designed counterparts. Of course, no significant degradation exists when receiving a monaural signal.

This 3-dB stereo SNR degradation increases when IBOC DAB is added to the analog FM signal. In order to scope the magnitude of the problem, simulations were performed using the modeled typical automobile FM stereo receiver which has ample protection from 38-kHz harmonics.

Three simulations were run: the first simulated performance in a well-designed receiver by adding Gaussian noise only to a quiet analog FM signal at a level which produced a 64-dB SNR in the left audio receiver channel. The second simulation added DAB only (from 78 kHz to 197 kHz) to the quiet analog FM signal, at a level which likewise produced a 64-dB SNR in the left audio channel. As shown in Figure E-19, the post-detection noise power in the 0-53-kHz audio band is identical for the two simulations (hence the equal 64-dB SNRs).

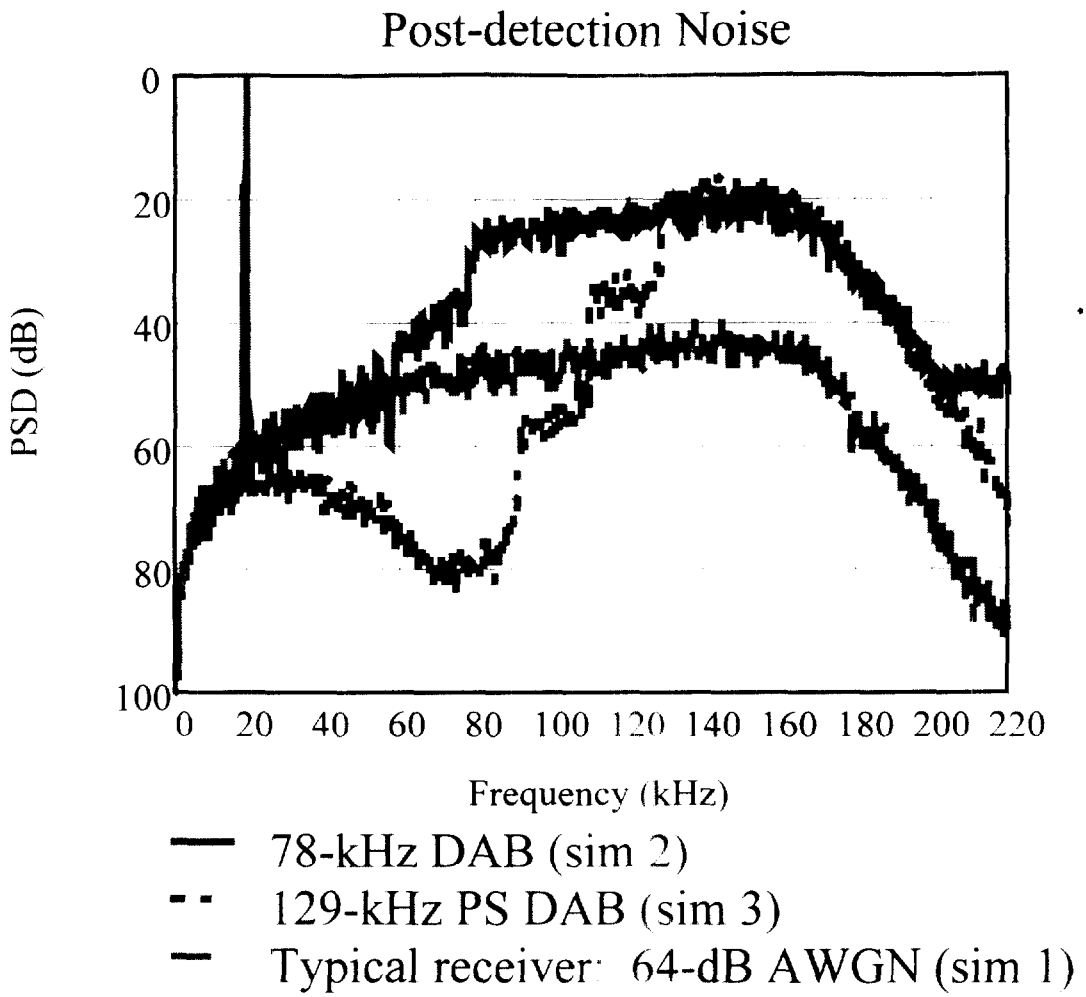

Figure E-19 - Effect of DAB on 114-kHz Noise Floor

Note, however, that the noise floors diverge above 60 kHz. In fact, the DAB-induced noise floor is approximately 25 dB higher in the 30-kHz band around 114 kHz. If the simulated receiver did not sufficiently filter the post-detection noise floor, the stereo noise increase would have degraded the audio SNR well below 64 dB in the second simulation.

It has been suggested that simply suppressing DAB energy in the 99-129 kHz band would eliminate the post-detection noise in this region. Due to the non-linear nature of the FM demodulator, this is not entirely the case. Instead, simulations have shown that such a notching

of DAB carriers creates a 12-dB improvement across the 30-kHz band around 114 kHz. Thus, simply limiting DAB bandwidth might still cause stereo SNR degradation in radios with inadequate post-detection filtering.

Significant improvements, however, were observed in the third simulation, in which the DAB signal was moved beyond 129 kHz *and* pulse shaping was applied. Pulse shaping causes a significant decrease in the noise floor across much of the post-detection band, as illustrated in Figure E-19 (129-kHz PS DAB). Figure E-20 provides a magnified view of the 30-kHz region around 114 kHz.

