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Combining Digital and Analog Signals for US IBOC FM Broadcasting

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Abstract

IBOC DAB (In-Band On-Channel Digital Audio Broadcasting) requires the simultaneous broadcast of an analog and a digital signal within one channel of the FM band. Because broadcasters are adding IBOC to their existing systems, it is vital that they achieve maximum power efficiency while working within their existing space and power limitations. There are currently three different strategies proposed for accomplishing this goal, each having its own advantages and disadvantages. One strategy is to establish a separate, second antenna for the digital service. The other two strategies involve combining the analog and digital signals, either in a single hybrid transmitter or at the output of separate analog and digital transmitters. This paper discusses the equipment required for accomplishing this last strategy.

Introduction

The strategy of combining separate analog and digital signals involves two different requirements. The first requirement is to design a filter that meets the FCC mask specifications (figure 1) for the combined digital and analog signal. The second requirement is to combine the two signals into one antenna without degrading either signal. This paper will explore the trade-offs involved in various methods used to accomplish the separate-signal strategy and examine them from the broadcaster's point of view.

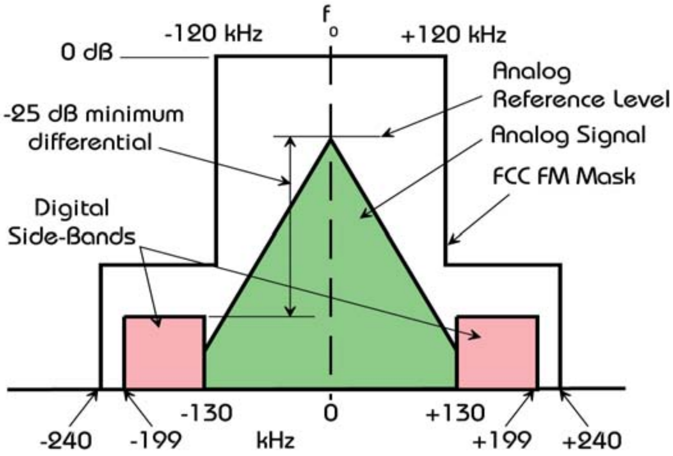

Figure 1. FCC FM Mask

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The challenge

Creating a filter/injector system compatible with the IBOC DAB system presents several distinct challenges. The optimum filter/injector needs to be highly selective, but must also physically fit into crowded transmitter rooms that will already be strained by the increased equipment required for the digital conversion. In addition, care must be given to balancing the operating efficiencies of the filter/injector between the analog and digital signals. These efficiencies will not only affect the sizing of the analog and digital transmitters, but also the infrastructure of the transmitter installation including air conditioning and electrical power distribution systems. Just as the physical size of the equipment will narrow the options available at many sites, the required analog transmitter power, air conditioning requirements, and electrical consumption will also limit options and inevitably drive up the cost of installation. For these reasons, operating costs and space requirements will be just as important to a successful filter/injector design as the electrical performance.

The mask filter

The filter portion of the IBOC DAB filter/injector ensures that the digital signal is maintained at a level that will protect the analog portion of the signal of the primary channel and the adjacent channels from interference while still supplying enough signal to provide a robust digital service. The ideal filter would have a response curve that resembles a square wave (figure 2). This would allow maximum attenuation outside of the passband while providing a flat, virtually lossless transmission response within the passband. Unfortunately, a response curve this sharp is not practical because of losses within the equipment. The objective is to design a filter with a response curve as close to this ideal square wave as possible without increasing the insertion loss or physical size of the filter inordinately.

