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IBOC DSB SYSTEM FOR OPERATION BELOW 30 MHZ

The attached material provides a system description and laboratory and field test results for an In-Band On-Channel (“IBOC”) Digital Sound Broadcasting (“DSB”) system being developed in the United States for operation at frequencies below 30 MHz. The IBOC DSB system is designed to operate in both a “hybrid” and “all-digital” mode. The mode of operation depends on the broadcast frequency, the existing use of the spectrum and the service requirements of the broadcaster. The hybrid mode of operation permits simultaneous broadcast of identical program material in both an analog and digital format within the channel currently occupied by the analog signal. The all-digital mode provides enhanced capabilities for operation in the same channel after removal of the existing analog signal.

The attached material describes a system optimized and tested for operation at MF in a 10 kHz channel spacing environment. These parameters were selected to address the specifications of broadcasting in the United States operating below 30 MHz. Notwithstanding the specifications presented herein, the system is designed to be adapted for operation at LF or HF and in a 9 kHz channel spacing environment. Additional system details and test results for those specifications will be available in the future.

1 System Description

Digital communication systems operating in a band-limited noisy channel must be designed to balance the conflicting requirements of high data throughput and high data reliability. For IBOC DSB, this amounts to a compromise between coverage area and audio quality. The IBOC DSB channel is statistically characterized with unique interference scenarios that are exploited in the design to maximize performance in most environments. The IBOC DSB system operating below 30 MHz was designed to provide significantly improved audio quality compared to analog broadcasting in these bands while maintaining sufficient coverage areas.

The IBOC DSB system is comprised of four basic components: the codec, which encodes and decodes the audio signal; FEC coding and interleaving which provides robustness through redundancy and diversity; the modem, which modulates and demodulates the signal; and blending, which provides a smooth transition from the digital to either the existing analog signal, in the case of hybrid operations, or a back-up digital signal, in the case of all-digital operations.

In addition to the improved audio quality, the IBOC DSB system also provides data services. There are three basic IBOC DSB data services: dedicated fixed rate, adjustable rate, and opportunistic variable rate.

In dedicated fixed-rate services, the data rate is set and cannot be changed by the broadcaster. Specifically, the iDAB Data Service (IDS) continuously offers an array of low-bandwidth “background” data services similar to those currently provided by the Radio Broadcast Data System (RBDS). The IDS effectively levies a “flat tax” on system capacity, leaving the balance for adjustable levels of audio, parity, and other data services.

Adjustable-rate services operate at a fixed rate, for a pre-determined period; however, unlike fixed-rate services, the broadcaster has the option of adjusting the data rate, trading data throughput for audio quality or robustness. For instance, the encoded audio bit rate could be reduced (in finite steps) to allow increased data throughput, at the expense of digital audio quality. Furthermore, specific groups of digital subcarriers could be dynamically allocated among parity, audio, and data services.

Opportunistic variable-rate services offer data rates that are tied to the complexity of the encoded digital audio. Highly complex audio requires more throughput than simpler passages. The audio encoder dynamically measures audio complexity and adjusts data throughput accordingly, without compromising the quality of the encoded digital audio.

1.1 System Components

1.1.1 Codec

CD digital audio has a data rate of 1.4112 Mbps (44,100 16-bit samples per second, for left and right channels). The channel bandwidth for operations below 30 MHz does not have the capacity to support this data rate. As a result, an audio codec (coder-decoder) is employed. An audio codec is a source-encoding device that removes the parts of the signal that are irrelevant to the auditory system, i.e. to the ear. The signal coded in this way will not be identical to the original when decoded but will be perceptually equivalent given a high enough bit-rate.

The IBOC DSB system uses state-of-the-art audio coding techniques. These codecs deliver high quality FM like stereo audio within the bandwidth constrains imposed on operations below 30 MHz. To further enhance the robustness of the digital audio beyond that provided by FEC and interleaving, special error concealment techniques are employed by the audio codecs to mask the effects of errors in the input bit-stream.

Furthermore, the audio codec bit-stream format provides the broadcaster the flexibility of providing data services if the program material warrants using lower audio encoding rates.

1.1.2 FEC Coding and Interleaving

Forward error correction and interleaving in the transmission system greatly improve the reliability of the transmitted information by carefully adding redundant information that is used by the receiver to correct errors occurring in the transmission path. Advanced FEC coding techniques have been specifically designed based on detailed interference studies to exploit the non-uniform nature of the interference in these bands. Also, special interleaving techniques have been designed to spread burst errors over time and frequency to assist the FEC decoder in its decision-making process.

A major problem confronting systems operating below 30 MHz is the existence of Grounded Conductive Structures that can cause rapid changes in amplitude and phase that are not uniformly distributed across the digital carriers. To correct for this the IBOC DSB system uses equalization techniques to insure that the phase and amplitude of the digital carriers are sufficiently maintained to ensure proper recovery of the digital information. The combination of advanced FEC coding, channel equalization, and optimal interleaving techniques allows the IBOC DSB system to deliver reliable reception of digital audio in a mobile environment.

1.1.3 Modulation Techniques

Several modulation techniques were evaluated for the IBOC DSB system before selecting Quadrature Amplitude Modulation (“QAM”). QAM has a bandwidth efficiency that is sufficient for transmission of “FM-like” stereo audio quality as well as providing adequate coverage areas in the available bandwidth.

A multi-carrier and a single carrier approach to transmit the digital signal were reviewed. A multi-carrier approach called Orthogonal Frequency Division Multiplexing (“OFDM”) was selected. OFDM is a scheme in which many QAM carriers can be frequency-division multiplexed in an orthogonal fashion such that there is no interference among the carriers. 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.

1.1.4 Blend

The IBOC DSB system employs time diversity between two independent transmissions of the same audio source to provide robust reception during outages typical of a mobile environment. The IBOC DSB system provides this capability by delaying a backup transmission by a fixed time offset (several seconds) relative to the digital audio transmission. This delay proves useful for the implementation of a blend function. During tuning, blend allows transition from the instantly acquired back-up signal to the full digital signal when it has been acquired. Once acquired, blend allows transition to the back-up signal when the digital signal is corrupted. When a digital signal outage occurs, the receiver blends seamlessly to the backup audio that, by virtue of its time diversity with the digital signal, does not experience the same outage.

Digital systems depend on an interleaver to spread errors across time and reduce outages. Generally longer interleavers provide greater robustness at the expense of acquisition time. The blend feature provides a means of quickly acquiring the back-up signal upon tuning or re-acquisition without compromising full digital performance for rapid digital acquisition.

1.2 Operating Modes

1.2.1 Hybrid MF Mode

The IBOC DAB system includes a hybrid mode, which allows for the introduction of the digital carriers under the existing analog signal. This enables the simultaneous broadcast of identical programming in both an analog and a digital format. The hybrid mode is designed for stations operating at MF in geographic regions where it is necessary to provide for a rational transition from analog to digital. The hybrid mode makes it possible to introduce the digital signal without causing harmful interference to the existing host analog signal. In areas with successful MF broadcasting, the hybrid mode will allow the broadcaster to introduce digital without harming existing analog while listeners acquire DAB receivers.

The current U.S. MF band allocation plan assigns stations 20 kHz of total bandwidth, with stations interleaved at 10 kHz spacings. The MF hybrid spectrum is shown in Figure 1. The hybrid IBOC DSB signal is comprised of the ±4.5 kHz analog MF signal and digital carriers distributed across a 30 kHz bandwidth. The digital carriers under the analog signal are in quadrature and set at a level that is sufficient to insure reliable digital service and low enough to avoid objectionable interference to the host broadcast.

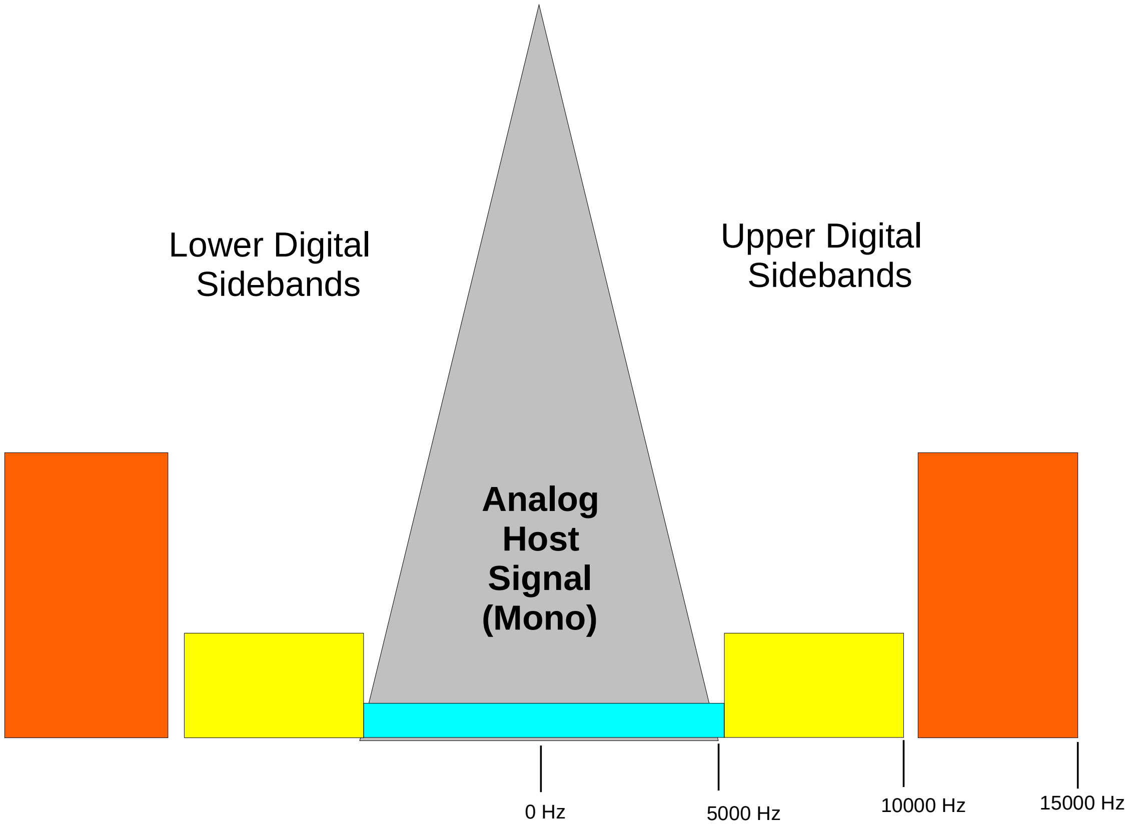

FIGURE 1

Hybrid MF IBOC DSB Power Spectral Density

1.2.2 All-Digital MF Mode

The all-digital mode allows for enhanced digital performance after deletion of the existing analog signal. Broadcasters may choose to implement the all-digital mode in areas where there are no existing analog stations that need to be protected or after a sufficient period of operations in the hybrid mode for significant penetration of digital receivers in the market place.

As shown in Figure 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.

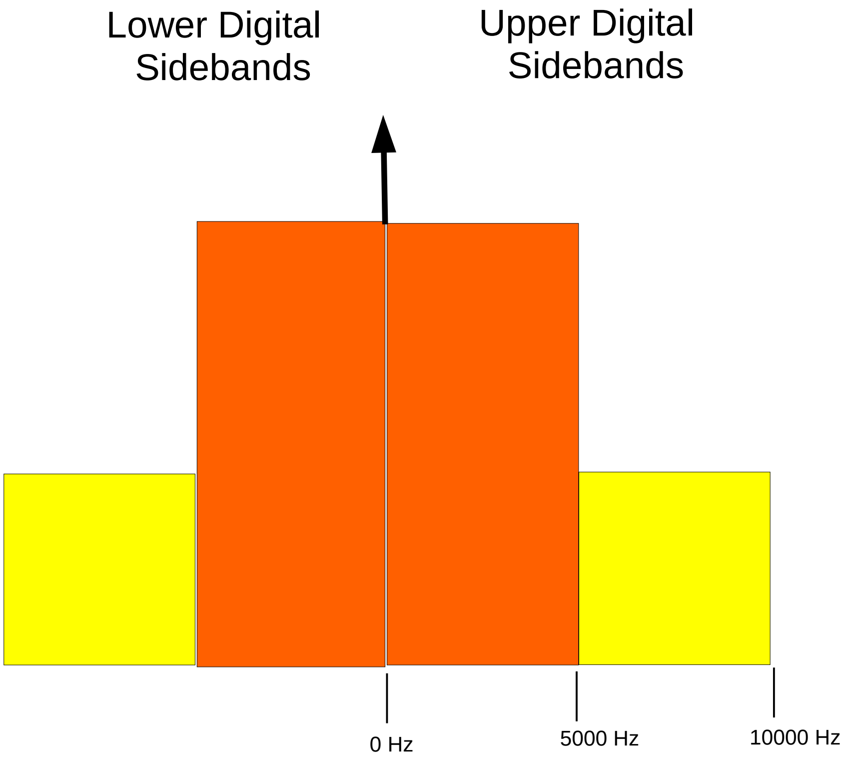

FIGURE 2

All-Digital MF IBOC DSB Power Spectral Density

1.2.3 HF All-Digital Mode

The IBOC DSB system also can be adopted for use at HF. Due to bandwidth limitations, only all-digital operations are envisioned at HF. Therefore, the IBOC DSB system would have to be implemented using a vacant channel or as a replacement for an existing analog broadcast.

