NRSC REPORT

NATIONAL RADIO SYSTEMS COMMITTEE

NRSC-R204
Evaluation of the iBiquity Digital Corporation IBOC System – Part 2 – AM IBOC
April 6, 2002

Part I - Report

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FOREWORD

NRSC-R204, Evaluation of the iBiquity Digital Corporation IBOC System – Part 2 – AM IBOC, documents the NRSC's evaluation of the AM IBOC system which was subsequently selected by the FCC in October 2002 as the technology that will permit AM radio broadcasters to introduce digital operations. The DAB Subcommittee chairman at the time of adoption of NRSC-R204 was Milford Smith; the NRSC chairman at the time of adoption was Charles Morgan.

The NRSC is jointly sponsored by the Consumer Electronics Association and the National Association of Broadcasters. It serves as an industry-wide standards-setting body for technical aspects of terrestrial over-the-air radio broadcasting systems in the United States.

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DAB Subcommittee

EVALUATION OF THE iBiquity DIGITAL CORPORATION IBOC SYSTEM

Part 2 – AM IBOC

**Report from the
Evaluation Working Group
Dr. H. Donald Messer, Chairman**

(as adopted by the Subcommittee on April 6, 2002)

Sponsored by the Consumer Electronics Association and the National Association of Broadcasters

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1 INTRODUCTION

This report on the performance and compatibility of iBiquity Digital Corporation's ("iBiquity's") AM in-band/on-channel (IBOC) digital radio system has been developed by the Evaluation Working Group (EWG, Table 1), Dr. H. Donald Messer, Chairman, of the National Radio Systems Committee's (NRSC's) Digital Audio Broadcasting (DAB) Subcommittee.

Table 1. Evaluation Working Group (EWG) participants†

ORGANIZATION	REPRESENTATIVE
Broadcast Signal Lab	David Maxson
Consumer Electronics Association	Dave Wilson, Director, Engineering (Secretary)
Greater Media, Inc.	Milford K. Smith, Vice President, Engineering
iBiquity Digital Corporation	Glynn Walden, Vice President Broadcast Engineering Albert Shuldiner, Esq., Vice President and General Counsel Greg Nease, Systems Integration & Verification Dr. Ellyn Sheffield
International Association of Audio Information Services (IAAIS)	Dave Andrews, Chief Technology Officer
International Broadcasting Bureau	Dr. H. Donald Messer, Chief, Spectrum Management (Chairman)
Journal Broadcast Group	Andy Laird, Vice President, Radio Engineering
National Association of Broadcasters	John Marino, Vice President, Science & Technology David Layer, Director, Advanced Engineering
National Public Radio	Jan Andrews, Senior Engineer
Susquehanna Radio Co.	Charles Morgan, Sr. Vice President
T. Keller Corporation	Tom Keller, President
Wye Consulting	Tom Mock, President

† *Additional organizations/individuals participating on a less-frequent basis included Advanced Television Technology Center, Clear Channel Communications, C. Crane Company, Dolby Laboratories, Mario Hieb and Sony.*

This work was done in pursuit of the DAB Subcommittee's Goals and Objectives, included in this report as Appendix A. The purpose of this NRSC IBOC evaluation is to determine if the iBiquity AM IBOC system is a significant improvement over the analog systems currently in use, and, to confirm that the impact of the IBOC digital sidebands on existing analog signals is both minimal and acceptable. Note that this report is not, itself, a standard for IBOC digital radio.

The evaluation effort culminating in this report is the latest in a series of similar evaluations done by the Subcommittee, starting in the 1995-96 timeframe (in conjunction with EIA/CEG, now CEA) on "first generation" IBOC systems,[1] then in 2000 when a "phase 1" evaluation of "next generation" IBOC systems was conducted.[2] This current evaluation effort is the most comprehensive one yet, and is the first to be based on a full set of AM IBOC system laboratory and field test data collected in strict accordance

[1] The 1995-96 DAB evaluation with EIA was conducted on four different types of DAB systems—terrestrial new-band (specifically, the Eureka-147 system), satellite (the VOA-JPL S-band system), terrestrial in-band/adjacent channel (IBAC), and terrestrial IBOC (both AM and FM). A report on the test results was published by the Consumer Electronics Manufacturers Association, see "Technical Evaluations of Digital Audio Radio Systems, Final Report," December 1997.

[2] The NRSC's "phase 1" IBOC evaluation was based on preliminary performance data submitted by Lucent Digital Radio (LDR), and USA Digital Radio (USADR); detailed reports on the results of these evaluations were published by the NRSC, see "DAB Subcommittee – Evaluation of Lucent Digital Radio's Submission to the NRSC DAB Subcommittee of Selected Laboratory and Field Test Results," April 8, 2000, and "DAB Subcommittee – Evaluation of USA Digital Radio's Submission to the NRSC DAB Subcommittee of Selected Laboratory and Field Test Results," April 8, 2000.

with NRSC-developed test procedures. Part 1 of this report (on iBiquity's FM IBOC technology) was adopted by the DAB Subcommittee on November 29, 2001.[3]

Preparatory work on this report began well in advance of the receipt of test data to be analyzed. The EWG first convened in its present form (and under its present leadership) in March 1999, and met 10 times that year to develop evaluation criteria upon which to judge candidate IBOC DAB systems, as well as an Evaluation Guidelines document[4] which outlined the process by which the EWG would evaluate the data submissions expected from LDR and USADR in December of that year (the so-called "phase 1" evaluation).[5] In the first three months of 2000, the EWG met another 10 times, resulting in the release of the two evaluation reports previously cited.[6]

The NRSC's focus then shifted to development of test procedures for the next phase of the evaluation, resulting in the development of AM and FM IBOC test procedures by the DAB Subcommittee's Test Procedures Working Group (TPWG).[7] The EWG re-convened on May 8, 2001 to begin preparing for receipt of data on iBiquity's AM and FM IBOC systems. Between May and August of 2001 the group reviewed and refined its evaluation criteria based both on the experience gained from the phase 1 evaluation as well as on operational details of the iBiquity IBOC technology (*e.g.*, its "blend to analog" feature). Data evaluation for the AM IBOC system began when, on January 4, 2002, a test data report prepared by iBiquity, the Advanced Television Technology Center (ATTC), Xetron Corporation, and Dynastat was delivered to the NRSC ("AM IBOC Test Data Report").[8]

The information contained in the data report was collected by either iBiquity, the ATTC or Xetron in the presence of one or more NRSC observers (Table 2, retained by NAB and CEA), broadcast consulting engineers familiar with both the NRSC's AM IBOC test procedures as well as the underlying technologies and measurement techniques. Subjective evaluations performed on portions of this data were conducted by Dynastat and are documented in the test data report, as well. The NRSC observers ensured that the tests were conducted according to the NRSC's procedures, that the data recorded (and ultimately submitted to the NRSC) was in fact the data obtained, and in addition because of their expertise were able to help resolve testing issues as they arose, often in consultation with NAB and CEA staff and the DAB Subcommittee's Test Program Steering Committee.

Table 2. NRSC observers

ORGANIZATION	REPRESENTATIVE(S)	TASKS
Denny & Associates	Alan Rosner, P.E. Robert G. Mallery	Principal field test observers – east coast and midwest
T. Keller Corporation	Tom Keller, President	Principal lab test observer
Hammett & Edison	Stan Salek, P.E. Robert D. Weller, P.E.	Principal field test observers – west coast

All of the conclusions and recommendations that follow in this evaluation report are based upon the information contained in the AM IBOC Test Data Report, upon information provided to the EWG from the NRSC observers, and upon subsequent analysis of this information. By and large, compatibility

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[3] *Evaluation of the iBiquity Digital Corporation IBOC System, Part 1 – FM IBOC,* National Radio Systems Committee DAB Subcommittee, November 29, 2001.
[4] See "DAB Subcommittee – In-band/on-channel (IBOC) Digital Audio Broadcasting (DAB) System Evaluation Guidelines," May 25, 1999 (published by the NRSC).
[5] USADR submitted a test report to the NRSC on December 15, 1999; LDR's submission was received on January 24, 2000.
[6] See footnote 2.
[7] The AM IBOC test procedures are included with this report as Appendices B and C.
[8] iBiquity Digital Corporation, *Third Report to the National Radio Systems Committee, AM IBOC DAB Laboratory and Field Testing,* January 4, 2002 ("AM IBOC Test Data Report"). See Appendix G for a table of contents of this data report.

with existing analog services and the coverage afforded the new, digital service were deemed of greater importance to the EWG than were some of the other aspects of IBOC system evaluation such as amount of auxiliary data capacity. This evaluation report is solely a technical evaluation and does not address costs of transition nor the costs of receiver implementation.

There are some important distinctions between the AM IBOC evaluation discussed in this report and the FM IBOC evaluation conducted by the NRSC (and reported on in Part 1) that need to be made:

- Radio broadcasters had much more operational experience with the FM IBOC system going into the NRSC test program than was the case with the AM IBOC system. This fact was reflected in the NRSC's ability to better craft test procedures and interpret the resulting data for FM IBOC than has proven possible for AM IBOC, and is responsible in part for there being (as will be seen) more unanswered questions for AM IBOC at the conclusion of the evaluation than was the case for FM IBOC.

- Signal propagation in the AM broadcasting service, by virtue of its use of medium wave broadcast frequencies, is far more complicated to analyze and predict than it is for FM, which operates in the VHF band and is essentially a "line of sight" service. As will be discussed in more detail below, while much has been learned about AM IBOC as a result of this evaluation, there are some unanswered questions that can only be answered by deploying the AM IBOC service on a larger scale than was possible for this test program. Such deployment is the only way to characterize a medium-wave service like AM IBOC with real certainty.

- The audio program material at the commercial AM stations used for AM IBOC testing was not able to fully demonstrate the higher fidelity, two-channel stereo capabilities of the AM IBOC system. This hampered the ability of the test program to highlight the enhanced audio capabilities of AM IBOC compared to existing analog services using "real-world" field test recordings. The only field test results that adequately demonstrate this difference were obtained at experimental station WD2XAM which utilized high fidelity, two channel stereo program material.

1.1 Test parameters

Detailed laboratory and field test procedures were developed by the DAB Subcommittee and are included with this report as Appendices B and C, respectively (these are discussed in greater detail in Section 3). These tests were conducted on the "baseline" iBiquity AM IBOC system (Table 3), commonly referred to as the "hybrid" mode of operation, generally recognized to be more technically challenging to implement than is the all-digital mode.[9] In addition, the hybrid mode represents the first step in the transition from analog to digital radio broadcasting and as such there is an immediate need to characterize its behavior.

[9] See AM IBOC Test Data Report, Appendix A, for information on the various modes of operation. Note that the emission limit "masks" included in this appendix (Figures 6-1 and 6-2) are preliminary and subject to change.