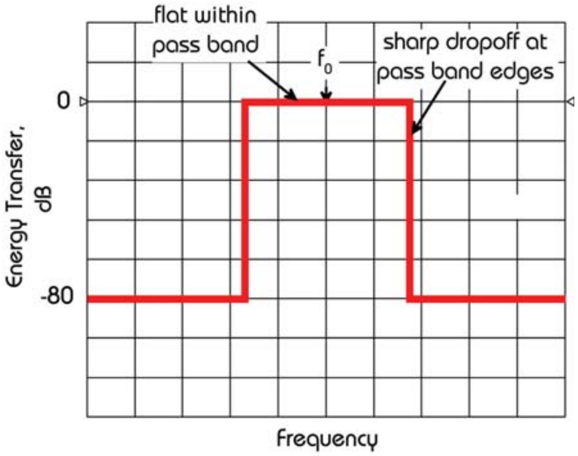

Figure 2. Frequency Response for Ideal Filter (Square Wave)

Creating the optimum filter for a given application involves balancing a number of competing performance variables, including insertion loss, bandwidth, isolation and group delay. Tuning the filter to enhance or minimize one variable will cause the other variables to change also. For example, adjusting the tuning to increase isolation also increases insertion loss and group delay, effects that are to be avoided. The net result of this intricate relationship of variables within a filter is sometimes referred to as the "Q" of the filter. To look at it another way, Q is the Quality Factor of the filter and in its most basic form can be defined as the ratio of reactance to resistance within a filter network. As the resistance decreases, the Q increases. With an increase in Q, we can expect a decrease in insertion loss and an increase in selectivity. Calculating the Q of a component or network is a complex task and beyond the scope of this paper; however, we can offer a number of values and general principles regarding Q and its interrelation with filter performance and design (figure 3).

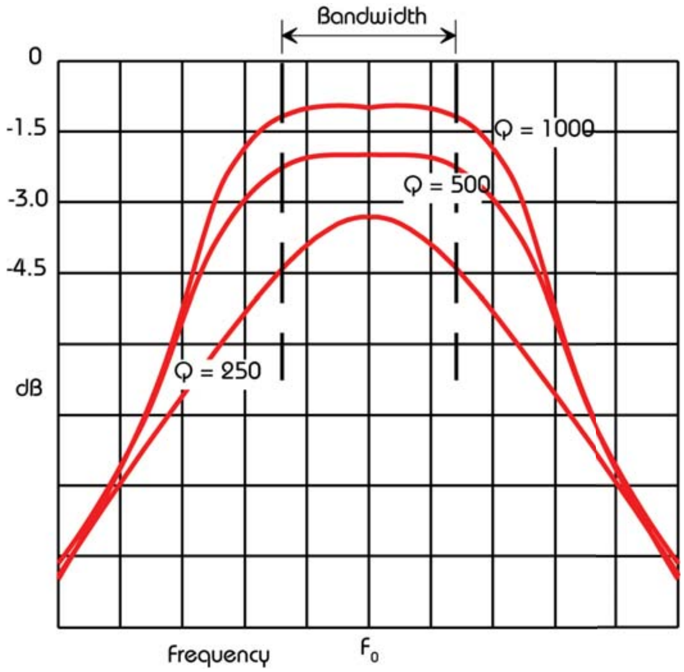

Figure 3. Q and Filter Performance

Resonant cavities

Size and number of resonant cavities both have an important effect on Q. The Q of a given filter network can be increased by increasing the size of the cavities. (A single, 24" square filter cavity has a Q of approximately 10,000).

Selectivity can be increased by adding more cavities, but the addition of reactive components will reduce Q, thereby increasing the insertion loss of the system. A four cavity, 24" square filter network will only have a Q of approximately 6,000.

Insertion loss can be mitigated to some extent by further increasing the size of the individual cavities. A 36" square cavity has a Q of approximately 20,000 and a four-cavity system will produce Q of 10,000. But this is contrary to the desire to keep the filter as small as possible. It is safe to say that a filter over twelve feet long will have limited applications in today's crowded transmitter rooms. In addition, at FM frequencies, performance begins to degrade above 36" cavity size for a variety of factors. Therefore, it is not possible to reach a satisfactory solution by simply adding bandpass cavities and/or increasing their size.