The HF all-digital waveform is presented in Figure 3 below.

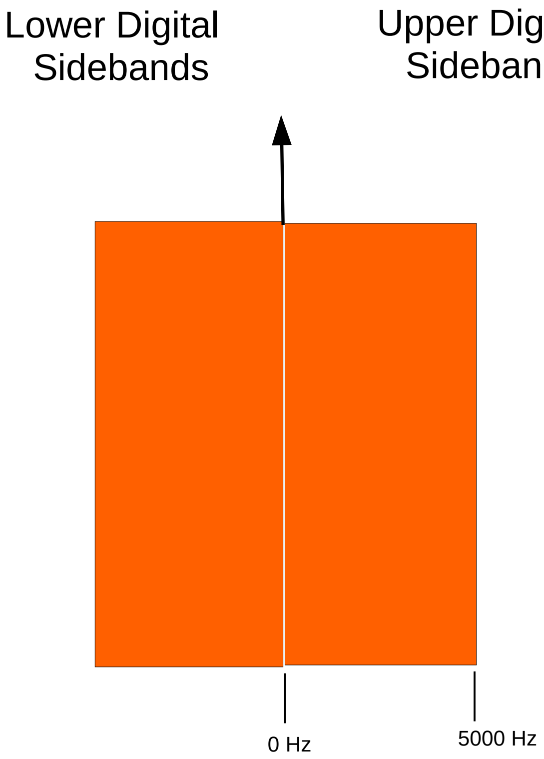

FIGURE 3

HF IBOC DSB Waveform

1.2.4 Generation of the Signal

A functional block diagram of the hybrid MF IBOC DSB transmitter is shown in Figure 4. The input audio source on the Studio Transmitter Link (“STL”) feeds an L + R monaural signal to the analog MF path and a stereo audio signal to the DSB audio. The DSB path digitally compresses the audio signal in the audio encoder (encoder) with the resulting bit stream delivered to the FEC encoder and interleaver. The bit stream is then combined into a modem frame and OFDM modulated to produce a DSB baseband signal. Diversity delay is introduced in the analog MF path and passed through the station’s existing analog audio processor and returned to the DSB exciter where it is summed with the digital carriers. This baseband signal is converted to magnitude ρ and phase ϕ for amplification in the station’s existing analog transmitter.[1]

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[1] Details such as data insertion and synchronization have been omitted here for simplicity.

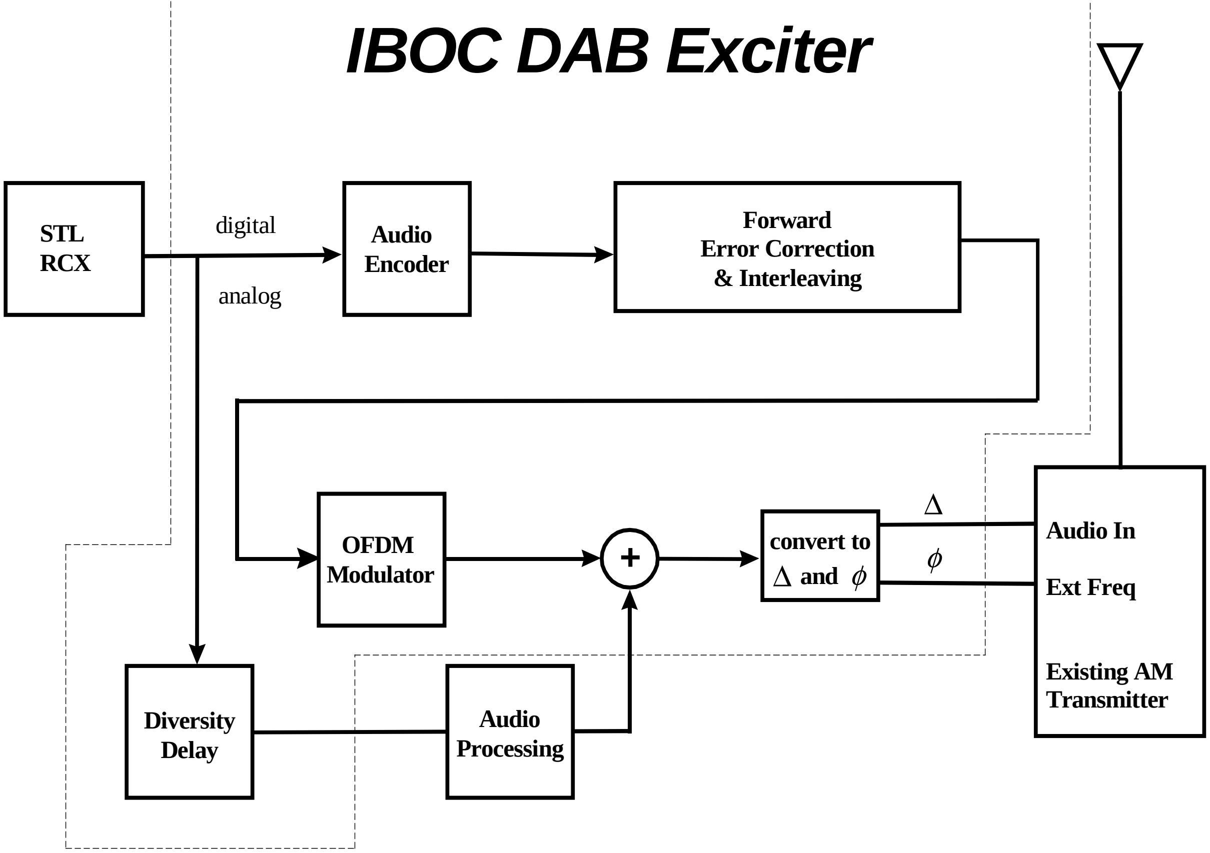

FIGURE 4

Hybrid MF IBOC DSB Transmitter Block Diagram

Several solid-state transmitters have been shown to have frequency response, distortion, and noise parameters that are sufficient to reproduce an IBOC hybrid waveform. The system has operated for many hours using a current production amplitude modulated transmitter for IBOC DSB transmission.

A similar approach is used for the all-digital system operating at MF or HF. In the all-digital system, however, the analog transmission path does not exist.

1.2.5 Reception of the Signal

A functional block diagram of an MF IBOC receiver is presented in Figure 5. The signal is received by a conventional RF front end and converted to IF, in a manner similar to existing analog receivers. Unlike typical analog receivers, however, the signal is filtered, A/D converted at IF, and digitally down converted to baseband in-phase and quadrature signal components. The hybrid signal is then split into analog and DSB components. The analog component is then demodulated to produce a digitally sampled audio signal. The DSB signal is synchronized and demodulated into symbols. These symbols are deframed for subsequent deinterleaving and FEC decoding. The resulting bit stream is processed by the audio decoder to produce the digital stereo DSB output. This DSB audio signal is delayed by the same amount of time as the analog signal was delayed at the transmitter. The audio blend function blends the digital signal to the analog signal if the digital signal is corrupted and is also used to quickly acquire the signal during tuning or reacquisition.

Noise blanking is an integral part of the IBOC receiver and is used to improve digital and analog reception. Receivers use tuned circuits to filter out adjacent channels and intermodulation products. These tuned circuits tend to “ring”, or stretch out short pulses into longer interruptions. A noise blanker senses the impulse and turns off the RF stages for the short duration of the pulse, effectively limiting the effects on the analog “listenability,” of ringing. Short pulses have a minimal effect on the digital data stream and increases “listenability of the analog signal.”[2]

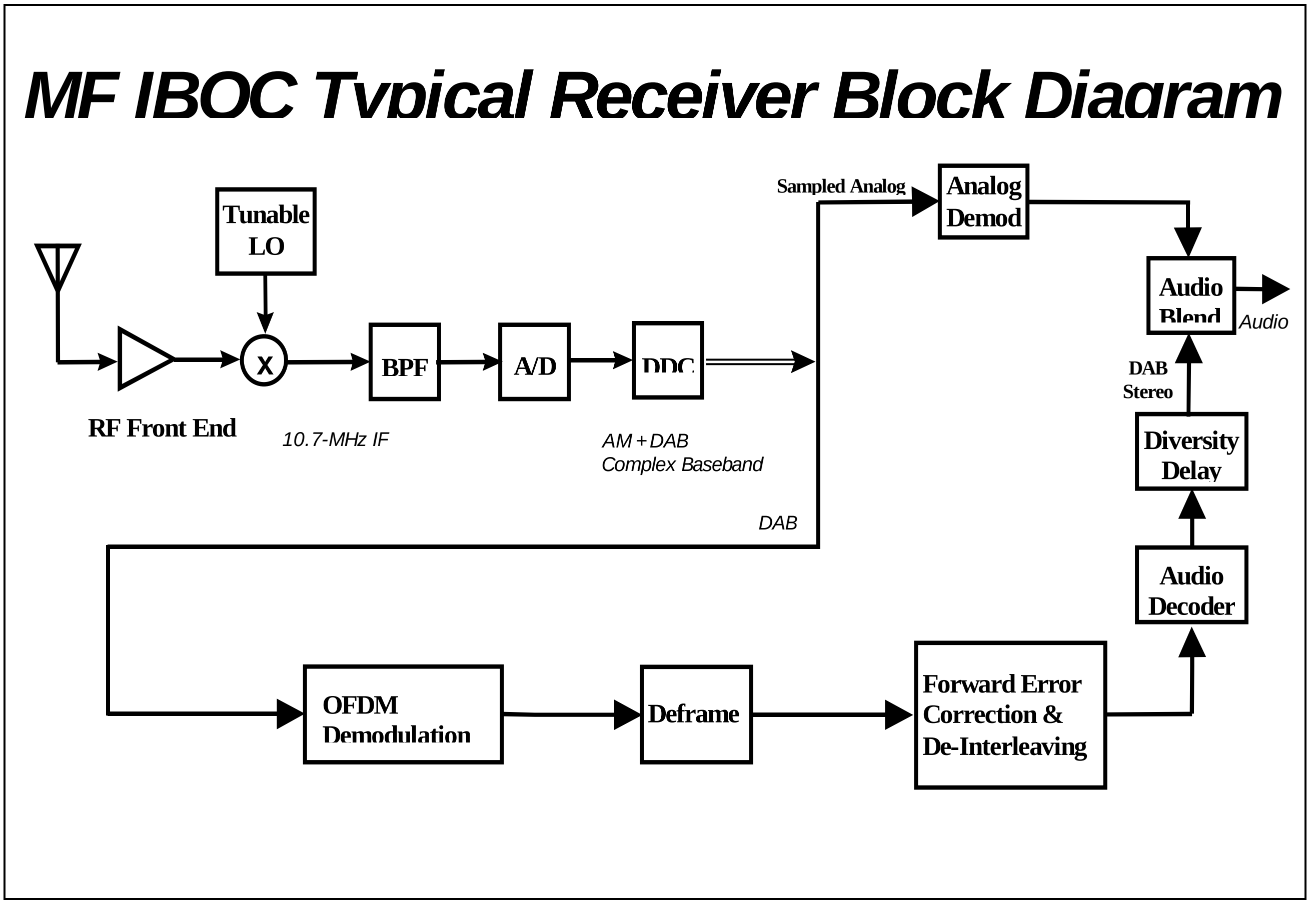

FIGURE 5

MF IBOC Hybrid Typical Receiver Block Diagram

A similar approach is used for the all-digital mode except the analog reception and demodulation and audio blend are not performed.

2 Simulations

2.1 Introduction

The goals of the simulation effort are threefold:

- Develop a realistic test bed to design and refine various algorithms within the system.
- To exercise the system design for a wide array of operating scenarios such that expected system performance can be predicted.
- Provide test results for lab verification of firmware implementations in a real–time system.

To meet the above goals, a computer simulation was developed to model the operation of the IBOC DSB system. The simulation was written such that system parameters could be easily changed to

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[2] The data paths and the noise blanker circuit are not shown for simplicity.

allow rapid trade-off studies. The simulation included all functions except the audio encoding algorithm and allowed modeling of a number of different phenomenon such as a clock difference between an exciter and receiver, carrier frequency and phase offset, asymmetrical analog modulation, various vehicle speeds, interfering stations, channel impairments, and a number of other phenomenon found in real-world systems.

The baseline simulation testing parameters are presented in Section 2.2. In Section 2.3, simulation results are compared to a case that can be analyzed theoretically. This provides a degree of verification of the simulation software. Section 2.4 presents results showing the expected performance of both the hybrid and all-digital IBOC DSB systems under a number of different operating conditions. Finally, Section 2.5 provides a summary.

2.2 Simulation Parameters

The simulation parameter values shown in Table 1 were used as the default values for all simulations unless otherwise noted.

TABLE 1

Standard simulation parameter values.

Parameter	Value	Reason for Selection
Analog Modulation Scaling	1	Sets analog modulation to +100% and –99%
Analog & Digital Modulation peak maximum % clip	140%	Typical hardware limit.
Additive White Gaussian Noise (AWGN) level	Off	AWGN interference tested separately
Carrier Frequency Offset	0 Hz	Frequency offset is odelled as an oscillator slip at the receiver
Carrier Phase Offset	0 degrees	Ideal selection
Oscillator Difference at Rx	0 ppm	Ideal selection
Analog signal	Pulsed USASI Noise	Models current programming
Adjacent Station Interference Levels	-50 dB	Levels increased for testing in specific interference scenarios

2.3 Calibration

In order to verify that the simulations were working properly, the pre-decoding bit error rates in a purely Additive White Gaussian Noise (“AWGN”) environment were determined and compared with theoretical calculations.