Table 3. iBiquity AM IBOC system – as tested

PARAMETER	VALUE
Main channel digital audio bit rate	36 kbps (16 kbps enhanced audio, 20 kbps core audio)[10]
IBOC digital sideband bandwidth (per side)	15 kHz[11]
IBOC digital sideband power level (total, with respect to total analog power level)	-30.8 dB (tertiary, 0-5 kHz from analog carrier) -27 dB (secondary, 5-10 kHz from analog carrier) -13 dB (primary, 10-15 kHz from analog carrier)
Auxiliary data rate (dedicated)	0.4 kbps[12]

1.2 Future work

There is one immediate IBOC-related task still facing the NRSC. All of the test results analyzed in this report were obtained on a version of the iBiquity AM IBOC system implemented with MPEG-2 AAC perceptual audio coding. Because iBiquity has stated that it intends to release its system commercially with its own proprietary audio coding technology (based on PAC, developed by Lucent Technologies), it has agreed to provide the NRSC with test results for its versions of the AM and FM IBOC systems that include this proprietary audio coding technology. Testing to obtain these results is currently underway, and these results will be evaluated by the NRSC when they become available.

The NRSC is, if requested, prepared to work with iBiquity and the FCC on further characterization of the nighttime performance of the AM IBOC system, when skywave propagation is present.

[10] A broadcaster can adjust the main channel digital audio bit rate down to 20 kbps in order to gain an additional 16 kbps of auxiliary data capacity. Doing this requires that the digital audio be monophonic. See AM IBOC Test Data Report, pg. 18. Also, a broadcaster can adjust the main channel digital audio bit rate up to 56 kbps at the expense of some error correction, thus resulting in a higher fidelity but less robust signal. See AM IBOC Test Data Report, Appendix A, pp. 7-8. None of these features were tested by the NRSC.

[11] See AM IBOC Test Data Report, Appendix A, pp. 17-18, for a precise spectral occupancy description.

[12] See footnote 10.

2 CONCLUSIONS and RECOMMENDATIONS

NRSC tests performed on the iBiquity AM IBOC system show that AM broadcasters have an opportunity to benefit significantly from this technology. IBOC offers a chance to revitalize AM broadcasting – offering near FM-quality stereo reception. Within the FCC protected coverage area of an AM station, broadcasters will not only be able to provide listeners an existing analog signal compatible with today's AM radios, but also a digital signal which will provide for IBOC receivers, immunity from noise, enhanced frequency response and full stereo.

The NRSC's evaluation of AM IBOC confirms that the iBiquity AM IBOC system will allow AM broadcasters to provide listeners with two-channel stereo audio rivaling existing analog FM stereo in quality, and that under daytime propagation conditions the digital performance of the AM IBOC system represents a significant improvement over today's existing analog services. AM IBOC will also make it possible for AM broadcasters for the first time to provide data services, and as with FM IBOC, puts broadcasters on an efficient path to an all-digital service.

Compared to analog AM, AM IBOC offers improved immunity from reception problems due to overhead power lines, grounded conductive structures (such as highway overpasses) and other forms of electromagnetic interference that plague existing services.

In order to enjoy the dramatic improvements that AM IBOC has to offer, AM broadcasters must consider a system specific trade-off. AM IBOC places digital carriers up to 15 kHz on either side of an AM station's main carrier. NRSC tests confirmed that a station transmitting an IBOC signal encounters very little, if any, interference to its own received signal. Although the IBOC digital carriers operate at very low power levels, in some cases stations on first adjacent channels may receive noticeable interference under certain listening conditions.

In order to justify this tradeoff, it must be recognized that the AM band has been plagued for decades with high levels of natural and man-made interference. Additionally, station allocations over the years have in many cases worsened the interference problem. The FCC made a valiant effort to improve the AM band in the 1980s. Rules were changed and the expanded band was opened allowing stations to move to this new spectrum with the hope of alleviating at least some of the interference on the original AM channels. AM stereo operation was approved but never fully implemented. These efforts have in reality accomplished very little toward improving AM listening. Moreover, the audio bandwidth of most AM receivers has been reduced to less than 3 kHz – as shown by the receiver characterization tests performed during this testing program. Therefore many AM listeners today are faced with listening to their favorite AM stations with less than telephone-quality audio bandwidth on these very narrow-band receivers.

AM broadcasters are now offered an opportunity with IBOC to take steps that have the potential to dramatically improve the AM listening experience. Generally, interference attributable to IBOC on first adjacent channels should only be noticeable in cases where listeners are located outside the protected interference-free contour and should not cause significant AM listening problems during daytime hours. This is shown by the test results in Section 4 of this report.

No test results were obtained by the NRSC, nor were they requested from iBiquity, on skywave reception. However due to the propagation mechanisms that support skywave reception, the NRSC expects that first adjacent interference may pose potential problems for listeners during nighttime hours. Additional testing would be needed before the NRSC could further comment on the nighttime compatibility of hybrid AM IBOC. The NRSC therefore recommends that stations desiring to operate with AM IBOC do so during daytime hours only.

Many AM broadcasters have long recognized the differences between day and night operation and listening habits. A vast number of AM stations operate with different directional patterns and power levels during day and night. It should not prove any more burdensome to switch off the IBOC digital signal during nighttime hours. This compromise will facilitate a rapid introduction of IBOC to the AM band with minimal interference concerns.

The NRSC feels that iBiquity has developed an attractive solution to improve AM listening based on the best of today's available technology. Considering what it has learned during these tests, the NRSC recommends that the iBiquity AM IBOC system as tested by the NRSC should be authorized by the FCC as an enhancement to AM broadcasting in the US as a daytime-only service. By authorizing this digital service as daytime only, AM listeners will immediately derive the benefit of improved quality and durability with minimal potential of additional interference. Night service can either be revisited by the Commission at a future date or made available once the iBiquity "all digital" mode is authorized.

2.1 Digital performance

Given here are the NRSC's findings for each of the eight digital performance evaluation criteria. Each of these findings is elaborated on in Section 4 below:

2.1.1 Audio quality

The iBiquity hybrid AM IBOC system with MPEG-2 AAC perceptual audio coding demonstrates significantly improved audio quality compared to existing analog AM in mobile listening environments (as tested in the field), and in a variety of impairment conditions tested in the laboratory. Laboratory tests have further shown that under these impaired conditions, AM IBOC audio quality is comparable to that achieved by analog FM radio in an unimpaired environment. Since the final version of this system will utilize a proprietary iBiquity perceptual audio coding algorithm and not MPEG-2 AAC, no direct findings on the unimpaired audio quality of the final system can be made at this time.

2.1.2 Service area

NRSC test results indicate that the hybrid AM IBOC digital coverage during the daytime is comparable to analog coverage along radial routes tested. Due to AM IBOC's improved resistance to various types of interference (e.g., co- and adjacent channel, impulse noise, power lines), AM IBOC service may be available in areas where analog service is currently of unacceptable quality due to such interference. At night, digital coverage fell short of the predicted nighttime interference-free (NIF) contours and the system had blended to analog before reaching this contour. In general, these results demonstrate that the adjacent interference experienced by the test stations during night operation restrict digital coverage.

2.1.3 Durability

NRSC test results demonstrate that the iBiquity hybrid AM IBOC system, compared to analog AM, is substantially more robust under impulse noise and co- and adjacent channel interference conditions.

2.1.4 Acquisition performance

The acquisition performance of the iBiquity hybrid AM IBOC system is identical to that of an analog AM radio since, by design, an IBOC receiver initially acquires the analog portion of the hybrid AM IBOC signal.

2.1.5 Auxiliary data capacity

The iBiquity hybrid AM IBOC system design incorporates an auxiliary data transmission feature with a minimum capacity of 0.4 kbps. This system feature was not tested by the NRSC. Since existing AM analog services do not support the broadcast of auxiliary data, this represents a new capability for the AM broadcast service.

2.1.6 Behavior as signal degrades

NRSC testing has demonstrated that the iBiquity prototype hybrid AM IBOC receiver's audio during the blend process is perceived to have either significantly better audio quality (enhanced to core) or similar audio quality (core to analog) as does the analog audio.

2.1.7 Stereo separation

AM IBOC receivers are expected to exhibit superior stereo separation compared to analog AM receivers (the vast majority of which offer no stereo capability at all) when reception conditions allow for the AM IBOC receiver to make full use of the enhanced digital audio data stream.

2.1.8 Flexibility

There are a significant number of features in the iBiquity AM IBOC system that should provide for system flexibility and should offer broadcasters and receiver manufacturers opportunities to customize services and equipment for their particular goals, and offer the possibility of performance improvements in the future. None of these features (except for establishing the subjective audio quality of both 36 kbps and 20 kbps audio) were tested by the NRSC.

2.2 Analog compatibility

These findings are based on the test results that were collected during the NRSC testing process, using the four receivers selected for this purpose.[13]

2.2.1 Host compatibility

For the conditions tested, the AM IBOC system has little effect on the host analog signal. The amount of interference to the host analog signal is receiver dependent. The narrow bandwidth automobile receivers were found to be the least sensitive to the digital signal. The wider bandwidth hi fi and portable radios were found to be more sensitive to the digital signal. Each receiver's frequency and phase response symmetry plays a part in its host compatibility.

The test results suggest that, although the introduction of AM IBOC will be noticeable to some listeners of the host analog station using certain analog receivers, these listeners are not expected to find their audio quality sufficiently degraded to impact listening.

2.2.2 Co-channel compatibility

The introduction of AM IBOC is not expected to have any impact on the level of co-channel interference due to the design of the AM IBOC system. Co-channel compatibility was not tested by the NRSC.

2.2.3 1st adjacent compatibility

Overall conclusions about 1st adjacent compatibility of the AM IBOC system are that the interference caused by the introduction of the IBOC signal is predominantly determined by the D/U ratio. Current FCC allocation rules permit 6 dB D/U ratios at an AM station's daytime protected contour.[14] At the 10 dB D/U point, all AM radios tested, when receiving speech programming, are unable to provide audio quality that would satisfy at least half of all listeners whether or not an interfering first adjacent station is broadcasting the AM IBOC signal. At the 15 dB D/U point existing automobile radios provide listenable audio, and would not be significantly affected by the introduction of IBOC; however, today's hi fi receivers do provide listenable audio that would become unlistenable with the introduction of IBOC. At the same 15 dB D/U point portable radios appear to provide unlistenable audio with or without IBOC. At the 30 dB D/U point, all radios appear to provide listenable audio with or without IBOC.

2.2.4 2nd adjacent compatibility

The data indicate that 2nd adjacent interference from AM IBOC will be receiver and D/U dependent. At the D/U ratios tested, narrowband (typically automobile) receivers are not sensitive to AM IBOC interference, though hi fi and portable receivers (*i.e.,* wideband receivers) will experience

[13] For more information about the receiver selection, see Section 3.4 and Appendix D.
[14] 47 CFR Section 73.37.

interference at the 0 dB D/U ratio, and at negative D/U ratios. Current FCC allocation rules permit 0 dB D/U ratios at an AM station's 5 mV/m groundwave contour.[15]

2.2.5 3rd adjacent compatibility

AM IBOC is not expected to have an impact on the amount of 3rd adjacent channel interference in the AM band, and the test results confirm this.

