 V/m Voltage threshold of waveguide filters (rectangular or cylindrical dual-mode) used for the construction high power sharp filters, and is a function of tuning probe penetration. Cavity resonance is tuned using a capacitive probe where the E-field is a maximum. The stored energy of a resonator can be used to evaluate the maximum E-field in the cavity for power handling. A plot of probe penetration vs E-field magnitude using the stored energy of resonator 6 is plotted in Figure 8.

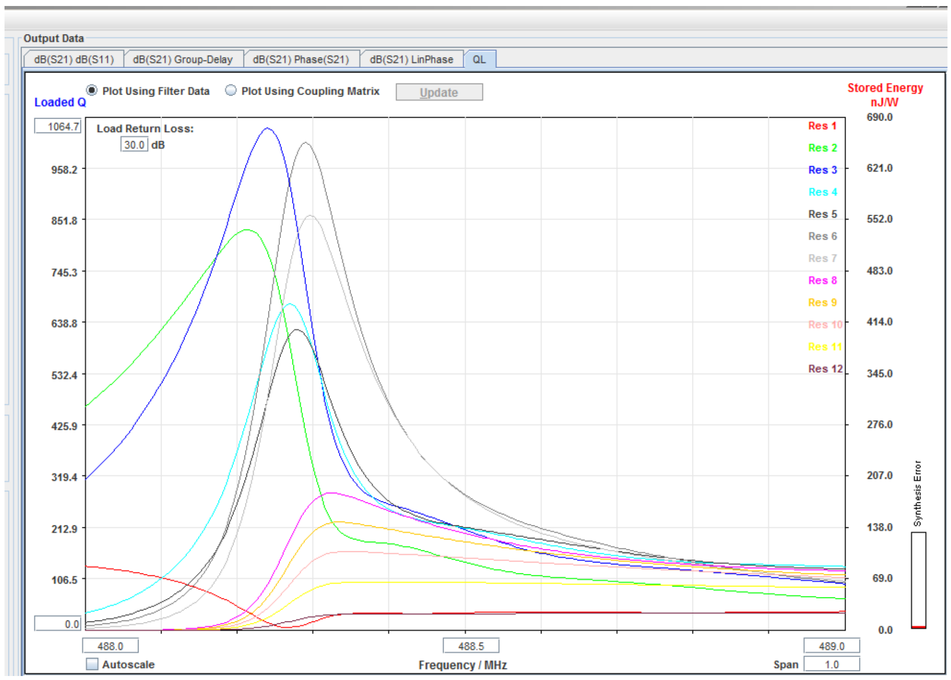

FIGURE 7: STORED ENERGY IN EACH RESONATOR FOR THE FILTER RESPONSE IN FIGURE 2.