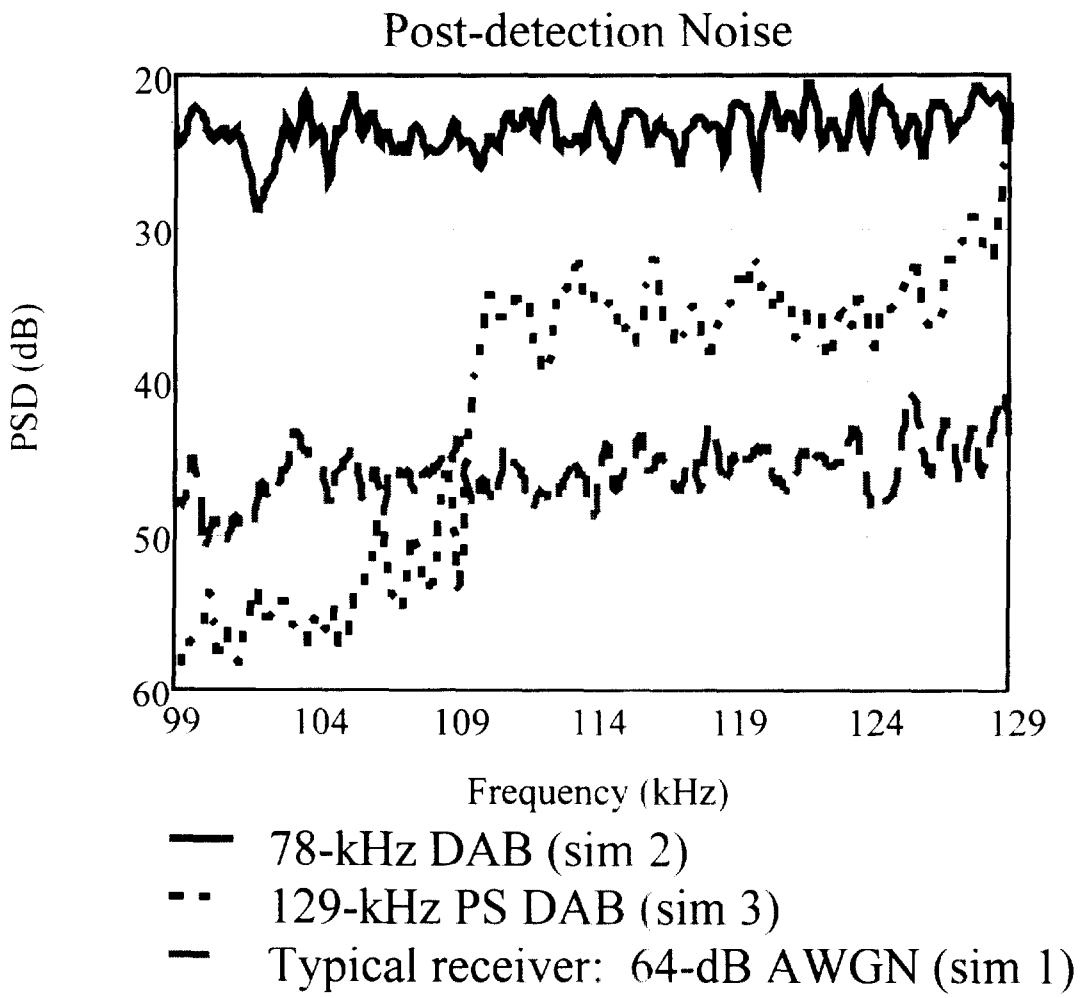

Figure E-20 - Effect of DAB Placement and Pulse Shaping on 114-kHz Noise Floor

Note that the noise floor steps up at 110 kHz, due to mixing of the Bessel-weighted 19-kHz pilot harmonics with the DAB signal during FM demodulation. As a result, above 110 kHz, an improvement of around 10 dB is gained over that afforded by 78-kHz (non-pulse-shaped) DAB. Below 110 kHz, however, a 30-dB improvement is observed. Thus, using DAB placement and pulse shaping, the overall stereo noise increase due to the addition of DAB in radios with inadequate filtering will be limited. Note that this problem has not been observed in typical automobile receivers.

Furthermore, in a typical listening and radio frequency environment, with inexpensive receiver implementations, it is possible that the degradation will be imperceptible to the listener.

4.2 Impact of co- and adjacent channel digital signal on analog host FM performance

USADR has explored the effects of first adjacent channel, second adjacent channel, and co-channel interference from analog, hybrid, and all-digital IBOC signals on desired analog signals.[26]

4.2.1 First Adjacent Channel Interference

4.2.1.1 Interference from analog FM signals

The interference from an analog-only signal onto a desired analog signal is identical to interference exhibited in the existing environment

[26] Herein, "desired analog" refers to either existing analog-only signals or the analog portion of hybrid signals.

4.2.1.2 Interference from hybrid IBOC signals

Digital interference from first adjacent hybrid IBOC channels located ±200 kHz from the host signal can be derived from the relationship of the adjacent signals shown in the plot of Figure E-21.

The FCC sets the Class B protected contour at 54 dBu for 50 percent of the locations, 50 percent of the time. Properly spaced Class B stations are protected to the 54 dBu contour from first adjacent channel interference exceeding 48 dBu in 50 percent of the locations for 10 percent of the time. Since the corresponding probability distributions are not defined, it is difficult to accurately predict expected interference levels. To achieve a conservative result, simulations set the static power of the analog portion of the hybrid interferer to be 6 dB below the desired host analog FM power.