A comparison of the simulation results with theoretical results is shown in Figure 6. From these results it can be seen that the simulation closely matches theoretical results. The slight degradation from the theoretical results can be attributed to receiver functions such as AGC and carrier tracking that are realistically modelled in the simulation but are assumed ideal in the theoretical model.

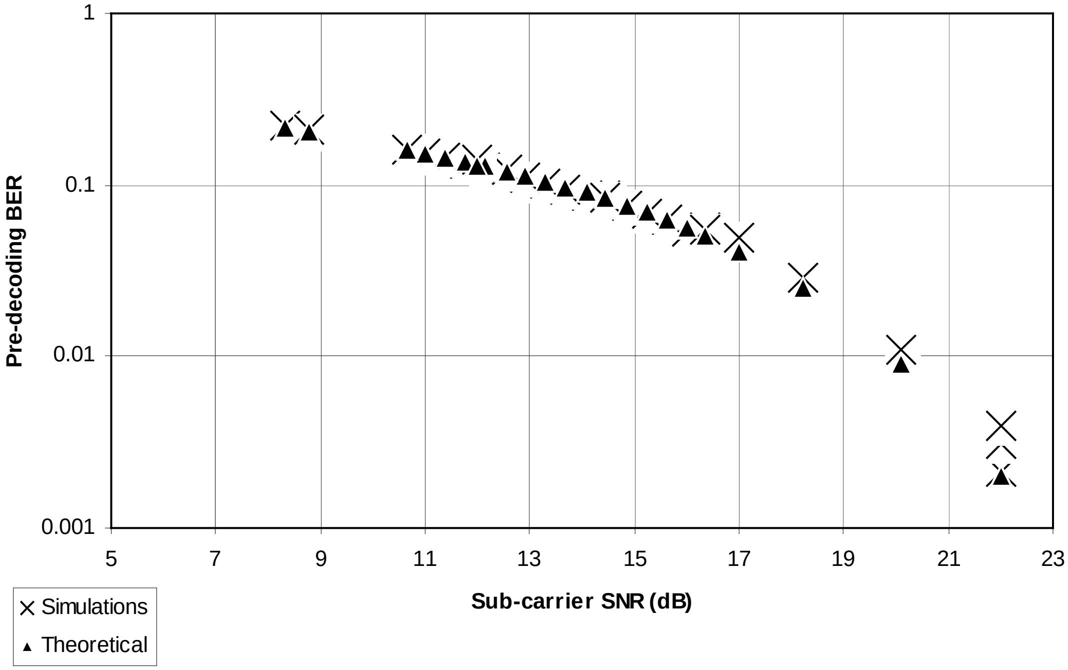


FIGURE 6

Comparison Between Simulation and Theoretical Pre-decoding BER Results in an AWGN Channel

2.4 Simulation Tests

The purpose of these tests is to determine when Threshold of Audibility (“TOA”) occurs under a variety of different interference conditions. It has been empirically determined that an audio block error rate of 0.01 or 1% is a good measure of TOA for the IBOC DSB system. This is the point where current error concealment techniques begin to break down, and a blend to analog or back-up digital will occur.

The operating conditions presented in this section are:

- System performance in (previously defined) AWGN
- System performance in the presence of interferers
- System performance in the presence of channel impairments

2.4.1 AWGN

The tests in this section analyze system performance in an AWGN environment.

2.4.1.1 Description of Tests

In all cases, the level of the AWGN interference is raised, in 2 dB increments, until the TOA is reached. The level of the noise is defined as the Carrier-to-Noise Ratio (“CNR”) in a 1 Hz bandwidth.

2.4.1.2 Results

The results of these tests are shown in Table 2 for the hybrid system and Table 3 for the all-digital system.

TABLE 2

Performance of IBOC hybrid DSB System in the presence of AWGN

C/No(dB/Hz)	Block Error Rate
70.6	0.0%
69.6	1.43%
68.6	10.29%

TABLE 3

Performance of IBOC all-digital DSB System in the presence of AWGN

C/No(dB/Hz)	Block Error Rate
56.6	0.0%
54.6	0.09%
52.6	18.41%

2.4.2 First Adjacents

The tests in this section determine system performance in the presence of first adjacent interferers. The tests determine the levels of simultaneous lower and upper first adjacent interferers that can be tolerated before the TOA is reached. The interfering signals are hybrid IBOC DSB signals.

2.4.2.1 Description of Tests

In all cases, the level of the odelled rs was raised until the TOA was reached. The levels of the interferers are reported as the ratio of the interfering carrier level to the desired carrier level in dB.

2.4.2.2 Results

Figures 7 and 8 show the simulation results for the hybrid and all-digital systems, respectively. Any combination of upper and lower first adjacent levels that falls below or to the left of the TOA curve will receive digital audio. Any interference scenario that falls above or to the right of the TOA curve will blend to analog audio or back-up digital.

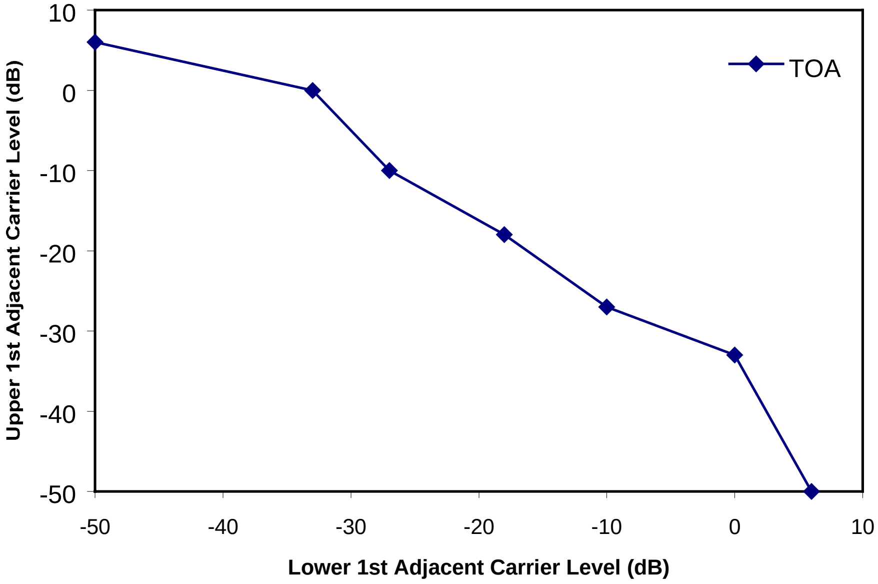


FIGURE 7

Hybrid IBOC DSB System Performance in the Presence of First Adjacent Interferers

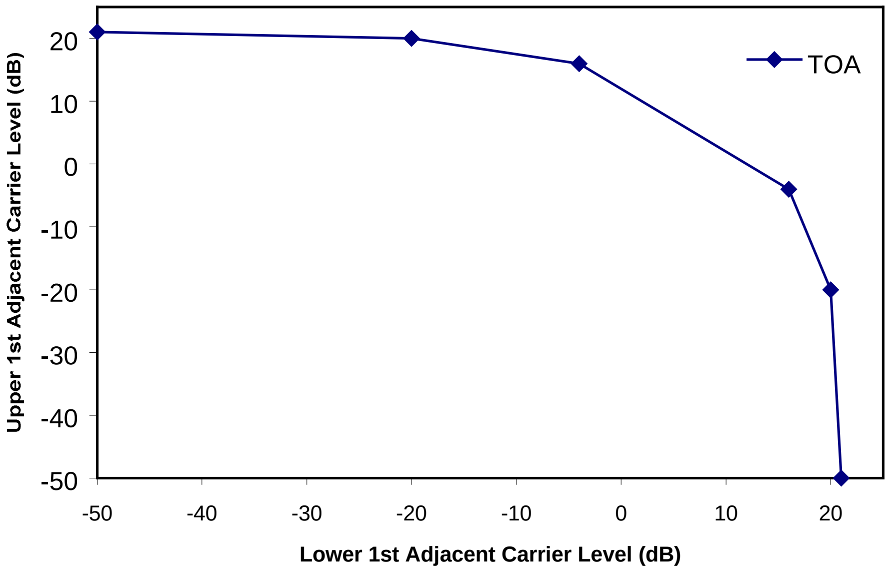


FIGURE 8

All-Digital IBOC DSB System Performance in the Presence of First Adjacent Interferers

2.4.3 Co-Channel and a First Adjacent

These tests are identical with those in the previous section, except that one of the first adjacent interferers was replaced with a co-channel interferer. All interferers are hybrid IBOC DSB signals.

2.4.3.1 Description of Tests

In all cases, the level of the interferers was raised until the TOA was reached. The levels of the interferers are reported as the ratio of the interfering carrier level to the desired carrier level in dB.

2.4.3.1 Results

Figures 9 and 10 show the simulation results for the hybrid and all-digital systems, respectively. Any interference scenario that falls below or to the left of the TOA curve will receive digital audio. Any interference scenario that falls above or to the right of the TOA curve will blend to analog or back-up digital.

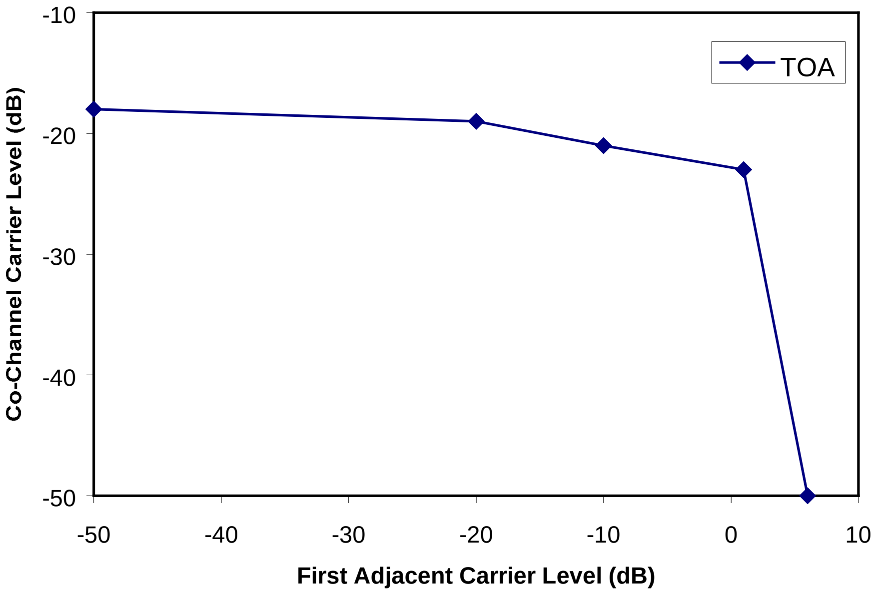


FIGURE 9

Hybrid IBOC DSB System Performance in the Presence of Co-Channel and First Adjacent Interferers

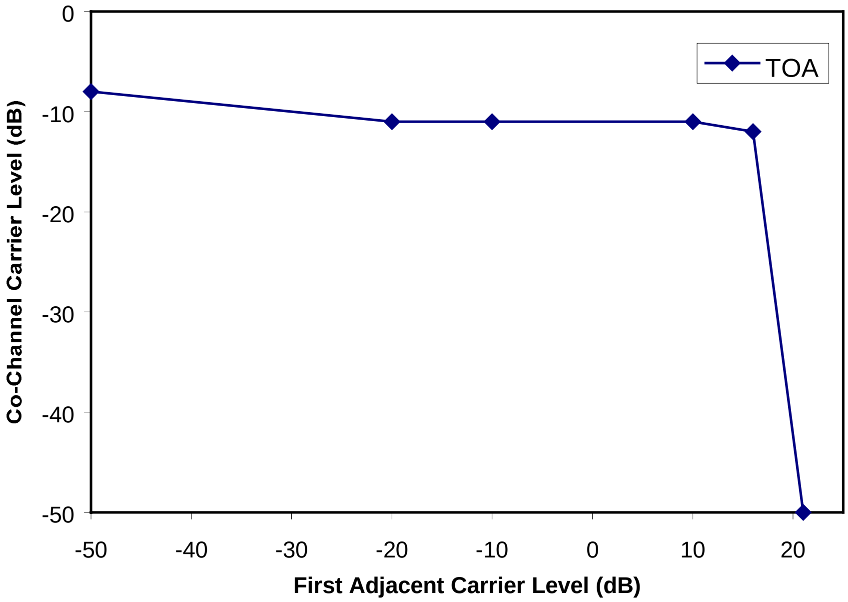


FIGURE 10

All-Digital IBOC DSB System Performance in the Presence of Co-Channel and First Adjacent Interferers

2.4.4 Grounded Conductive Structures

A study was performed to characterize wave propagation impairments in the MF channel defined as 510-1710 kHz. Unlike higher frequency channels, traditional multipath is rarely seen in the MF channel because large structures are required to reflect an incident wave. However, certain structures, such as bridges and power lines, can cause the magnitude and phase of the incident wave to change. The goal of the study was not to determine the physical mechanism causing these channel perturbations, but rather to measure and characterize the magnitude and phase changes caused by the impairments in order to minimize such effects in the system.

Measurements were taken using center frequencies of 740 kHz and 1660 kHz in Cincinnati, Ohio and 1150 kHz in Boston, Massachusetts in the United States. The choice of these frequencies was sufficient to obtain measurements at the low, middle, and high sections of the band. For each center frequency used, measurements were taken in a variety of locations including urban, suburban, and rural.