Transmission zeros

A reject "notch" cavity is used to reject a given frequency. It can be thought of as an inverse bandpass filter and follows many of the same rules and restrictions (figures 4 & 5). Larger size yields higher Q, which in turn equals better performance with greater selectivity. When used in conjunction with a bandpass filter, a reject cavity can be tuned to create a transmission zero, or null, in the bandpass response (figure 6). This zero, when properly placed, can improve the selectivity of the bandpass filter by increasing rejection at a specific frequency. Unfortunately, adding two reject cavities to a four-cavity filter (figure 7) results in higher insertion loss. It also increases the size and cost of the filter.

To avoid the addition of the two reject cavities, a technique known as cross-coupling can be used. A cross-coupling section (figure 8) creates two zeros at desired frequencies by introducing phase and magnitude changes that cause the desired frequencies to cancel each other. This improves the selectivity of the filter without increasing the size of the filter network, and minimizes the addition of resistive elements. By implementing cross-coupling in conjunction with a high-Q bandpass filter, a response can be attained that meets the FCC FM mask specifications. A 12-inch cross-coupled filter will have an insertion loss on the order of 0.5 dB, compared to a more typical 0.2 - 0.25 dB found in a larger 24-inch cavity system. However, the relatively small power levels involved with the digital signal make this an attractive trade-off for the smaller overall package.

The injector system

The second requirement in the design of an IBOC DAB filter/injector is to combine the separate analog and digital signals into an existing FM antenna. In order for the system as a whole to be successful, it must have maximum power efficiency while requiring a minimal amount of