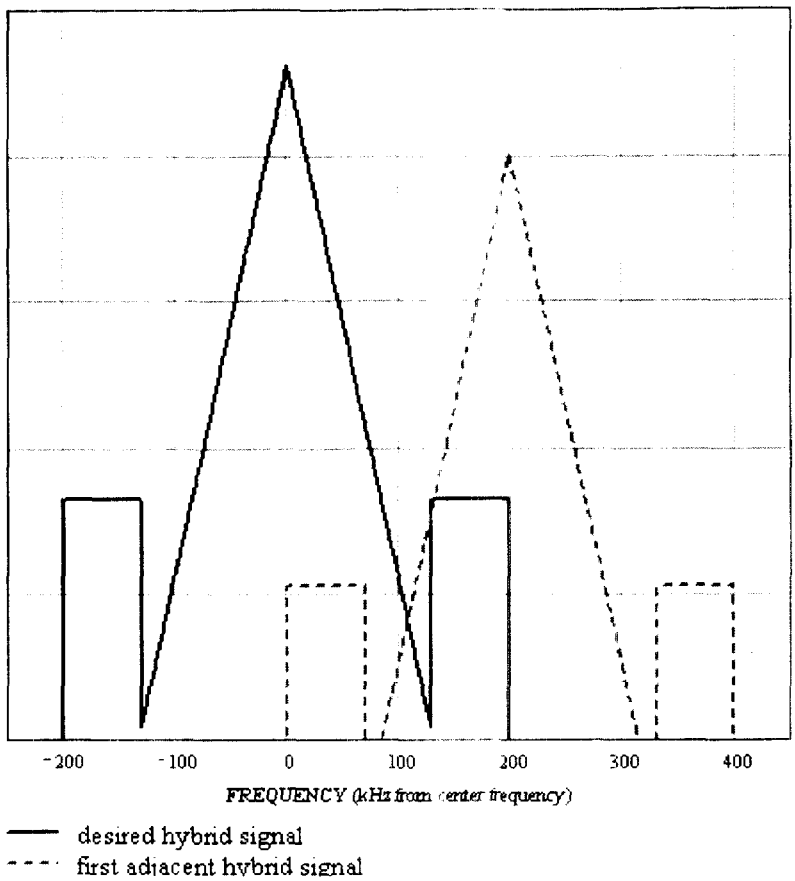

Figure E-21 - Interference Scenario Showing Hybrid First Adjacent at -6 dB

Simulations have quantified the amount of degradation that would be introduced into the analog portion of the hybrid signal when a typical automobile receiver is located at its 54-dBu contour and is subject to digital interference from a -6 dB hybrid IBOC DAB first adjacent.

A 54-dBu field strength corresponds to a -91.1 dBW carrier power.[27] USADR has measured ambient noise power in the FM band, and has found that a noise temperature of 10,000 K is representative (in the absence of interfering FM stations); in a 15-kHz bandwidth, this

[27] *See* Section 2.1.1 above.

temperature produces a noise power of -146.8 dBW. Hence, a carrier power of -91.1 dBW at the receiver antenna terminals would yield a 55.7 dB/15 kHz carrier-to-noise ratio (CNR). The receiver noise characteristic enables one to determine audio SNR given an input CNR. Using the measured noise characteristic of the simulated FM stereo receiver, this input CNR corresponds to an audio SNR of 64.4 dB/15 kHz.

Recall that a -22-dB pulse-shaped IBOC DAB signal starting at 129 kHz yielded an audio SNR of 77.6 dB in the modeled receiver at the transmitter (and at the 54-dBu contour if ambient noise were ignored). The preceding calculations demonstrate that, at the 54-dBu contour, the contribution to audio SNR is dominated by ambient noise; the effects of -22-dB, 129-kHz pulse-shaped IBOC DAB are negligible.

In the simulation, a -22-dB pulse-shaped DAB signal starting at 129 kHz was added to both a quiet analog FM host at the transmitter (10%-deviated 19-kHz pilot, with no audio or SCAs) and a -6 dB, fully modulated first adjacent. A 150-kHz pre-detection filter (300-kHz total 3-dB bandwidth) was used in the simulated typical automobile FM stereo receiver. The signal at the input to the FM demodulator is shown in Figure E-22.

Results indicate that introduction of the adjacent IBOC DAB channel degrades the audio SNR to 50.0 dB. Although the simulation was performed with the desired signal located at its transmitter, it is clear that the introduction of noise associated with translation to the 54-dBu contour would be negligible. Therefore, when a -6-dB first adjacent hybrid IBOC DAB signal impinges on a quiet FM/hybrid signal at the 54 dBu contour, the SNR of the analog signal in the simulated receiver degrades from around 64 dB to 50 dB. Figure E-23 illustrates this effect.