The measured data from this study has been incorporated directly into the simulation. In this way, the transmitted waveform can be corrupted in ways identical to what is seen in the field.

2.4.4.1 Description of Tests

A total of 24 channel impairment files was selected for analysis. Approximately 8 impairments were selected from each of the center frequencies noted above. The specific channel impairments were selected as a representative cross section of the various types of impairments, fading depths, and frequency selectivity. Each of the 24 impairment files was run for vehicle speeds of 25 and 70 miles per hour (mph) (approximately 40 and 113 kilometers per hour) resulting in a total of 48 simulations. Since the channel impairments vary in duration, block error rate is not a valid indicator of system performance in the presence of impairments. Therefore, for each of the 48 simulations it was noted if post-FEC decoding errors resulted.

2.4.5 Results

The simulation results for channel impairments are shown in Table 4 below. An X indicates that no post-FEC errors resulted. Even for cases where post-FEC errors were obtained, blending to analog, for the hybrid system, would not be required if codec error concealment techniques can be used to mitigate the errors.

TABLE 4

Performance of both hybrid and all-digital IBOC DSB system in the presence of channel impairments

Number	**Description**	**Hybrid**		**All-Digital**	
		25 mph (40 kph)	70 mph (113 kph)	25 mph (40 kph)	70 mph (113 kph)
1	Freq selective	X	X	X	X
2	Typical flat fade	X	X	X	X
3	Freq. Selective	X	X	X	X
4	Shallow hole in mag.	X	X	X	X
5	Freq selective	X	X	X	X
6	Three fades	X	X	X	X
7	Two sharp fades	X	X	X	X
8	Fade freq selective slightly	X	X	X	X
9	Three fades	X	X	X	X
10	Many fades	X	X	X	X
11	Freq selective in phase	X	X	X	X
12	Dip on center	X	X	X	X
13	Two close fades	X	X	X	X
14	Three fades	X	X	X	X
15	4 repeated fades	X	X	X	X
16	Freq selective	X	X	X	X
17	Long fade	X	X	X	X
18	Sharp fade	X	X	X	X
19	Fades in phase	X	X	X	X
20	Long fade	X	X	X	X
21	Two long fades	X	X	X	X
22	1 flat, 1 freq selective	X	X	X	X
23	Freq selective “Y plot”	X	X	X	X
24	Fades of –155 to –80 dB	X	X	X	X

2.5 Summary and Conclusions

An extensive simulation of all aspects of the IBOC DSB systems, including the transmitter, receiver, and channel, has been developed. This simulation has been used to develop IBOC DSB systems that will provide the performance necessary to deliver FM-like digital audio and robust coverage.

This section has presented performance results from the simulation effort. The results include performance in the presence of AWGN and interferers and performance in the presence of channel impairments. The AWGN results matched a theoretical analysis, providing a degree of verification for the simulation. The interferer tests showed that the system could survive even in the presence of strong first adjacent and co-channel interferers. The channel impairment tests showed that the system is robust against channel impairments that typically plague the MF band. In all cases, the all-digital system outperformed the hybrid system. This is not unexpected due to the increased power of the all-digital system in the ±5 kHz region.

3 Performance Laboratory Test Report

3.1 Overview

The IBOC DSB system hybrid mode has been carefully designed to provide superior digital audio performance while minimizing the impact to existing analog signals. In the initial phase of development, the system was modelled and simulated to verify that the resulting design would indeed exhibit acceptable performance in an environment comprised of both analog and IBOC signals. As the development progressed, computer models have been replaced by hardware implementations of IBOC DSB exciters and receivers. The prototype exciters and receivers are allowing verification of system performance in both a laboratory environment and in the field.

The results of the performance laboratory tests of the hybrid IBOC DSB system are reported below. These results are important because they verify the performance of a physical implementation of the design under controlled and repeatable conditions.

The quality and coverage of MF broadcasts is often limited by two factors: noise and interference. Interference is caused mainly by other MF stations that either share the same frequency as the desired station (co-channel), or are one or two channels removed (adjacent channel).

In an attempt to faithfully reproduce the full range of expected environments in a controlled laboratory setting, a number of tests have been performed to measure the performance of the hybrid IBOC DSB system in the presence of various combinations of co- and adjacent channel hybrid IBOC interferers. In particular, the following tests were performed:

> *Performance in Gaussian Noise*: This test measured system performance in the presence of AWGN.
>
> *Performance in the Presence of Interference*: This test measured performance in the presence of co-channel and first adjacent hybrid IBOC signals.
>
> *Performance in the Presence of Interference and Gaussian Noise*: This test measured performance in the simultaneous presence of AWGN and interferers.

3.2 Definitions and Assumptions

Performance of the hybrid and all-digital IBOC DSB system was verified by testing physical implementations of an exciter, channel, and receiver in a laboratory environment. Accurate interpretation of the results is incumbent on a thorough understanding of the assumptions and definitions described below.

3.2.1 Signal

The MF IBOC hybrid signal consists of an MF carrier modulated by a band limited (± 4.5 kHz) analog signal and digitally modulated subcarriers placed on each side as well as under the main carrier occupying the spectrum within ± 15 kHz. For the following tests, the analog portion of the

MF IBOC signal consisted of Pulsed USASI noise. Pulsed USASI noise simulates aggressively processed MF program material. The modulation index was set to 100%.

The MF IBOC all-digital signal consists of an MF carrier and digitally modulated subcarriers placed on each side occupying the spectrum within ± 10 kHz.

3.2.2 Block Error Rate Curves

Performance in a given environment is shown in terms of block error rate curves. Blocks are simply large groups of information bits at the input to the audio decoder. Each block has an assigned Cyclic Redundancy Check ("CRC") that detects errors in a packet of bits. If the CRC is incorrect, the block is deemed in error. Block error rate is computed by dividing the number of blocks in error by the total number of blocks received.

Block error rate is used as a metric since it provides the most accurate indication of the threshold of audibility ("TOA"). TOA is defined as the block error rate above which noticeable audio impairments may just be detected. For the hybrid IBOC DSB system, the TOA is defined as 0.01 or 1% block error rate.

C/No, used in the Gaussian Noise test, is defined as the ratio of the power in the MF carrier to the power of the noise in a 1 Hz bandwidth. The noise was produced using a Noise/Com Gaussian noise generator, and was summed with the signal just prior to the receiver input.

3.2.3 Interference Tests

Interference tests were performed in the presence of various combinations of co-channel and first adjacent channel interferers. The MF all-digital IBOC DSB system has a total bandwidth of 20 kHz and hence the effect of second adjacent interferers is insignificant. Therefore, no testing of the all-digital system was performed in the presence of second adjacent interferers. All analog and digital interferers were mutually uncorrelated. The analog portion of the interference signals was modulated with Pulsed USASI noise to improve repeatability and to match the conditions used in the simulations described above.

3.3 Test Procedures

3.3.1 Performance in Gaussian Noise

This test measured system performance in the presence of AWGN. Performance is depicted using block error rate curves, which describe the system's block error probability in terms of C/No. The test set-up is shown in Figure 11. The test procedure is as follows:

- Transmit a desired IBOC signal. Add white Gaussian noise at a level that produces the desired C/No.
- Run until either 100-block errors are observed, or 10 minutes have elapsed, whichever takes longer. Record the block error rate.
- Repeat Steps 1 and 2 for a least two other points. Attempt to set the C/No so that the resulting curve intersects the TOA.

3.3.2 Performance in the Presence of Interference

Performance is depicted using block error rate curves, which describe the system's block error probability in terms of the level of the interferers relative to the desired signal. The test set-ups are shown in Figures 11 through 13. The test procedure is as follows:

- Transmit a desired IBOC signal.
- Add upper and lower first adjacent interferers.

- Run until either 100-block errors are observed, or 10 minutes have elapsed, whichever takes longer. Record the block error rate.
- Repeat steps 1 and 2 for at least one other point. Attempt to set the power of the interferer(s) so that the resulting curve intersects the TOA.
- Remove one of the interferers such that the other interferer's performance can be measured.
- Repeat steps 1 through 4, replacing the upper first adjacent interferer with a co-channel interferer.
- Repeat steps 1 through 4, replacing the upper first adjacent interferer with a second adjacent interferer.

3.3.3 Performance in the Presence of Interference and Gaussian Noise

This test measured system performance in the presence of a single first adjacent or co-channel hybrid IBOC interferer and AWGN. Performance is depicted using block error rate curves, which describe the system's block error probability in terms of C/No for the AWGN and the level of the interferer relative to the desired signal. The test set-up is shown in Figures 11 and 12. The test procedure is as follows:

- Transmit a desired IBOC signal.
- Add a first adjacent interferer.
- Run until either 100 block errors are observed or 10 minutes have elapsed, whichever takes longer. Record the block error rate.
- Repeat steps 1 and 2 for at least one other point. Attempt to set the C/No (by raising/lowering the noise) so that the resulting curve intersects the TOA.

Repeat steps 1 through 4, replacing the first adjacent interferer with a single co-channel interferer.

