Spectral Regrowth

Abstract

Intermodulation products, or spurs, can develop within the analog and digital transmitters in combined systems using high-level injection. In some cases, spurs can result in sub-optimal signal quality or even cause stations to interfere with each other's signals. The term spectral re-growth was coined to describe intermodulation products generated when a digital transmitter is added to an analog transmission system.

In the early days of digital implementation, external filtering was often used to eliminate or reduce interference. As the technology has evolved, however, only subtle adjustments to the system, such as the addition of a fine-matching transformer to the dummy load, have proven necessary to reduce distortion and interference to meet the FCC's digital FM mask.

There are two sets of spurs that have to be dealt with. The first set of spurs is generated within a digital transmitter as the two sidebands interact. The second set of spurs is also generated in the digital transmitter and is a product of each digital sideband combining with the analog signal. The signal level of these spurs is a function of the isolation between the analog and digital transmitters.

This paper provides a basic overview of how high-level injectors work, their weaknesses, and how they can best be optimized, as is essential to the design, installation, tuning and operation of a modern analog/digital FM station.

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The FCC digital mask

The characteristic FM analog/digital mask is shown in Figure 1. The analog modulated carrier occupies ±100 to 120 KHz, depending on how hard the modulation is pushed. As will be shown later, subcarriers (SCAs) can be part of this analog carrier. The digital carriers start at ±129 KHz and go out to ±199 KHz. The digital signal is made up of two identical sets of 191 Orthogonal Frequency-Division Multiplex (OFDM) carriers. Just for general information, the mode of modulation for this signal is Quadrature Phase Shift Keying (QPSK). The power levels are referenced to the analog carrier or 0 dBc. One OFDM carrier is -45.8 dBc, when all 191 carriers are present for one side-band the power level is -23 dBc, and when both side-bands are added together the power level is -20 dBc. This is defined as the analog-to-digital ratio of 20 dB.

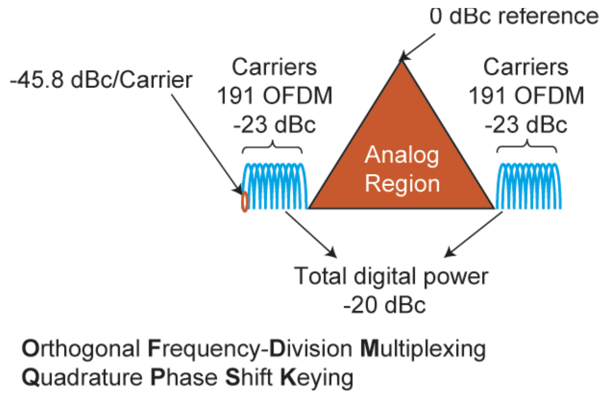

Figure 1. Digital Power Distribution Referenced to the Analog Carrier

Sideband-interaction spurs

In order to evaluate the first set of spurs that are generated inside of the digital transmitter, it is necessary to simplify the digital side bands. Figure 2 shows that the center frequencies of the digital side bands are at ± 164 kHz from the center of the FM channel. That means that there are 328 kHz between the centers of the side bands.

If the third-order intermodulation products are evaluated, you will see that there are a set of spurs at ± 492 kHz (Figure 3), between the second and third adjacent channels. At the same time there are a set of fifth-order intermodulation products at ± 820 kHz, which is just above the fourth adjacent channels.

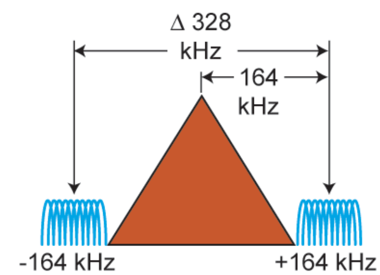

Figure 2. Midpoints of the Sidebands in Sideband-Interaction Spurs

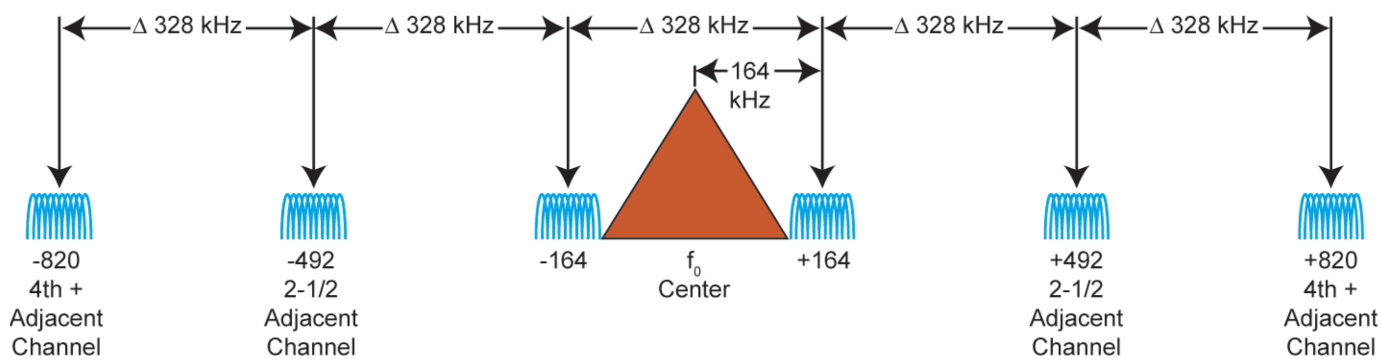

Figure 3. Third- and Fifth-Order Sideband-Interaction Spurs at ± 328 MHz Intervals

Digital-sideband-to-analog interaction spurs

This second set of spurs is the result of the analog transmitter getting into the digital transmitter. Figure 4 is a graphical illustration of where the spurs occur.

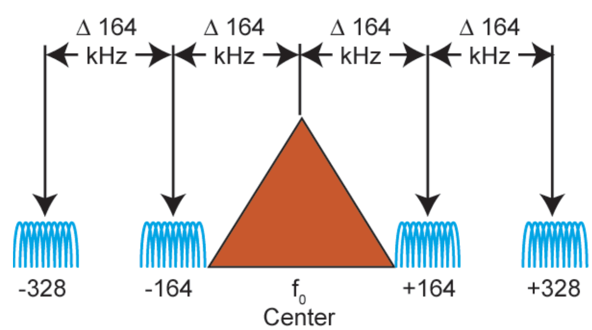

Figure 4. Third-Order Digital-Sideband-to-Analog Interaction Spurs

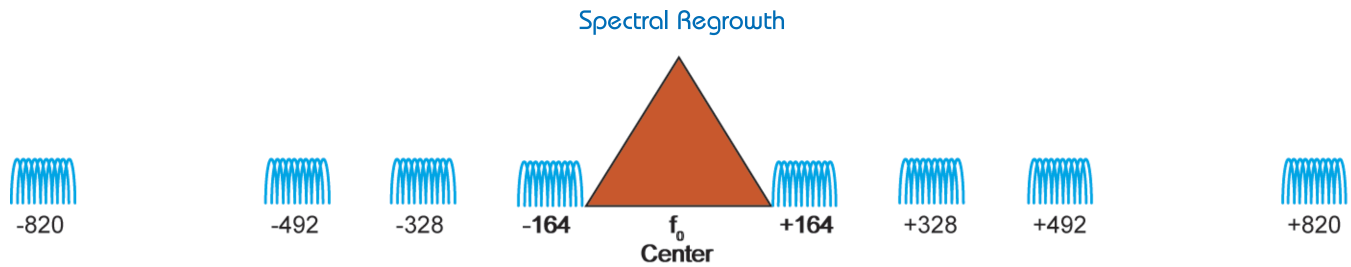

Figure 5. Sideband-Interaction and Digital-Sideband-to-Analog Interaction Spurs

Figure 5 shows a summation of all the groups of spurs that were discussed in Figures 3 and 4.

Figure 6 is a photo taken of a spectrum analyzer showing the output of a digital transmitter, and as you can see the spurs are exactly where they are predicted to be and at a level that will cause interference.

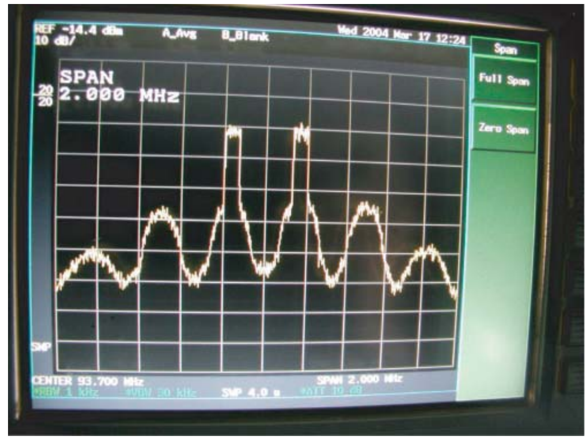

Figure 6. Uncorrected Digital Transmitter Output

Figure 7 is a printout of the display of a spectrum analyzer, superimposing the spurs and the FCC digital mask.