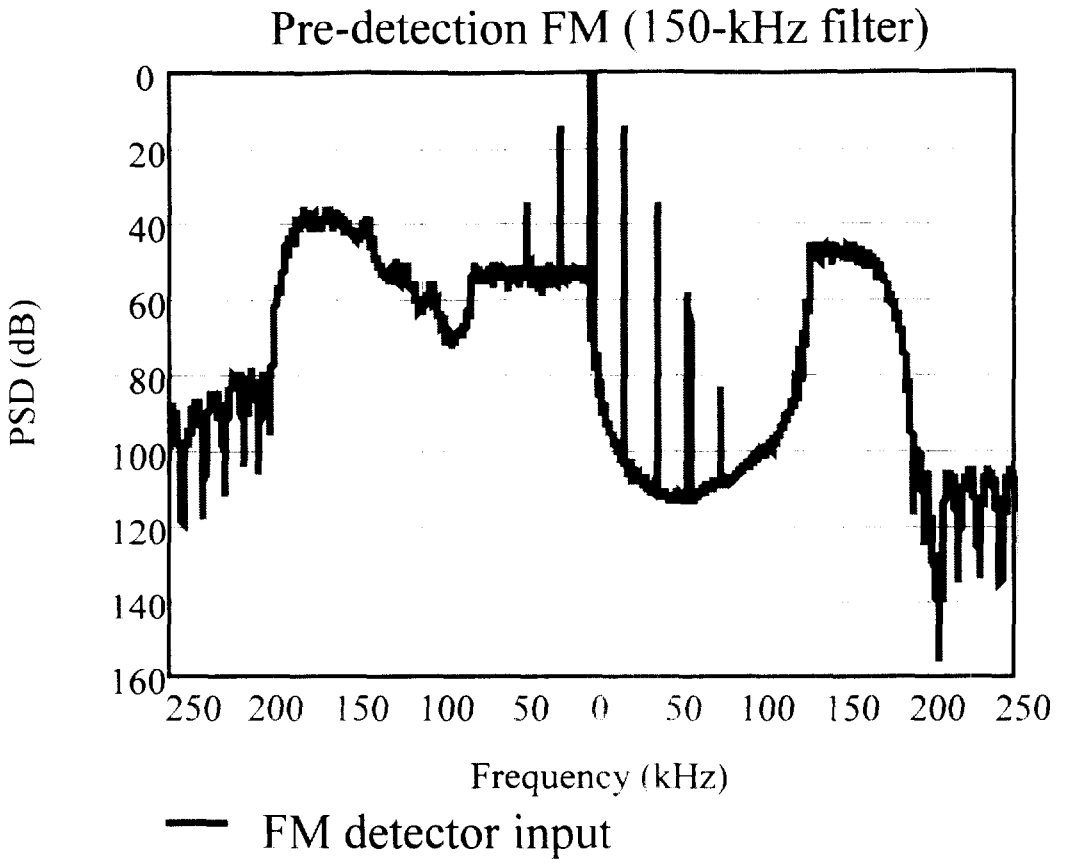

Figure E-22. Pre-detection Effect of First Adjacent with 129-kHz PS DAB at 54-dBu contour.

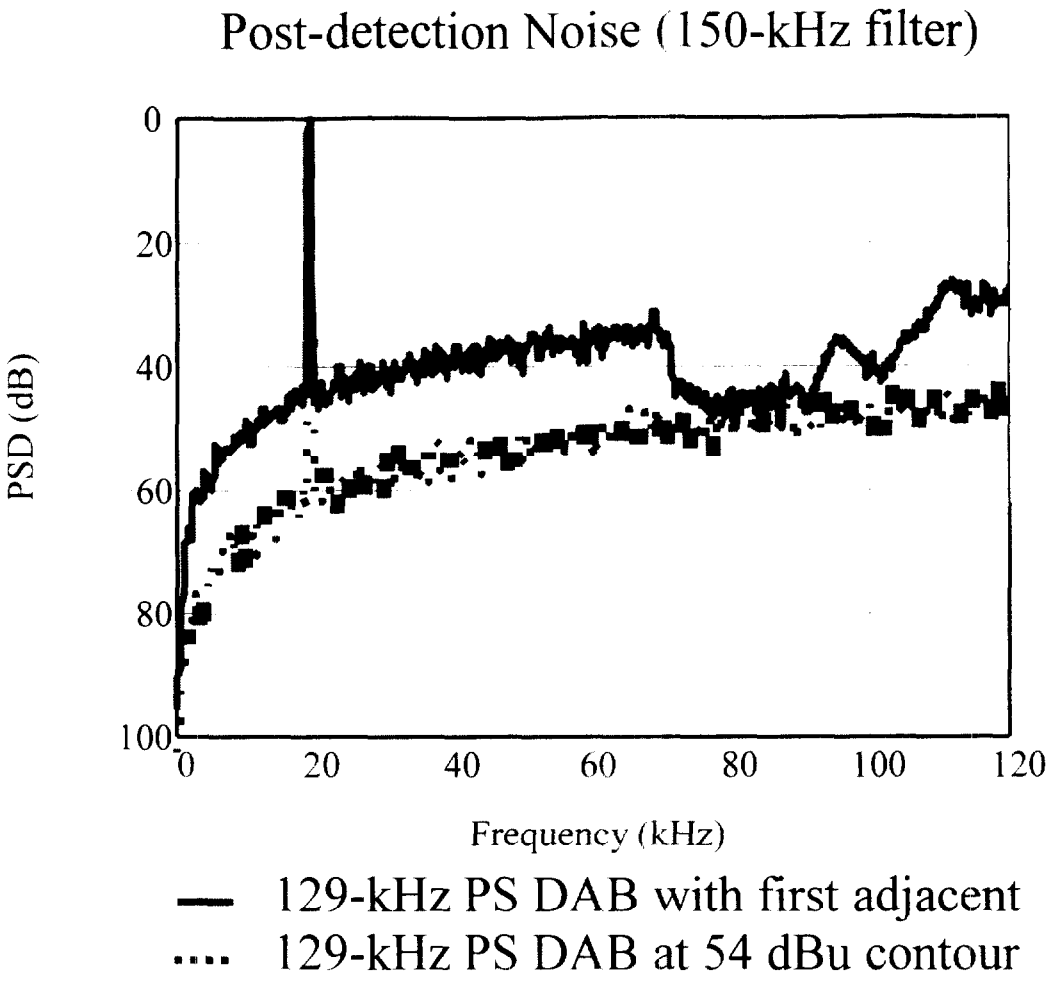

Figure E-23 - Post-detection Effect of First Adjacent with 129-kHz PS DAB at 54-dBu contour