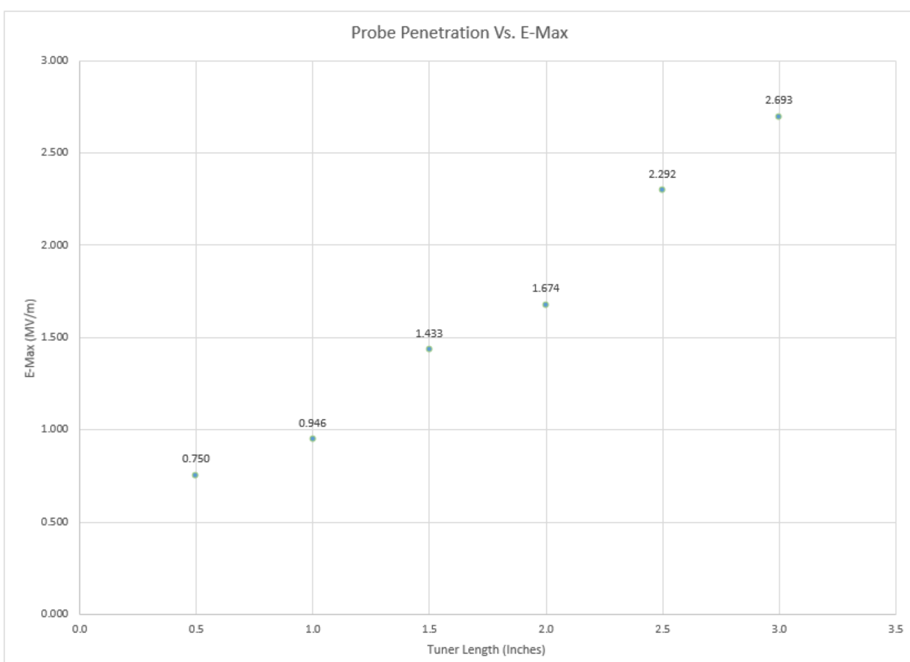

FIGURE 8: E-FIELD MAXIMUM VS WAVEGUIDE TUNING PROBE PENETRATION USING THE STORED ENERGY OF RESONATOR 6

The data in Figure 8 illustrates the importance of cavity design for Very-Sharp Filters. The E-field in a waveguide cavity must be optimized using proper cavity length to reduce probe penetration. E-field thresholds can be further reduced (by a factor of 2) by using full-wave cavities over half-wave cavities.

Enhanced Linear Precorrection

V. Linear Precorrection principle

As previously discussed, the RF mask filter produces unwanted distortions within the RF passband of the DTV transmitter. The steep filter edges produce amplitude frequency response and group delay distortions in the passband that must be compensated in order to ensure the best signal quality.

This compensation is achieved using a digital processing technique called Linear Precorrection that is implemented within the DTV exciter. From a RF feedback signal sample, the channel filter distortions can be estimated in real-time and compensated for in the time domain (after the IFFT process is completed within the DTV exciter). Two types of compensations are dynamically performed: amplitude and group delay. Typical RF signal performance figures monitored at the output of the channel filter are:

- MER (Modulation Error Ratio)
- IMD Shoulder levels (Intermodulation)
- Amplitude vs frequency response
- Group delay vs frequency response

In ATSC 1.0, there is a specific constraint due to the 8-VSB pilot carrier, which is located close to the spectrum edge and consequently very sensitive to the channel filter distortion. As required by ATSC 1.0, the pilot carrier amplitude shall be precisely maintained to 11.3dB below the average data power.

VI. Challenge with Very-Sharp Tuned Filter Compensation

When a Very-Sharp Tuned Filter is connected to the output of the DTV transmitter, signal levels close to the spectrum edges can be attenuated and the level variation can be very high. The Finite Impulse Response (FIR) filter traditionally used for standard linear precorrection is limited in terms of complexity (mainly due to hardware implementation constraints) and is not able to compensate such high variations of the signal. Furthermore, the precorrection algorithm which normally processes the level linearization within the bandwidth generates unwanted signal spikes on both edges of the RF spectrum (see Figure 9).

FIGURE 9: FILTER INPUT SIGNAL USING STANDARD ALGORITHM

Although expected from the precorrection, the signal spikes provide little benefit to overall MER performance and can impact filter reliability. The energy from the signal spikes falls within the band in which the E-fields are highest within the mask filter. A balance had to be reached that minimizes the signal spikes at the channel edges without severe degradation to the overall MER performance.

VII. Improved Linear Precorrection for Very-Sharp Tuned Filter

In order to manage the correction needs of the transmitter system when connected to a Very-Sharp Tuned RF mask filter, and to reduce those signal spikes, a specific digital filtering algorithm has been designed to work in conjunction with optimized linear precorrection. Three Sharp Filter Profiles (SFP) have been implemented (low/medium/high) within the EXACT DTV exciter (Figure 10). The SFPs are user selectable in the exciter's web GUI control interface. Users can then choose the tradeoff between the spectrum filtering effectiveness and the achieved signal performance (MER). During this development, TeamCast designers have faced several challenges such as:

- Limit as much as possible the impact of the filtering on the overall signal MER
- Maintain the pilot carrier amplitude at the desired level in ATSC 1.0