2.3 "Baseline" mode of operation

The NRSC only studied operation of this system using the baseline parameters (Table 3 above). The conclusions and recommendations in this report apply to that mode of operation only.

[15] 47 CFR Section 73.37.

3 NRSC TEST PROGRAM

In this section, background information on the NRSC's AM IBOC test program is provided, including some of the basic attributes of the iBiquity AM IBOC system that were taken into account when the NRSC test procedures (Appendices B and C to this report) were developed.

To evaluate an IBOC radio system, two basic types of tests are required (done in both the laboratory and the field), both of which are found in the NRSC's IBOC test procedures:

- Performance tests: in the context of the NRSC's test procedures and evaluation reports, "performance tests" (sometimes called "digital performance tests") are those used to establish the performance of the IBOC digital radio system itself. Performance test results are obtained using an IBOC receiver or through direct observation of the received signal.

- Compatibility tests: in the context of the NRSC's IBOC evaluation, "compatibility tests" (sometimes referred to as "analog compatibility tests") are designed to determine the effect that the IBOC digital radio signal has on existing analog signals (main channel audio and subcarriers). Compatibility testing involves observing the performance of analog receivers with IBOC digital sidebands alternately turned on and off; test results are obtained using either analog AM receivers or through direct observation of the received signal.

For each type of test, two basic types of measurements are made:

- Objective measurements: where a parameter such as signal power, signal-to-noise ratio, or error rate is measured, typically by using test equipment designed specifically for that particular measurement (e.g., power meter, error rate test set).

- Subjective measurements: where human interpretation or opinion is used to "measure" system performance or compatibility. In the NRSC test program, subjective measurements involve determining the quality of audio recordings by having people listen to them and rate them according to a pre-defined quality scale.

Subjective evaluation is especially important when trying to assess the quality of IBOC digital audio because the IBOC radio system relies upon perceptual audio coding for audio transmission. The listening experience of audio that has passed through a perceptually coded system is not best characterized by many of the normal objective audio quality measures such as signal-to-noise, distortion, or bandwidth. The instruments used to make such measurements do not adequately respond to the perceptual aspects of the system. This is one of the reasons why the NRSC's test program includes such a comprehensive subjective evaluation component.[16]

The NRSC's AM IBOC test program did not include any tests specifically designed to evaluate the digital performance or host compatibility of the IBOC system under skywave propagation conditions, for example, as distant listeners of a clear-channel AM station might experience at night. In addition, there were no provisions in the test program for evaluating the impact of a skywave IBOC interferer on either analog or IBOC desired signals. Such testing was beyond the scope of the NRSC's accelerated test

[16] See AM IBOC Test Data Report, Appendices E and F, for a detailed description of the subjective testing methodology used in the NRSC's test program.

program, given the highly variable and statistical nature of skywave propagation conditions that make the collection of statistically significant test data extremely difficult and time-consuming.

3.1 iBiquity AM IBOC system

The iBiquity AM IBOC system supports transmission of digital audio and auxiliary digital data within an existing AM channel allocation by placing six groups of digitally modulated carrier signals within and adjacent to an analog AM signal as shown in Figure 1. Because digitally modulated carriers are inserted within the same spectrum occupied by the analog AM signal, the AM IBOC system is not compatible with analog AM stereo signals. Corresponding sideband groups on either side of the carrier (*i.e.,* upper primary and lower primary) are independent in that only one of them is needed for an IBOC receiver to be able to generate digital audio. However, in order to generate stereo (or enhanced fidelity) digital audio the secondary and tertiary sideband groups are needed. Orthogonal frequency division multiplexing ("OFDM") modulation is utilized.

The digital audio modulated onto these OFDM carriers is perceptually coded, allowing for high-quality digital audio using a relatively low bit rate (36 kbps was the digital audio bit rate used for the NRSC tests). At the transmission site, the audio coder creates two audio streams — a "core" stream and an "enhanced" stream — and the system assigns the streams to different parts of the spectrum. The core stream (20 kbps for the system tested by the NRSC) carries monaural audio and the enhanced stream (16 kbps for the system tested by the NRSC) at the broadcaster's option carries enhanced fidelity stereo audio.[17] For the NRSC tests, the audio codec was set to provide stereo audio in the enhanced portion of the audio stream. At the receive site, the listener will hear either enhanced or core digital audio or analog audio depending upon the reception conditions.

[17] The audio bandwidth for the digital audio (both enhanced and core modes) is approximately 15 kHz.

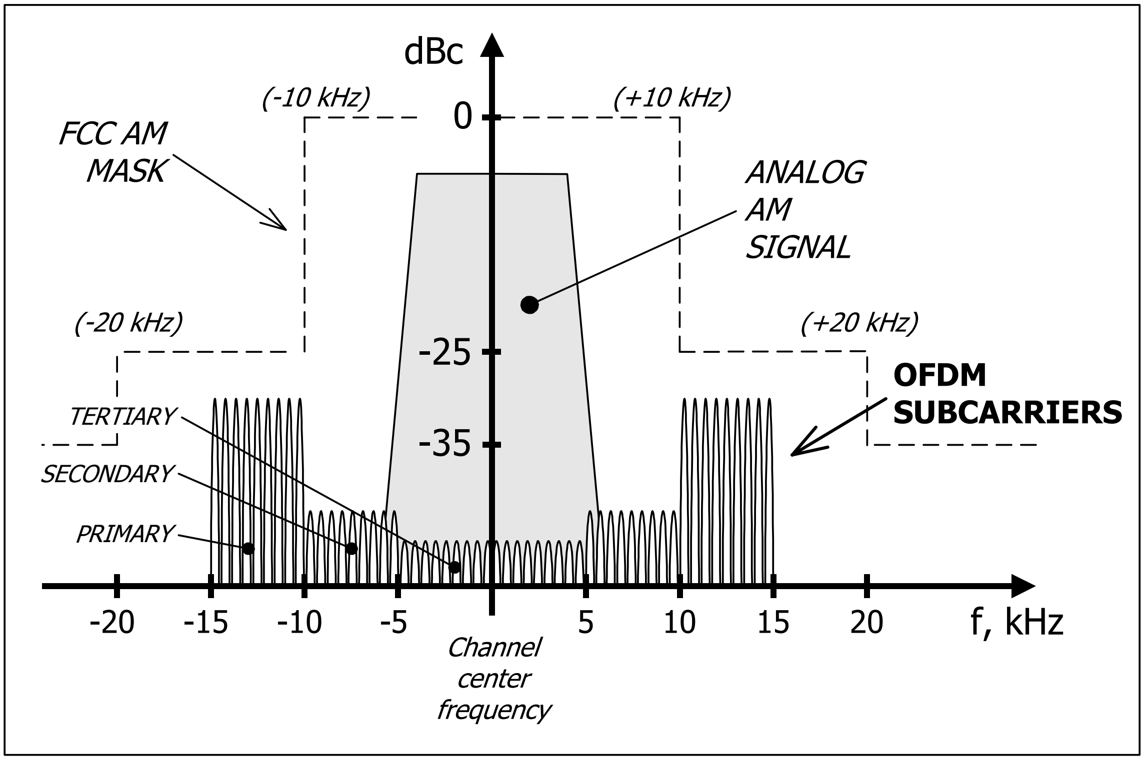

Figure 1. iBiquity AM IBOC system signal spectral power density

A complete description of the AM IBOC signal is given in the AM IBOC Test Data Report.[18] This system incorporates a 4½ second delay between the analog and digital (simulcast) audio signals to improve performance in the presence of certain types of interference, which may affect how broadcasters monitor off-air signals.[19] Some of the specific attributes of this system that influenced the design of the NRSC's test program are listed here:

- Proximity of digital sidebands to 1st-adjacent channel signals: the digital sidebands of the AM IBOC signal are located such that they could potentially interfere with (and receive interference from) a 1st-adjacent analog AM signal (Figure 2). The NRSC test procedures include tests that characterize this behavior, including tests of IBOC performance when there are two 1st-adjacent channel signals, one on either side of the desired signal (hence digital sidebands on both sides of the carrier are experiencing interference).

[18] See AM IBOC Test Data Report, Appendix A ("IBOC AM Transmission Specification").
[19] For additional information on this see AM IBOC Test Data Report, Appendix A, pgs. 5 and 14.

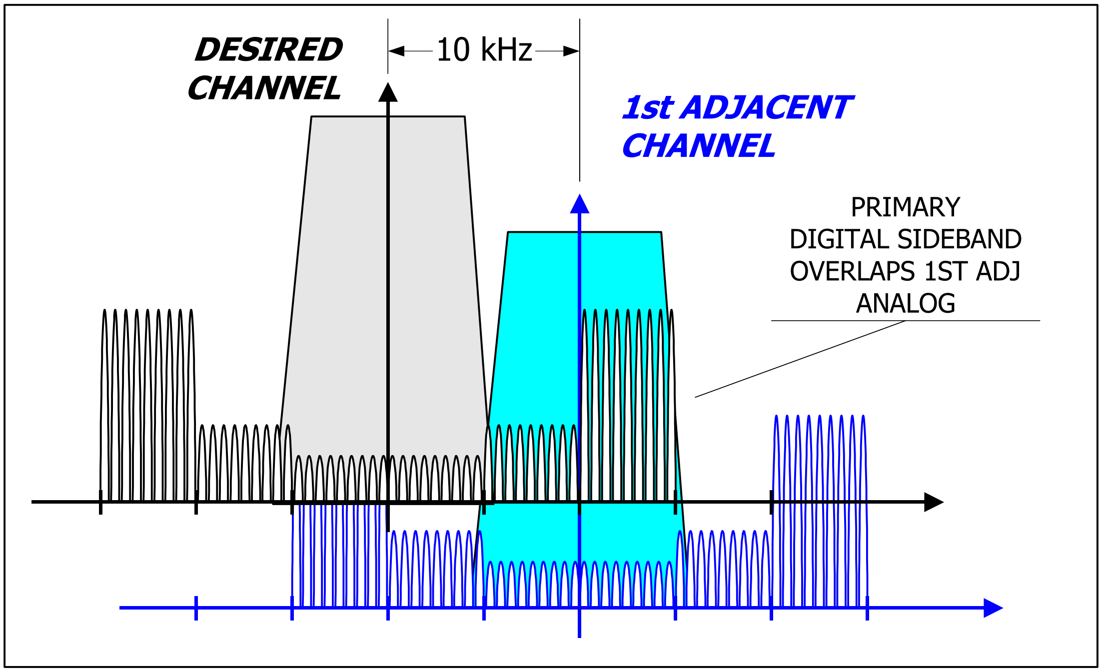

Figure 2. Illustration of potential interference to/from 1st-adjacent analog signals by AM IBOC digital sidebands

- Proximity of digital sidebands to 2nd-adjacent channel signals: the digital sidebands of the AM IBOC signal are located such that they could potentially interfere with (and receive interference from) a 2nd-adjacent AM signal's digital sidebands (Figure 3). The NRSC test procedures include tests that characterize this behavior, including tests of IBOC performance when there are two 2nd-adjacent channel signals, one on either side of the desired signal (hence digital sidebands on both sides of the carrier are experiencing interference).

