Appendix C

FM System Description

I. FM IBOC System Requirements

USADR has designed its FM IBOC DAB system to meet a number of primary requirements governing system function and performance. These requirements and the system's ability to meet these requirements are discussed below.

- **The system must deliver virtual CD-quality audio beyond the FCC-protected interference contour in both a mobile and fixed environment.**

The term "virtual CD-quality" implies that the listener should perceive the audio quality of the received signal to be virtually identical to that of a compact disc.[1] Because mobile reception presents a significantly greater number of challenges than reception in a fixed environment, primarily due to the need for high immunity to multipath-related outages, USADR's description and analysis herein concentrates on the mobile environment.

A station's digital coverage must mirror actual analog coverage existing today. For example, properly spaced Class B stations are protected to the 54-dBu contour in 50% of the locations for 10% of the time from the following types of interference:

(a) 34-dBu co-channel interference (+20 dB D/U[2])

(b) 48-dBu first-adjacent channel interference (+6 dB D/U)

(c) 94-dBu second-adjacent channel interference (-40 dB D/U)

These interference specifications do not take into account two important situations which must be addressed by the DAB system. First, significant numbers of stations are short-spaced,

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[1] *See* Appendix J for a more detailed discussion of audio quality issues.

[2] D/U is the ratio of desired to undesired signal power

which results in non-standard interference environments. Second, many listeners beyond a station's protected contour continue to listen to and depend on its signal. More than half of all commercial FM stations are short-spaced, and will therefore exhibit interference levels higher than those that would be predicted based on the FCC's protected contours.[3] Similarly, in the absence of interference constraints, listeners do not stop listening to a station simply because they are outside the protected contour.[4]

Hence, the IBOC DAB system must be able to deliver virtual CD-quality audio in a multipath channel beyond the protected contour, in the presence of some combination of interfering channels. These interfering channels may be analog, hybrid IBOC, or all-digital IBOC signals.[5]

- **The FM IBOC waveform must fit within the FCC spectral emissions mask.**

The existing FM spectrum mask limits the power level and bandwidth of analog transmissions in order to minimize adjacent channel interference. The IBOC DAB system is designed to include the digital carriers within this mask in order to minimize interference to adjacent analog signals.[6]

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3 *See* Appendix D.

4 For example, for a Class B station, its 54 dBu protected contour extends out approximately 40 miles. USADR's studies have indicated, however, that without interference constraints a signal is perceived by the average listener as "listenable" out to its 44 dBu contour, which extends approximately 55 miles from the transmitter. USADR's system is designed to mirror existing analog coverage, including this 15 mile extension beyond the Class B protected contour. *See* Appendix D for a more detailed discussion of actual coverage issues.

5 Performance results from simulations are detailed in Appendix E.

6 USADR has proposed in Appendix A draft Rule 73.325 which would establish new interference masks for the digital signal to minimize digital-to-digital interference and build upon the protections against digital-to-analog interference set out in the Rule 73.317 analog mask.

- **Interference to the host analog FM and adjacent analog channels must be minimized.**

Adding a digital signal to the analog FM host should not engender interference in the analog host. In addition the system must minimize interference to adjacent analog channels from hybrid and all-digital IBOC signals.[7]

- **The system must provide for a rational transition from existing analog service to digital service.**

The DAB system must accommodate the new digital signal in the existing channel and existing AM and FM frequency band to ensure existing radios are not immediately rendered obsolete. Likewise, the IBOC DAB system should be forward compatible; the design should allow for a rational transition from hybrid to all-digital without compromising adjacent hybrid performance or rendering obsolete the early generation DAB receivers.

- **The system must provide capacity for auxiliary services.**

Some system throughput must be reserved for transmission of auxiliary services, much as current FM subcarriers do today. Auxiliary services could, for example, take the form of program-associated data, station information, advertisements, or subscription applications (e.g., stock quotes).

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[7] Appendix E details the simulation results demonstrating performance against this requirement.

- **The system must allow graceful degradation of the received signal.**

As a digital receiver approaches the edge of coverage, its signal quality deteriorates abruptly. In fact, audio quality can change from virtually unimpaired to non-existent almost instantly. This "all-or-nothing" quality drop-off could annoy listeners who are accustomed to graceful analog degradation (or perhaps even cause them to suspect equipment malfunction). As a result, the IBOC DAB system must provide a means of gracefully degrading the signal as the edge of coverage is approached or as the signal quality is impaired.

- **The system must allow rapid channel acquisition and tuning.**

Digital receivers that are designed to be robust in a mobile environment typically have extended acquisition times. When a listener opts to change a channel on a digital receiver, there is usually a significant period of time -- perhaps on the order of a few seconds -- before the associated audio is heard. This delay is due to processing that is specific to digital receivers (such as de-interleaving and decoding). The IBOC system must have a means of quickly acquiring the signal upon re-tuning or re-acquisition in a manner that is equivalent to what listeners are used to when tuning between analog stations.

These requirements drive the basic design of the USADR FM IBOC DAB system, as explained in the following section.

II. FM IBOC System Overview

The USADR FM IBOC DAB system is primarily comprised of four basic components: the modem, which modulates and demodulates the signal; the codec, which source encodes and decodes the audio signal; forward error correction ("FEC") coding and interleaving; and blending. All of these core functional areas have been designed and integrated to produce a system which complies with the primary functional requirements described above.

A. Modulation Technique

USADR evaluated several modulation techniques for the IBOC DAB FM system before selecting Quadrature Phase Shift Keying ("QPSK"). QPSK has robust performance while providing sufficient throughput for virtual CD-quality digital audio. It permits the use of advanced FEC coding techniques which exploit knowledge of the non-uniform interference environment. QPSK is also simpler and more robust than higher-order forms of modulation, especially in a multipath environment. Since QPSK has a bandwidth efficiency of two bits per second per Hertz, it supports an information bit rate that is sufficient for transmission of virtual CD-quality audio in the bandwidth available.

USADR reviewed whether to use a multi-carrier or single-carrier approach to transmit the digital signal, and chose a multi-carrier approach called Orthogonal Frequency Division Multiplexing ("OFDM"). OFDM is a scheme in which many QPSK-modulated carriers can be frequency-division multiplexed in an orthogonal fashion such that each carrier does not interfere with each adjoining carrier. OFDM offers a high level of robustness to multipath.

When combined with FEC coding and interleaving, the digital signal's robustness is further enhanced. The OFDM structure naturally supports FEC coding techniques that maximize performance in the non-uniform interference environment. The most important bits can modulate OFDM carriers that are located in the most protected regions of the channel. The inherent flexibility of OFDM also allows carriers to be added or removed at the discretion of the broadcaster.

B. Source Coding

CD digital audio has a data rate of 1.4112 Mbps (44,100 16-bit samples per second, for left and right channels). The FM channel bandwidth does not have the capacity to support a sufficiently high data rate to provide virtual CD-quality audio without some form of compression. As a result, an audio codec (coder-decoder) must be employed. An audio codec is a source-encoding device that removes redundant information from a digital audio signal in order to reduce the bit rate, and hence the bandwidth required to transmit the signal. The codec must perform this bit rate compression while minimizing the generation of perceptible artifacts.