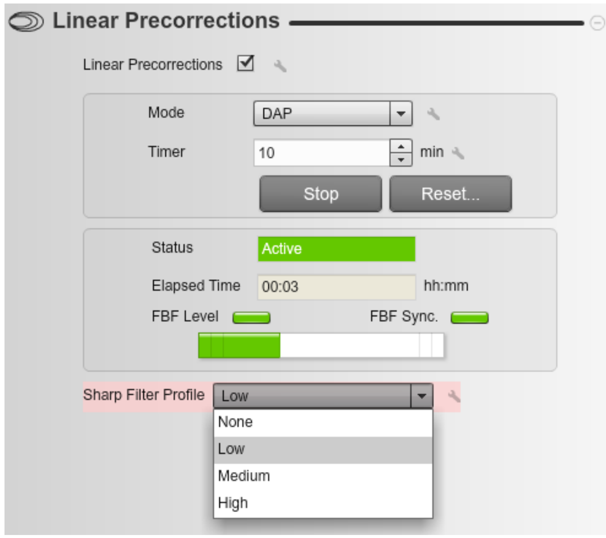

FIGURE 10: SHARP FILTER PROFILE SETTING MENU IN EXACT DTV EXCITER GUI

TEST RESULTS

VIII. Test results in ATSC 1.0

An existing DTV transmitter facility on RF channel 17 (488-494MHz) was upgraded with new EXACT ATSC 1.0 exciters (Figure 11) in order to achieve greater MER performance and provide future upgradeability to ATSC 3.0. The DTV transmitter is IOT based with a Transmitter Power Output (TPO) of 47kW necessary to achieve the licensed 1MW ERP. This particular DTV site uses a Very-Sharp Tuned RF mask filter to eliminate the interference with co-located land mobile system.

FIGURE 11: EXACT DTV EXCITER 1RU HARDWARE PLATFORM

Prior to installing new DTV exciters, the existing RF signal performance was measured. Directional couplers were installed at the RF output of the exciters to monitor correction performance. A spectrum analyzer was used to measure the average power difference with and without the correction for each exciter. Of particular interest was the power difference in the first and last 250kHz of the passband. Prior to the installing the new EXACT DTV exciters, there were two different older generation exciter technologies installed on this particular transmitter. These older generation exciter platforms produced performance between 24dB and 28.5dB SNR. Figure 12 shows a typical block diagram for proof of performance testing of a high power DTV transmitter.

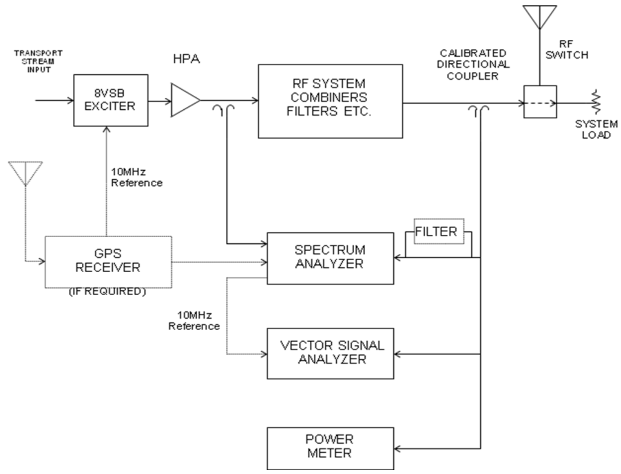

FIGURE 12: TYPICAL DTV TRANSMITTER TEST SETUP

After the new exciters were installed, connected to the system and the precorrection algorithms were allowed sufficient time to correct the non-linear and linear signal distortion, MER performance of 33 and 35dB was achieved. However it was noted that the correction was causing “signal spikes” at the band edges (signal spikes were measured prior to the mask filter). These signal spikes needed to be reduced to avoid damage to the probes in the sharp tuned RF mask filter.