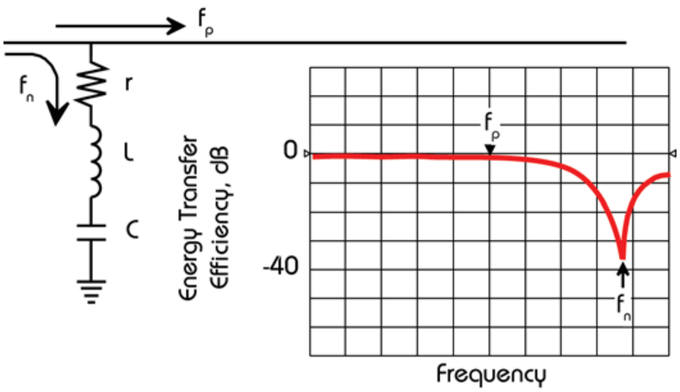

Figure 4. Band-Reject (Notch) Filter

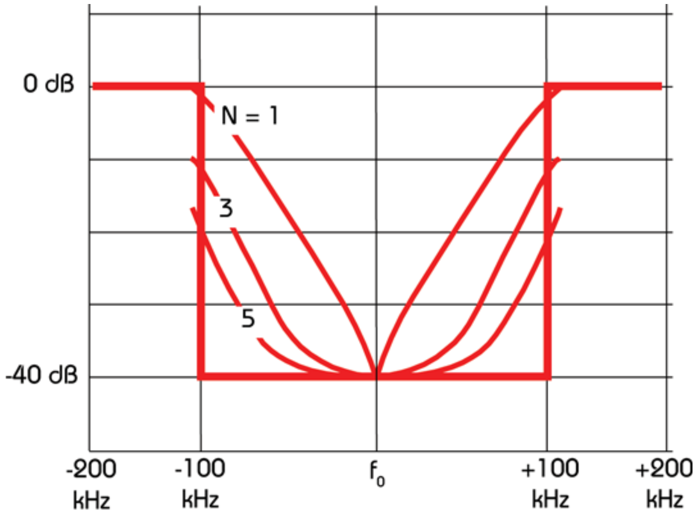

Figure 5. Notch Filter Response

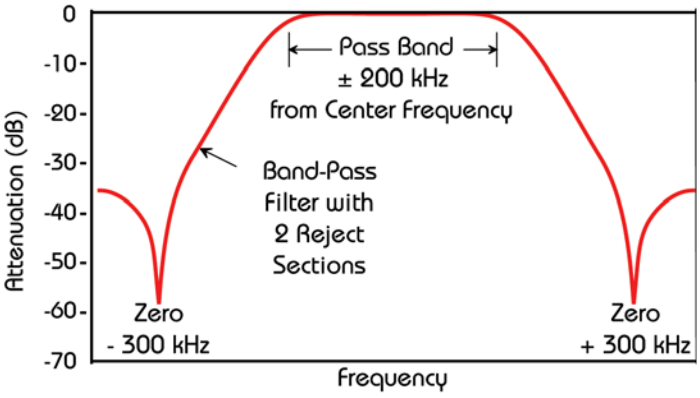

Figure 6. Bandpass Filter with Zeros

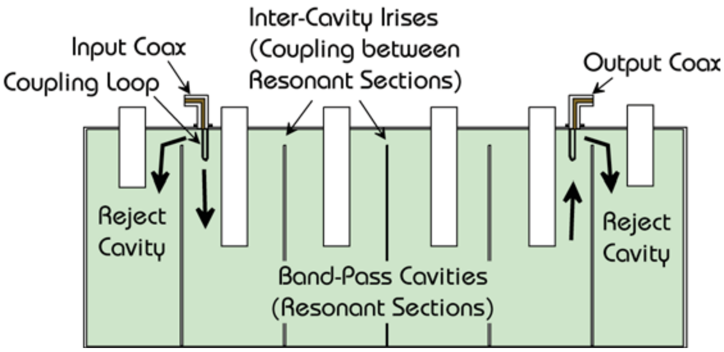

Figure 7. Bandpass Filter with Reject Cavities

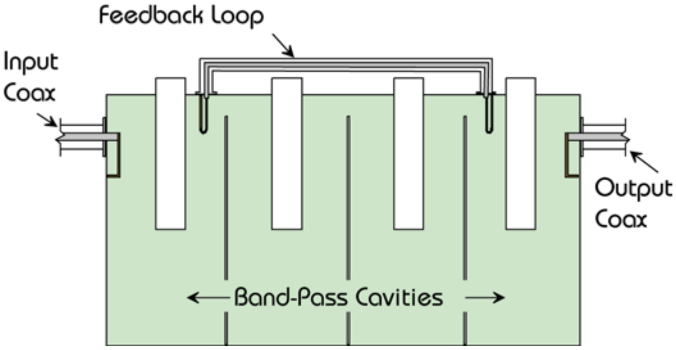

Figure 8. Bandpass Filter with Cross-Coupling

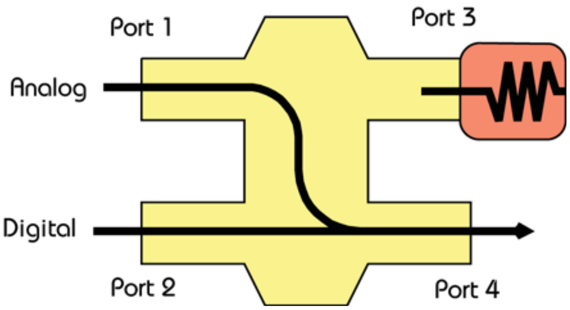

Figure 9. Hybrid Used as a Signal Combiner

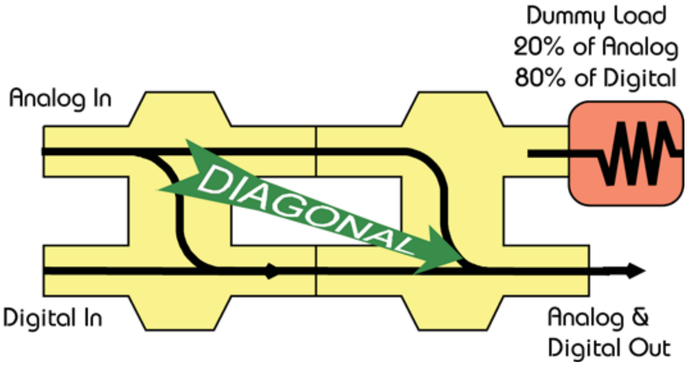

Figure 10. Hybrid Ring

space.