USADR will use the MPEG AAC codec in its IBOC DAB systems. The AAC codec compresses the CD bit stream to 96 kbps, delivering audio that the listener will perceive to be virtually the same quality as a CD. Use of the AAC codec meets the raw throughput requirement of the modulation and FEC coding techniques. In addition, special error concealment techniques employed by the codec help to ensure graceful degradation of the received digital signal.[8] In addition to its ability to meet the USADR system's audio compression requirements, AAC offers the advantage of being an open system based on the MPEG family of ISO standards.

C. FEC Coding and Interleaving

Forward error correction and interleaving greatly improve the reliability of the transmitted information. Advanced FEC coding techniques exploit the non-uniform nature of the interference. Special interleaving techniques spread burst errors over time and frequency to assist the FEC decoder in its decision-making process. The combination of these advanced FEC coding and interleaving techniques, together with superior modem performance, allow the IBOC

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[8] Additional information on the AAC codec is contained in Appendix J.

system to deliver virtual CD-quality audio beyond the FCC-protected signal strength contour in a mobile environment.[9]

D. Blend

The USADR system employs time diversity between two independent transmissions of the same audio source to provide robust reception during outages typical of a mobile environment. In addition, the blend function allows graceful degradation of the digital signal as the receiver nears the edge of a station's coverage. The FM IBOC DAB system provides this capability by delaying a backup transmission by a fixed time offset (several seconds) relative to the digital audio transmission.[10] When the primary digital signal is corrupted, the receiver blends to the backup audio which, by virtue of its time diversity with the primary signal, does not experience the outage. In the hybrid mode, the backup channel is the analog signal. In the all-digital mode, the backup channel is a low bit rate digital signal.

The blend feature also provides a means of quickly acquiring the signal upon tuning or re-acquisition. Without blend, a digital receiver would incur a significant delay after tuning to a station before the listener hears the audio. The blend feature will allow the receiver to instantaneously acquire the analog signal (in the hybrid mode) or the backup digital signal (in the all-digital mode). This allows the listener to hear the selection while the receiver is acquiring the primary digital signal. After acquisition, the receiver then blends to the primary digital signal.

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9 The results of simulations and analyses are given in Appendix E.

10 *See* Appendix K for a more detailed discussion of time diversity and blend.

E. Hybrid Mode

The FM hybrid spectrum is shown in Figure C-1. Low-level digital sidebands are added to each side of the analog signal. The bandwidth is limited to ±200 kHz from the center frequency. USADR has conducted simulations and analyses[11] which verify that restricting the digital carriers to the 70-kHz regions between 129 and 199 kHz from the center frequency on either side of the analog spectrum minimizes interference to the host analog and adjacent channels without exceeding the existing FCC spectral mask. This bandwidth is wide enough to support a robust hybrid IBOC service with virtual CD-quality audio that mirrors the coverage area of existing radio stations.

The dual-sideband OFDM structure enables the use of frequency diversity to further combat the effects of multipath fading and interference. The system simultaneously transmits the 96 kbps digital audio information plus auxiliary services[12] on each DAB sideband. Each sideband can be independently detected and decoded, permitting operation on one sideband while the other is corrupted. However, when neither sideband is corrupted, advanced FEC coding techniques allow combination of both sidebands to provide additional signal power and coding gain.

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11 *See* Appendix E.

12 *See* Appendix K.

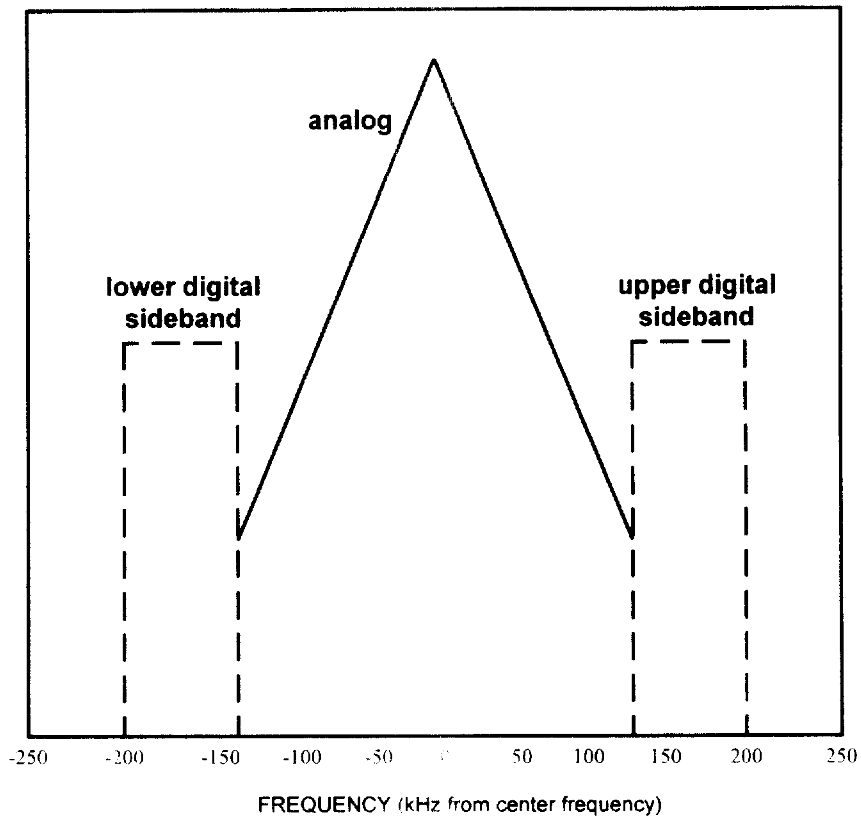

Figure C-1 - Hybrid FM IBOC Power Spectral Density

F. All-Digital Mode

The all-digital mode differs from the hybrid mode primarily through deletion of the analog signal at the center of the channel, leaving the two digital sidebands, as shown in Figure C-2. The power of the sidebands is increased, making them more robust than the hybrid DAB sidebands; however, each remains within the current FCC spectral mask. The number of OFDM carriers is also increased such that each sideband occupies a bandwidth of 100 kHz. The additional 30 kHz in each sideband carries backup audio, additional auxiliary services, or additional FEC overhead. Low-level OFDM carriers added to the central 200-kHz region can support multichannel sound or enhanced auxiliary services.