DTV Exciter Test Condition	**SNR/MER**	**Lower CE 250kHz power change**	**Upper CE 250kHz power change**
No pre-correction applied	14.3dB	0dB	0dB
Existing DTV Exciter	28.5dB	3.14dB	3.33dB
EXACT DTV Exciter	34.0dB	5.11dB	8.89dB
EXACT w/SFP	30.8dB	3.20dB	3.50dB

TABLE 2: LINEAR CORRECTION OF D17 SHARP TUNED FILTER WITH AND WITHOUT SFP

Additional correction was applied to the DTV transmitter system by using the each of the Sharp Filter Profiles that are available in the DTV exciter. After testing each of the selections (low/medium/high), the transmitter was able to achieve approximately 31dB MER performance while eliminating the signal spikes previously mentioned. The Table 2 summarizes the system performance. Figure 13 shows the RF system performance into the station’s system load (measured through the Very-Sharp Tuned Filter).

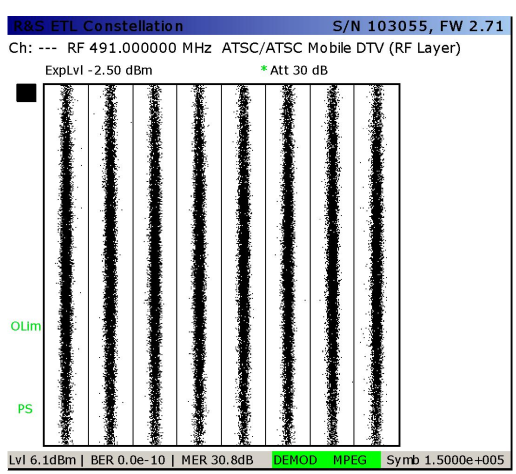

FIGURE 13: SYSTEM MEASUREMENT (8VSB CONSTELLATION) THROUGH THE VERY-SHARP TUNED FILTER WITH SFP ENABLED

IX. ATSC 3.0 Considerations

The current industry accepted method for RF shoulder measurement (ATSC 1.0 ~ 8VSB) is based on measuring the shoulders in a 500kHz wide "power band" as compared to the in channel signal in a 6MHz wide "power band". The FCC specification for RF shoulders is 47dB (Figure 14). It appears that the FCC will not change the spectral mask requirements when the modulation standard changes from ATSC 1.0 to ATSC 3.0.

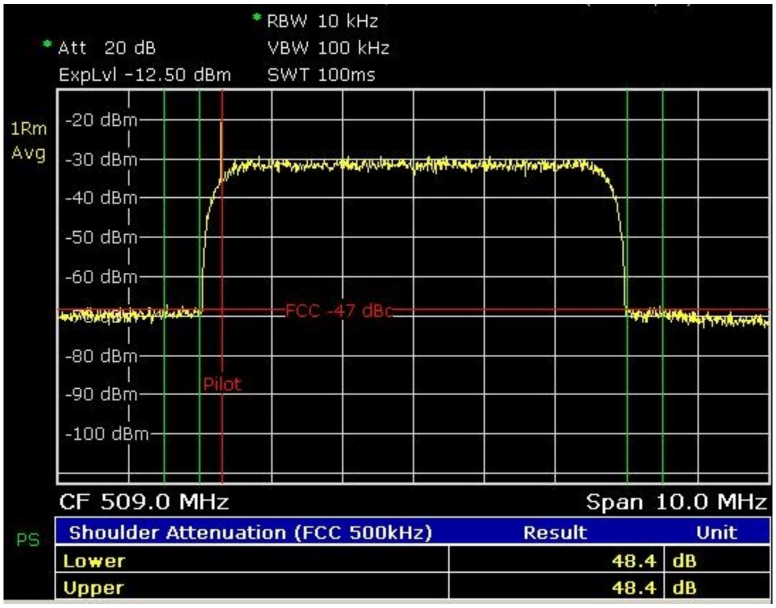

FIGURE 14: ATSC 1.0 RF SHOULDER MEASUREMENT

The measurement technique for RF shoulders of an OFDM based signal such as ATSC 3.0 differs from that required by the FCC for the current ATSC 1.0 signal. When measuring an OFDM signal, the measurement is commonly done by the simple use of markers both in band and on each shoulder. These two types of measurements result in a measured difference on the same signal of approximately 11dB making the 47dB current specification for shoulders "appear" like 36dB as measured with markers on the ODFM signals on the test instrument (Figure 15).