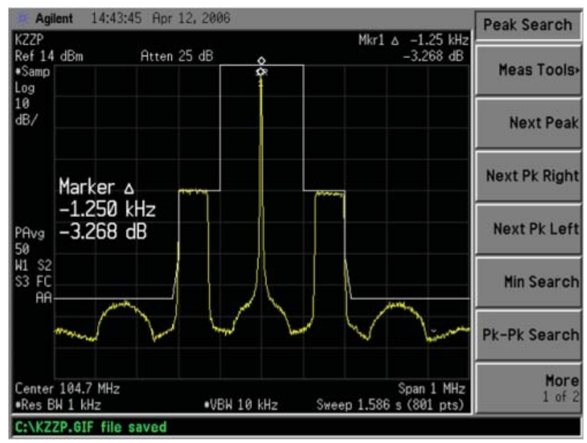

Figure 7. Spurs vs. FCC Digital Mask

The WMKK case study

Now for a case study. WMKK's transmitter site is located north of Boston in the city of Peabody, MA (Figure 8). When WMKK turned their digital transmitter on, spurs appeared at ± 828 kHz and caused interference to stations WBOS and WJMN within 1/2 mile of WMKK's transmitting tower.

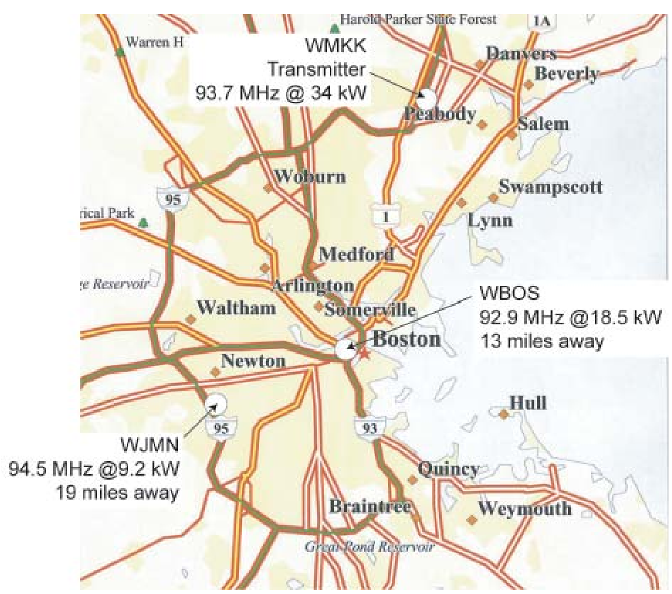

Figure 8. Three Boston Area Stations

High-level injection

Before going further I would like to review the operation of a 10 dB high-power injector/combiner used to inject or combine the digital signal into the analog RF stream, often referred to as high-level injection or high-power combining. Figure 9 is a cutaway view of such a high-powered injector. Because of the electrical characteristics of this large directional coupler, 10% of the analog power is coupled into the dummy load port of the injector. This 10% loss has to be made up by increasing the output power of the analog transmitter.

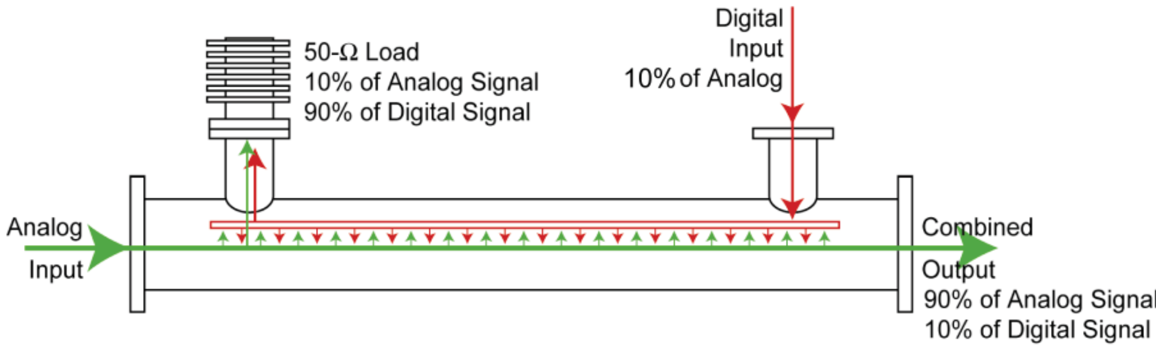

Figure 9. High-Power Injector

The proper analog-to-digital signal ratio of 100:1 is needed at the output of the injector. In order to attain this ratio, the digital transmitter output power is set at 10% of the analog power. Due to the losses of the directional coupler, 90% of the digital power is conducted to the dummy load port, and only 10% coupled to the main transmission line, for a net output of 1% of the analog power.

Correcting the interference

In order to analyze this interference a directional coupler was attached to the output of the digital transmitter and a spectrum analyzer was attached to the forward loop of the coupler. The photo in Figure 6 clearly shows the interfering spurs at ± 820 kHz. The photo also shows a set of spurs at ± 492 kHz, and even though these spurs are strong enough to cause interference, there were no 2nd or 3rd adjacent stations in the immediate area that were affected.

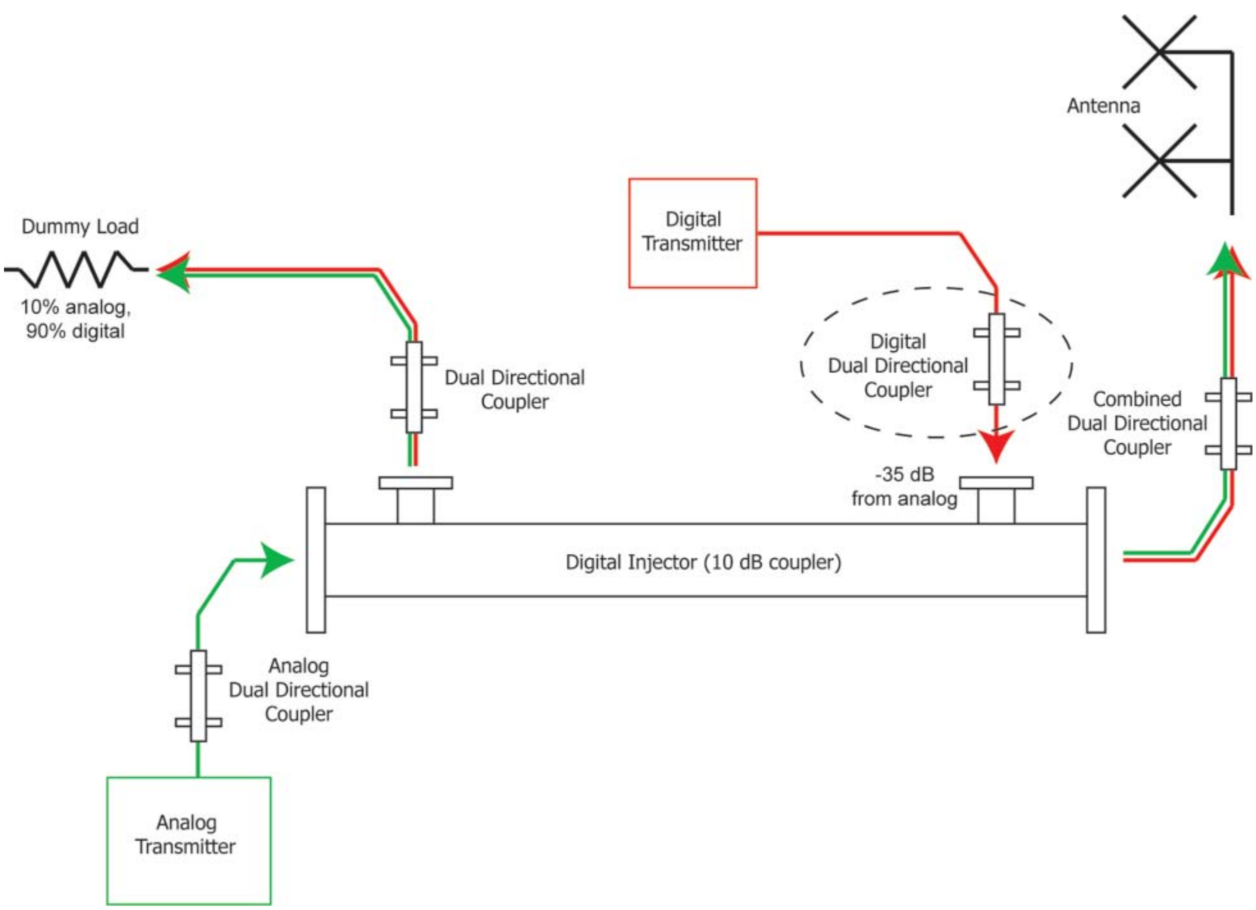

Figure 10. Analog/Digital Transmission System with High-Level Injection

In order to reduce the power level of the ± 820 kHz spurs a bandpass filter (digital mask filter) was installed between the digital transmitter and the high-level injector (Figure 11).