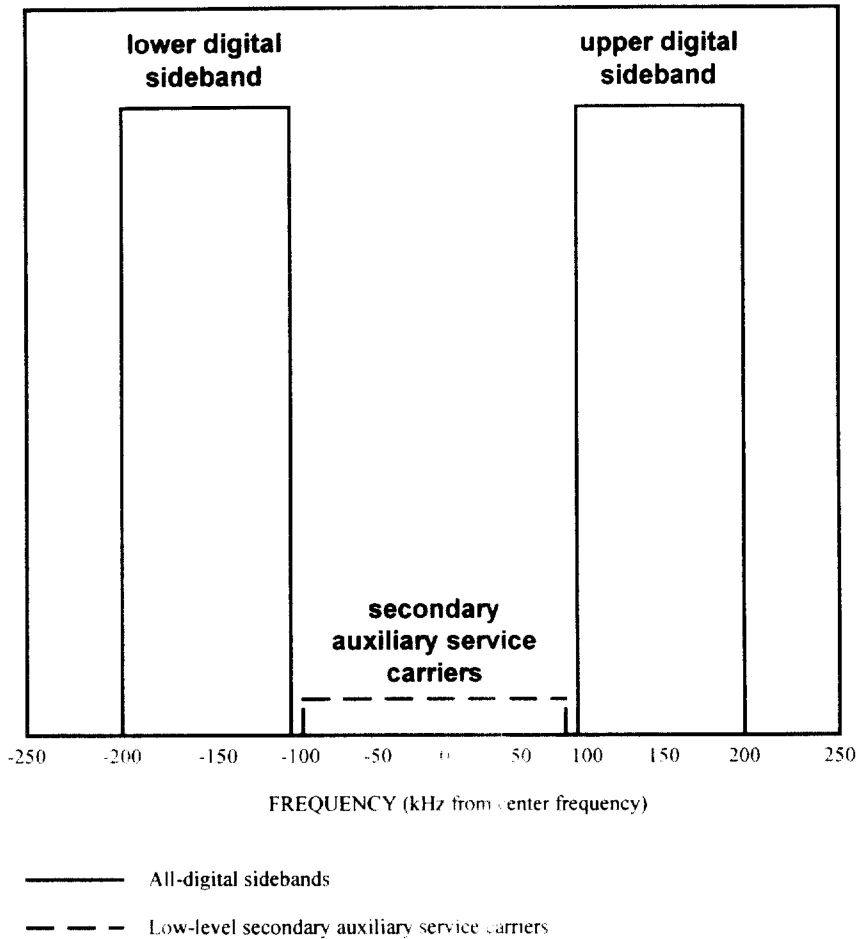

Figure C-2 – All-Digital FM IBOC Spectrum

The all-digital mode is similar to the hybrid mode in that the digital signal is split into two sidebands. However, the energy in the all digital signal is not concentrated around the center of the channel as it is in the existing FM signal. There are a number of reasons for this "split" structure.

First, the split sideband spectrum maximizes compatibility with adjacent IBOC signals. The all digital signal does not interfere with digital sidebands, either all digital or hybrid. This effectively eliminates interference between primary digital services.

Second, splitting the signal enables the use of frequency diversity to combat the effects of multipath fading and interference. Each sideband can be independently detected and decoded, permitting operation on one sideband when the other is corrupted. However, as with the hybrid mode, in the usual case when neither sideband is corrupted, advanced FEC coding techniques allow combination of both sidebands to provide additional signal power and coding gain.

Third, the dual-sideband format is a natural extension of the hybrid format. The broadcaster simply increases the power in the DAB sidebands, adds a number of additional carriers, stops transmitting the analog signal, and can add auxiliary service carriers in the center of the channel. As a result, the all-digital system is virtually identical in complexity to the hybrid system, and requires little additional receiver processing. Thus, even the earliest IBOC receivers will be capable of receiving both hybrid and all-digital signals, for virtually no additional cost.

G. Compatibility

During the transition to the all-digital period, analog-only, hybrid, and all-digital stations may exist next to each other on the dial; thus, each must be compatible with the other such that digital-to-digital interference is minimized. The USADR IBOC DAB FM system is designed to operate in this scenario.

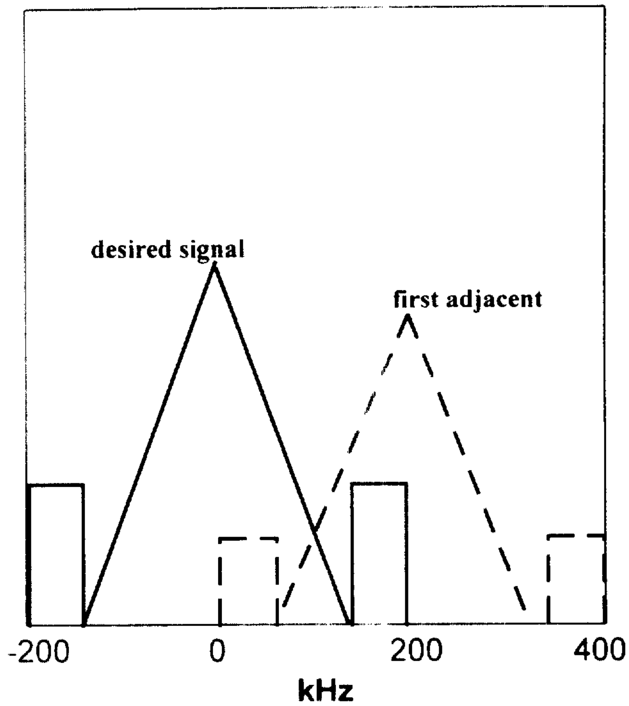

Figure C-3 - Interference scenario showing hybrid first adjacent at -6 dB

Figure C-3 shows a potential scenario in which a desired hybrid signal and an upper first-adjacent hybrid interferer can co-exist. This is a typical interference scenario during the interim hybrid period. The figure shows that there is no interference between the hybrid digital sidebands. However, the analog portion of the first-adjacent hybrid signal interferes with the upper digital sideband of the desired hybrid signal. In an effort to reduce analog interference to the digital sideband, USADR has developed a technique known as First Adjacent Cancellation ("FAC").[13] In addition, the use of frequency diversity and advanced FEC coding techniques further improve performance of the desired digital signal under these conditions.

Figure C-3 also shows that adjacent hybrid digital sidebands can increase the noise level in the analog portion of the desired hybrid signal. However, in typical receivers, this interference

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13 *See* appendix E for performance results on FAC.

may be no worse than that currently engendered by analog first adjacents.[14]

When broadcast of the all-digital signal is permitted, hybrid and all-digital signals can co-exist. Figure C-4 shows a potential scenario in which a desired all-digital signal and an upper first-adjacent hybrid interferer can co-exist. As in the scenario depicted in Figure C-3, the analog portion of the first adjacent hybrid signal interferes with the upper digital sideband of the desired all-digital signal. Since the all-digital sidebands will have more power than the hybrid sidebands, the all-digital signal will be more robust than the hybrid signal when subject to this same level of interference.