Degradation in typical receivers caused by first adjacent analog interference was characterized for five different receivers in an EIA study.[28] The audio stereo SNR of the five receivers was also measured in the absence of interference. The EIA results and the derived DAB degradation (to the nearest 0.1 dB) are summarized in the following table:

[28] From EIA Report "Digital Audio Radio Laboratory Tests Transmission Quality Failure Characterization and Analog Compatibility," Appendix H, dated August 11, 1995.

Table E-8 - Analog First Adjacent Channel Degradation of Typical FM Receivers

Receiver	S/N with no Interferer (dB)	D/U Required for 45 dB S/N (dB)	S/N at 6 dB D/U (dB)	Additional degradation from DAB (dB)
Delco	50	6	45	1.2
Denon	62	2.5	39.5	0.4
Ford	56	-6	53	4.8
Panasonic	57	27	24	0.0
Pioneer	61	21	30	0.0

These results indicate that the degradation from an analog-only first adjacent signal in typical automotive (Delco and Ford), home (Denon and Pioneer) and boombox (Panasonic) receivers masks additional interference introduced by a first adjacent hybrid signal. Although the results of the simulation were obtained using the modeled typical automobile receiver, they can be directly applied to the performance of the actual receivers in Table E-8. The simulated receiver has high immunity from a first adjacent analog signal. Therefore, nearly all the degradation measured in the simulation can be attributed to the digital portion of the interfering hybrid IBOC signal. Since the digital interference falls completely within the passband of the desired analog FM signal as shown in Figure E-21, it can be treated as noise and added to the noise engendered by first adjacent analog interference in the receivers listed in Table E-8.

Using the Delco radio as an example, we observe that an analog first adjacent FM D/U of 6 dB results in a 45-dB SNR. The digital portion of the hybrid IBOC signal results in an SNR of 43.8 dB. This degradation from 45 to 43.8 dB is the result of adding a -50 dB noise floor to the noise reported in the fourth column of Table E-8. Therefore, the hybrid DAB signal introduces an additional 1.2 dB of degradation. This result is reported in the fifth column of Table E-8 along with a similar calculation for the other four receivers.

While the SNR is diminished for some receivers, it should be noted that the degradation is highly geographically localized; performance would improve if the receiver moved farther from the interfering station or closer to the desired station, or if a directional antenna were employed. Most automotive analog receivers are blended to mono at the 54-dBu contour anyway, mitigating the effects of first adjacent DAB interference. This would improve audio SNR by removing the effects of noise around the stereo subcarrier.

Note that properly spaced Class B stations are protected to the 54 dBu contour from co-channel interference exceeding 34 dBu in 50 percent of the locations for 10 percent of the time. This implies that, at the 54-dBu contour, it is possible to see a 20-dB SNR at the receiver input, or an audio SNR of only about 30 dB/15 kHz. This currently existing interference is 20 dB worse than interference that could be engendered by the digital portion of high-level first adjacent hybrid IBOC signals.

4.2.1.3 Interference from all-digital IBOC signals

The total power of the all-digital sidebands will be 11.5 dB higher than the power in the hybrid digital sidebands. As a result, the SNR of a desired analog signal in the modeled typical automobile receiver in the presence of an all-digital first adjacent should decrease by nearly 11.5 dB to roughly 38.5 dB.[29]

4.2.2 Second Adjacent Channel Interference

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[29] Broadcast of the all-digital mode will be delayed by a number of years. By that time, many listeners will have IBOC radios.

4.2.2.1 Interference from analog FM signals

The interference from an analog-only second adjacent signal onto a desired analog signal is identical to interference exhibited in the existing environment.

4.2.2.2 Interference from hybrid IBOC signals

Interference from second adjacent hybrid IBOC channels located ±400 kHz from the host signal can be derived from the relationship of the adjacent signals shown in the plot of Figure E-24.