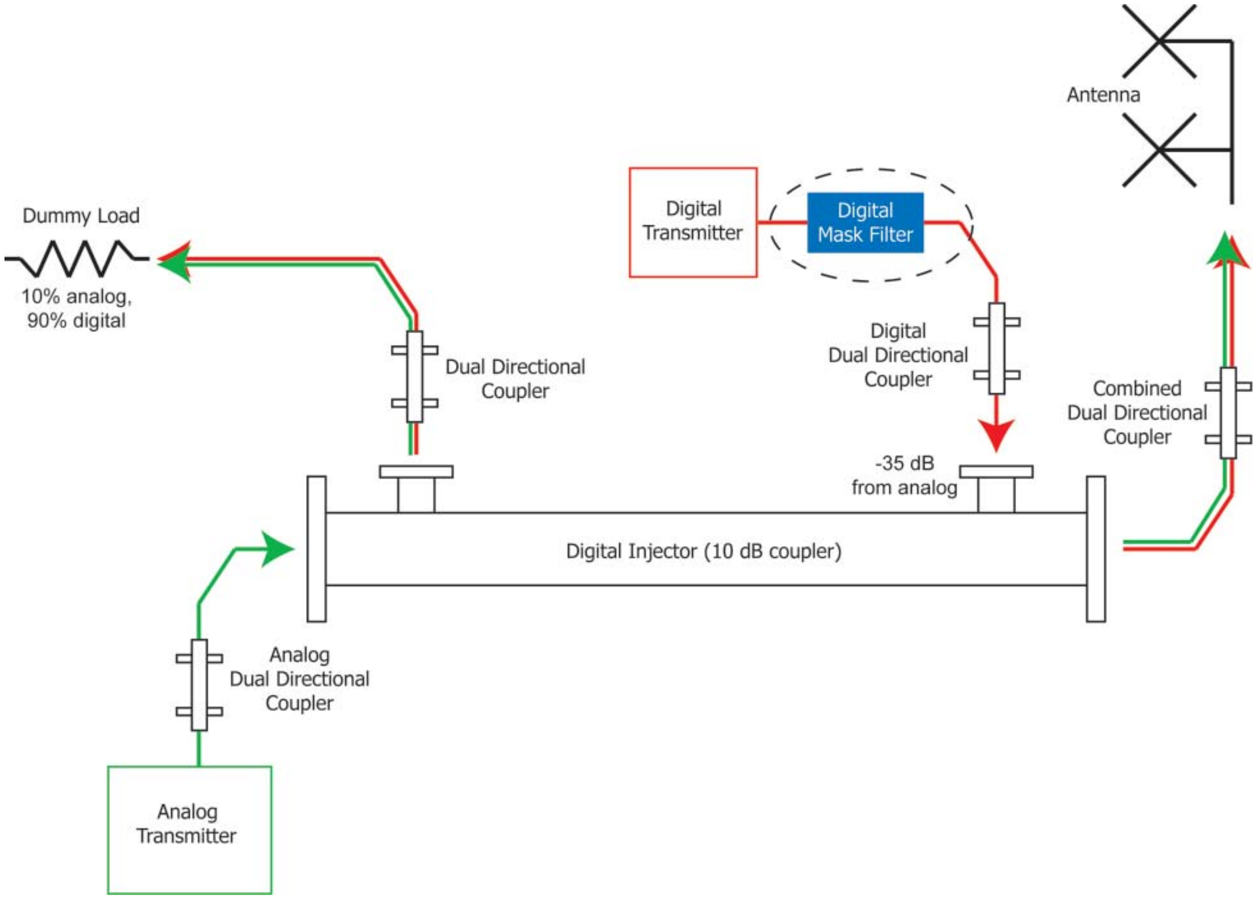

Figure 11. Addition of Digital Mask Filter

Figure 12 is a plot of the frequency response of the filter being used to suppress the spurs. From the plot, the suppression of the spurs at ± 820 kHz is approximately 45 dB.

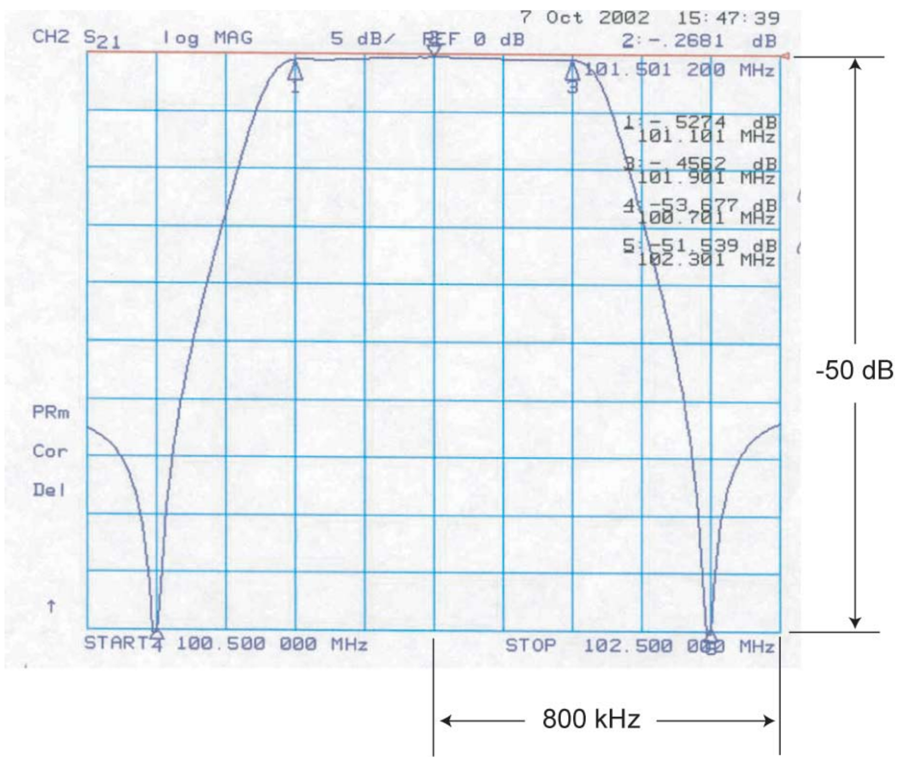

Figure 12. Response Curve of Digital Mask Filter

With the filter in place the spectrum analyzer was attached as before and Figure 13 shows that the ± 820 kHz interfering spurs are suppressed below the noise floor of the analyzer.

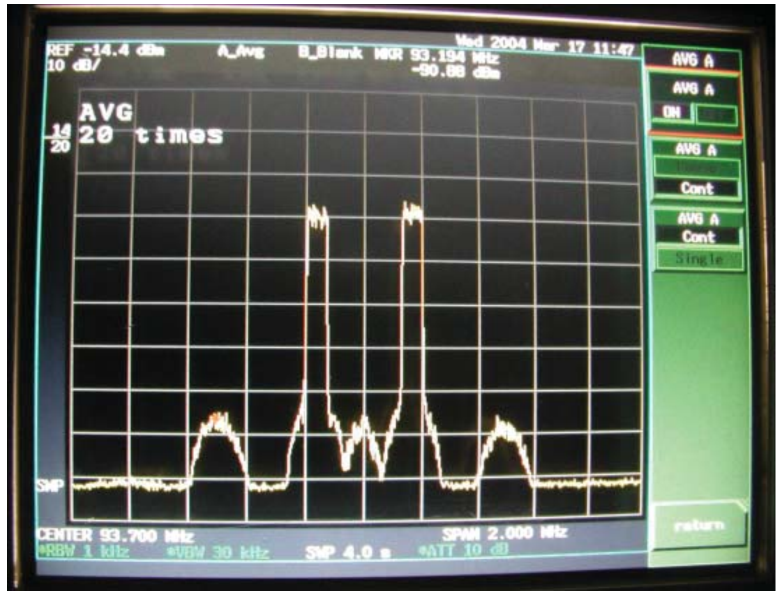

Figure 13. Uncorrected Digital Transmitter with Filter

The spectrum analyzer was then attached to the directional coupler at the combined output of the high-level injector. Figure 14 shows the suppression of the ± 492 kHz spurs and the elimination of the ± 820 kHz spurs.