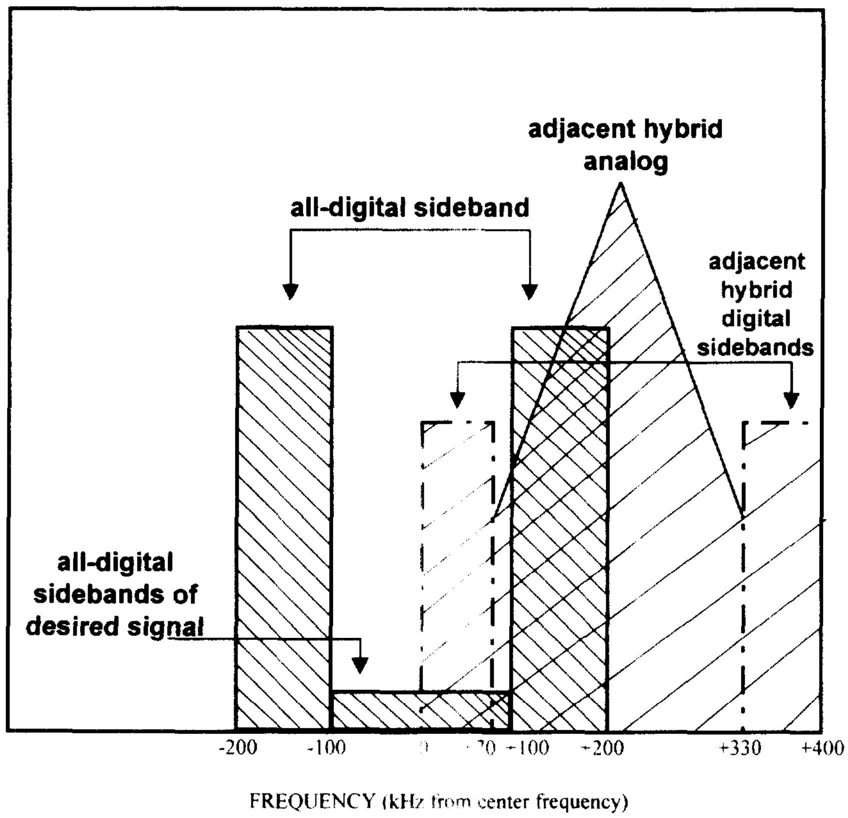

Figure C-4 Hybrid and All-Digital Compatibility

Figure C-4 also shows that the upper digital sideband of the desired all-digital signal

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14 *See* Appendix E, section 4.2.1.2 for detailed analysis.

interferes with the desired analog portion of the adjacent hybrid signal. However, broadcast of the higher-powered all-digital signal is not permitted for some time. By then, there will be many IBOC receivers that will receive the interference-free digital transmission. The all-digital signal has been designed to protect newly introduced IBOC receivers, rather than older analog receivers; therefore, the digital to analog interference is not a primary concern. Note that this analysis also applies to analog-only interfering signals.

The USADR design insures that the newly introduced primary digital services do not interfere with each other. This is illustrated in Figure C-4, which shows that the upper sideband of the all-digital signal does not overlap with the lower sideband of the first-adjacent hybrid signal. Note that there is an overlap between secondary auxiliary services in the desired all-digital signal and the lower sideband of the first-adjacent hybrid signal. The power levels of the secondary auxiliary services have been set to preclude interference to primary adjacent sidebands, but are subject to interference from them.[15] Advanced FEC coding techniques help to overcome this interference. While the coverage area and robustness are not as good as the all-digital primary sidebands, acceptable levels of performance are achievable within the protected contour, except in areas with two large first-adjacent signals.

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[15] *See* appendix A for protection rules for secondary auxiliary services.

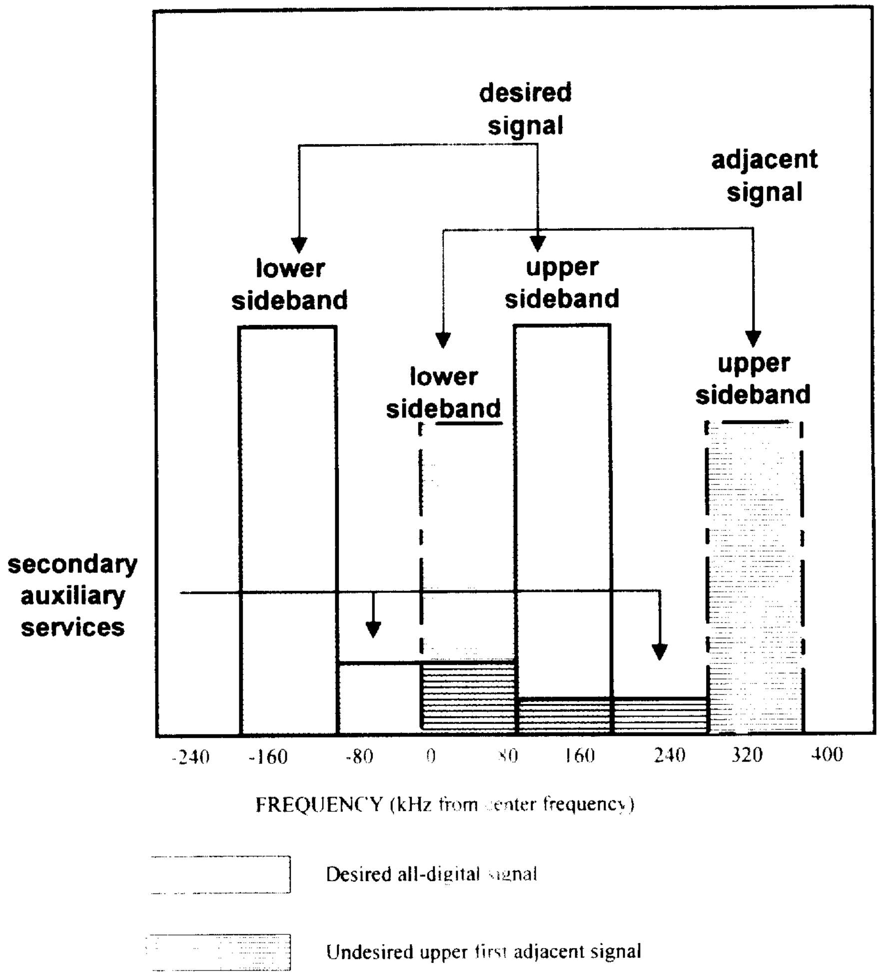

Figure C-5 All-Digital to All-Digital Compatibility

Finally, during the all-digital period, the USADR IBOC design ensures adjacent all-digital signals can co-exist. Figure C-5 shows a potential scenario in which a first-adjacent all-digital signal resides next to a desired all-digital signal. As discussed above, there is no interference between primary digital services; the upper desired sideband in Figure C-5 does not overlap with the lower sideband of the first adjacent signal. Likewise, the secondary auxiliary services of the desired signal are too low in power to interfere with the primary lower digital sideband of the first adjacent signal. As in Figure C-4, the lower sideband of the first-adjacent signal does interfere with the secondary auxiliary services of the desired signal, which as discussed above may still achieve acceptable performance.

Because there is no overlap of digital sidebands when all broadcasters are transmitting in the all-digital mode, adjacent-channel interference between primary services will be eliminated. The sidelobes of the all-digital and hybrid sidebands are minimized by employing special sidelobe reduction techniques in the modulator In addition, USADR is working closely with transmitter manufacturers, who can produce transmitters with sufficient sidelobe attenuation to protect adjacent channels.[16]

In summary, the USADR IBOC system maintains compatibility among analog, hybrid and all-digital modes.