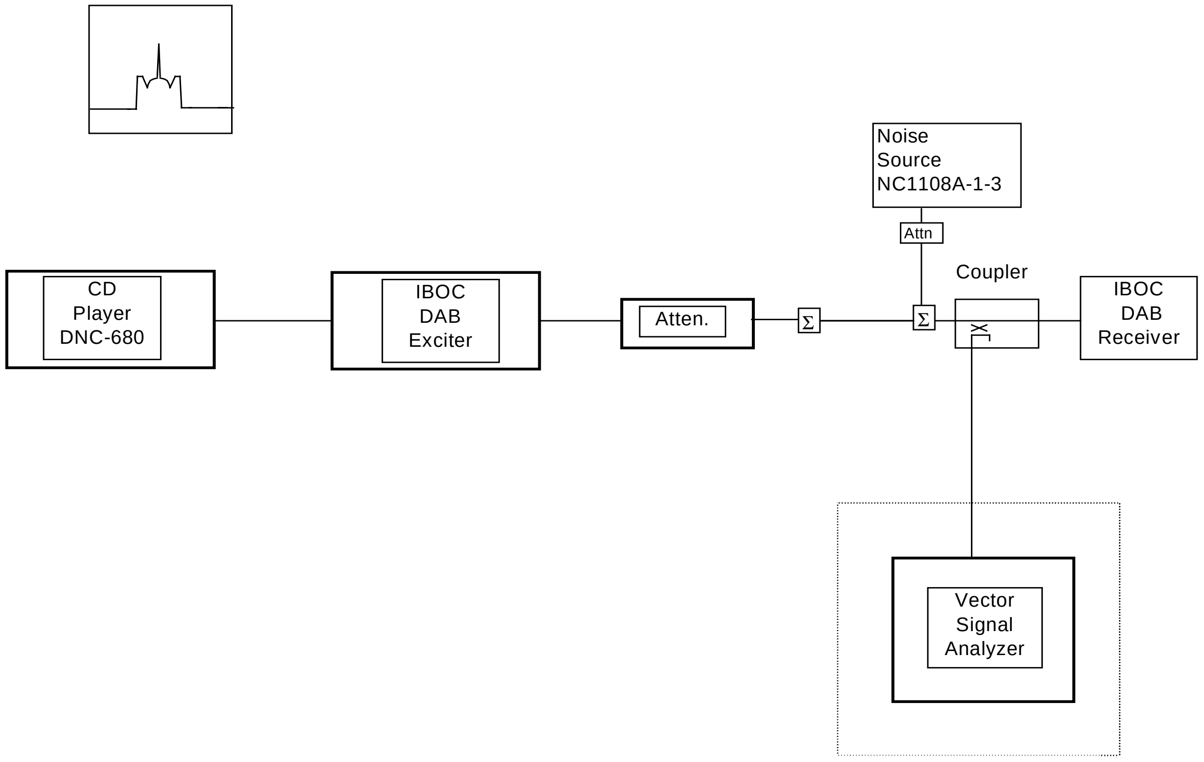


FIGURE 11

Test Setup for Testing with no Interferers Present

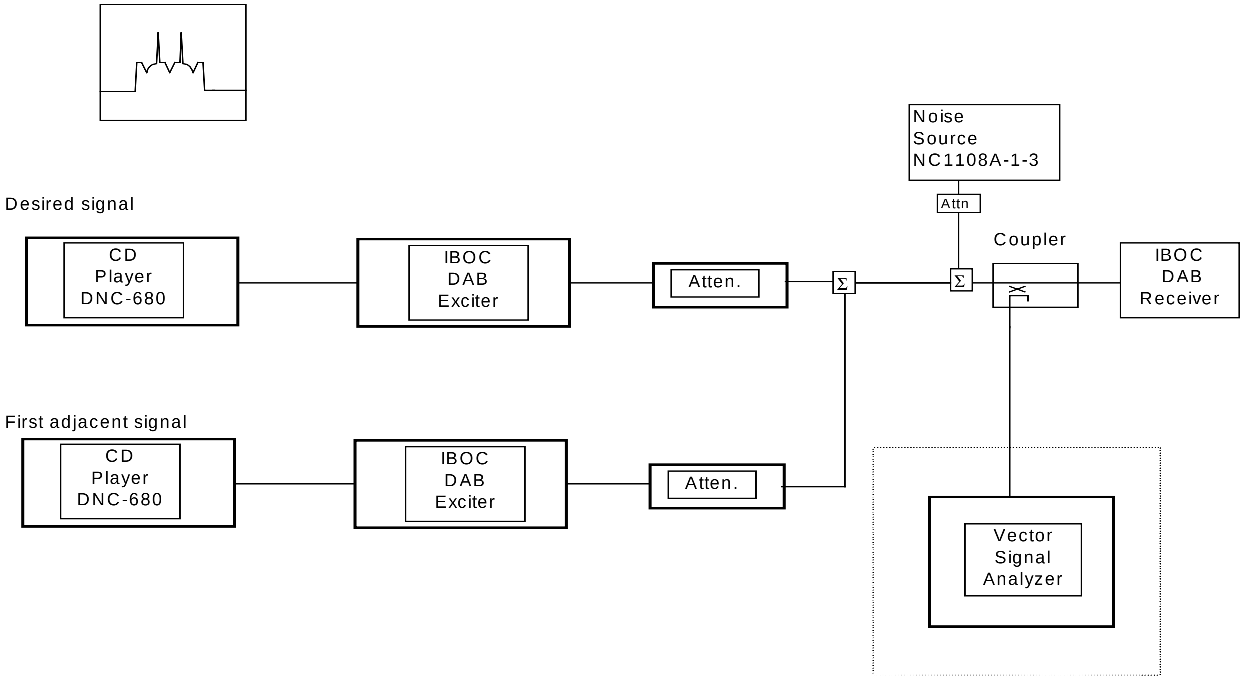


FIGURE 12

Test Setup for Testing with First Adjacent Interferers Present

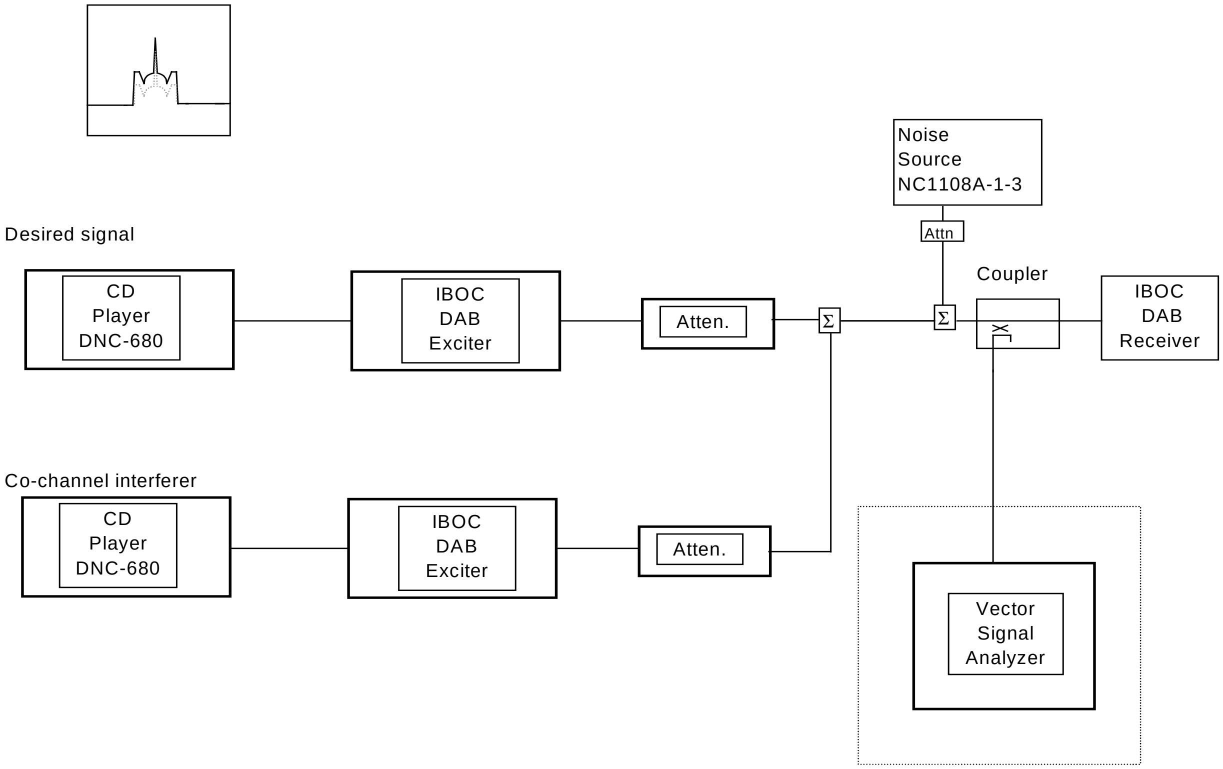
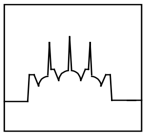


FIGURE 13

Test Setup Used for Co-Channel Interference Tests



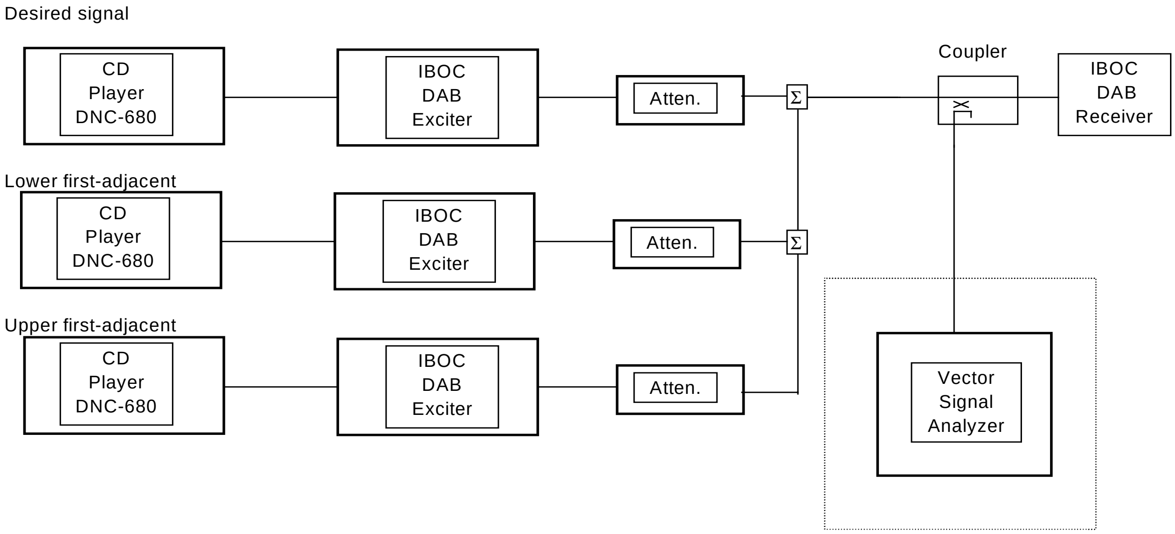


FIGURE 14

Test Setup for Dual First Adjacent Testing

3.4 Test Results

Laboratory performance tests were performed to characterize the performance of both the hybrid and all-digital IBOC digital signals in the presence of Gaussian noise and interference. The results are summarized in Figures 15 thru 18. The interference level is given in units of dBc, which is defined as dB relative to the carrier power of the desired IBOC signal.

3.4.1 Calibration

In order to verify that the hardware/software implementation was working properly, the pre-decoding bit error rates in a purely Additive White Gaussian Noise (“AWGN”) environment were determined and compared with theoretical calculations.

A comparison of the measured results with theoretical results is shown in Figure 15. From these results it can be seen that the hardware implementation closely matches theoretical results.

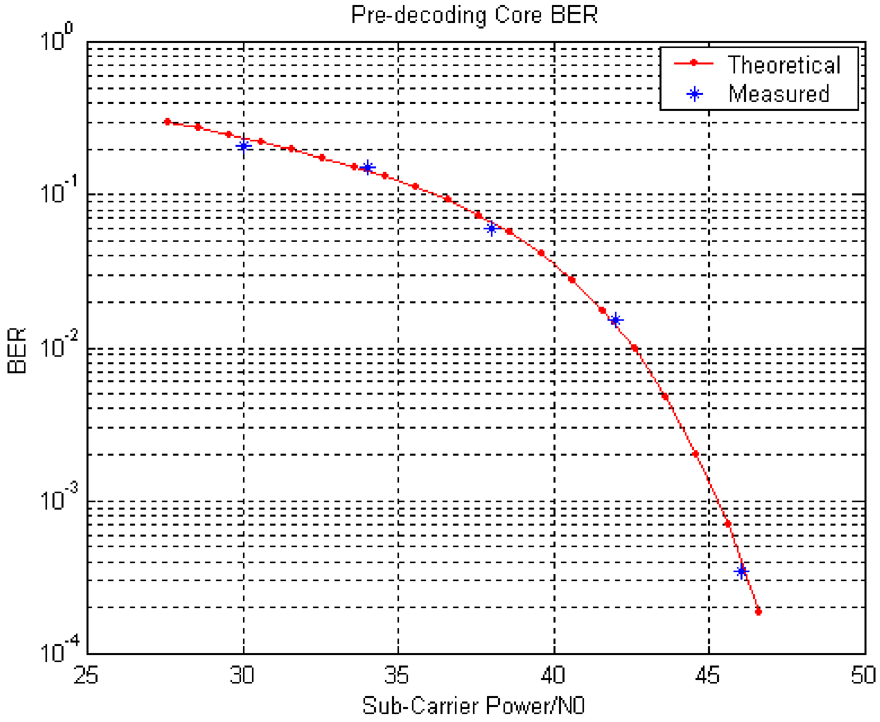


FIGURE 15

Comparison between measured and theoretical pre-decoding BER results in an AWGN channel

3.4.2 Performance in Gaussian Noise

Performance in Gaussian noise is shown in the block error rate curves of Figure 16. For comparison the results reported in Section 2.0 above are included on this plot. It can be seen that the hardware and software implementation of the system performs nearly identically to that predicted by the simulations. In addition, Figure 16 shows that the TOA for the hybrid system is approximately 70 dB/Hz and the TOA for the all-digital system is approximately 55 dB/Hz.

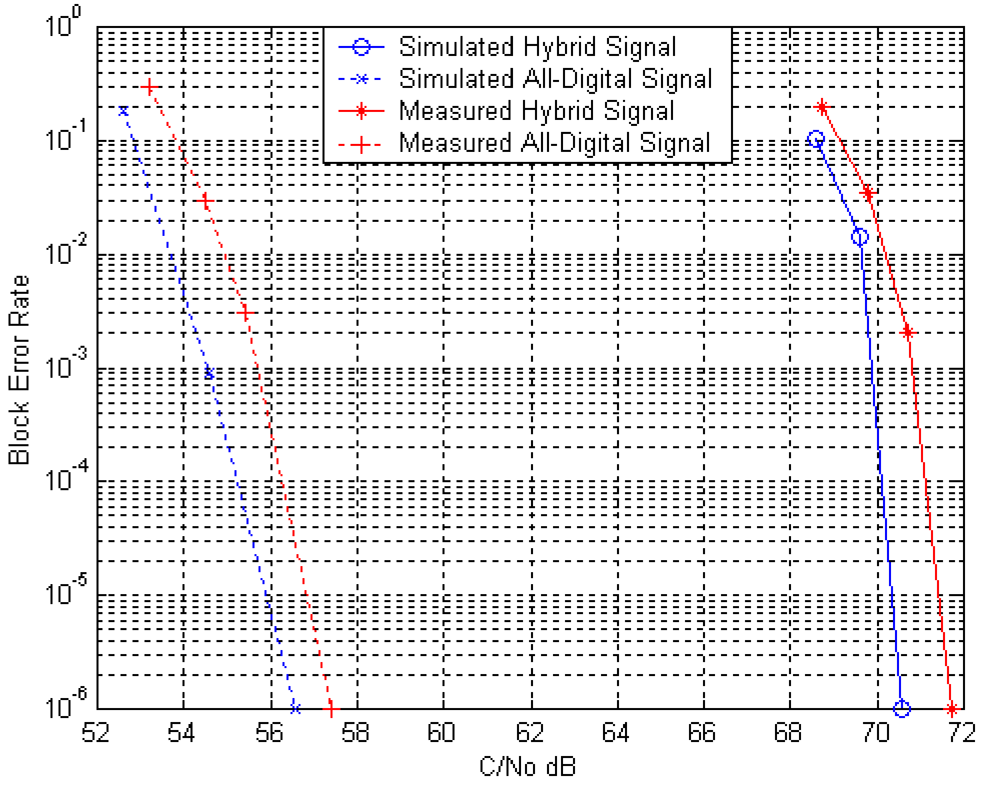


FIGURE 16

IBOC performance results in the presence of AWGN

3.4.3 Performance in the Presence of Interference

Results for performance in the presence of a signal first adjacent interferer is shown in Figure 17, while the results for the performance in the presence of a co-channel interferer is shown in Figure 18. In both cases the interfering signal is a hybrid IBOC signal. As can be seen, TOA for a single first adjacent occurs when the interferer is approximately 9 dB above the desired signal for the hybrid system and 9 dB above the desired signal for the all-digital system. TOA for a co-channel interferer occurs when the interferer is approximately 15 dB below the desired for the hybrid system and 5 dB below the desired for the all-digital system.

Results for the performance in the presence of a single second adjacent interferer is shown in Table 5. Again the interfering signal is a hybrid IBOC signal. As can be seen, the TOA for a single second adjacent occurs when the interferer is approximately 24 dB above the desired signal.