Figure 14. Filtered System Output

The spectrum analyzer was than moved outside of the transmitter building for an off-air measurement. Figure 15 is a photo of the WMKK channel as the reference. The spurs at ± 492 kHz are not causing interference and WJMN and WBOS show no interference.

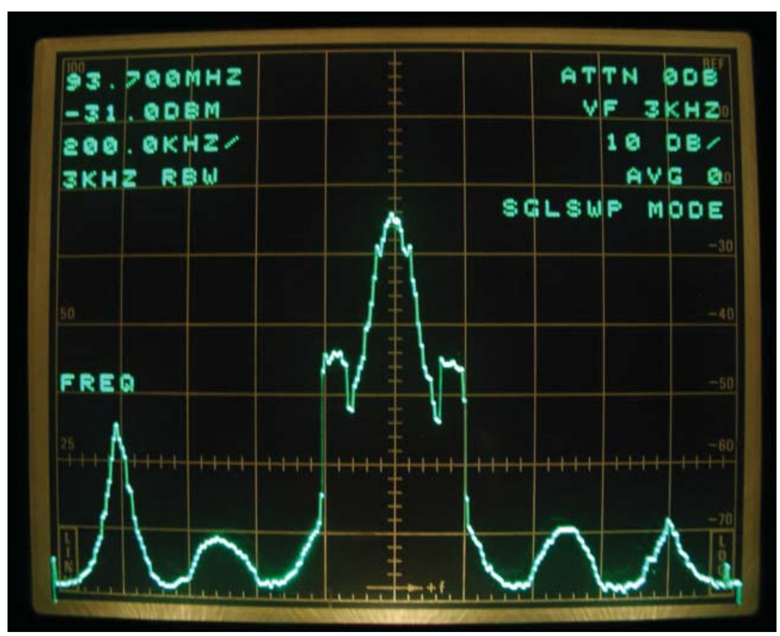

Figure 15. Off-Air Measurement

The WBUR case study

The next case study was set up as an experiment to see what could be learned from evaluating a station that is in compliance with the FCC's digital mask. WBUR is operating with the same style of high level injection that was discussed above. At this site there are two SCAs in the analog transmission, which adds another aspect to the analysis of this station's operation.

At the start of our experiment, we disconnected the digital transmitter from the injection system to calibrate the instrumentation to the analog transmitter with no interfering signal. We connected a spectrum analyzer to the forward loop of the directional coupler attached to the output of the analog transmitter, as shown in the highlighted area of Figure 16.

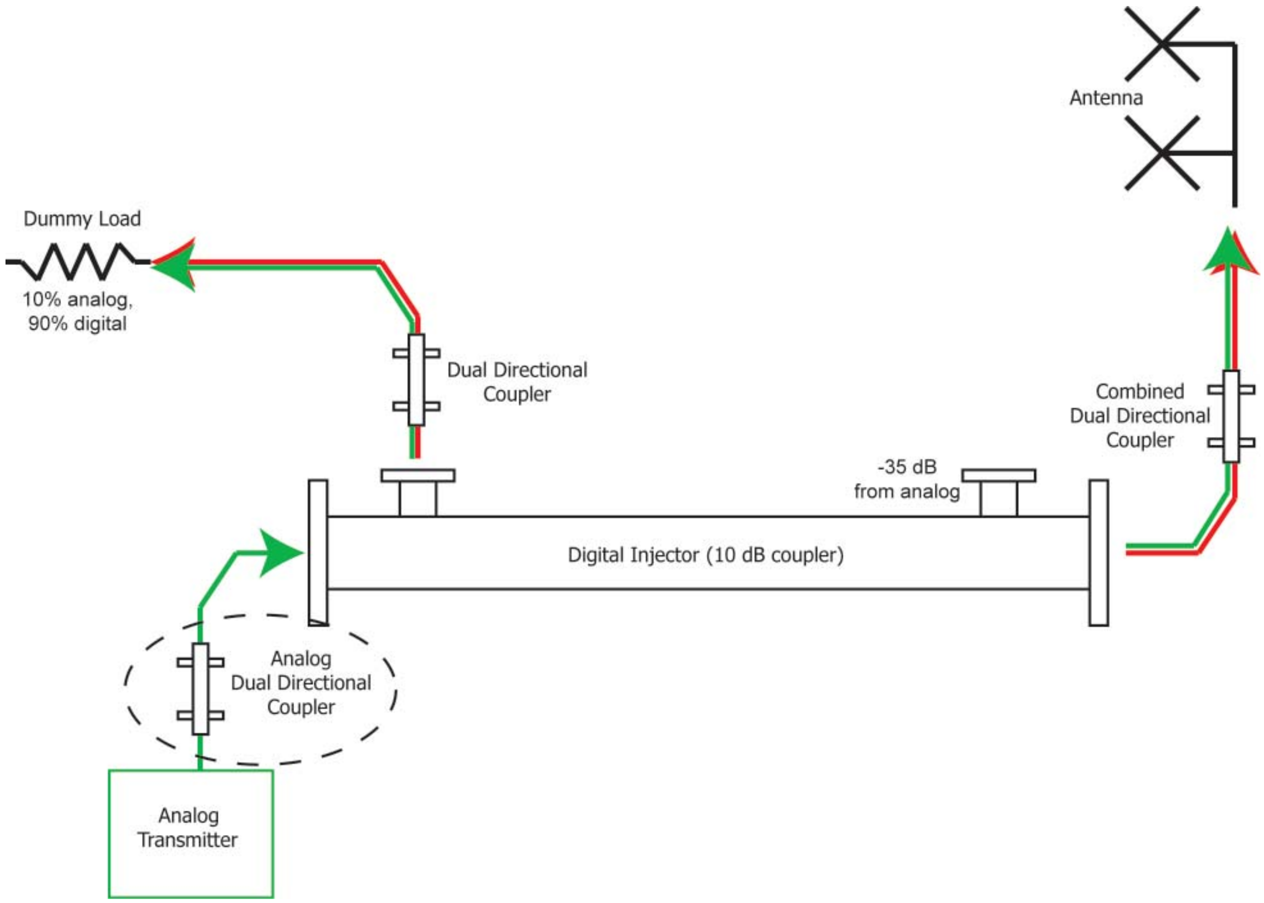

Figure 16. Analog Transmission System, WBUR

The analyzer was set up so that the peak power level of the transmitter could be determined under conditions of normal modulation but with no digital signal. In order to make this measurement, the analyzer's video bandwidth (VBW) and resolution bandwidth (RBW) were set at 30 and 300 kHz respectively. Figure 17 shows the result. The FCC's digital mask template, shown by the red line, was placed in the memory of the analyzer and should be disregarded for most of this discussion.

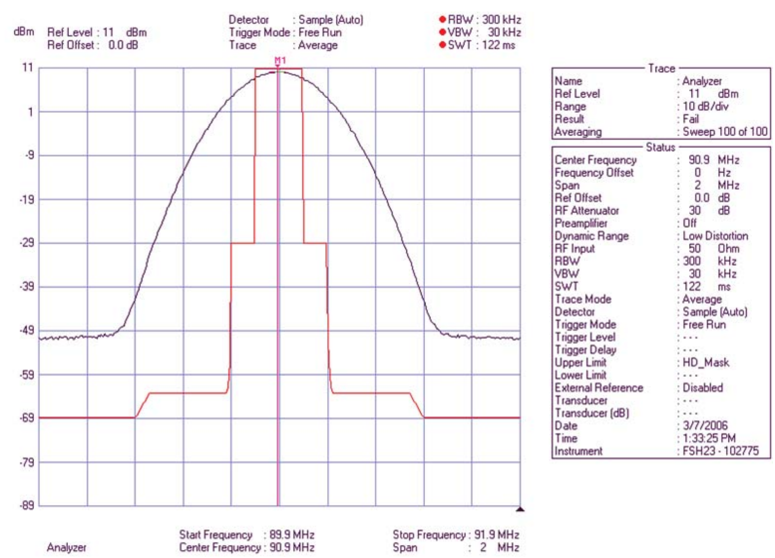

Figure 17. Forward Peak Power Reference Level, WBUR

The analyzer was then connected to the reverse loop of the same directional coupler and the measurement obtained is an indication (Figure 18) of the VSWR of the system. As you can see, there is a 30 dB difference between the forward and reflected loops, which represents a VSWR of 1.05: 1.