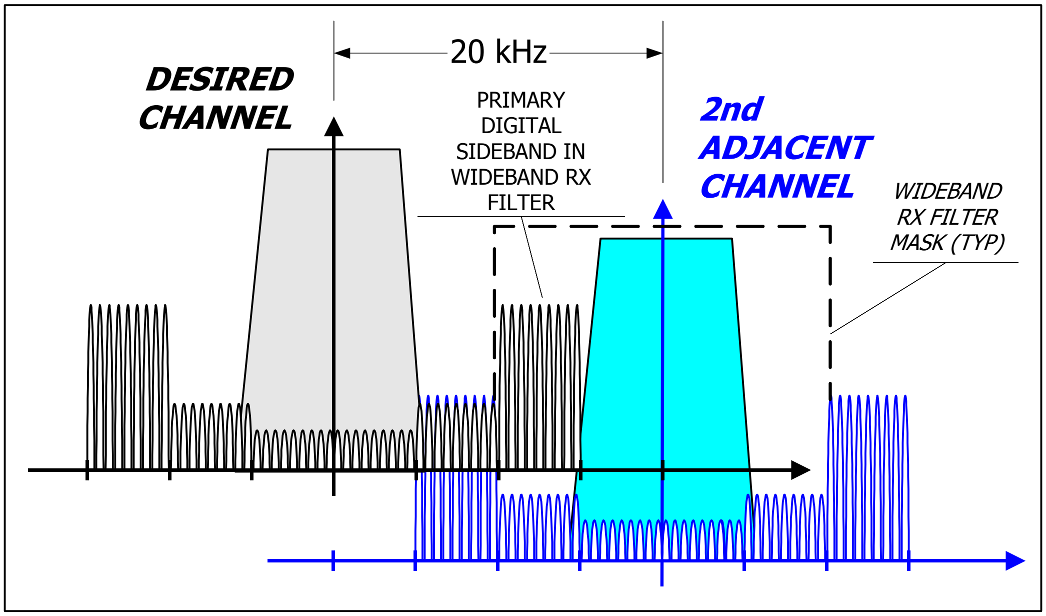

Figure 3. Illustration of potential interference between 2nd-adjacent AM IBOC signals

- Proximity of digital sidebands to 3rd-adjacent channel signals: the digital sidebands of the AM IBOC signal are located such that they could potentially interfere with (and receive interference from) a 3rd-adjacent AM IBOC signal's digital sidebands (Figure 4). The NRSC test procedures include tests that characterize this behavior.

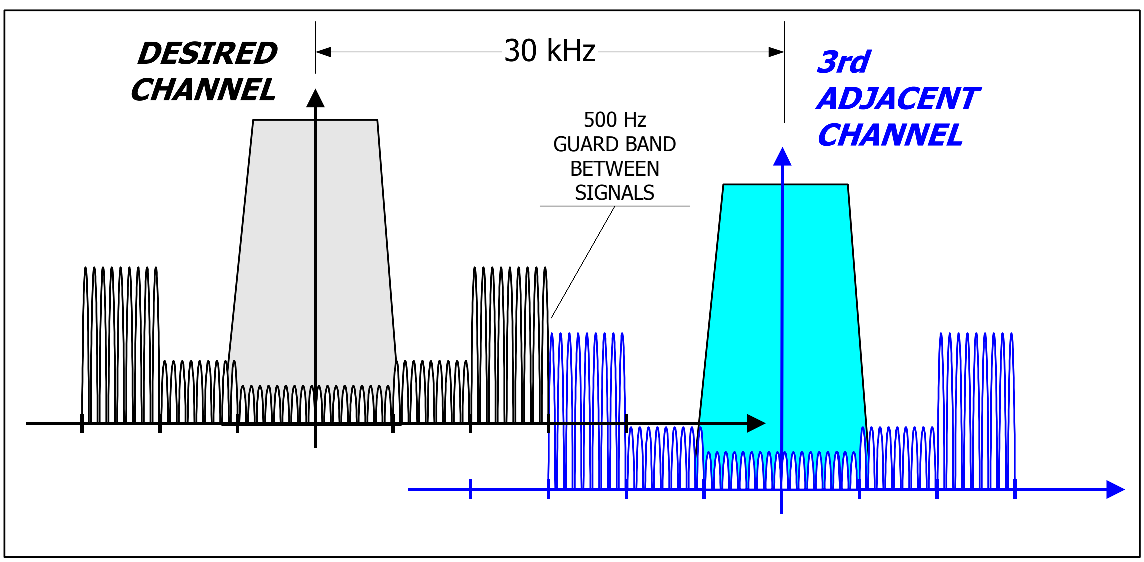

Figure 4. Illustration of potential interference between 3rd-adjacent AM IBOC signals

- Blend from enhanced to core: as discussed above, the audio coder in the iBiquity system creates two digital audio streams — enhanced and core. When all sideband groups (primary, secondary, and tertiary) are receivable, an AM IBOC receiver will decode both of these streams and provide enhanced digital audio quality to the listener. As reception conditions degrade such that the secondary and tertiary sideband groups experience errors but the primary sideband groups are still of acceptable quality, the receiver audio will "blend" from enhanced quality to core quality.

- Blend-to-analog: the iBiquity AM IBOC system simulcasts a radio station's main channel audio signal using the analog AM carrier and IBOC digital sidebands, and under certain circumstances, the IBOC receiver will "blend" back and forth between these two signals. Consequently, depending upon the reception environment, the listener will either hear digital audio (transported over the IBOC digital sidebands) or analog audio (delivered on the AM-modulated analog carrier), with the digital audio being the primary condition.

  The two main circumstances under which an IBOC receiver reverts to analog audio output are during acquisition (*i.e.* when a radio station is first tuned in, an IBOC receiver acquires the analog signal in milliseconds but takes a few seconds to begin decoding the audio on the digital sidebands) or, when reception conditions deteriorate to the point where approximately 10% of the data blocks sent in the digital sidebands are corrupted during transmission. Many of the tests in the NRSC procedures are designed to determine the conditions that cause blend-to-analog to occur in this second circumstance, since at this point the IBOC system essentially reverts to analog AM.

  iBiquity has indicated that the analog section of the prototype IBOC receiver used for the NRSC tests is a "software radio" and has not yet been optimized to the point where it performs commensurate with existing analog radios (automotive radios in particular). Consequently, the NRSC elected not to do any evaluations on the IBOC receiver output after it had blended to analog, but instead, would evaluate the output of an existing analog receiver operating under the same signal conditions as those which resulted in blend-to-analog in the IBOC receiver, when such evaluation was required. Typically, tests specify recording of the IBOC receiver output just before (with respect to the test conditions) it blends to analog, guaranteeing that it will be operating in digital audio mode, and recording of the audio from an existing analog receiver under identical conditions, then these recordings are subjectively evaluated so that digital and analog receiver performance near the (IBOC receiver) point of blend-to-analog can be compared.

3.2 Lab tests

Laboratory tests are fundamental to any characterization of a new broadcast system such as AM IBOC. The controlled and repeatable environment of a laboratory makes it possible to determine how the system behaves with respect to individual factors such as presence or absence of RF noise, or co- and adjacent-channel signals. These factors all exist in the "real world" but because they exist simultaneously and are constantly changing, it is virtually impossible to determine, in the "real world," the effect each has on system operation.

For the NRSC test program, two independent testing facilities—the Advanced Television Technology Center (ATTC) and Xetron Corporation—were selected to conduct all laboratory tests. Prior to testing, the ATTC and Xetron each developed and carried out a test bed "proof of performance" plan, and submitted the results of these proofs to the NRSC.[20] As discussed above in Section 1, NRSC

[20] See "Digital Audio Broadcasting – Test Bed Proof-of-performance Plan," ATTC doc. No. 00-05, December 2000, rev. 1.1, and "Digital Audio Broadcasting – Test Bed Proof-of-performance," ATTC doc. No. 01-01, January 2001, rev. 1.0. See also "NRSC AM Compatibility Lab Testing - Calibration Documentation," Xetron Corporation, Cincinnati, OH, June 2001.

observers were present for the vast majority of all lab tests conducted at both laboratories. The ATTC was also involved in preparing the recorded audio cuts for the subjective evaluation, which was done by another independent testing contractor, Dynastat, Inc.

3.3 Field tests

Field testing of a new broadcast system is necessary to determine performance in "the real world" where all of the various factors that impact propagation and reception of radio signals exist to varying degrees depending upon time of day, geographic location and environmental factors. For the NRSC test program, four AM stations were selected for use in field testing (Table 4).

Table 4. AM IBOC field test stations

STATION	FORMAT	LOCATION	PRINCIPAL TEST CONDITION(S)†	COMMENTS
WD2XAM 1660	Test	Cincinnati, OH	(a) low interference and no grounded conductive structures (b) low interference and grounded conductive structures (f) power lines (not high-tension) overhead in urban areas	10.0 kW, 1 tower Daytime 1660 kHz 1 kW, 1 tower Nighttime 1650 kHz Experimental
WWJ 950	News/talk	Detroit, MI	(a) low interference and no grounded conductive structures (b) low interference and grounded conductive structures (f) power lines (not high-tension) overhead in urban areas	50 kW (day), 50 kW (night) DA2 5 towers
WTOP 1500	News/talk	Washington, DC	(a) low interference and no grounded conductive structures (b) low interference and grounded conductive structures (c) single first adjacent interferer (d) single second adjacent interferer (f) power lines (not high-tension) overhead in urban areas	50 kW (day/night) DA2 3 towers
KABL 960	Adult Standards	Oakland, CA	(a) low interference and no grounded conductive structures (b) low interference and grounded conductive structures (f) power lines (not high-tension) overhead in urban areas	5 kW (day/night) DA1 3 towers

†letters in parentheses refer to test condition designations used in AM field test procedures

Data collection in the field was done using a test vehicle provided by Xetron (shown in Figure 5 and Figure 6). It was outfitted with an array of test equipment and computers, and utilized four analog AM receivers (see Table 6) and an iBiquity AM IBOC prototype receiver for capturing analog and IBOC radio transmissions, respectively.

Figure 5. Field test vehicle and roof-mounted receive antenna (inset)

Figure 6. Interior view of field test vehicle showing analog and IBOC receivers, computer, and test equipment

NRSC field test observers were present during collection of all field test data, which was collected principally with the test vehicle in motion, although most of the analog compatibility measurements done in the field were done with the test vehicle stationary. NRSC observers also participated in the preparation of audio cuts obtained in the field for subjective evaluation. As was true for the laboratory tests, an independent test contractor, Dynastat, Inc., conducted the subjective evaluations.