One possible solution to this problem is the 90° 3-dB hybrid. A single hybrid could be used to combine the two signals into the same line (figure 9). However, in the process, half of the power of each signal would be dissipated into the load at the isolated port.

Hybrid rings

In order to shift this 50% power loss to favor the analog signal, two hybrids can be combined to create a hybrid ring (figure 10). The analog signal would now lose only 20% of its output power, but the loss to the digital signal would increase to 80%. Since the signal level of the IBOC DAB signal needs to be no less than 25 dB lower than the analog, this configuration would seem more feasible than a single hybrid alone. However, the hybrid ring is very sensitive to the output load. Any change in the load (the antenna) will create an imbalance in the input-to-input isolation in the hybrid ring, and would cause crosstalk between the analog and digital transmitters. This would be perceived as noise. Another drawback is the relatively large size of hybrids needed to accommodate the analog power involved.

Balanced combining systems

Theoretically, hybrids can be used in combination with either two reject filters or two bandpass filters to create a balanced combining system of the analog and digital signals (figure 11). The reject filter configuration would reject the incoming analog signal, sending it to the antenna, and would pass the digital signal, thus combining the two. The bandpass combiner arrangement would do the opposite; it would reject the incoming digital signal, sending it to the antenna, and pass the analog through the filters, thereby merging the two signals. The problem with these approaches is that in order for either of them to work, the bandpass and reject filters would need at least 40 dB of rejection between the analog and digital signals. This rejection would have to occur in approximately a 20-kHz span from the edge of the analog signal's passband to the attenuated edge of the digital signal. A network having this much selectivity would require an extremely high Q and would be prohibitively large.

The 10-dB injector

A smaller and much more efficient solution is the 10-dB injector (figures 12 & 13), actually a directional coupler used to inject the digital signal into the analog signal. This configuration will pass 90% of the analog signal, adding 10% of the digital signal to it. The remainder of the digital signal is dissipated in the rejection load of the injector. The actual 10-dB injector is approximately the size of the analog output transmission line, so it takes up almost no additional room from equipment that is already installed. The reject load, however, will take up some additional space.

The 90% loss to the digital signal may seem excessive. However, since the digital signal must be injected onto the analog at at least 25 dB below the level of the analog signal, total digital transmitter power will be much less than that of the analog transmitter. Thus we can afford a higher percentage loss on the digital side, since it still amounts to less total power loss. Second, total power dissipated to heat is minimized; this is important because of its impact on the power and air conditioning consumption of the installation. Third, we minimize the chance that a larger analog transmitter will be required.

Let's look at a comparison for a station requiring 30 kW of analog TPO to meet its licensed ERP. This station will require 300 watts of digital TPO (-20 dB):

With a hybrid ring, 20% of the analog signal will be lost, and the loss to the digital signal is will be 80%. The station's analog transmitter must produce 37.5 kW [30 / 0.8], while the output of the digital transmitter must be 1.5 kW [0.3 / 0.2]. The total energy dissipated in the loads will be 8.7 kW [(37.5 – 30) + (1.5 – 0.3)]. The implications:

- The station will require 37.5-kW TPO from its analog transmitter and 1.5-kW TPO from its digital transmitter.
- The power supply system must support a total of 39 kW of transmitter power.
- The air conditioning will have to accommodate 8.7 kW of dissipated energy.