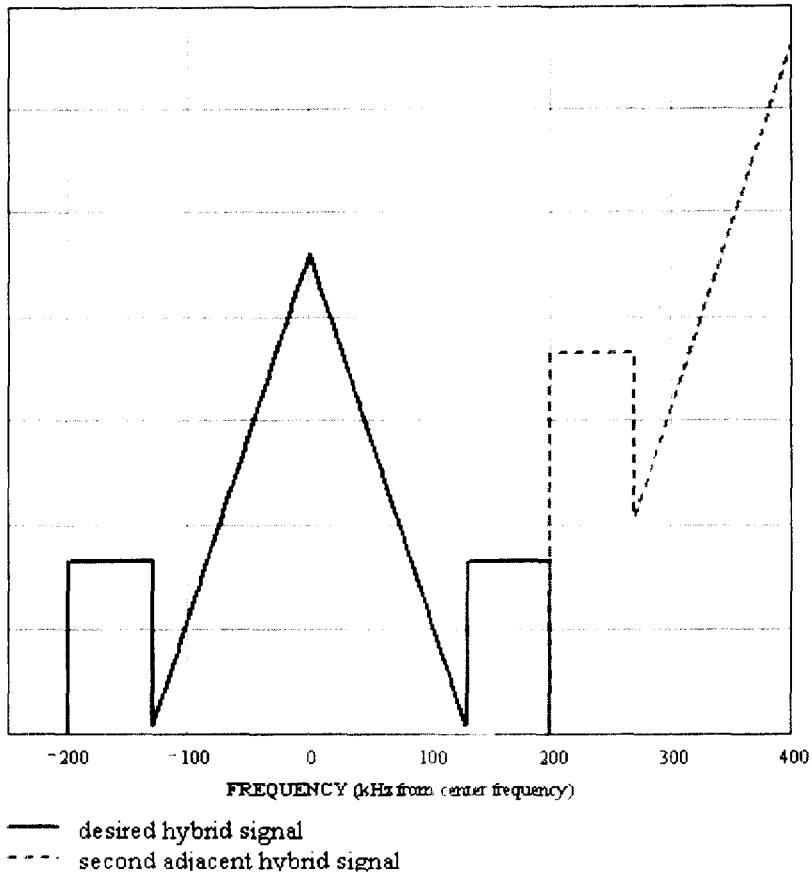

Figure E-24 - Interference Scenario with Hybrid Second Adjacent

The digital sidebands of the hybrid second adjacent signal fall well outside the bandwidth of the host analog FM signal. FM pre-detection filtering in the receiver front end should reject most of the DAB system energy. As a result, the effects of second adjacent hybrid IBOC signals should be negligible.

4.2.2.3 Interference from all-digital IBOC signals

Like those of the hybrid second adjacent interferer, the all-digital sidebands lie well outside the bandwidth of the desired FM signal, and should be rejected by the receiver pre-detection filter. Thus, the effects of second adjacent all-digital IBOC signals should also be negligible.

4.2.3 Co-Channel Interference

4.2.3.1 Interference from analog FM signals

The interference from an analog-only co-channel signal onto a desired analog signal is identical to interference exhibited in the existing environment.

4.2.3.2 Interference from hybrid IBOC signals

Interference from a hybrid co-channel will be dominated by the analog portion of the hybrid signal. As a result, the performance of a desired analog signal in the presence of a hybrid IBOC co-channel should be similar to its performance in the presence of an analog FM co-channel interferer.

4.2.3.3 Interference from all-digital IBOC signals

The analog portion of a co-channel interferer is not present in the all-digital system. In addition, the digital energy is concentrated away from the center of the desired channel, and its total power is 10.5 dB less than that of an analog FM interferer. As a result, the interference

from a co-channel all-digital signal should be far less than that currently incurred from analog FM co-channel signals.

4.3 Analog FM performance summary

USADR has analyzed the impact on performance of the host FM signal in the presence of various IBOC DAB configurations. Simulations and analysis indicate that FM performance is least affected when a pulse-shaped DAB signal is placed between 129 kHz and 199 kHz from the analog FM carrier. Modulation and coding tradeoffs have been exercised to provide the spectral efficiency required to fit the DAB signal within this bandwidth.

This DAB configuration yields an audio SNR of nearly 78 dB in the simulated typical automobile receiver during periods of minimum deviation, with noise during louder passages rendered inaudible to the listener via a masking effect. Even when quiet, noise due to DAB could be masked by the noise produced in many typical receivers. SCA interference with the host FM was likewise inaudible in the simulated receiver, while the SCAs themselves should perform with SNRs of around 20-30 dB/10 kHz. A degradation may be observed during stereo subcarrier demodulation in existing inexpensive FM stereo receivers. This degradation, which has not been demonstrated in car radios, has been mitigated via careful design of the IBOC waveform and may prove imperceptible in typical listening environments.

When a -6-dB first adjacent hybrid IBOC interferer is present, the audio SNR of the host FM in the simulated receiver degrades to 50 dB at the 54-dBu protected contour. However, this interference should be masked in typical receivers by degradation from the analog portion of the first adjacent. In addition, the degradation is localized, most automotive receivers are blended to mono at this point, and these effects are no worse than those allowed via currently existing analog co-channel interference. The impact of second adjacent and co-channel hybrid and all-

digital interference should prove negligible, or no worse than that currently engendered by analog FM interference.

Appendix F

AM System Description

I. AM IBOC System Requirements

For a successful implementation of IBOC DAB, improved reception and audio quality will be necessary. In order to meet these goals, IBOC systems must deliver vastly improved sound quality, while overcoming a number of reception impairments including noise, interference, and signal loss resulting from bridges, signs, and power lines.

- **AM IBOC DAB must minimize interference to other stations and withstand the AM band interference environment.**

Interference is a primary limiting factor in the coverage of analog AM broadcasting and will have the same impact on AM DAB. AM broadcast stations are licensed at 10 kHz increments in the AM band and operate with 20 kHz bandwidths, resulting in overlapping sidebands and interference. Thus, delivering DAB in the highly congested AM band is a challenge. Wide disparities in interference conditions exist from station to station, and interference conditions change from day to night. During the day, the interference signals propagate primarily via groundwave; at night, interference increases because distant signals reflect off the ionosphere.[1] Co-channel interference is well understood and the FCC rules adequately protect stations. The rules do provide minimal protection during daytime channel conditions, however, there were no adjacent channel protection during nighttime conditions until 1993.[2] IBOC systems will have to be sufficiently robust to withstand existing interference from

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[1] *See* Appendix H for a more detailed discussion of skywave.