Note that, because of limitations of the audio program used at the three commercial field test sites (WTOP, KABL, WWJ), the digital audio generated at those stations could not take full advantage of the improvements in audio bandwidth that AM IBOC has to offer. This makes the comparison between AM IBOC and analog audio recordings obtained from these commercial sites less meaningful than similar comparisons done using recordings obtained from WD2XAM. As an experimental station it was set up to take full advantage of the AM IBOC system (i.e. full-bandwith, stereo audio plant and stereo audio program material).

3.4 Analog AM Receivers

Four commercially-available analog AM receivers were used for compatibility testing of main channel audio services (see Table 6 below). These receivers were chosen to be representative of the vast majority of receivers used in the U.S. In December, 2000, CEA's Market Research Department provided the NRSC with the names of three of the top five brands, listed alphabetically, for each of three general receiver categories (Table 5), indicating that any model of radio from one of the brands indicated in Table 5 would represent one of the top-selling models in the U.S. in December, 2000.

Table 5. CEA AM/FM receiver market research results -- December 2000

RECEIVER TYPE	3 OF TOP 5 BRANDS
Home (hi-fi)	Pioneer, Sony, Technics
CD boom box	Aiwa, Philips, Sony
Auto aftermarket CD	Kenwood, Pioneer, Sony

To determine that these receivers were representative of typical receivers on the market, nine different AM receiver models were characterized by Mr. Robert McCutcheon, who has performed extensive radio receiver tests for the NRSC in the past.[21] In light of the CEA receiver market data, and Mr. McCutcheon's analysis, it was concluded that these receivers are, in fact, representative of the performance of typical AM receivers on the market.

Table 6. Analog AM receivers used in the NRSC test program

MANUFACTURER	MODEL NO.	TYPE
Delphi	09394139	OEM automotive receiver
Pioneer	KEH-1900	Aftermarket automotive receiver
Sony	CFD-22S	Portable radio
Technics	SA-EX140	Home hi fi receiver

[21] See Appendix D for data resulting from Mr. McCutcheon's characterizations.

4 DISCUSSION OF FINDINGS

In this section a detailed explanation of the EWG's review of test data submitted to the NRSC will be presented. References are made throughout to specific test results from the AM IBOC Test Data Report, in particular in summary tables (*e.g.*, Table 9) given at the beginning of many of the sub-sections below. In these tables, references to page numbers, appendices, figures, tables, and so forth, are taken from the AM IBOC Test Data Report, and are provided here to identify specific test results that the EWG used during its evaluation. The findings presented here, and for that matter every aspect of the NRSC's IBOC test program, have been divided into two specific areas - *digital performance* and *analog compatibility*.

4.1 Digital performance

Digital performance refers to the performance of the IBOC digital radio system itself. As discussed below in Section 4.3, eight specific areas of digital performance have been considered by the EWG. All of the test results obtained on digital performance were obtained using an iBiquity prototype AM IBOC receiver (Figure 7) or through direct observation of the received signal. At least two examples of the iBiquity IBOC receiver were used during testing – one in the field test vehicle, and one in the laboratory at the ATTC.

Figure 7. iBiquity prototype receiver –as used in field test vehicle

For AM IBOC, the investigation into digital performance involves an assessment of two specific digital modes of operation – core and enhanced. These modes are supported by two independent (from a transmission standpoint), simultaneous bit streams, which are each characterized by their own block error rate, etc. Note that while the system mode tested by the NRSC (MA1) utilized a 36 kbps audio transmission (20 kbps core audio data stream, 16 kbps enhanced audio data stream), the results obtained for the core mode would also be applicable for a situation where the transmission consisted of a 20 kbps core audio and 16 kbps of data not related to the main program audio signal. Digital performance also needs to be assessed for both daytime and nighttime operation, due to the significant differences in signal propagation experienced by AM band signals versus time-of-day.

In evaluating the digital performance of the system, the EWG's task was to determine if the digital performance demonstrated by the test results was a "significant improvement over existing analog services," as directed by the Subcommittee's Goals and Objectives statement. Guiding the EWG as it attempted to determine this was a set of performance goals it developed (Table 7) defining in more concrete terms what a "significant improvement over existing analog services" consists of.

Table 7. AM IBOC performance goals as established by the EWG

CATEGORY		PERFORMANCE GOALS – AM IBOC
Fidelity	Frequency response & distortion	Deliver fidelity that approaches present FM analog fidelity
		To alleviate the effects of channel impairments and interference, it may be acceptable to diminish distortion and frequency response fidelity to maintain audio free of dropouts and noticeable artifacts.
	Noise	May be acceptable to compromise noise fidelity to maintain dropout- and artifact-free audio
	Stereo separation	May be acceptable to compromise in response to channel impairments
	Fidelity of digital technologies	a) Source coding should not cause artifacts that noticeably reduce fidelity throughout the service area b) Should have sufficient apparent dynamic range so that low level and dynamic content reproduce with the same fidelity as aggressively processed audio
Durability	Interference	Digital systems should reach a service area that matches or exceeds the actual interference-limited service area of the analog host
	Impairments	Digital technology will be considered to be better than analog against impairments if digital impairment and fade artifacts have the following characteristics: a) They are demonstrably less objectionable, less frequent in time and less prevalent in location than those of analog services b) They maintain higher fidelity than analog for a preponderance of occurrences c) They result in fewer total losses of intelligible audio than analog, and recovery from total loss is not significantly longer than analog in similar circumstances
Flexibility	Flexibility of transmission systems *(includes COMPATIBILITY with existing analog services)*	A successful digital technology will: a) Reasonably protect the performance and flexibility of its analog host and adjacent channel stations (i.e. is compatible with existing analog services); b) Provide a platform that can be improved in software, firmware and hardware in a manner that is compatible with its original technology; c) Give broadcasters tools to create features to enhance the listener experience and permit the medium to remain relevant and competitive in the coming decades.

In anticipation of the need for a comparison between analog and digital performance, the NRSC's test procedures in most cases required the collection of analog data (using existing analog AM receivers) and hybrid IBOC data (using the iBiquity prototype IBOC receiver) either simultaneously (utilizing the IBOC host as the analog signal) or sequentially (for example, in the laboratory), such that a valid comparison could be made. Figure 8 offers a perfect example of how this approach can lead to a meaningful comparison of IBOC and analog from which conclusions about digital performance can be drawn.

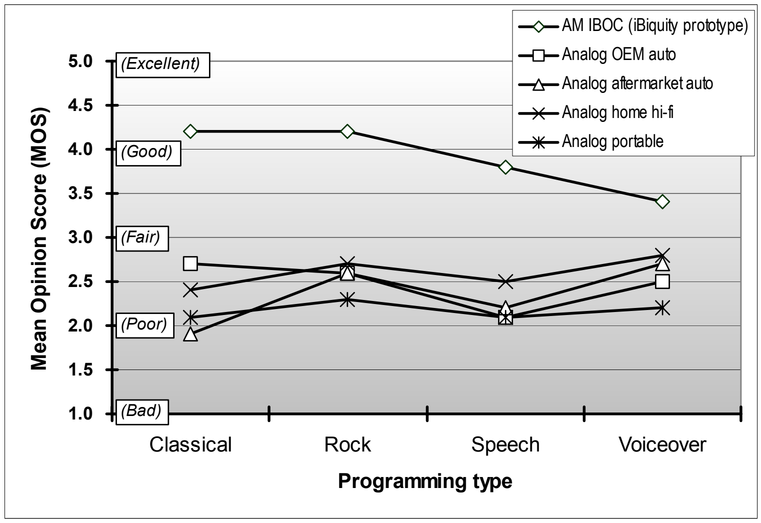

Figure 8: Comparison of AM IBOC and analog audio subjective evaluation results

In Figure 8, the subjective evaluation scores of audio samples collected in the lab, for both AM IBOC and analog, have been plotted by program type illustrating the differences perceived by listeners between digital and analog performance. Note that identical analog and digital audio cuts were obtained under identical impairment conditions and that consequently this data offers an excellent opportunity to fairly and accurately compare digital and analog performance. Referring to the figure, the data indicate that while the analog quality is in the "fair" to "poor" range, the IBOC quality is in the "good" range, representing a very significant difference between the two. Clearly, this data suggests that for all program types tested, the digital performance was a consistent and significant improvement over the analog.

4.2 Analog compatibility

The other area of investigation undertaken by the EWG is that of analog compatibility. Analog compatibility pertains to the effect that the IBOC digital radio signal has on reception of existing analog signals. Because of the fact that an AM IBOC signal adds additional energy within a radio station's existing frequency allocation (see Figure 1 above) it is reasonable to expect that analog receivers, not designed with this extra signal energy in mind, may experience interference from this additional energy. The role of the NRSC here is to confirm that IBOC has either no impact or an "acceptable" impact on how existing analog signals are received.

Whether or not interference will exist depends on a variety of factors, one of the most important being the signal level of the IBOC digital sidebands with respect to the host analog signal. This is a critical parameter—the sideband level must be set high enough to provide for good digital coverage, but low enough so that the impact on analog signals is minimized—and is in fact one of the most difficult tradeoffs that IBOC system designers have to deal with.

There are five general types of compatibility – host, co-channel, 1st adjacent channel, 2nd adjacent channel, and 3rd adjacent channel. Host compatibility relates to the impact the IBOC system has on analog reception of the station the IBOC system is installed on. Co-channel relates to the impact that the IBOC system has on analog reception of another station on the same frequency. 1st-adjacent channel compatibility relates to the impact the IBOC system has on analog reception of a station located 10 kHz above (or below) the station broadcasting the IBOC signal (see Figure 2 above). Similarly, 2nd-adjacent channel compatibility relates to the impact the IBOC system has on analog reception of a station located 20 kHz above (or below) the station broadcasting the analog signal (see Figure 3 above), and 3rd-adjacent channel compatibility relates to the impact the IBOC system has on analog reception of a station located 30 kHz above (or below) the station broadcasting the analog signal (see Figure 4 above).

4.3 Evaluation criteria

The EWG utilized 10 criteria for evaluating the data contained in the AM IBOC Test Data Report. Each criterion falls into one of the (previously mentioned) two general categories of results: "digital performance," which applies to performance of the IBOC digital signal, and "analog compatibility," which addresses the impact of the IBOC signal on reception using existing analog receivers. Table 8 lists the evaluation criteria according to category; refer to Appendix E for a detailed description of each criterion, and to Appendix F for a matrix that illustrates which tests (contained in the test procedures) have a bearing upon which criteria.

Table 8. EWG evaluation criteria

DIGITAL PERFORMANCE	ANALOG COMPATIBILITY
Audio quality	Host analog signal impact
Service area	Non-host analog signal impact
Durability	
Acquisition performance	
Auxiliary data capacity	
Behavior as signal degrades	
Stereo separation	
Flexibility	

As previously mentioned, the goals listed in Table 7 above were used to guide the EWG's assessment of how the IBOC system performed compared to existing analog services. In many cases (as is noted in the "analog benchmark" columns of the test result tables in sections 4.4 through 4.9) analog benchmark data was collected along with the IBOC system data; for compatibility tests, the "IBOC off" data was used as a benchmark (and compared against the "IBOC on" data obtained under otherwise identical conditions, four and one-half second time delay between analog and digital notwithstanding).