TABLE 5

Second adjacent interference results

U/D (dBc)	Block Error Rate
24.4	1.2×10^{-2}
22.8	2×10^{-3}

Figure 19 shows the TOA results for co-channel and a single lower first adjacent for the hybrid system. Figure 20 shows TOA results for dual first adjacents interferers for the hybrid system. Symmetry of results was assumed in this interference scenario. Comparison of the simulation results with the hardware and software implementation results shows nearly exact agreement.

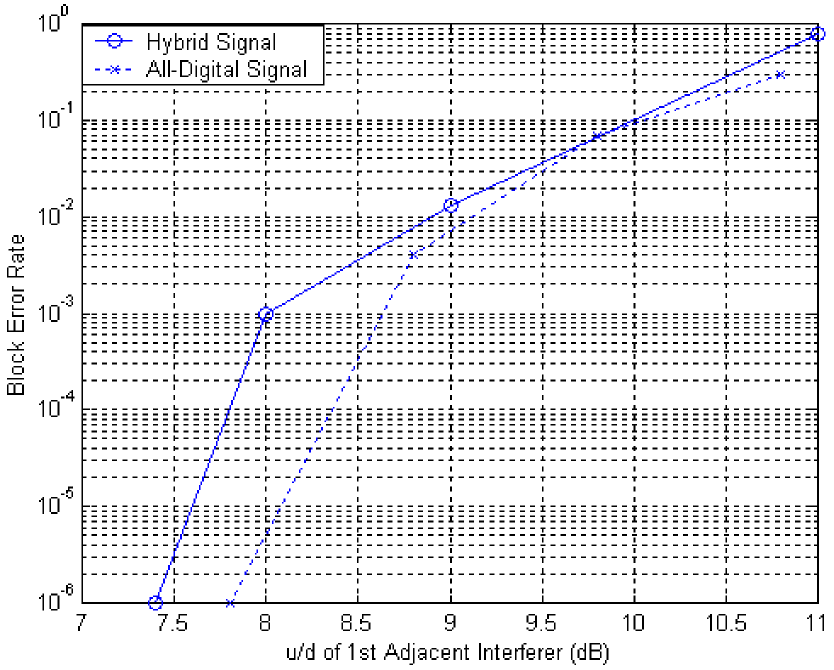


FIGURE 17

Lab results for a single lower first adjacent interferer

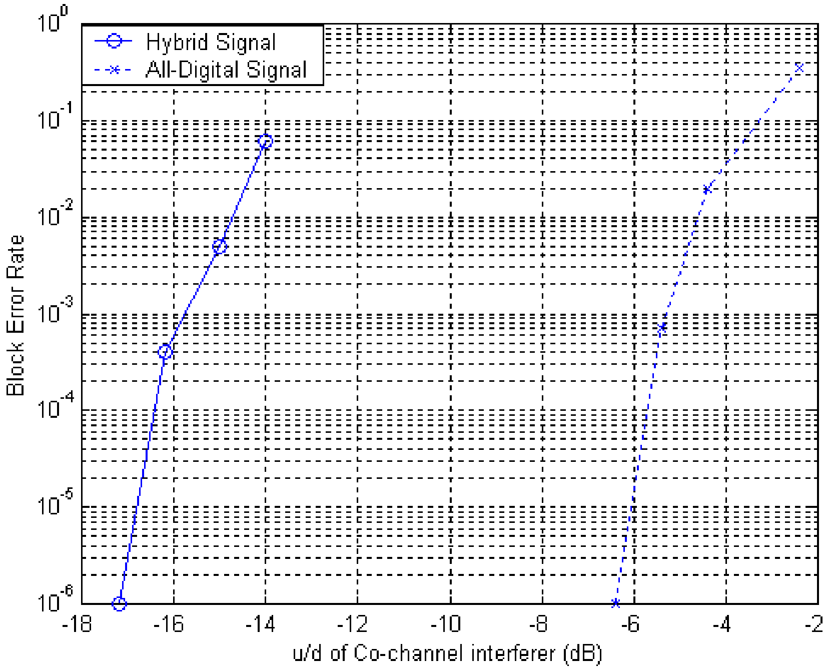
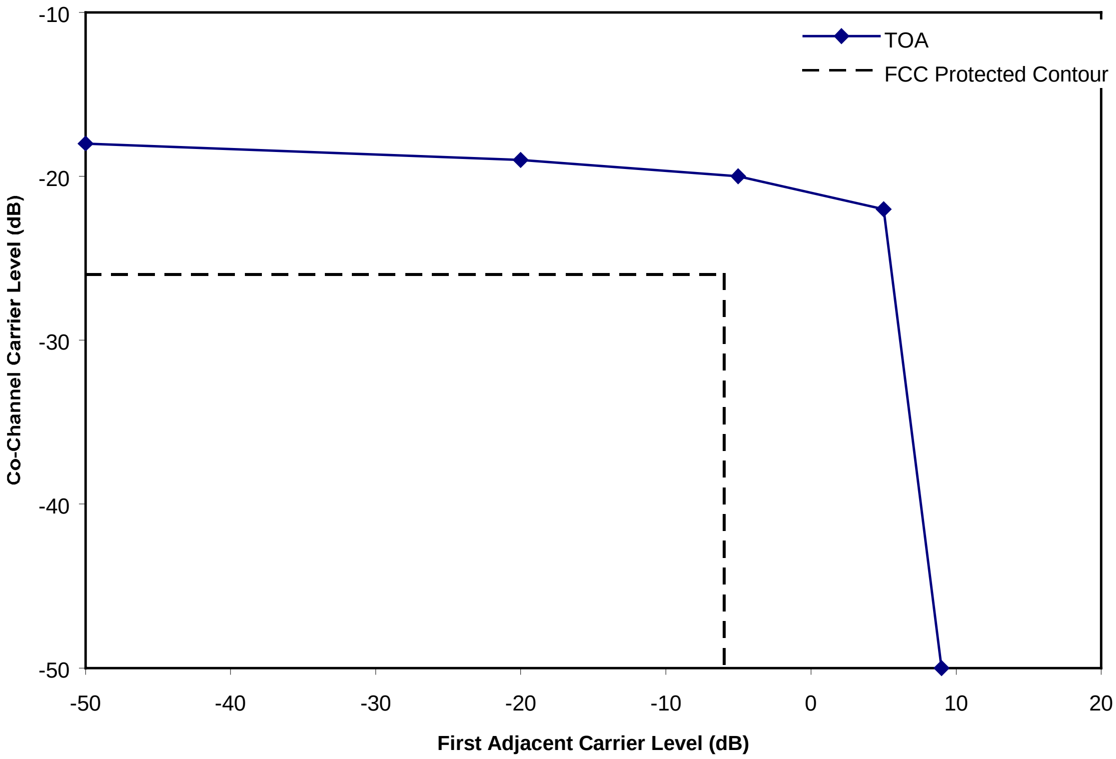


FIGURE 18

Lab Results for Co-Channel Hybrid Interference

In the United States, the Federal Communications Commission mandates that all classes of stations receive 6 dB protections at their 0.5 mV/m contour from first adjacent interference. In addition, the FCC defines the coverage of an MF station as the signal level where its co-channel interferers sum to a signal strength that is 26 dB weaker. The dashed lines in both Figures 19 and 20 depict these protected regions. In Figure 19 the IBOC DSB hybrid performance is entirely outside the envelope set by the protected contours. In Figure 20, the DSB coverage includes a large portion of, but not the entire, protected area. However, the dashed lines in Figure 20 apply to a signal strength of 0.5 mV/m. For higher desired signal strengths, more coverage area would be obtained. The regions not covered by DSB are those where strong dual first adjacents exist. Based on interference studies done in the past, this situation is rare during daytime operations but may occur at night due to skywave propagation effects. In addition, when both first adjacents are strong many analog radios will also suffer dramatic levels of cross talk from adjacent channel interferers. However, the hybrid IBOC DSB system will cover the majority of the regions currently covered by today's analog systems.



FIUGRE **19**

IBOC DSB System Performance in the Presence of Co-Channel and First Adjacent Interferers

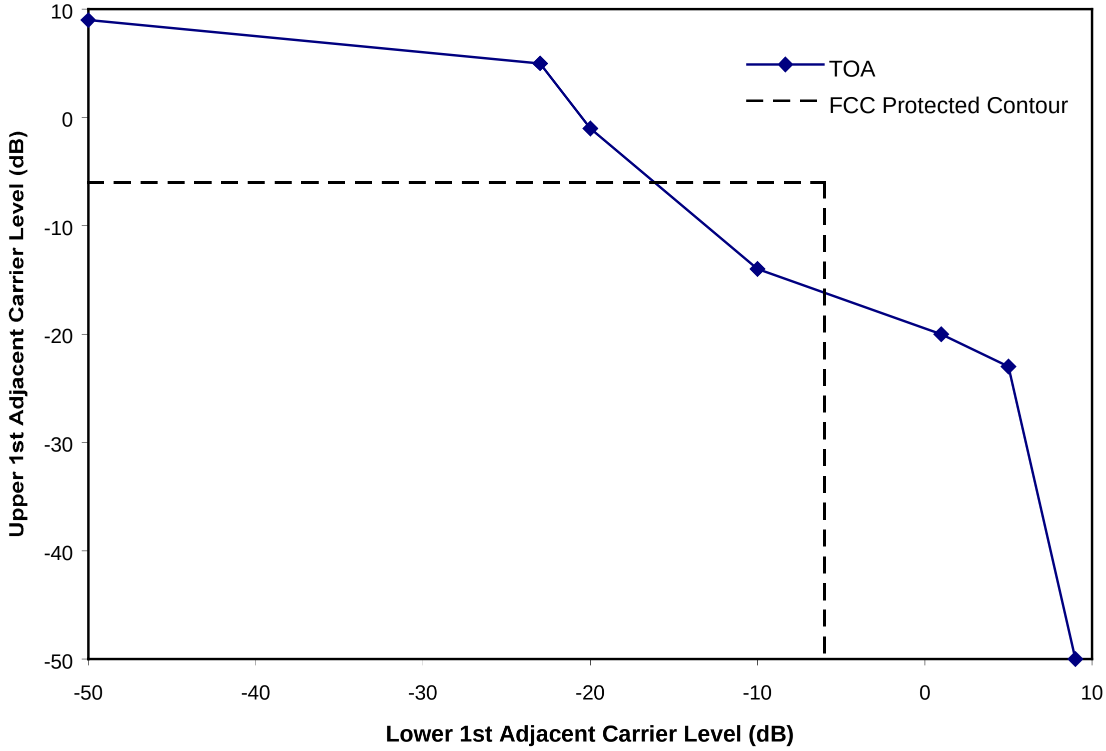


FIGURE 20
IBOC DSB System Performance in the Presence of First Adjacent Interferers

3.4.4 Performance in the Presence of Interference and Gaussian Noise

Results showing the hybrid system performance in the presence of AWGN and interferers are given in Figure 21, and summarized in Table 6. Similar results for the all-digital system are shown in Figure 22. Figures 21 and 22 show that the presence of a strong first adjacent interferer has the largest effect on the coverage area of the system, as one might expect. On the other hand, co-channel interference below the 26 dB-protected contours has a minimal effect.

TABLE 6

Performance in the Presence of Interference and Gaussian Noise
(TOA is defined as a block error rate of 1%)

Interference Scenarios	C/No (dB/Hz)	Block Error Rate
+6 dB 1st Adjacent Interferer	83.4	0.224%
	82.4	4.036%
	81.4	17.068%
0 dB 1st Adjacent Interferer	79.8	0.796%
	78.6	3.040%
	77.4	8.020%
-6 dB 1st Adjacent Interferer	77.4	0.968%
	76.4	4.00%
	75.4	12.427%
-24 dB 1st Adjacent Interferer	89.4	0%
	86.4	0%
	84.4	0%
-24 dB Co-Channel Interferer	73.4	0.758%
	72.4	4.198%
	71.4	14.938%
-30 dB Co-Channel Interferer	72.4	0.408%
	71.4	2.679%
	70.4	15.395%
-30 dB Co-Channel Interferer	82.4	0%
	81.4	0%
	80.4	0%

FIGURE 21

Performance Results for the Hybrid IBOC DSB System in the Presence of Both AWGN and Interference

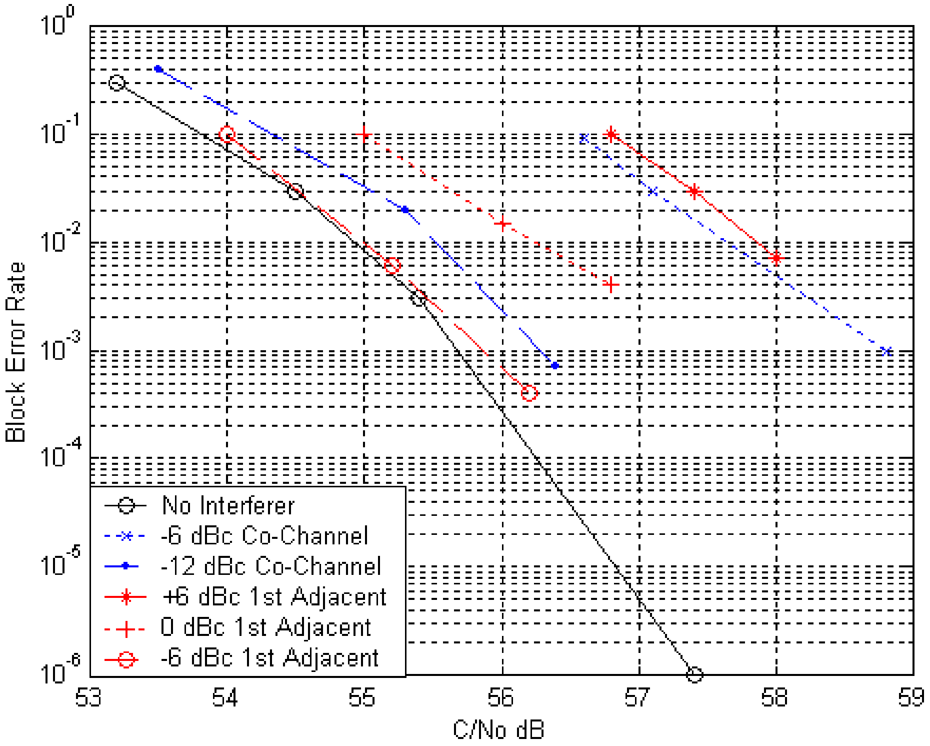


FIGURE 22

Performance results for the all-digital IBOC DSB system in the presence of both AWGN and interference

3.5 Summary and Conclusions

Laboratory tests were conducted to characterize the performance of the hybrid IBOC signal in the presence of Gaussian noise and the results are depicted in Figure 21. These tests demonstrate that the IBOC digital signal is tolerant of high levels of adjacent channel interference. Furthermore the co-channel performance exceeds the defined protected contour by greater than 7 dB. These tests verify the real-time performance of the hardware as predicted by the computer simulations. Testing has provided substantial evidence that the hybrid IBOC DSB system provides coverage near or in excess of the defined protection criteria.