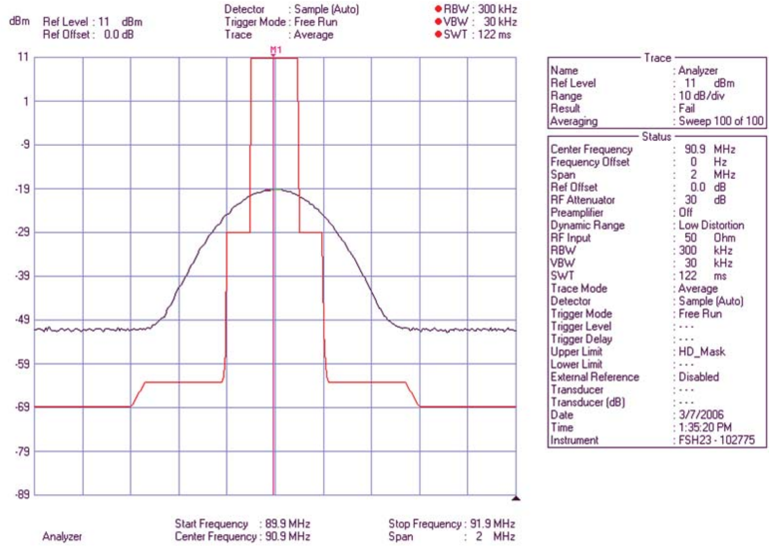

Figure 18. Reflected Peak Power Reference Level, WBUR

Figure 19 shows the results of changing the analyzer's video bandwidth and resolution bandwidth to observe the same forward sample of the modulated FM signal.

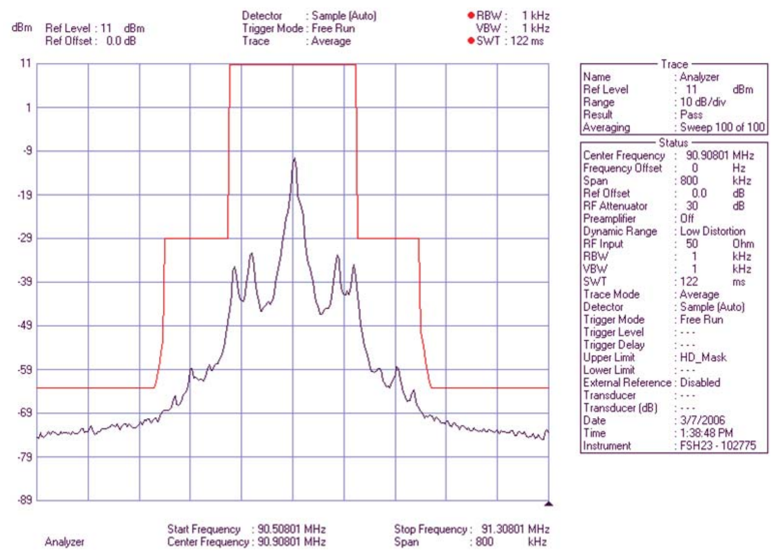

Figure 19. Forward Sample Modulated FM Signal, WBUR

Figure 20 shows the corresponding reflected FM signal. Here you can clearly see the standard analog signal with the two SCAs in operation. If you compare these two figures with Figures 17 and 18, you will see that the VSWR is still 1.05: 1. Note that the artifacts of the SCAs at approximately ± 160 kHz from the center of the channel are at a level that does not cause any interference.

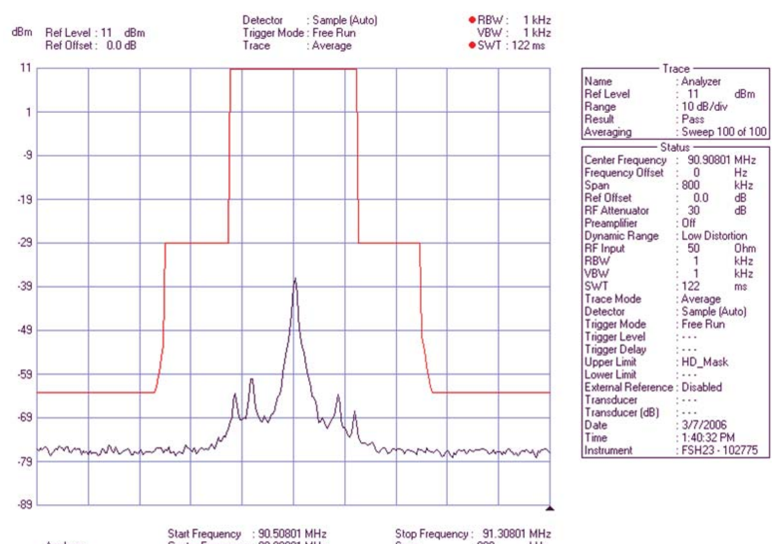

Figure 20. Reverse Sample Modulated FM Signal, WBUR

Now that we have our reference measurements, we reconnected the digital transmitter, as shown in Figure 21, and attached our analyzer to the forward port of the directional coupler at the digital transmitter's output, expecting to see a nice clean digital spectrum.

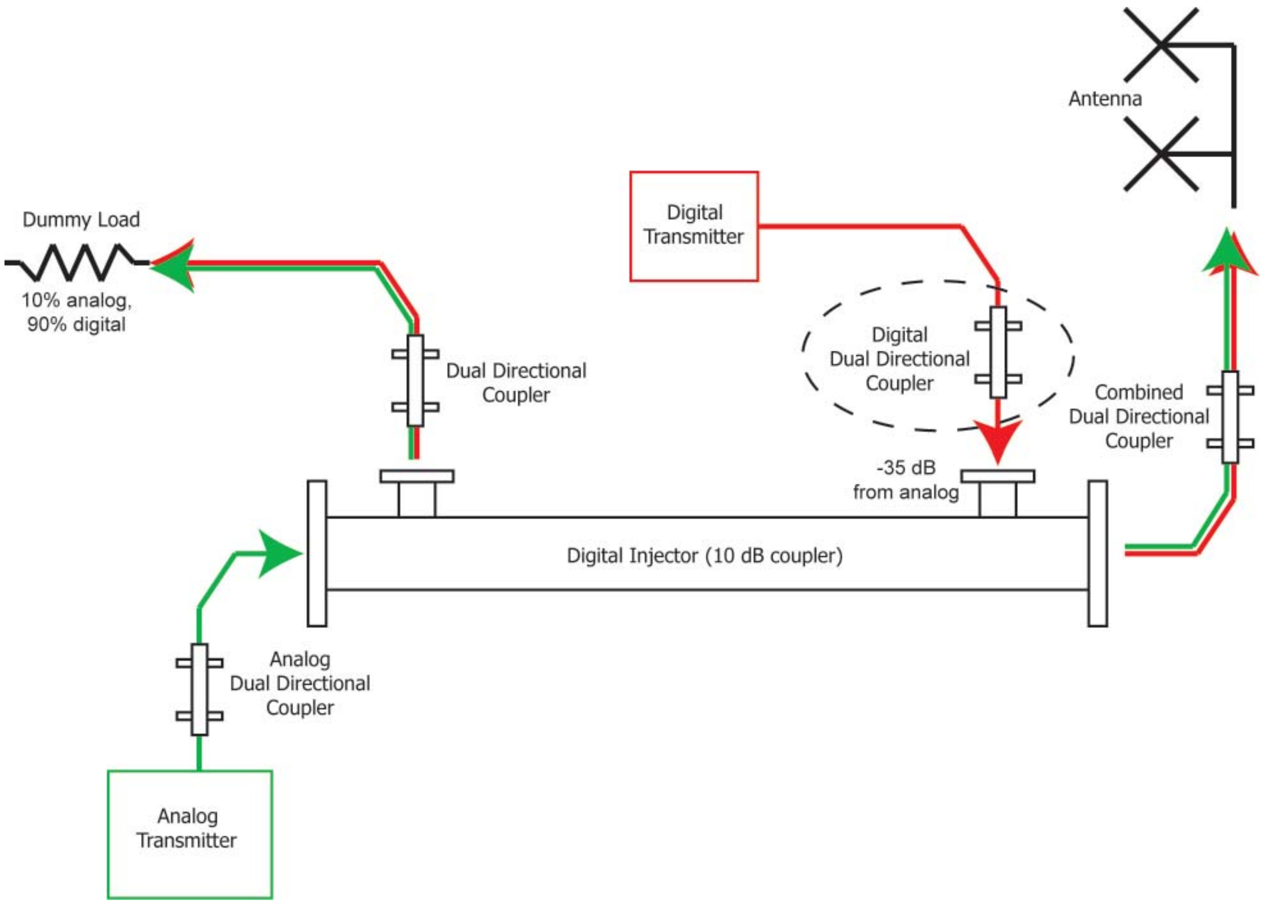

Figure 21. Digital Input of Combined Transmission System, WBUR

Instead, what we found (still ignoring the red digital mask) was a complex presentation (Figure 22). Not only were there intermodulation products, as discussed earlier, but the analog signal is showing up in the digital output, meaning that a component of the analog signal is coming out of the digital transmitter.