III. FM IBOC Signal Generation

Both the FM hybrid and all-digital IBOC waveforms require linear amplification; as a result, many stations will need to purchase a new transmitter. USADR has shared its IBOC transmission specification with broadcast transmitter manufacturers. Discussed below are options which are the subject of discussions between USADR and manufactures. For early FM adopters, and those FM stations seeking the lowest up-front cost, a small, outboard linear amplifier with a high-level power combiner provides an attractive option. The amplifiers must be constructed to operate in a broadcast environment with the levels of reliability, quality, and remote-control capability presently available in broadcast equipment. Ultimately, broadcasters

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16 USADR is working with a number of transmitter manufacturers whose transmitters can generate the IBOC DAB signal. USADR has also transmitted over 700 watts of DAB power at its test station in Columbia, Maryland.

are going to look to transmitter manufacturers to provide high-efficiency linear amplifiers that meet their needs in the hybrid era and be capable of transmitting all-digital in the future.

A. FM Transmitter Functional Description

A functional block diagram of a hybrid FM IBOC transmitter is presented in Figure C-6. The sampled stereo audio source feeds both the analog and DAB signal generation paths. A diversity delay is introduced in the analog path for blend to backup audio purposes. In the power combiner method shown here, the audio is processed within the exciter just as an analog FM signal would be, prior to amplification by the high power amplifier ("HPA").

The DAB path first source encodes the audio signal in the audio encoder. The audio encoder removes redundant information from the audio signal to reduce the bit rate, and hence the bandwidth required to transmit the signal. To ensure that the communication of information through the fading channel is robust, the compressed bit stream is then passed through the FEC coding and interleaving function. The resulting bit stream is packaged into a modem frame and QPSK and OFDM modulated to produce the DAB baseband signal. This baseband signal is upconverted and amplified before being power combined with the analog signal.[17]

As shown in Figure C-7 below, the all-digital transmitter replaces the analog signal path with a shorter interleaver and FEC.

[17] Details such as data insertion and FM/DAB blend synchronization have been omitted here for simplicity.

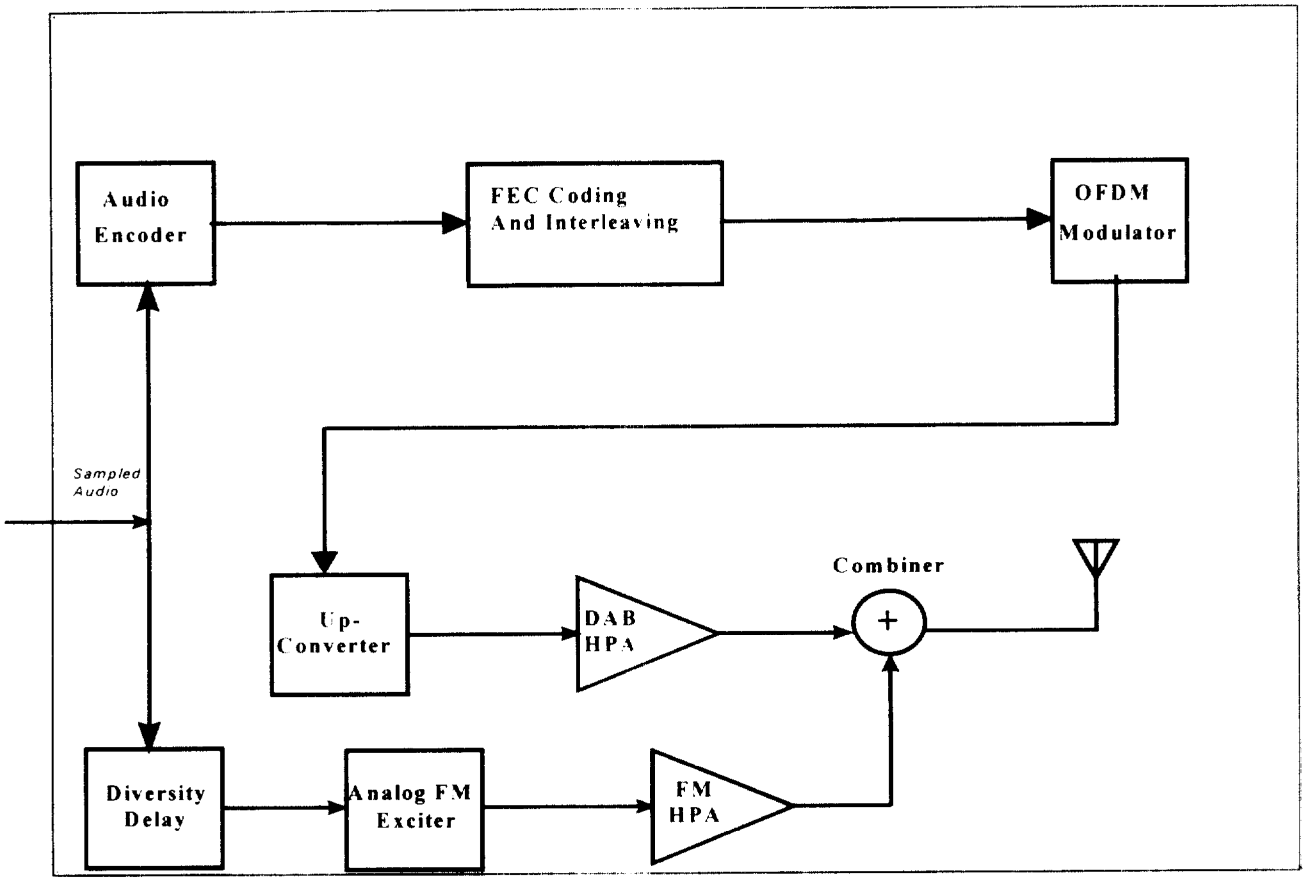

Figure C-6 - FM IBOC Hybrid Transmitter Functional Block Diagram
Showing Power Combiner Method