4.4 Criterion 1 – Audio quality

Table 9 lists the test results pertaining to audio quality of the iBiquity AM IBOC system.

Table 9: AM IBOC test results pertaining to audio quality

TEST NO. (PROCEDURES)	OBJECTIVE DATA	SUBJECTIVE DATA	ANALOG BENCHMARK	RESULTS / COMMENTS
Lab – various	n/a	Main report: - Fig. 3, pg.7	FM analog audio quality (OEM automotive receiver)	Subjective evaluation of lab test data – aggregated results IBOC audio quality (combination of enhanced and core) judged comparable to FM analog
Lab – various	n/a	Main report: - Fig. 3, pg.8	AM analog audio quality (all 4 NRSC receivers)	Subjective evaluation of lab test data – aggregated results IBOC audio quality (combination of enhanced and core) good while analog poor to fair for all cases
Field – B.1 – System performance - low interference and low multipath	Appendix D5 (WD2XAM cov. maps)	Main report: - Fig. 5, pg. 9 (same as Appendix L, Fig. 1, pg. 3)	AM analog audio quality (OEM and aftermaket auto receivers)	IBOC audio quality (combination of enhanced and core) consistently better than analog quality

As defined by the EWG, this criterion relates specifically to the audio quality of the main channel audio signal received under unimpaired conditions i.e. in the absence of RF noise, interfering signals, multipath interference, weak signal conditions, or any other circumstance which would adversely affect reception. Because the results of such tests are in effect a test of the perceptual audio coding algorithm used, and because the iBiquity system hardware tested for the purposes of this evaluation did not utilize the audio coding algorithm to be used in the final deployed version of the system, the NRSC is, strictly speaking, not able to come to any conclusions for this criterion.

However, subjective evaluations of audio obtained in the lab (for example, Figure 8above) strongly suggest that the audio quality of IBOC digital audio will be a significant improvement over the audio quality of existing AM analog if the definition of audio quality is expanded to include that experienced by listeners under a variety of impaired conditions. This of course assumes that the performance of the iBiquity audio coding algorithm meets or exceeds that of the MPEG-2 AAC algorithm used in the hardware tested by the NRSC.

Subjective evaluation of audio samples obtained at field test site WD2XAM (the only field test station able to fully demonstrate the enhanced audio capabilities of AM IBOC) offers further insight into the enhanced mode audio quality of the system under mildly impaired mobile conditions. As discussed in Appendix L of the AM IBOC test data report, audio samples from each of the four test radials at WD2XAM were obtained at fixed distances from the transmitter for IBOC and analog receivers and subjectively evaluated. These results, shown in Figure 9, again demonstrate a consistent improvement in audio quality offered by the IBOC receiver versus the analog automotive receivers.

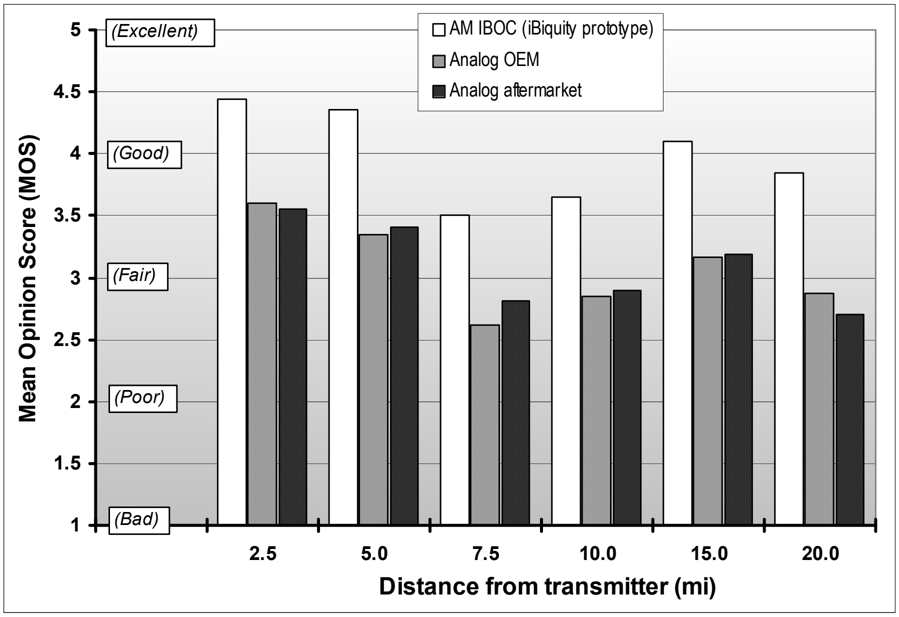

Figure 9. Comparison of AM IBOC and analog subjective evaluation results for WD2XAM[22]

In Figure 10 a comparison of the AM IBOC enhanced digital and core digital audio quality is given. The audio recordings evaluated here were made under AWGN channel conditions and for each case the noise level was set at a point corresponding to 2 dB before the onset of blending due to the addition of AWGN noise (blending from enhanced digital to core digital for the "enhanced" curve, and from core digital to analog for the "core" curve).

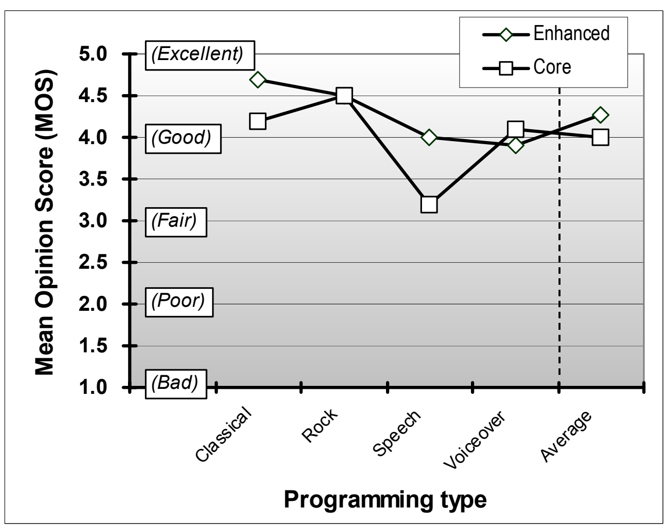

Figure 10. Comparison of AM IBOC subjective evaluation results for enhanced digital and core digital audio quality under laboratory AWGN conditions

[22] Note that both enhanced and core audio ratings are included in the IBOC results shown here.

Also of interest are results comparing AM IBOC audio quality to that of unimpaired analog FM audio quality (Figure 11),[23] a comparison directly addressing one of the NRSC's performance goals for AM IBOC (Table 7). These results show that on average AM IBOC achieves virtually the same audio quality as FM analog, and are especially significant since the AM IBOC results shown here include recordings made in both enhanced digital and core digital modes.

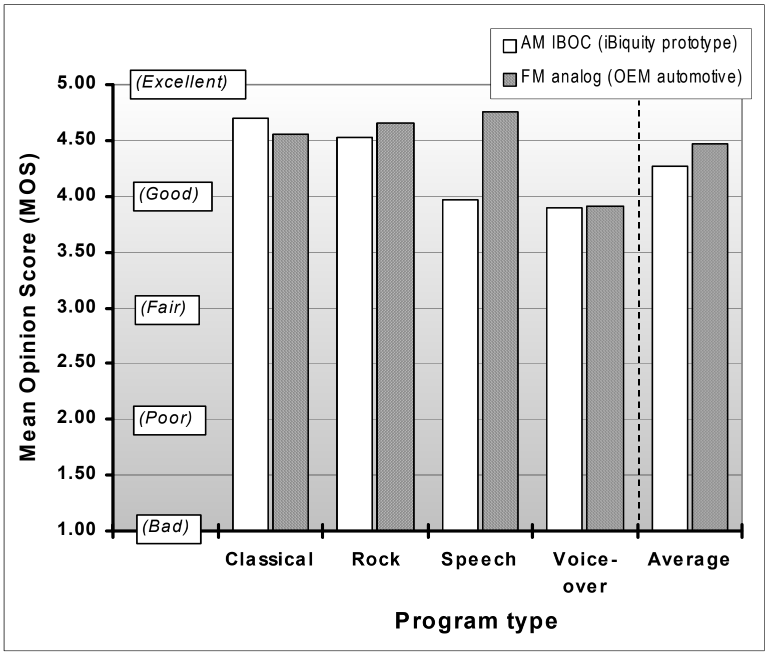

Figure 11. Comparison of AM IBOC and FM analog subjective evaluation results aggregating all laboratory test conditions[24]

4.4.1 Findings

The iBiquity hybrid AM IBOC system with MPEG-2 AAC perceptual audio coding demonstrates significantly improved audio quality compared to existing analog AM in mobile listening environments (as tested in the field), and in a variety of impairment conditions tested in the laboratory. Laboratory tests have further shown that under these impaired conditions, AM IBOC audio quality is comparable to that achieved by analog FM radio in an unimpaired environment. Since the final version of this system will utilize a proprietary iBiquity perceptual audio coding algorithm and not MPEG-2 AAC, no direct findings on the unimpaired audio quality of the final system can be made at this time.

4.5 Criteria 2, 3 – Service area, durability

Table 10 lists the test results pertaining to service area and durability of the iBiquity AM IBOC system. These two criteria have been combined in this section because they essentially share the same list of tests (from the test procedures) from which conclusions can be drawn.

[23] Taken from pg. 7 of main text of AM Test Data Report.
[24] See footnote 22.