4 Hybrid IBOC DSB Field Test Results

4.1 Overview

The goals of the MF field testing program are four fold: (1) Demonstrate significant improvements over current analog audio quality; (2) Demonstrate robustness of the digital signal in the harsh MF environment (e.g., robustness to interferers as well as channel impairments); (3) Demonstrate coverage areas large enough such that significant numbers of listeners currently receiving analog broadcasts will be able to receive digital broadcasts; and (4) show that the hybrid IBOC DSB signal is compatible with existing analog signals.

Summarized below are the procedures used for MF field testing and results. These tests are important because they verify the performance of a physical implementation of the design under real-world conditions.

4.2 Test Setup

4.2.1 Transmitter Test Sites

WD2XAM, an experimental, 10 kW station operating at a frequency of 1660 kHz, was used for MF field testing. The transmit antenna is located at Xetron Corporation in Cincinnati, Ohio, at a longitude of 84° 28’ 40’’ W and a latitude of 39° 18’ 16’’ N.

4.2.2 Station Configuration

Figure 23 shows the equipment configuration that is being used to generate the transmitted signal. The source material to be played was recorded on a CD. The Denon DN-C680 CD player sampling frequency was synchronized to the oscillator in the IBOC exciter to prevent data underflow or overflow errors for the audio encoder. Synchronization was accomplished by inputting a 44.1 kHz signal from the exciter to the CD player external synchronization input. The CD player output was input to an Orban Optimod 9200 audio processor. The processed source material was input to the IBOC exciter via an AES/EBU connection. The audio signal was encoded by the exciter, and the hybrid DSB signal, containing the analog and digital components, was generated.

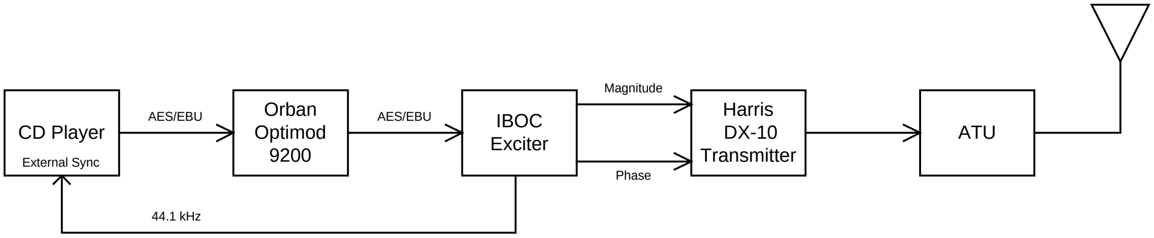


FIGURE 23

Diagram of MF Transmitter Setup

The IBOC exciter produced magnitude and phase components that are input to a DX-10 transmitter supplied by Harris Corporation. The phase signal was input to the external oscillator input on the Harris DX-10. The magnitude signal produced by the exciter contains the DC bias needed for MF broadcasting. Although the Harris DX-10 transmitter usually provides the DC bias, the modulation index and the level of the digital signal relative to the analog signal could be conveniently and precisely controlled by having the exciter provide it.

A modulation index was adjusted to be consistent with normal operating levels (-99, +125%). This level refers to the modulation of the analog signal only. The modulation levels were checked by observing the Harris DX-10 transmitter modulation-monitor sample signal, and the signal received at the test van, with an oscilloscope.

The signal from the Harris DX-10 transmitter was sent to the antenna tuning unit (“ATU”) using a 580 foot (177 meter) section of Andrew LDF6-50 Heliax coaxial cable. The output from the antenna tuning unit was input to the transmit antenna. Central Tower Corporation supplied the transmit antenna, which is 150 feet (46 meters) high and base-fed. The antenna has a ground system consisting of 120, 150’ buried radials.

4.2.3 Van Configuration

Mobile test platforms were created to collect data while performing field tests. Test vans were modified to support the equipment and interfaces shown in Figure 24. Test data is acquired and stored using a proprietary Field Test PC application. Table 7 describes the manufacturer and model number of the test equipment in the van.

The signal was received through a 31 inch (79 cm) whip antenna mounted on top of the test van. The antenna was connected to the receiver using a 4.5 foot (1.4 meter) piece of RG62 coaxial cable, which has a characteristic impedance of 93 ohms. This particular antenna and cable were used because they are typical of equipment on many automobiles.

The Field Test PC provides a graphical user interface ("GUI"), similar to that shown in Figure 25. This application controls and collects data from three sources:

- GPS receiver
- Spectrum analyzer
- DSB receiver

4.2.3.1 GPS Receiver Data and Processing

The following data is collected by the GPS receiver over an RS-232 interface[3]:

- GPS time
- GPS position (latitude and longitude)

During setup, the operator enters the position of the transmitter. Current latitude and longitude are then taken directly from the GPS receiver and displayed. The application uses this information to compute and display the current distance from the transmitter.

4.2.3.2 Spectral Data and Processing

The following data is collected by the Spectrum Analyzer over a GPIB interface:[4]

- Lower first-adjacent signal level
- Upper first-adjacent signal level
- Lower second-adjacent signal level
- Upper second-adjacent signal level
- Desired signal level

This data is then displayed directly by the Field Test PC application.

4.2.3.3 DSB Receiver Data and Processing

The following data is collected from the DSB receiver over an RS-232 interface:

- Desired signal strength
- DSB receiver audio mode (digital or analog)
- Cumulative blend counter, which increments whenever the receiver changes its blend status.

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[3] RS-232 is an industry standard serial communications link used by PCs and test equipment.

[4] GPIB is a communications protocol and interface used by PCs to communicate with test equipment.

4.2.3.4 PC Application

This application displays new data from each device every eight seconds. All data shown on the display is also stored to a file. The data stored in this file is then re-formatted to generate a strip-chart recording, which plots the variation of select parameters with time over the length of the test.

4.2.3.5 Video Processing and Storage

Video cameras are mounted on the front and back of each test van. The output from each camera, along with the video display from the spectrum analyzer, are multiplexed into one image by a quad-screen controller, and recorded on videotape. The operator keeps logs to coordinate the stored images with the data collected by the Field Test PC application.

4.2.3.6 Audio Processing and Storage

During Digital Coverage testing, the Akai DR8 digital audio recorder is capable of simultaneously recording audio from the Delco and IBOC receivers. For First-Adjacent and Host Compatibility Testing, the digital audio recorder is capable of simultaneously recording audio from all analog test receivers and the IBOC receiver. All audio and video equipment is controlled manually.

TABLE 7

Test Equipment Manufacturer and Model numbers

Type	Manufacturer	Model
Spectrum Analyzer	Hewlett Packard	HP-8591
Video Multiplexer	Capture	CPT-MQ4
VCR	AVE	RT195
Video Camera(s)	Marshall	V1212BNC
GPS Receiver	Garmin	GPS II
Digital Recorder	Akai	DR8 Hard Disk
Car Stereo	Delco	16195167

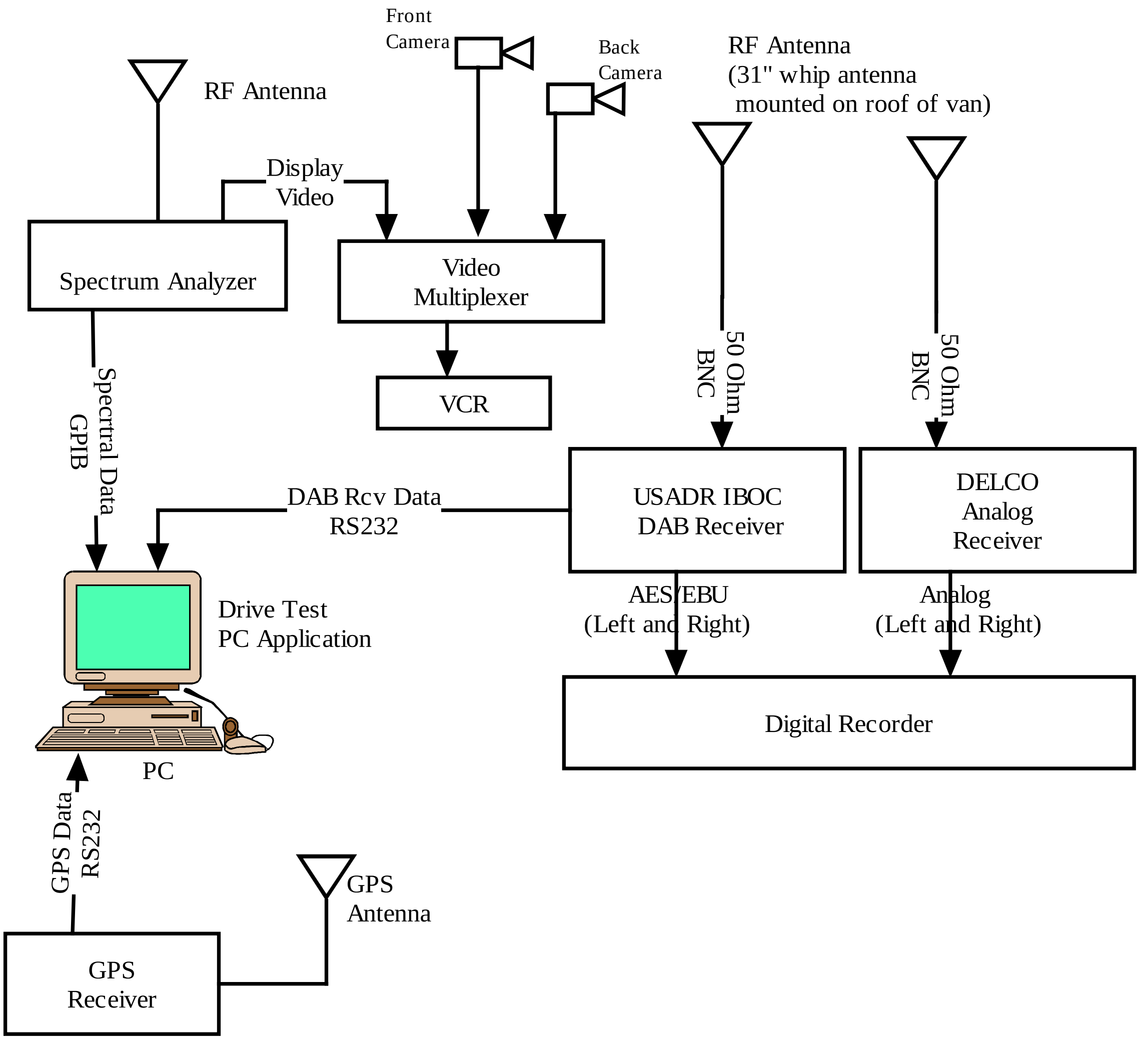
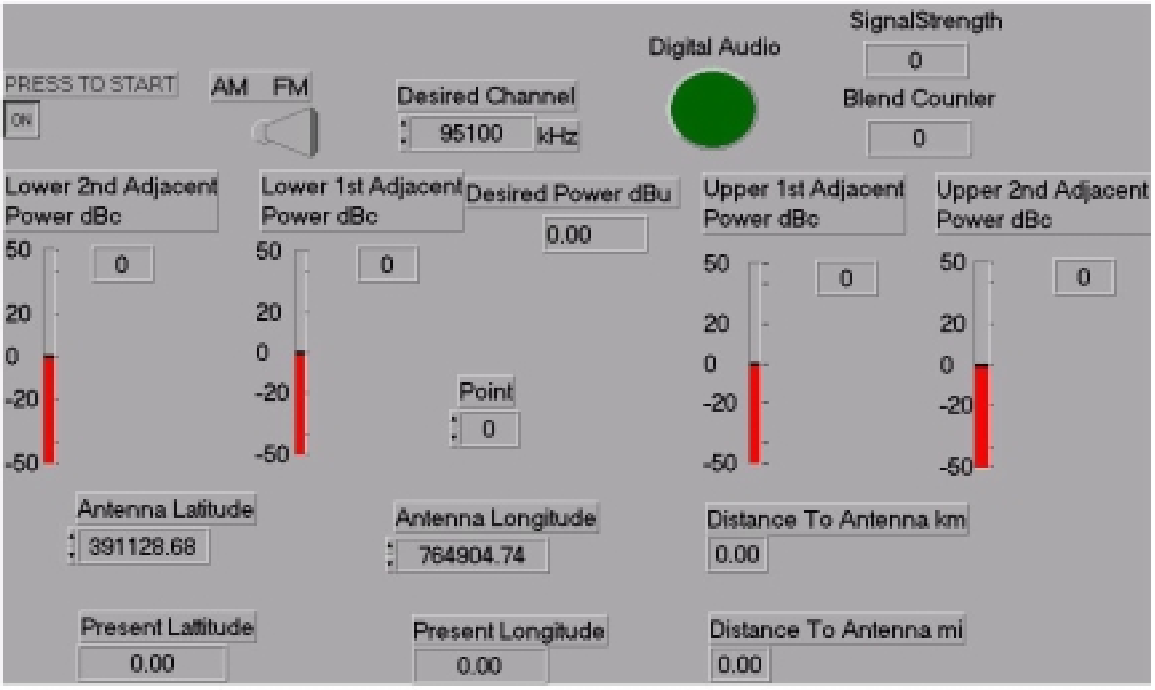