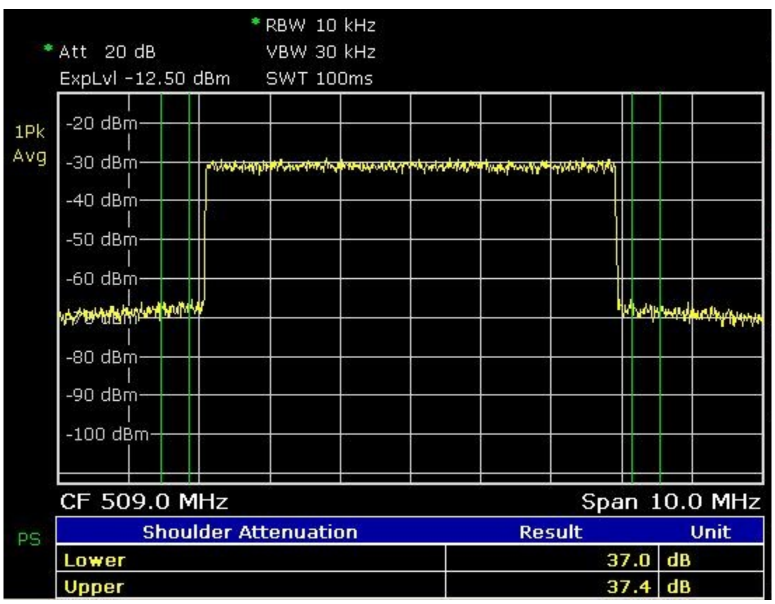

FIGURE 15: ATSC 1.0 RF SHOULDER MEASUREMENT

As previously discussed, there is a difference in the occupied bandwidth of ATSC 1.0 vs. 3.0. ATSC 1.0 has an occupied bandwidth of 5.38MHz; ATSC 3.0 is 5.84MHz. This 8.4% increase in occupied bandwidth allows for higher data throughput but it also has implications to the RF mask filter system. ATSC 3.0 does allow situations where operation at bandwidths less than the full amount may be necessary. Table 3 below defines the coefficient, the number of carriers and the actual occupied bandwidth.

C_{red_coeff}	Number of Carriers (NoC)			Occupied BW (MHz)
	8K FFT	16k FFT	32k FFT	
0	6913	13825	27649	5.832844
1	6817	13633	27265	5.751844
2	6721	13441	26881	5.670844
3	6625	13249	26497	5.589844
4	6529	13057	26113	5.508844

TABLE 3: ATSC 3.0 CARRIER REDUCTION VS. OCCUPIED BANDWIDTH

Operating an ATSC 3.0 transmitter into a Very-Sharp Tuned Filter will likely be one of these situations. The protocol defines a carrier reduction coefficient, C_{red_coeff} that reduces the actual occupied bandwidth by reducing the number of carriers.

Conclusion

The transmitter system integrator such as Hitachi-Comark has the responsibility to understand the impacts of all aspects of the transmitter facility and how they may affect RF signal performance. The concerns of OEM suppliers across a broad range of products need to be considered and balanced to achieve the most effective overall system design. At times industries with considerably different areas of expertise can be brought together to complement each other's designs. Areas that must have careful consideration include:

- Amplifier IMD performance as it relates to RF shoulder levels and MER and how various components within the system impact this
- FCC compliance; especially circumstances beyond standard mask requirements such as channel 14 and 17 allocations
- The implication and limitations of using various RF filter masks including Very-Sharp Tuned Filter responses
- RF channel combiners and the impacts to RF system performance
- Precorrection techniques that are used to minimize the effects of both linear and non-linear distortion on the transmitter facility
- Impacts of ATSC 1.0 vs. ATSC 3.0

The FCC repack will have a far reaching impact on the DTV transmitter industry in total due to reduced UHF spectrum allocations. These allocations are expected to increase the likelihood of adjacent DTV channels in most major metropolitan markets and as such the industry must anticipate the possible scenarios and have solutions to overcome potential performance limitations of the transmitter system.

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