Table 10. AM IBOC test results pertaining to service area and durability

TEST NO. (PROCEDURES)	OBJECTIVE DATA	SUBJECTIVE DATA	ANALOG BENCHMARK	RESULTS / COMMENTS
Lab - B.1 – AWGN	Appendix I: - Fig. 5-1, pg. 9	Appendix I: - Table 5-2, pg. 8 Appendix G, pg. 4	None	Enhanced and core audio quality similar for Rock, Voiceover types; enhanced better than core for Classical, Speech types
Lab – C.1 – Impulse noise	Appendix I: - Fig. 5-2, pg. 12 (120 Hz) - Fig. 5-3, pg. 13 (120 Hz, 1st adj.) - Fig. 5-4, pg. 13 (330 Hz) - Fig. 5-5, pg. 14 (330 Hz, 1st adj.) - Fig. 5-6, pg. 14 (510 Hz) - Fig. 5-7, pg. 15 (510 Hz, 1st adj.) - Fig. 5-8, pg. 15 (1200 Hz) - Fig. 5-9, pg. 16 (1200 Hz, 1st adj.) - Fig. 5-10, pg. 16 (1800 Hz) - Fig. 5-11, pg. 17 (1800 Hz, 1st adj.) - Fig. 5-12, pg. 17 (2000 Hz) - Fig. 5-13, pg. 35 (2000 Hz, 1st adj.) - Fig. 5-14, pg. 18 (PN) - Fig. 5-15, pg. 19 (PN, 1st adj.)	Main report: - Fig. 11, 12, pg. 16-17 Appendix I: - Table 5-4, pgs. 10-12 Appendix G, pg. 3 (only 120 Hz, 510 Hz, 1800 Hz subjectively evaluated)	Subjective only – MOS scores for OEM and aftermaket automotive receivers	Sensitivity to impulse noise increases with repetition rate, duty cycle IBOC audio quality, no 1st-adj. chan. interferer – <u>Core</u>: fair to good while analog poor for all 3 cases <u>Enhanced</u>: IBOC audio quality good while analog poor to fair for all 3 cases IBOC audio quality with +6 dB upper 1st-adj. – <u>Core</u>: fair to good while analog poor to fair for all 3 cases <u>Enhanced</u>: enhanced data not receivable irrespective of impulse noise level
Lab – D.1 – Co-channel IBOC ⇒ IBOC	Appendix I: - Fig. 5-16, pg. 25	Main report: - Fig. 8, pg. 13 Appendix I: - Table 5-6, pg. 21 Appendix G, pg. 5	Subjective only – MOS scores for analog aftermarket auto, home hi-fi receivers	Blend D/U point +15 dB IBOC audio quality good to excellent while analog poor to fair
Lab – D.2 – Single and dual 1st adjacent IBOC ⇒ IBOC	Appendix I: - Fig. 5-17, pg. 26 (single 1st) - Fig. 5-18, pg. 26 (dual 1st)	Main report: - Fig. 9, pg. 14 Appendix I: - Table 5-6, pg. 21, 22 Appendix G, pg. 5	Subjective only – MOS scores for all 4 NRSC analog receivers	Blend D/U point: Single 1st, enhanced: +7 dB Single 1st, core: <-14 dB Dual 1st, core: 18 dB IBOC audio quality, single 1st: <u>Core</u>: fair to good while analog either bad or failed <u>Enhanced</u>: fair to good while analog poor to fair IBOC audio quality, dual 1st: <u>Core</u>: fair to good while analog poor to fair <u>Enhanced</u>: enhanced data not receivable irrespective of impulse noise level

TEST NO. (PROCEDURES)	OBJECTIVE DATA	SUBJECTIVE DATA	ANALOG BENCHMARK	RESULTS / COMMENTS
Lab – D.3 – Single and dual 2nd adjacent, simultaneous single 2nd and single 1st adjacent IBOC ⇒ IBOC	Appendix I: - Fig. 5-19, pg. 27 (single 2nd) - Fig. 5-20, pg. 27 (lower 2nd, upper 1st) - Fig. 5-21, pg. 28 (dual 2nd)	Main report: - Fig. 10, pg. 15 Appendix I: - Table 5-6, pg. 23, 24 Appendix G, pg. 6	Subjective only – MOS scores for analog portable, home hi-fi receivers	Blend D/U point: Single 2nd, enhanced: -24 dB Single 2nd, core: -33 dB Dual 2nd, enhanced: 24 dB Dual 2nd, core: 1 dB Single 2nd, single 1st, core: 3 dB IBOC audio quality, single 2nd: Core: fair to good while analog either bad to poor or failed Enhanced: good while analog poor to fair IBOC audio quality, dual 2nd: Core: fair to good; same for analog Enhanced: enhanced data not receivable irrespective of impulse noise level
Lab – D.4 – Single 3rd adjacent IBOC ⇒ IBOC	Appendix I: - Fig. 5-22, pg. 28	Appendix I: - Table 5-6, pg. 24, 25 Appendix G, pg. 6	Subjective only – MOS scores for analog portable, home hi-fi receivers	IBOC signal extremely robust when subjected to 3rd-adj. channel interference
Field – B.1, B.2 – System performance - low interference and low multipath, 1st adj. channel interference	Main report: - Fig. 6, pg. 10 (WWJ coverage daytime) Appendix D2 (WTOP cov. maps) Appendix D3 (WWJ cov. maps) Appendix D4 (KABL cov. maps) Appendix D5 (WD2XAM cov. maps)	Main report: - Fig. 5, pg. 9 (WD2XAM in strong signal conditions) Appendix G, pg. 1	Audio quality of host analog signal on OEM and aftermaket automotive receivers (recorded simultaneously with IBOC audio)	Daytime digital coverage comparable to analog coverage along test radials. Nighttime digital coverage fell short of the predicted nighttime interference-free (NIF) contours Subjective: IBOC audio quality was good to fair while analog was fair to (nearly) poor
Field – B.3 – System performance – 2nd adj. channel interference	Appendix D2 (WTOP cov. maps)	Appendix G, pg. 1	Audio quality of host analog signal on OEM and aftermaket automotive receivers (recorded simultaneously with IBOC audio)	Daytime digital coverage comparable to analog coverage along test radials. Nighttime digital coverage fell short of the predicted nighttime interference-free (NIF) contours Subjective: Strong interference - IBOC audio quality comparable to analog Moderate interference – IBOC audio quality comparable to analog aftermarket auto, slightly worse than analog OEM auto

TEST NO. (PROCEDURES)	OBJECTIVE DATA	SUBJECTIVE DATA	ANALOG BENCHMARK	RESULTS / COMMENTS
Field – various	n/a	Main report: - Table 5, pg. 17 Appendix G, pg. 1	Audio quality of host analog signal on OEM and aftermaket automotive receivers (recorded simultaneously with IBOC audio)	Subjective: IBOC audio quality on average higher than analog

As evident from the numerous entries in Table 10, the NRSC's test program contained a substantial number of tests pertaining to these criteria. This seems appropriate because service area and coverage are arguably the most important aspects of a broadcasting service, those that all other aspects build upon. In the sections that follow, test results and details on how service area and coverage are impacted by various types of interference will be given.

In general, these results demonstrate that the daytime "digital" service area of a radio station broadcasting AM IBOC should be an improvement with respect to existing analog service, due primarily to AM IBOC's robustness in the presence of impulse noise and grounded conductive structures. Farther out from the transmitter, as signal strength decreases, the AM IBOC receiver at some point blends to analog (the data suggests this typically occurs at signal levels of 1-2 mV/m) and consequently radio service on the edge of coverage will be preserved in its present form for stations broadcasting in hybrid AM IBOC mode. Where exactly blending occurs in these outer areas will depend on strength of interferers, prevailing noise levels, ground conductivity between the receiver and the transmitter, etc.

At night, coverage (for both analog and digital service) is mostly limited by interference from other stations. For almost all of the test radials, digital coverage fell short of the predicted nighttime interference-free (NIF) contours and the system had blended to analog before reaching this contour. In general, these results demonstrate that the co-, first-, and second-adjacent interference experienced by the test stations during night operation restrict digital coverage. Furthermore, nighttime digital service coverage does not extend to the same signal levels where coverage is experienced during the day (see Figure 23 below).

4.5.1 With impulse noise

Impulse noise interference can occur in both mobile (*e.g.*, from ignition circuits in automobiles) and household (*e.g.*, from vacuum cleaner motors) environments, reducing the audio quality of radios. The NRSC subjected the iBiquity AM IBOC prototype receiver and the two analog automotive receivers to impulse noise interference at various repetition rates under laboratory conditions. Audio recordings were made under these circumstances (for rep. rates of 120 Hz, 510 Hz, and 1800 Hz only) for a variety of program types and then subjectively evaluated, the results of which are shown in Figure 12. For these tests, the impulse noise energy was increased until the point where the impulse noise interference would cause the digital audio to blend from enhanced to core (plot on left) then further increased until it blended from core to analog (plot on right).

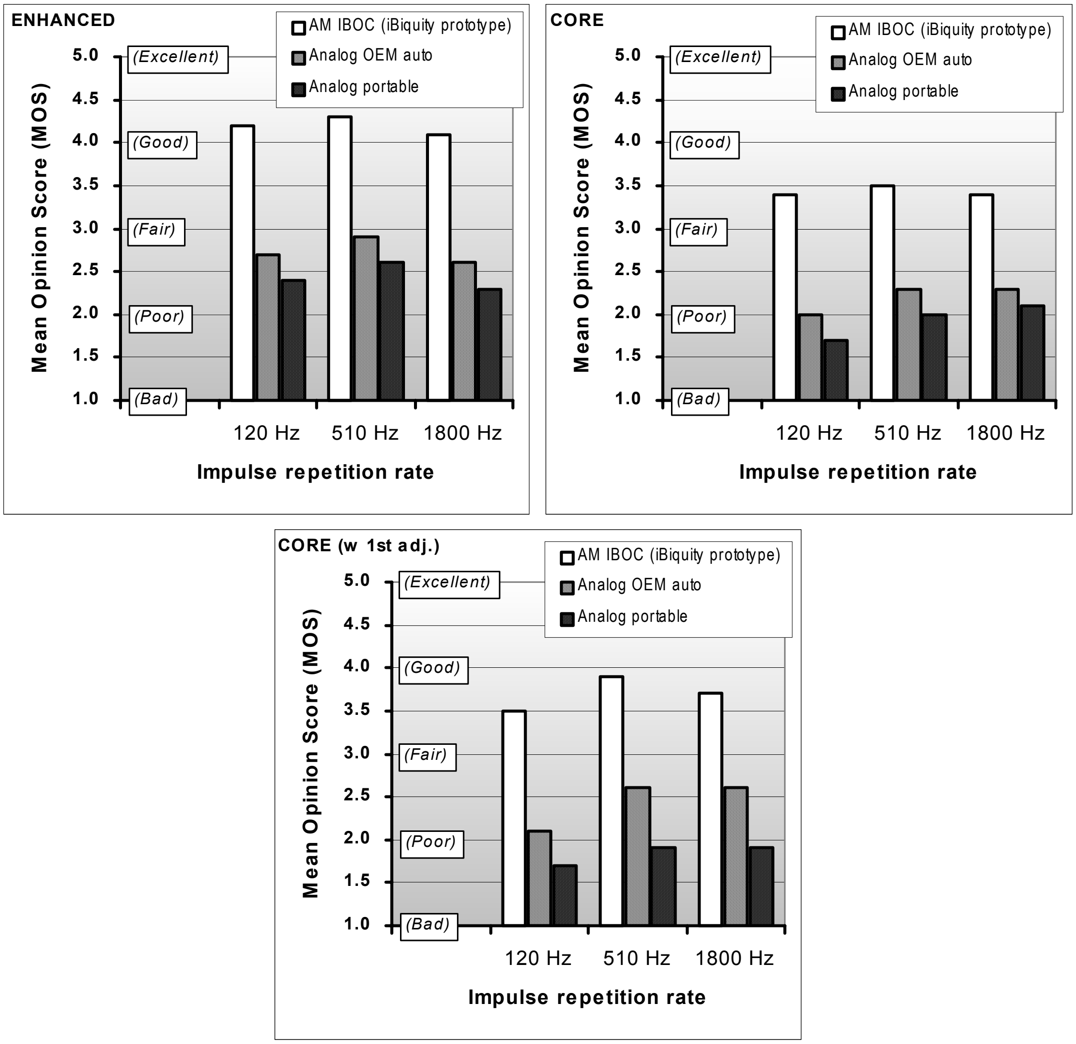

Figure 12. Comparison of AM IBOC and analog audio subjective evaluation results under laboratory impulse noise conditions (aggregated for all program types)

These results indicate that the AM IBOC receiver performs significantly better than the analog automotive radios for the 120 Hz, 510 Hz, and 1800 Hz repetition rate cases. A second test, identical to the one just described except with the addition of an upper 1st-adjacent channel interferer (at +6 dB D/U, bottom plot in Figure 12) yielded similar results however in this case it was found that the enhanced data could not be received regardless of the impulse noise level.