[2] Amended by Order in Docket 87-267, effective June 11, 1993, 50 FR 27944.

first and second adjacent channels, while at the same time protecting the host and adjacent analog signals.

- **AM IBOC DAB must be sufficiently robust to overcome impairments.**

In addition to interference, the AM channel is subject to impairments from bridges, overhead signs and power lines (referred to as grounded conductive structures or "GCS") and noise.[3]

- **AM IBOC DAB must improve AM audio quality.**

Because the existing channel conditions and available channel bandwidth limit digital throughput, the best quality the AM IBOC system can currently support is stereo "FM-like" quality. Because "FM-like" quality may not be attainable by all stations for the entire coverage area, the AM IBOC DAB system will have to trade audio quality (bit rate) for robustness in order to achieve the best possible audio quality.

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

The existing AM spectral mask limits the power level and bandwidth of analog transmissions in order to minimize interference. The IBOC DAB system is designed to include the digital carriers within this mask in order to minimize interference to analog signals.[4]

- **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

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[3] *See* Appendix H for a more detailed discussion of AM band impairments.

[4] USADR has proposed in Appendix A draft Rule 73.130 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.

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. Auxiliary services could, for example, take the form of program-associated data, station information, advertisements, or subscription applications (*e.g.*, stock quotes).

- **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 AM IBOC DAB system, as explained in the following section.

II. AM IBOC System Overview

The USADR AM 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; FEC coding and interleaving; and blending. All of those 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 AM system before selecting 32 Quadrature Amplitude Modulation ("QAM"). Since 32-QAM has a bandwidth efficiency of five bits per second per Hertz, it supports an information bit rate that is sufficient for transmission of "FM-like" audio quality 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 QAM carriers can be frequency-division multiplexed in an orthogonal fashion such that each carrier does not interfere with each adjoining carrier.

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 AM channel bandwidth does not have the capacity to support such a high data rate. 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 a maximum audio rate of 48 kbps, delivering audio that the listener will perceive to be "FM-like." The system also operates at two other audio rates of 32 kbps and 16 kbps. 32 kbps provides more robust operation under interference conditions and delivers quality stereo. 16 kbps offers the most robust operation by delivering noise free monaural digital audio. 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.[5]

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

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

assist the FEC decoder in its decision-making process. Grounded conductive structures cause rapid changes in amplitude and phase that are not uniformly distributed across the digital carriers. Carrier-by-carrier equalization is used to insure that the phase and amplitude of the digital carriers is sufficiently maintained to ensure proper recovery of the digital information. The equalization has been shown to deal adequately with these channel perturbances and improve reception. The combination of these advanced FEC coding and interleaving techniques, together with the use of an equalizer, allow the IBOC system to deliver "FM-like" audio in a mobile environment.[6]

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. This "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.[7] 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

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[6] The results of simulations and analyses are given in Appendix H.

[7] *See* Appendix K for a more detailed discussion of time diversity and blend.

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 audio while the receiver is acquiring the primary digital signal. After acquisition, the receiver then blends to the primary digital signal.

E. Hybrid Mode

The AM hybrid spectrum is shown in Figure F-1. The hybrid AM IBOC DAB signal is comprised of the ±5-kHz band-limited analog AM signal and digital carriers. Quadrature digital carriers are added under the analog signal at a level that is sufficient to insure reliable digital service and low enough to avoid harmful interference to the host broadcast.

Currently, the U.S. AM band allocation plan assigns stations 20 kHz of total bandwidth, with stations spaced at 10 kHz intervals. The USADR hybrid mode IBOC DAB system reduces the total analog bandwidth to 10 kHz to prevent interference to the digital sidebands, which are placed in the remaining 5 kHz on either side of the analog signal. This change in total analog bandwidth will need to be adopted when an AM station moves from analog-only to hybrid mode operation. The change in bandwidth, however, will have no discernable impact on listeners dependent on the analog signal, because AM receivers in use today typically limit audio bandwidth to less than 5 kHz.