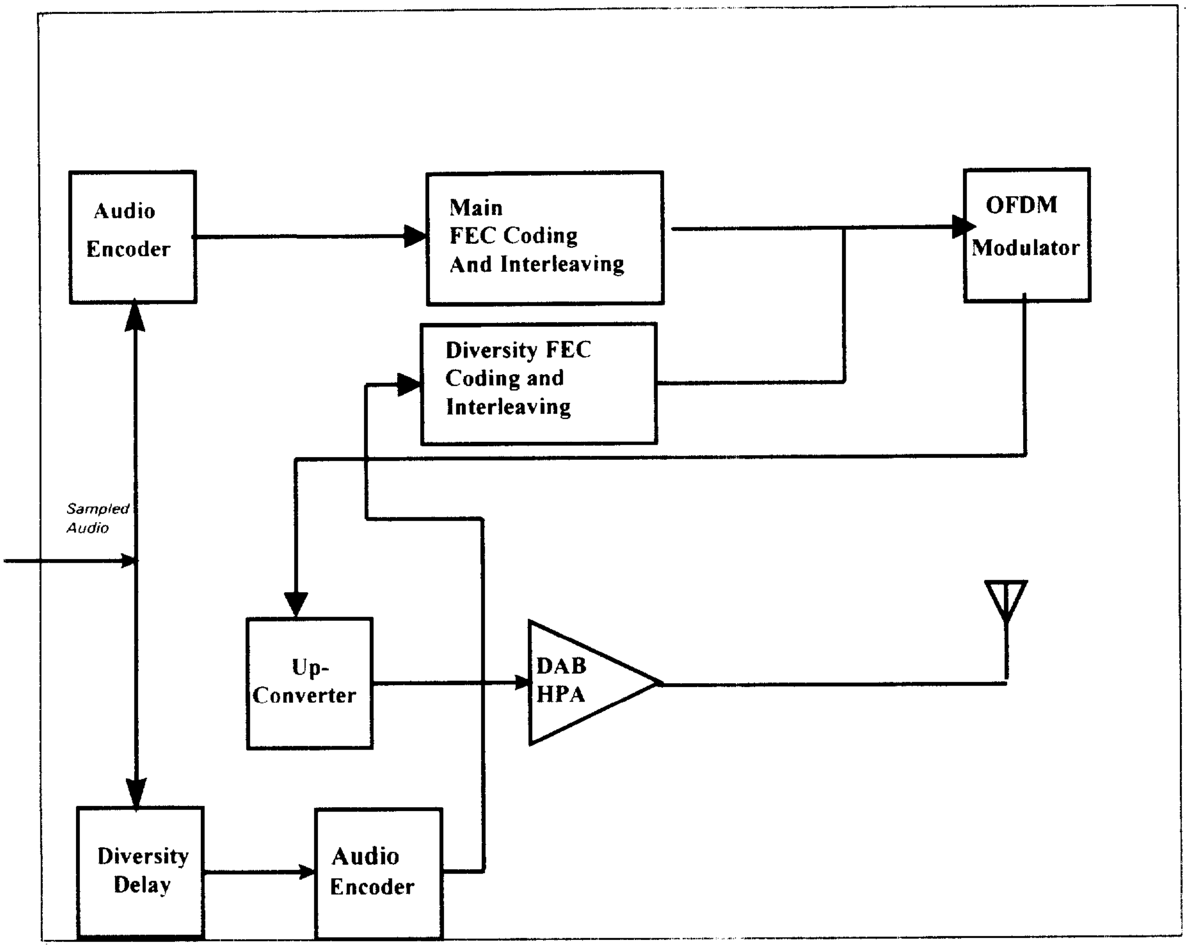

Figure C-7 - FM IBOC All-DigitalTransmitter Functional Block Diagram

B. FM Transmitter Physical Description

Current FM transmitters operate in a Class C nonlinear mode and are incapable of passing a digital waveform. The only method currently known for generating the digital portion of the hybrid FM IBOC signal is to apply the digital waveform to a linear amplifier and to combine it with the analog FM transmitter at high power levels as shown in Figure C-8. An output from the DAB exciter will be made available, at carrier frequency, for subsequent linear amplification.

The DAB signal generation functions identified in Figures C-6 and C-7, including the audio encoder, FEC coding and interleaving, OFDM modulator, and up-converter are all implemented in the FM DAB Exciter block in Figure C-8. In addition, the diversity delay and analog FM exciter functions identified in Figure C-6 are implemented in the analog FM exciter block in Figure C-8.

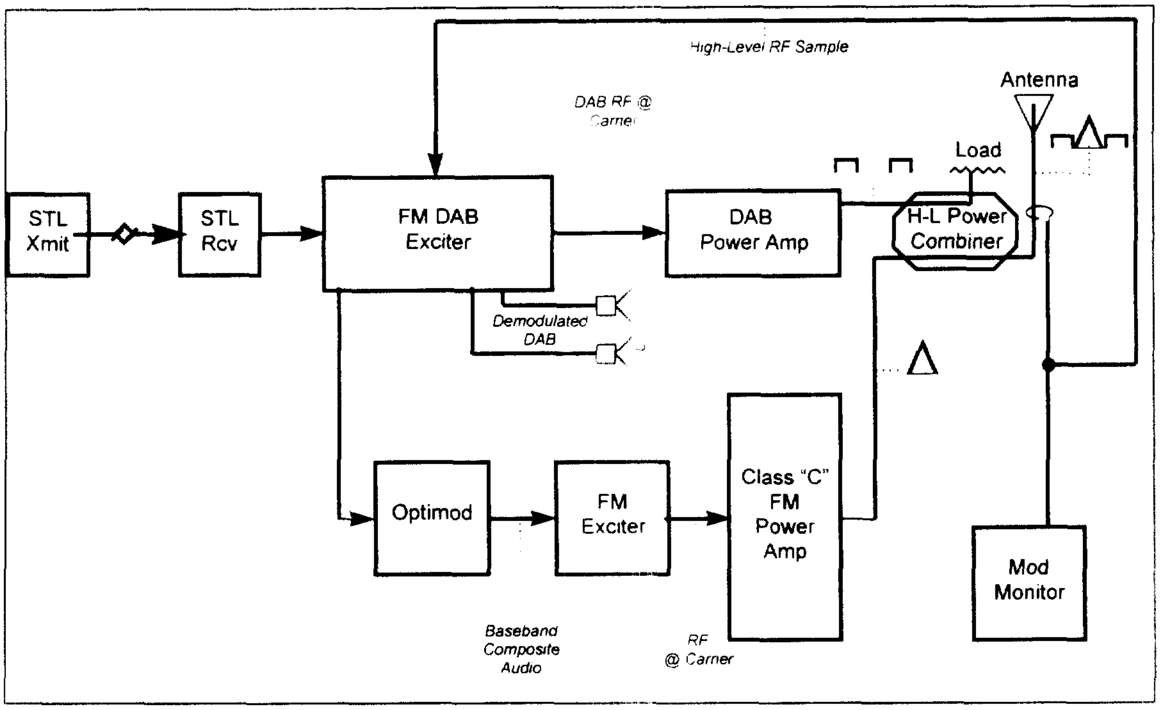

Figure C-8 – High-Level Combined IBOC DAB FM Hybrid Transmission System

Current models of digitally generated analog FM exciters are potentially capable of generating the analog FM signal, along with the hybrid IBOC waveform at carrier frequency. Figure C-9 depicts a modified version of these digitally generated FM exciters, with inputs that are independent of the analog baseband components

The digitally generated FM exciter accepts In-Phase ("I") and Quadrature - Phase ("Q") inputs from the IBOC digital exciter. It employs pre-distortion and RF feedback techniques to compensate for the amplitude-modulated components of the DAB waveform engendered during amplification by a conventional solid-state FM transmitter. This technique could be possible for the hybrid waveform, because the transmitter needs to be linear for only the low-level digital carriers.