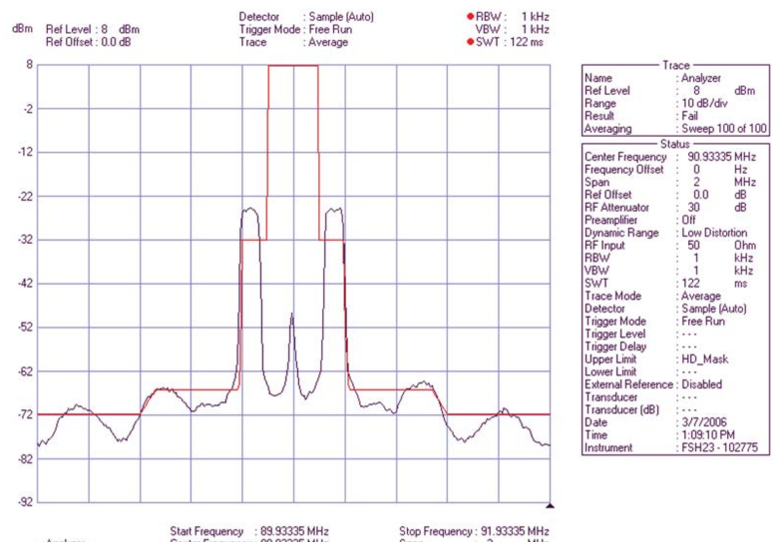

Figure 22. Combined Digital Forward Power, WBUR

Where is this analog signal coming from? To find out, we attached the analyzer to the reflected port of the same directional coupler (Figure 23), and we found:

- The presence of the analog signal in the reflected loop of the digital directional coupler indicates the amount of analog power that is being coupled to the digital port of the injector. This is referred to as the isolation of the injector.
- The analog signal level was higher going into the digital transmitter than coming out of it. This attenuation of the analog signal in the digital transmitter is called the turnaround loss of the digital transmitter, which to our knowledge had never been measured before.
- The digital signal level demonstrates that the VSWR of the system is the same 1.05: 1 as the analog. This must be a coincidence and not inherent in the system design, because the analog and digital transmission paths are separate and different. This return loss puts them below the noise floor of the analyzer, and they are no longer visible.

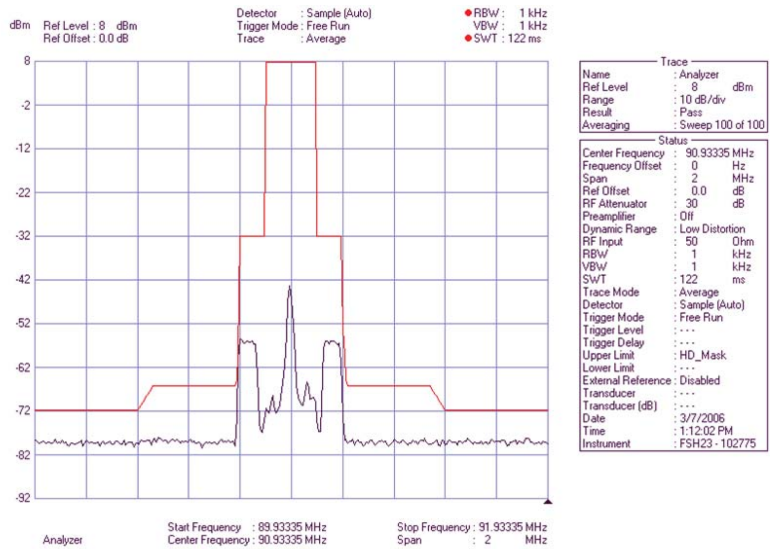

Figure 23. Combined Digital Reflected Power, WBUR

So if the analog signal gets into the digital transmitter, does the digital signal return the favor? We connected the analyzer to the reflected loop of the analog transmitter's output coupler to find out (Figure 24).

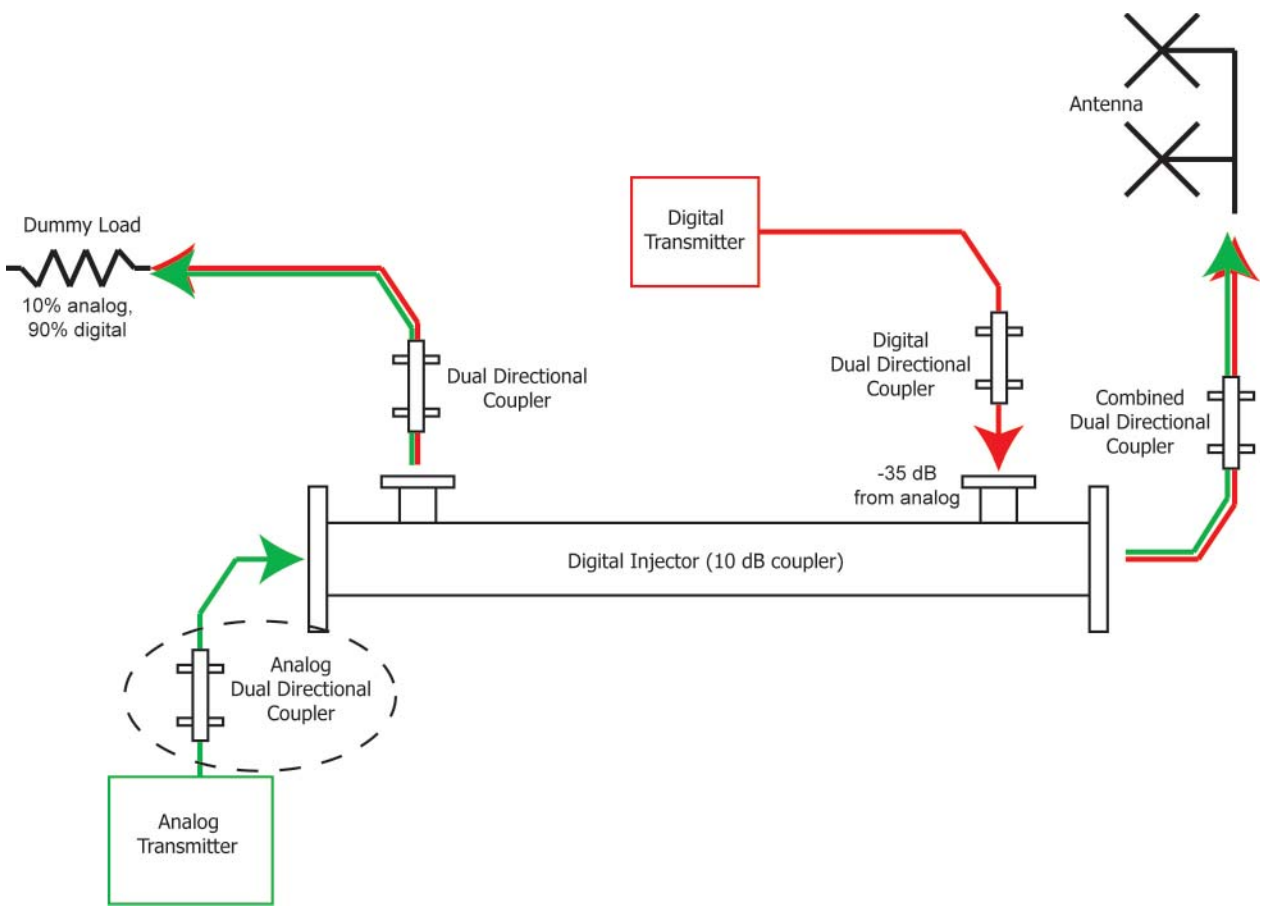

Figure 24. Analog Input of Combined Transmission System, WBUR

Figure 25 shows the result. The digital signal does indeed get into the analog transmitter. In order to see what happens to the digital signal in the analog transmitter, we attached the analyzer to the forward loop of the analog transmitter's directional coupler.