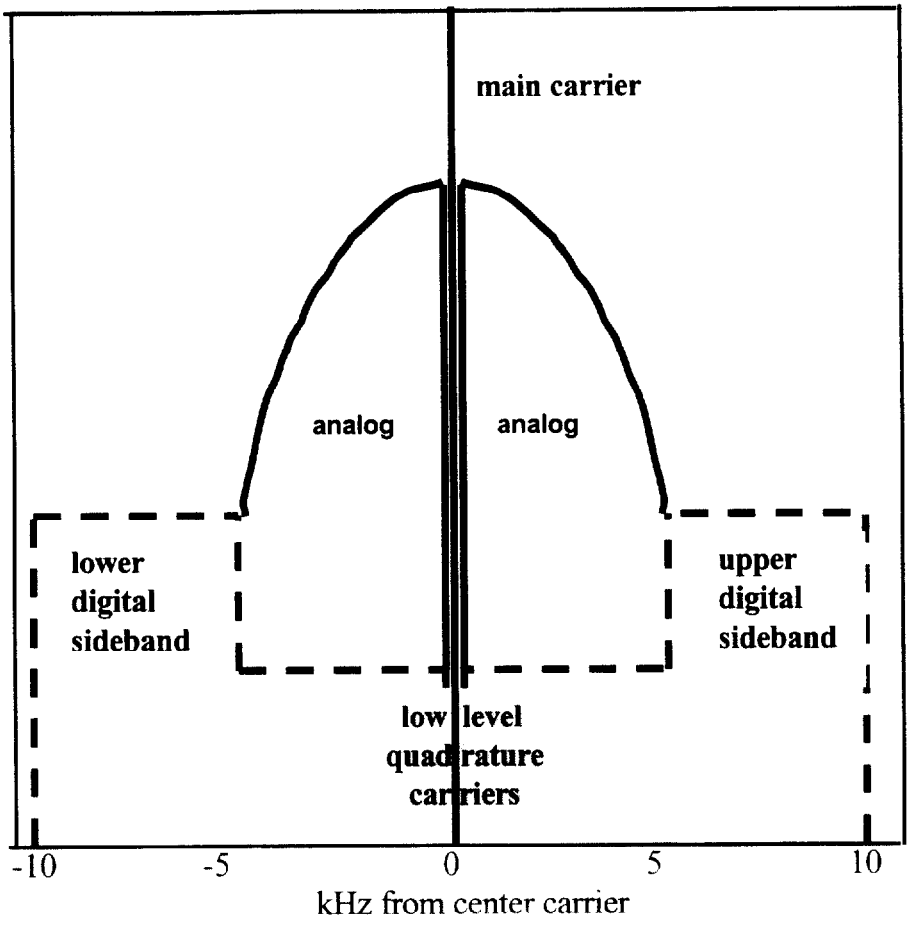

Figure F-1 – Hybrid AM IBOC Power Spectral Density

F. All-Digital Mode

As shown in Figure F-2, the principal difference between the hybrid mode and the all-digital mode is deletion of the analog signal, the increase in power of the quadrature carriers that were previously under the analog signal, and the addition of a low-bit-rate, digital backup and tuning channel. The additional power in the all-digital waveform increases robustness, and the "stepped" waveform is optimized for performance under strong adjacent channel interference.

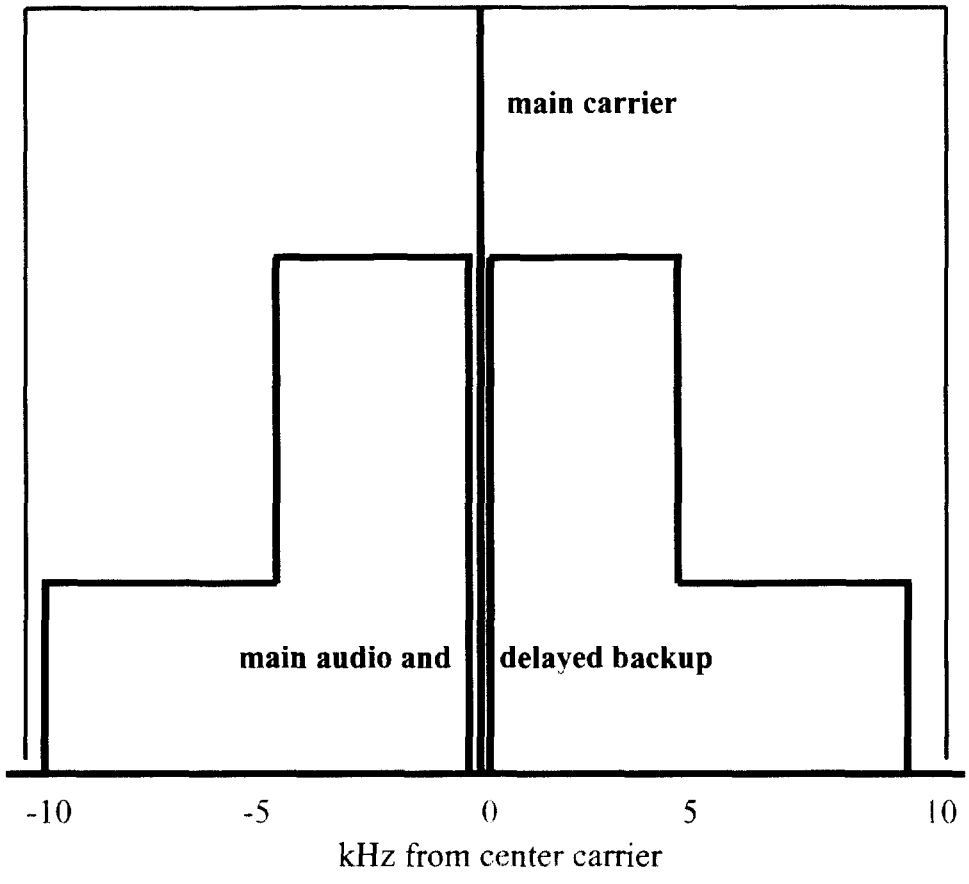

Figure F-2 – All-Digital AM IBOC Spectrum

III. Generation of the Signal

A functional block diagram of the hybrid AM IBOC transmitter is presented in Figure F-3. The input audio source on the Studio Transmitter Link ("STL") feeds an L + R monaural[8] signal to the analog AM path and a stereo audio signal to the DAB codec. The DAB path digitally compresses the audio signal in the audio encoder (codec). The bit stream out of the audio encoder is then FEC encoded and interleaved. The resulting bit stream is combined into a

[8] IBOC DAB cannot be transmitted simultaneously with AM stereo as both systems use the quadrature relationship with the analog signal. However, the loss of the stereo signal by the very few stations currently employing stereo in the AM band is more than offset by access to the higher audio quality digital signal.