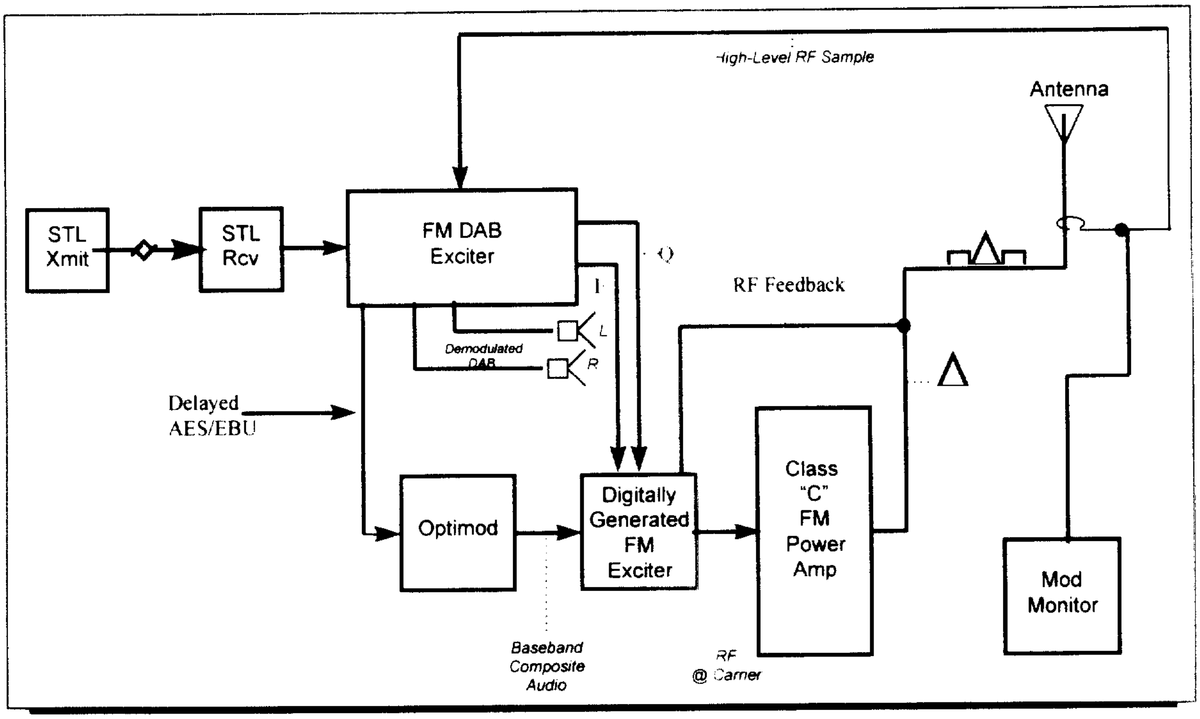

Figure C-9 – Linearized IBOC FM Transmission System

All-digital IBOC waveforms require linear amplification to pass the signal. Currently there are no suitable transmitters manufactured in the required power ranges for broadcasting that meet this specification. Linear amplifiers are undesirable due to their poor efficiency.

An alternate approach is to apply techniques used to generate IBOC waveforms in current amplitude-modulated transmitters. Figure C-10 depicts an FM transmitter that is capable of amplitude modulation, and therefore high efficiency amplification of an IBOC waveform.

Amplitude-modulated linear amplification may be accomplished by converting the baseband I and Q outputs of the FM DAB exciter into magnitude and phase components. The phase signal is applied to the digitally generated FM exciter, and the magnitude signal is applied to the amplitude-modulated FM power amplifier. Transmitters of this design would be beneficial to broadcasters, since they would be compatible with the hybrid and all-digital modes. The hybrid waveform places minimal requirements on the linearity of high power FM transmitters. The transmitters need only the linear over the power range of the IBOC signaling. Manufacturers or third parties may choose to modify existing transmitters to pass the low level amplitude modulated component of the hybrid IBOC waveform. These transmitters will have input ports that accept the baseband magnitude component.

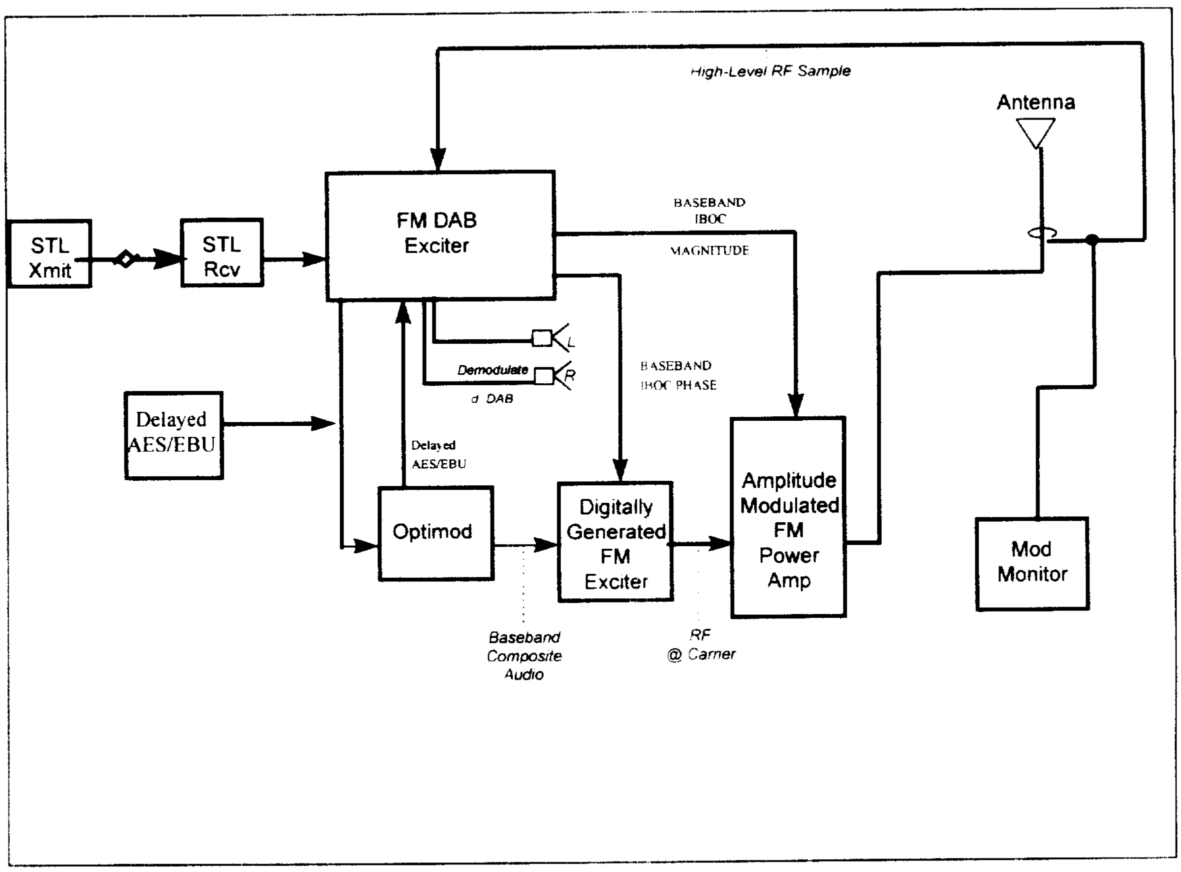

Figure C-10 – Amplitude Modulated FM Transmission System

A. FM Receiver Functional Description

A functional block diagram of an FM IBOC receiver is presented in Figure C-11. The signal is received by the antenna, passed through an RF front end, and mixed to Intermediate Frequency ("IF"), as in existing analog receivers. Unlike typical analog receivers, however, the signal is then digitized at IF, and digitally down-converted to produce in-phase and quadrature baseband components. The hybrid signal is then separated into an analog FM component and a DAB component. The analog FM stereo signal is digitally demodulated and de-multiplexed by the FM receiver to produce a sampled, stereo audio signal.