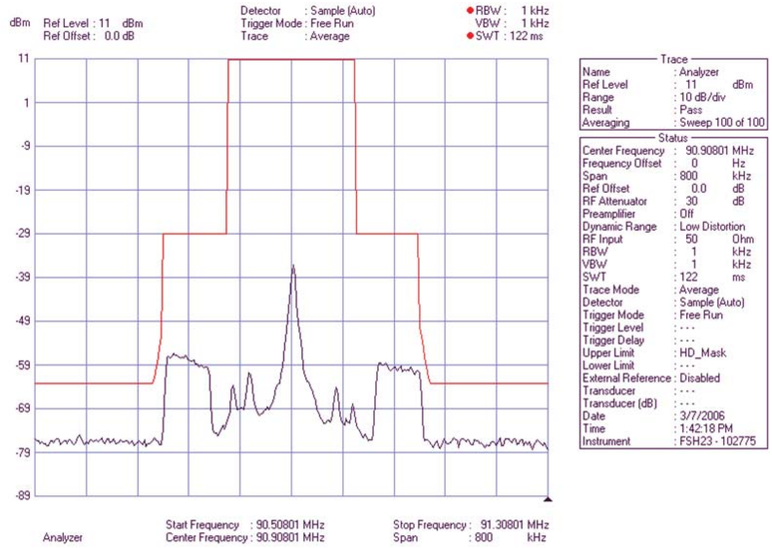

Figure 25. Combined Analog Reflected Power, WBUR. Note digital sidebands

Compare the result, Figure 26, with Figure 19 above. Note the following:

- The shape and amplitude of the subcarriers have changed.
- The subcarrier artifacts at ± 160 kHz have almost disappeared.
- There is no visible retransmission of the digital signal.

Interestingly, although the subcarriers appear distorted, there are no off-air reports of interference or distortion of the subcarriers.

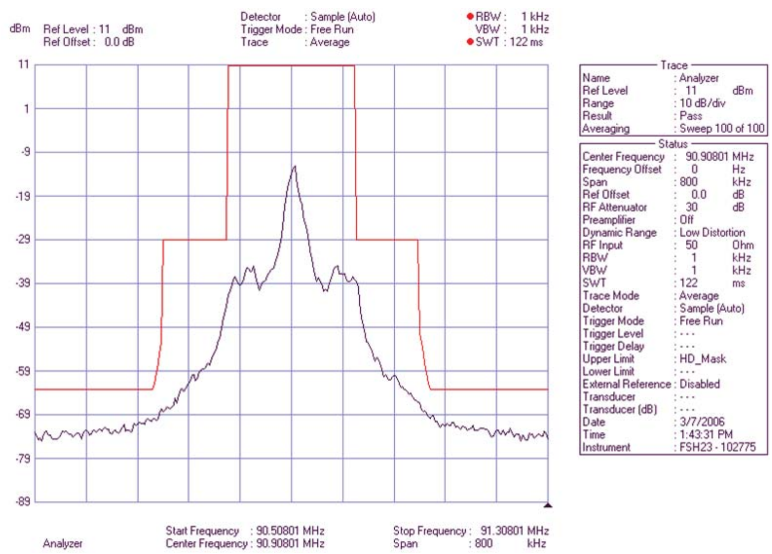

Fig. 26. Combined Analog Forward Power, WBUR

Now that we've looked at the analog and digital inputs and outputs, we now analyze the combined system output, as shown in Figure 27.

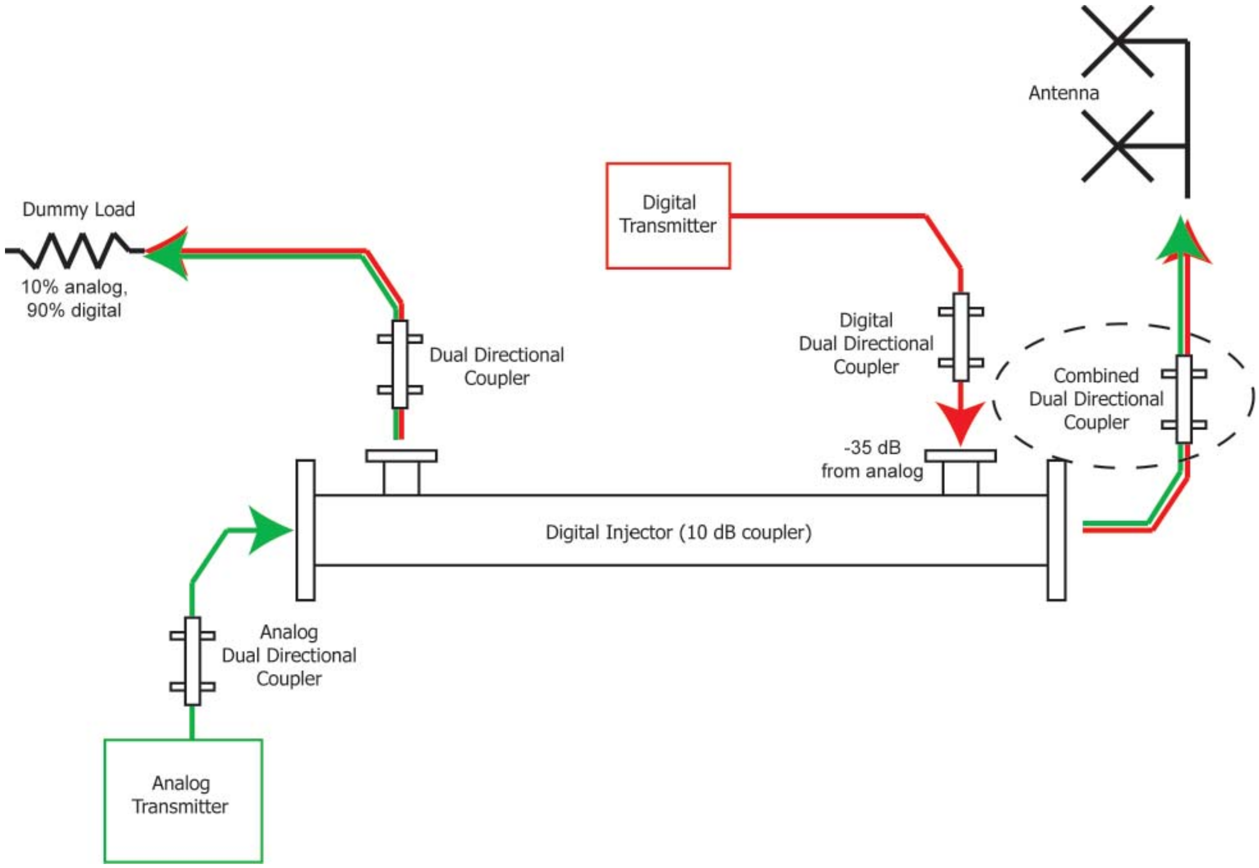

Fig. 27. Output Coupler of Combined Transmission System, WBUR

The plot in Figure 28 shows the analog with SCAs, the two digital carriers, and intermodulation products, all within the FCC's digital FM mask. The station is operating without interference to other broadcasters.

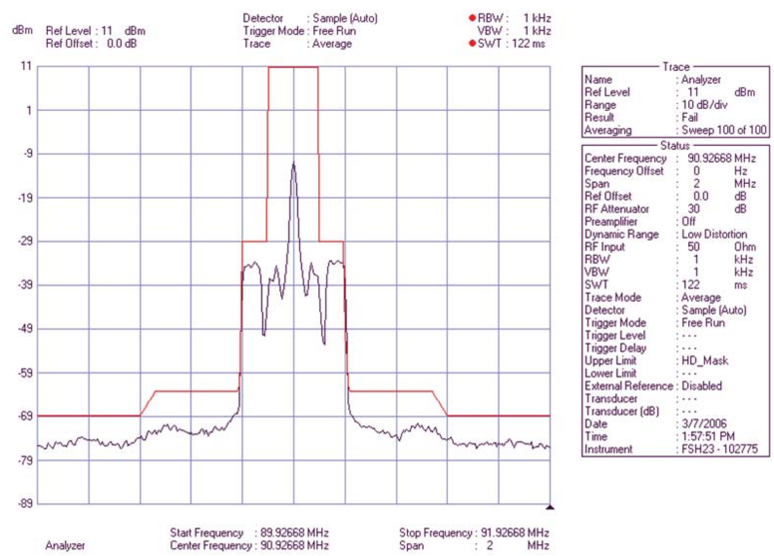

Fig. 28. Combined System Output

While monitoring the same directional coupler, we increased the digital transmitter's output power by approximately 1 dB, or about 20%. The only change we observed was the increase in the intermodulation products at ± 492 kHz, as shown in Figure 29.

We did this experiment because in the future, WBUR is going to be allowed to increase their analog ERP. The digital transmitter power will also have to be increased. Because the digital transmitter was adjusted for a specific power level for minimum intermodulation products, in the future it will have to be re-adjusted to minimize the increased intermodulation products shown in Figure 29.