FIGURE 24

Test Van Equipment Setup



PRESS TO START ON

AM FM

Desired Channel 95100 kHz

Digital Audio

SignalStrength 0

Blend Counter 0

Lower 2nd Adjacent Power dBc 0

Lower 1st Adjacent Power dBc 0

Desired Power dBu 0.00

Upper 1st Adjacent Power dBc 0

Upper 2nd Adjacent Power dBc 0

Point 0

Antenna Latitude 391128.68

Antenna Longitude 764904.74

Distance To Antenna km 0.00

Present Latitude 0.00

Present Longitude 0.00

Distance To Antenna mi 0.00

FIGURE 25

Field Test PC Application Display (GUI)

4.3 Digital Coverage Test

4.3.1 Overview

This test measured the digital coverage of the WD2XAM hybrid IBOC signal. During the test the following information was stored:

- Data from the Field Test PC application
- Video from the spectrum analyzer
- Video from the front and back cameras
- Audio from the Delco and IBOC receivers

4.3.2 Route Selection

The following steps were followed to create the routes traveled by the test vans:

- Radials were plotted for the selected azimuth lines from the transmitter site.
- The shortest driving routes were selected to approximate the desired radials.[5]
- Driving instructions from commercial mapping software were obtained for each route.
- Efforts were made to route the van through areas of varying terrain, with urban and suburban population densities.

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[5] Preferences were given to major roads along each route.

4.3.3 Test Procedure

- At the starting location, tune the PC, the IBOC receiver, and the Delco receiver to the desired operating frequency. Enter the GPS coordinates of the transmitter site into the PC. Load the recording media into the Digital Audio Recorder, set the analog audio levels, and label the audio cut. Place a tape into the VCR and setup to record.
- All notes, tapes, and data should have the same time reference, which is derived from the GPS. Be sure all clocks are synchronized.
- Simultaneously begin recording on the VCR, Digital Audio Recorder, and PC.
- Follow driving instructions for the selected radial. Proceed to the end of the planned route, or to a point several miles beyond the edge of digital coverage.
- Close all files, and remove and mark all tapes.
- Repeat steps for all radials.

4.3.4 Test Results

Figure 26 shows results of the coverage tests performed. This map, using data recorded by the Field Test PC application, color codes the audio mode of the IBOC receiver along each field test radial. The colors signify three main regions of IBOC coverage:

- Region 1 (green) indicates the portion of the radial where digital audio is virtually uninterrupted;
- Region 2 (yellow) indicates the portion of the radial where the audio is blending between analog and digital;
- Region 3 (red) indicates the portion of the radial where digital audio is no longer available, and the receiver has blended to analog.

IBOC field performance may be further illustrated by analyzing the full suite of test data recorded along each of the radials. For illustration purposes, one of these radials was selected for analysis in this report: the radial that runs northeast along Route 71 away from Cincinnati.

The test data, presented via strip-chart recording comprised of data logged by the Field Test PC application, is shown in Figure 27. The strip chart displays the variation of select parameters with time over the entire length of the radial. The following parameters are included on the strip chart:

- Desired signal strength, in mV/m (red)
- Upper (blue) and lower (yellow) first-adjacent signal strength, in mV/m
- Upper (black) and lower (magenta) second-adjacent signal strength, in mV/m
- Distance from the transmitter, in km (orange)
- Receiver audio mode, digital or analog (green)

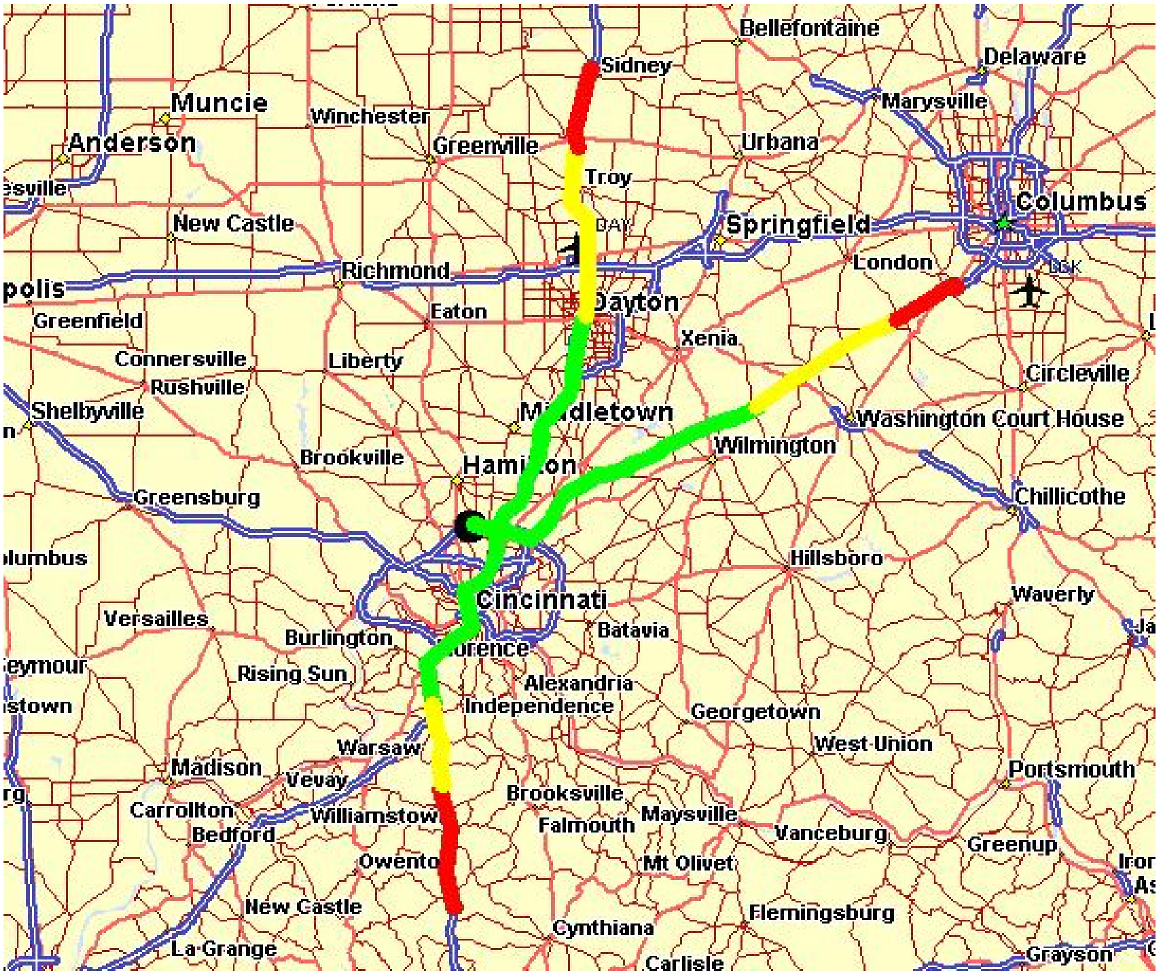

FIGURE 26

WD2XAM AM IBOC Coverage Map

Scale: 1 inch = 20 miles
1 cm = 12.7 km

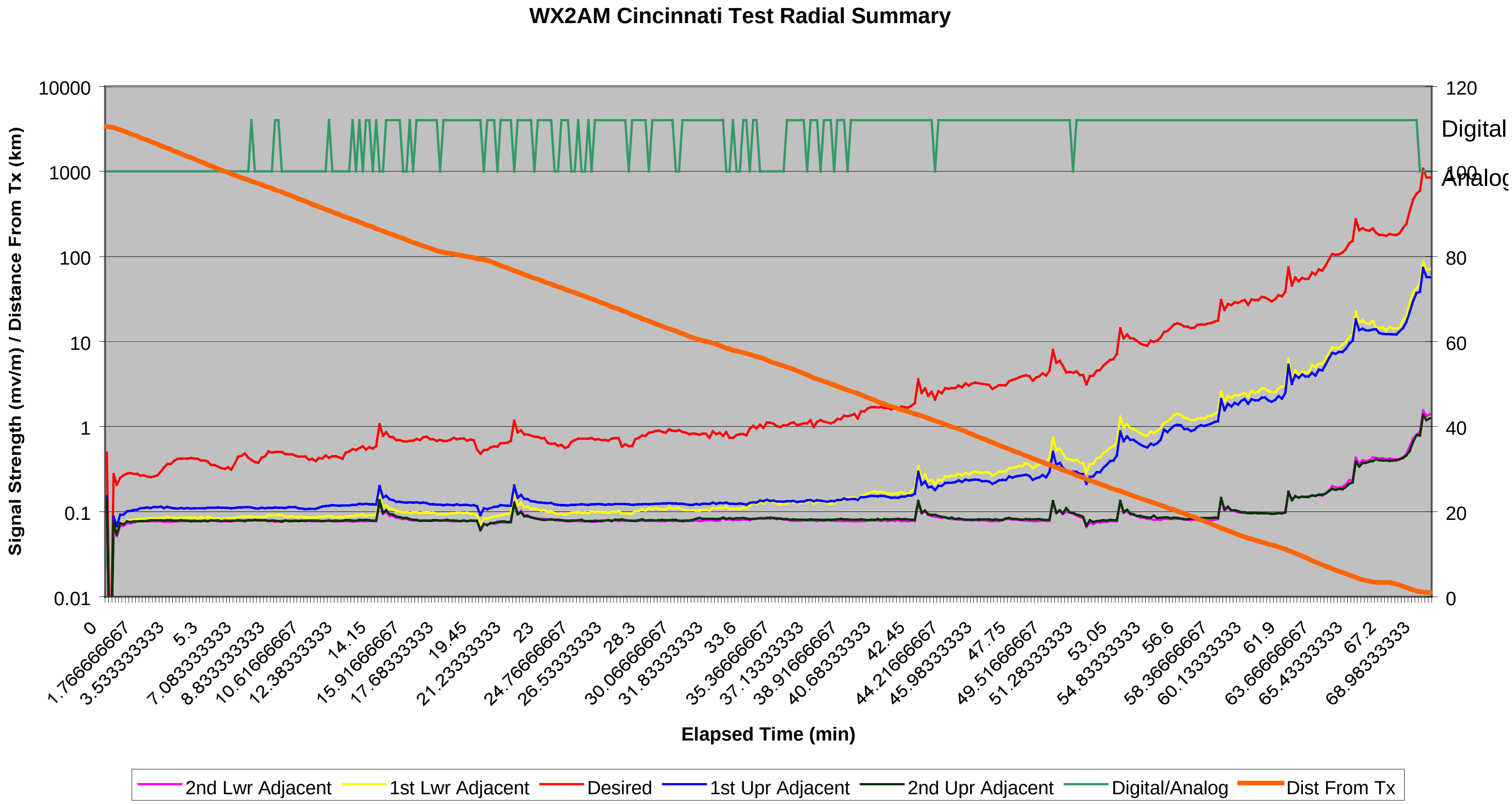

FIGURE 27

WD2XAM MF IBOC Coverage Map

Conversion of the desired signal level, as measured by the spectrum analyzer in dBm, to field strength in mV/m, was accomplished by taking measurements at several locations using the spectrum analyzer and a Potomac Instruments FIM-41 field strength meter, and calculating an appropriate conversion factor. From these measurements the following conversion formula has been obtained.

Field Strength (V/m) = 3.7 * 10^(Spectrum Analyzer Measurement in dBm / 21).

Figure 27 shows what appears to be first adjacent interferers, but actually these are only portions of the desired DSB sidebands being measured

As can be seen from these figures, the coverage of the digital signal extends 90 km from the transmitter. The field strength where the system begins to blend frequently is approximated at 1 mV/m and where the signal no longer blends back to digital is approximated at 0.6 mV/m. The occasional outages of the digital signal during the route are due to particularly severe grounded conductive structures.

4 Conclusions

These field tests demonstrate that the MF IBOC system delivered, within a 20 kHz MF channel, a high quality “FM Like” stereo digital broadcast. The DSB signal was free from noise, distortion, and delivered a digital signal to approximately the 1 mV/m signal with minimal blending to analog. Beyond the 0.6 mV/m signal the receiver operated primarily in the analog mode.