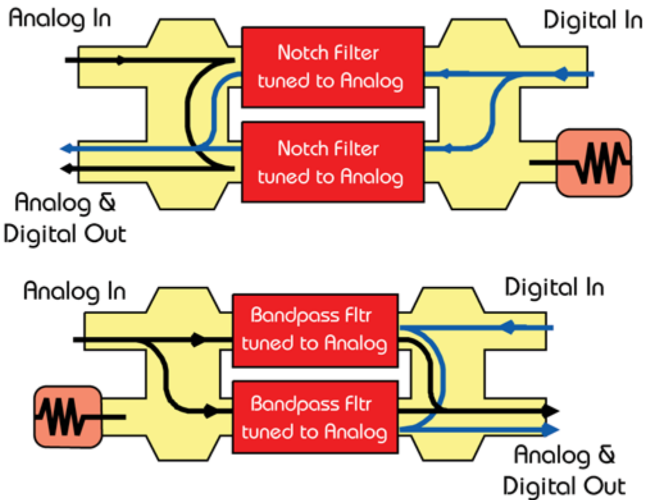

Figure 11. Balanced Combiners

On the other hand, with a 10-dB filter/injector, the 10% loss to the analog signal and the resulting 90% loss to the digital signal mean that 33.33 kW of analog transmitter power and 3 kW of digital power are required. The combined dissipated energy of the analog and digital transmitters would total 6.03 kW.

- The station will only need 33.33-kW TPO from its analog transmitter. There's a better chance its transmitter won't have to be upgraded.
- The power supply system will only have to support 36.33 kW transmitter power.
- The air conditioning will only have to be sized to accommodate 6.03 kW of heat dissipated.

In addition, should the digital injection level in the future be improved from –25 dB, the digital power will be increased significantly, while due to the tighter coupling ratio, there will be a small reduction in the transmitted analog signal. It is clear that using an injection system that minimizes the analog losses is the most cost-effective solution.

Future digital-only operation

Some of the extra operation and infrastructure savings associated with the 10 dB injector system will be offset by the need to buy a digital transmitter that is twice as large as would be used with a hybrid ring system. However, when FM evolves from a hybrid analog/digital mode to an all-digital mode, the required digital transmitter power will increase 10 dB. This means that a digital transmitter sized for use with the 10-dB injector will already be correctly sized for digital-only operation.

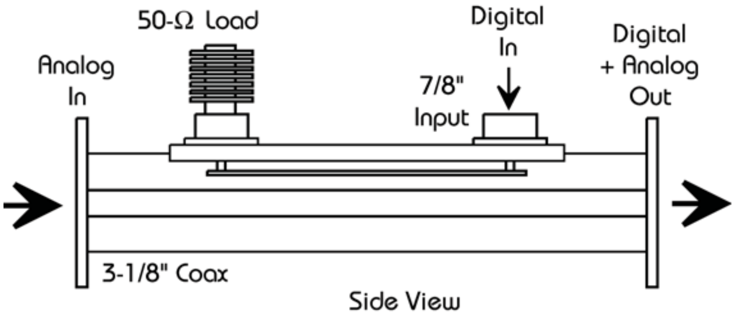

Figure 12. 10-dB Injector (directional coupler)

Conclusion

In conclusion, it is apparent that while several different methods exist for post-transmitter combining of digital and analog signals for IBOC DAB transmission, the total costs to the broadcaster of each of these systems is quite different. In order for equipment to be successfully adopted by the industry, care must be taken to address not only the FCC mask requirements of the system, but also operational expenses such as power and air conditioning consumption, space requirements, and replacement of current and future transmitters.

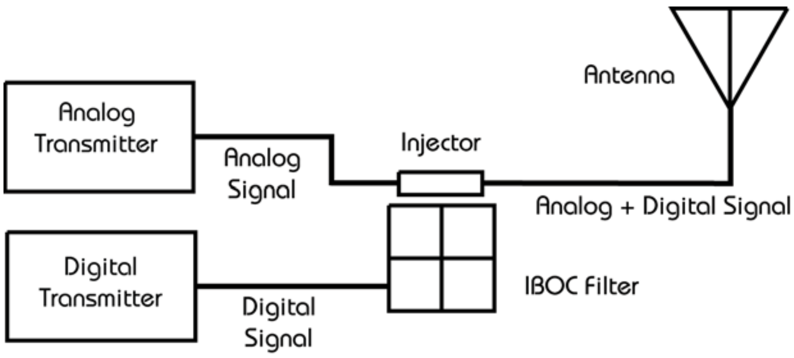

Figure 13. IBOC iDAB System

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