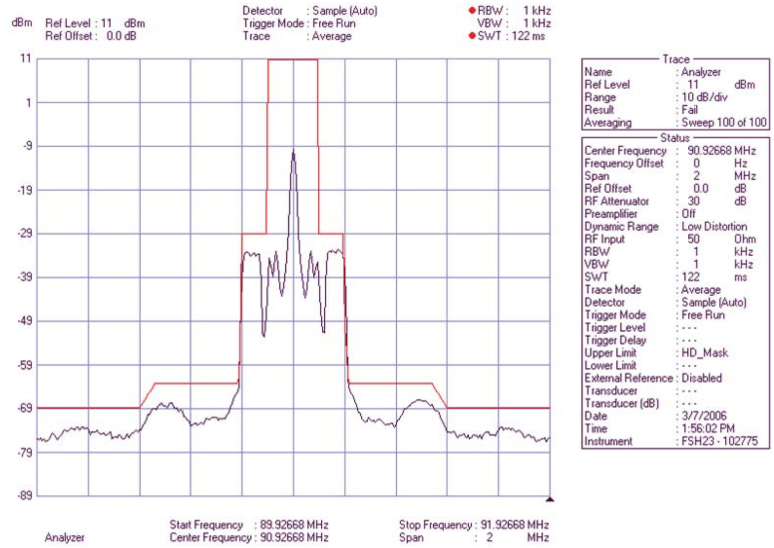

Figure 29. Combined System Output with Increased Digital ERP

Optimizing the injector to reduce intermodulation products

As more and more stations have added their digital signals using high-level injection, experience has shown that in some cases, the overall spectral picture is not perfect. Although each transmitter's performance has been optimized, some intermodulation products show up - though they may or may not cause interference to adjacent channels - and the roll-off slope of the digital carriers at ± 225 kHz shows the digital signal slightly exceeding the original iBiquity mask. Inability to meet the spectral mask in this region is so prevalent that iBiquity has proposed relaxing the mask requirements out to ± 250 kHz.

Experimentally, it has been found that if you place a tuning slug in the transmission line between the dummy load and the injector, you can optimize the performance of the injector and reduce the above problems. However, a fine-matching transformer (Figure 30) gives the same result with a lot less effort and can be adjusted under full power.

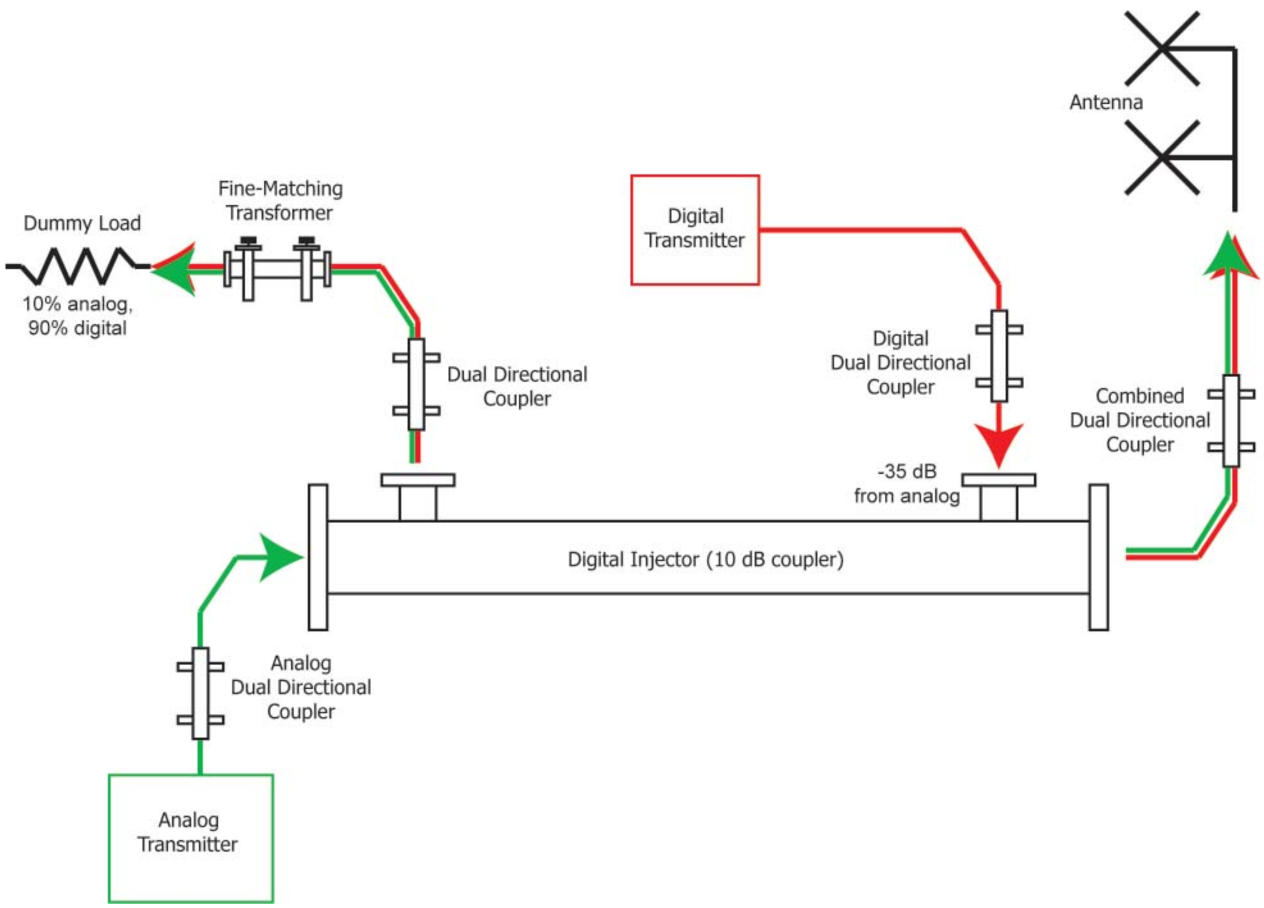

Figure 30. Optimized Injection System

Figure 31 is a plot of such an optimized "almost-perfect" system that meets the iBiquity digital FM mask.

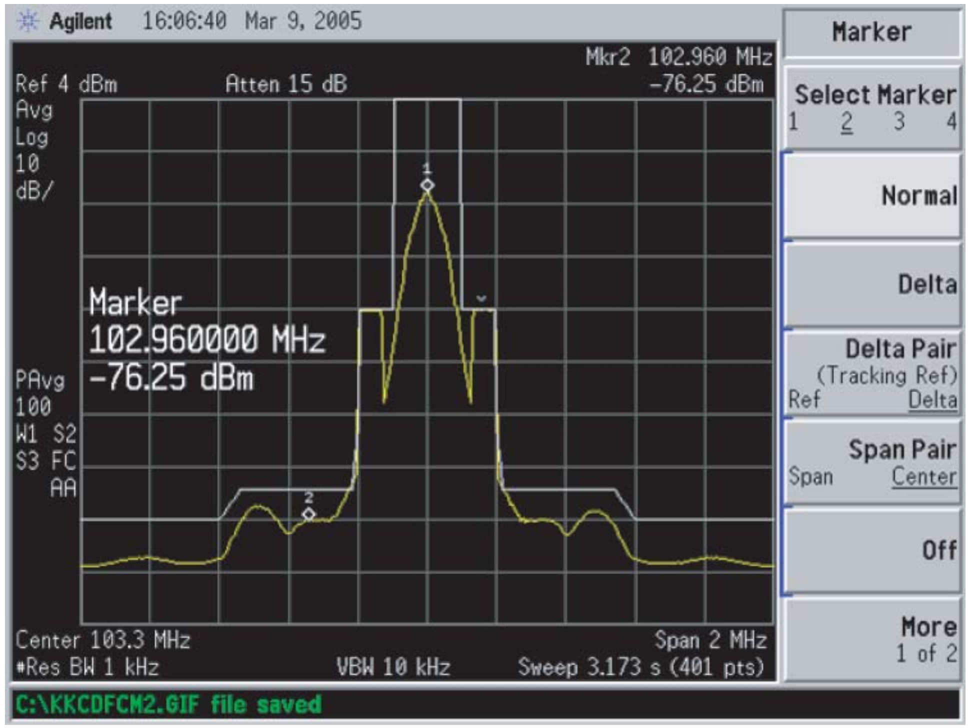

Figure 31. Almost Perfection

Conclusion

Intermodulation products can develop within the analog and digital transmitters in combined systems using high-level injection, resulting in suboptimal signal quality or even causing station-to-station interference. In the early days of digital implementation, external filtering was often used to eliminate or reduce interference. However, as the technology has evolved and we have achieved a better understanding of high-level injectors, subtle adjustments to the system, such as the addition of a fine-matching transformer to the dummy load, have proven adequate to reduce distortion and interference to meet the iBiquity digital FM mask.

About the contributors

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Albert G. Friend, Technical Writer/Editor for Shively Labs, edited the text and created the illustrations.

Shively Labs's Web site, containing this and other technical bulletins, is www.shively.com.