The baseband DAB signal is first sent to the modem, where it is processed by the FAC to suppress interference from potential first-adjacent analog FM signals. The signal is then OFDM demodulated, deframed, and passed to the FEC decoding and de-interleaving function. The resulting bit stream is processed by the codec function to decompress the source-encoded digital audio signal. This DAB stereo audio signal is then passed to the blend function.

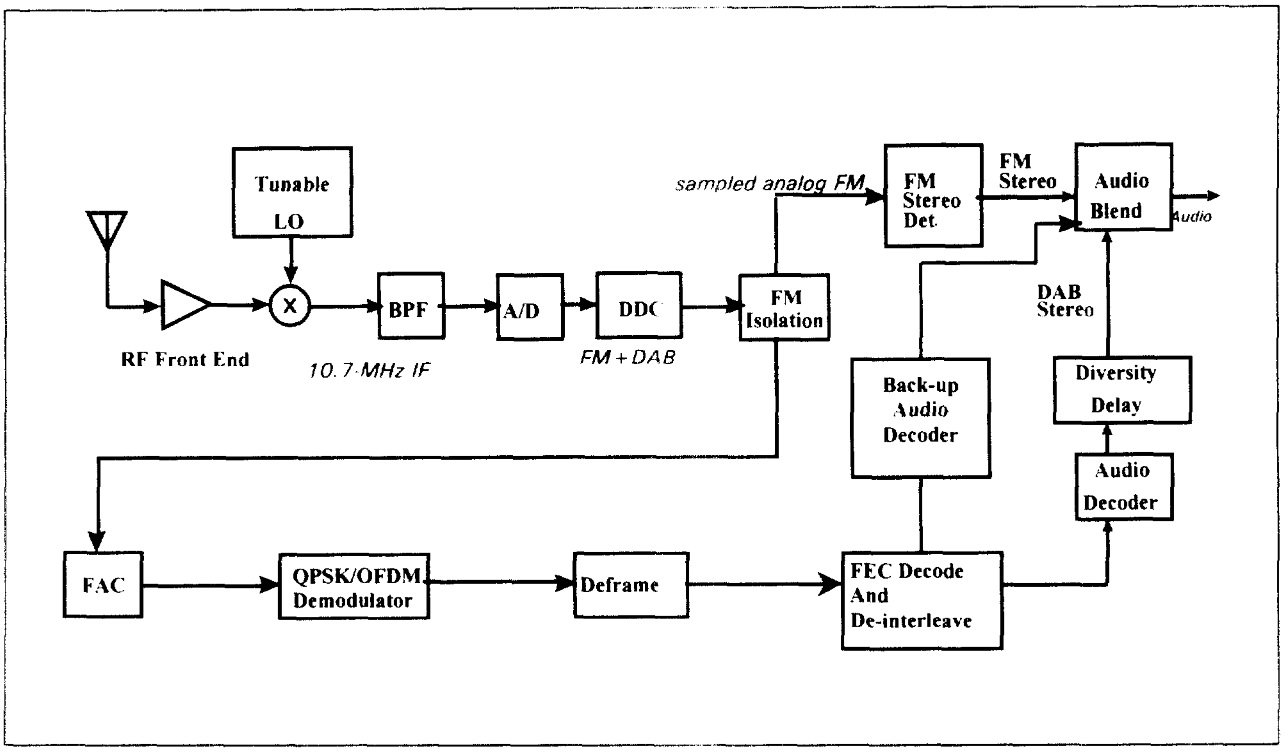

Figure C-11 - FM IBOC Receiver Functional Block Diagram

B. FM Receiver Physical Description

A physical block diagram of an FM IBOC receiver is presented in Figure C-12. The analog front end and digitization functions of Figure C-11 are easily mapped to Figure C-12. However, the direct digital down-conversion to baseband, the FM/DAB isolation, analog FM demodulation and de-multiplexing, and the DAB processing (including the modem, FEC coding and interleaving, codec, and blend functions) are all performed by a digital signal processing chip-set.

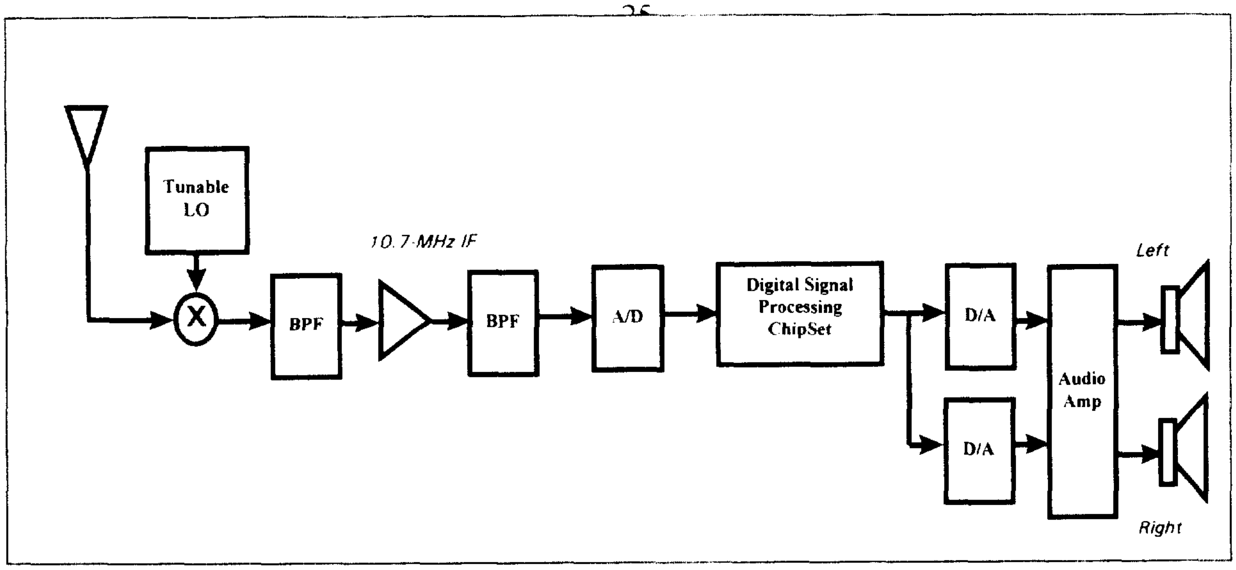

Figure C-12 - FM IBOC Receiver Physical Block Diagram

IBOC receivers will enhance audio quality for both analog and digital signals. Digital signal processing technology will introduce many features that are simply too expensive to implement using discrete components prevalent in today's analog receiver designs. Improved analog reception can be performed digitally at no additional cost in the IBOC receiver, since the processing requirements are driven by the digital signal, rather than the analog. Analog FM reception will be enhanced through improved digital filters, digital demodulation, and a sinusoidal local oscillator in the stereo subcarrier demodulator (to eliminate odd harmonics of the 38-kHz subcarrier which plague conventional receivers).

Although its front end may be similar to that of an existing analog radio, the remainder of the IBOC DAB receiver will differ in some important respects. First, the IBOC receiver performs IF digitization and direct digital down-conversion of the received signal. Although not widespread, this approach is currently being used in some consumer analog radios. The USADR IBOC receiver will leverage this development to minimize cost.