Note that the apparent improvement in performance illustrated in the subjective evaluation results (for the core data) with the addition of the 1st adjacent channel interferer is due to the fact that blending (from core to analog) occurred at a lower level of impulse noise energy in the 1st adjacent channel case. Consequently, the recordings in the 1st-adjacent channel case represent operation with less impulse noise than the corresponding recordings for the case without 1st-adjacent channel interference.

Overall these results demonstrate that AM IBOC is significantly more robust when subjected to impulse noise interference than is existing analog AM.

4.5.2 With co-channel interference

To determine the performance of the AM IBOC system in the presence of (AM IBOC) co-channel interference in the laboratory, the test procedure called for a co-channel interferer to be introduced and increased in power level until the desired AM IBOC signal blends from enhanced to core, and then from core to analog. However it was determined during testing that for the co-channel test, these transitions occurred simultaneously, at a +15 dB D/U ratio. This is likely due to the fact that in the co-channel case, the interference to the primary (contains core audio stream) and secondary/tertiary (contains enhanced audio stream) digital subcarriers increases at the same relative rate resulting in the simultaneous enhanced/core failure.

After establishing this blend point, the level of interference was reduced by 2 dB in accordance with the test procedure (resulting in a +17 dB D/U ratio and enhanced mode digital audio performance) and recordings of the AM IBOC receiver audio and audio from the analog aftermarket and home hi-fi receivers were made. Note that both the desired and undesired signals supplied to the analog receivers were AM analog (not hybrid IBOC), set for a D/U of +17 dB. The analog and IBOC recordings were then subjectively evaluated (Figure 13).

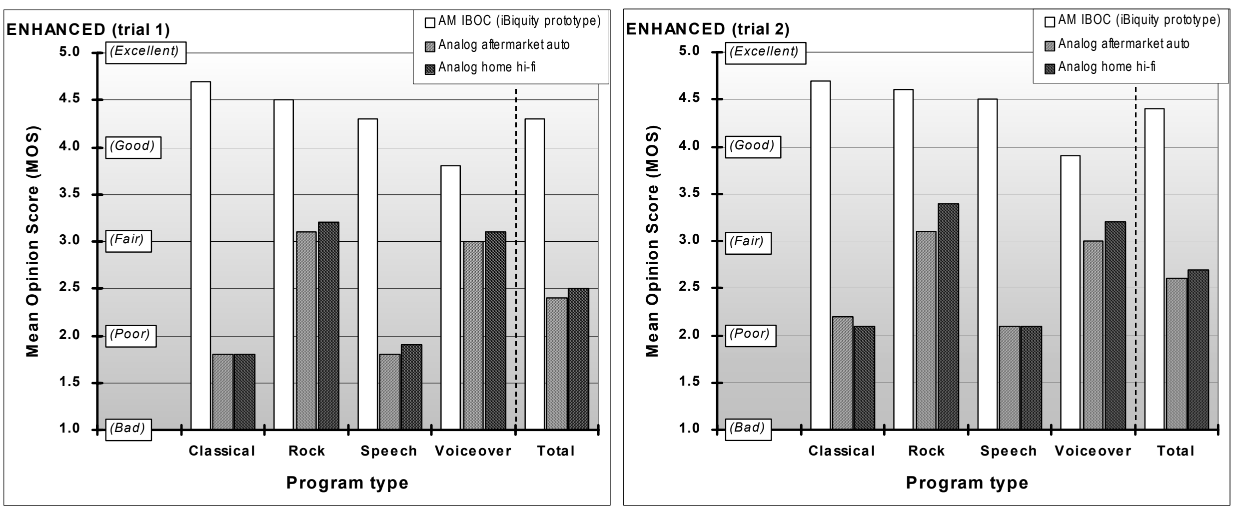

Figure 13. Comparison of AM IBOC and analog audio subjective evaluation results obtained in the laboratory with co-channel interference (+17 dB D/U)

The plots in Figure 13, in addition to presenting co-channel interference results, also serve to validate the subjective evaluation process used in this testing program and offer some indication of the variability inherent in this process. The reason for this is that the data represented in the two plots was obtained separately using different audio cuts (but always at the +17 dB D/U operating point) and evaluated independently. A comparison of these plots (marked "trial 1" and "trial 2" to emphasize that the same data was evaluated twice, by different groups of subjective evaluators) shows that while not identical, they do demonstrate a high degree of correlation.

These results demonstrate that AM IBOC is significantly more robust to co-channel interference than is existing analog AM. Note that the operating point at which the digital audio blends to analog is well beyond (by 9 dB) the value to which analog stations are currently protected from co-channel interference.

4.5.3 With 1st adjacent channel interference

Extensive testing was conducted in the laboratory to determine the performance of the AM IBOC system in the presence of 1st-adjacent (hybrid AM IBOC) interference. This is an important case to consider because as a consequence of the system design, the digital sidebands of an AM IBOC signal are vulnerable to interference from a 1st-adjacent signal (as shown in Figure 2 above).

Subjective evaluation results using lab test data collected on AM IBOC performance with single and dual 1st-adjacent channel interferers are given in Figure 14. The graphs included in this figure compare the AM IBOC audio quality with that of the audio quality obtained using the four NRSC receivers when subjected to the same 1st-adjacent channel D/U ratio (except with analog interference in the analog receiver cases). An inspection of these graphs indicates that the AM IBOC audio quality either equals or surpasses that of the host analog signal under 1st-adjacent channel interference conditions—note in particular that in the CORE test, with the D/U ratio set at an operating point 2 dB before the onset of blending to analog, the AM IBOC receiver's audio quality is in the fair to good range while at the same operating point the analog receivers are either exhibiting bad audio quality or are failed altogether.

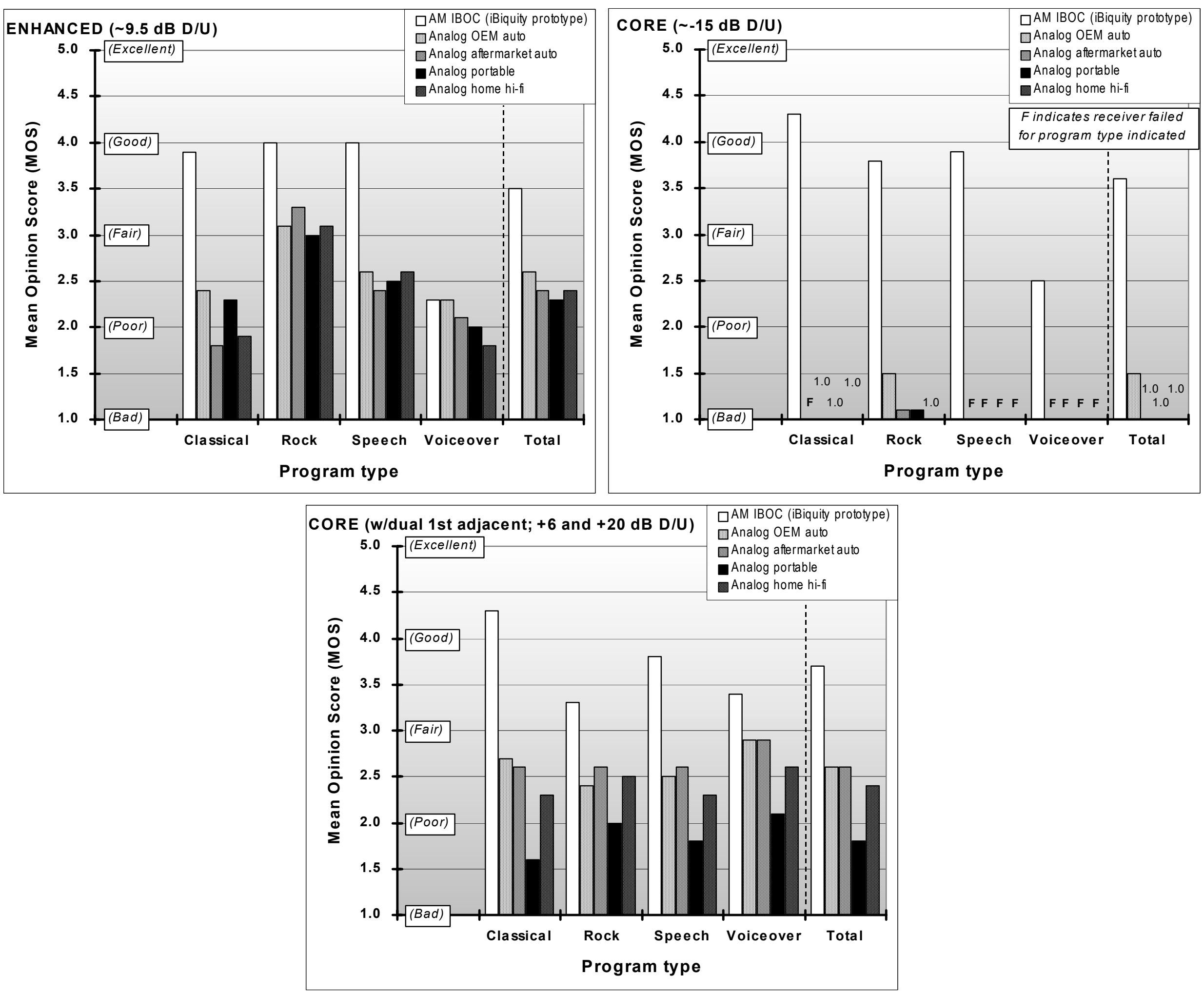

Figure 14. Comparison of AM IBOC and analog audio subjective evaluation results obtained in the laboratory with 1st-adjacent channel interference

The operating point at which this core-to-analog blend occurs for a single 1st adjacent interferer (-15 dB D/U) would fall well outside an AM station's 0.5 mV/m contour, since during the day, ground wave allocations hold 1st adjacent interferers to 0.25 mV/m at the 0.5 mV/m contour, corresponding to a +6 dB D/U at that contour.

Tests were also done (in the field) on digital performance in the presence of dual 1st-adjacent channel hybrid IBOC interferers (Figure 15) for speech and voiceover program types.

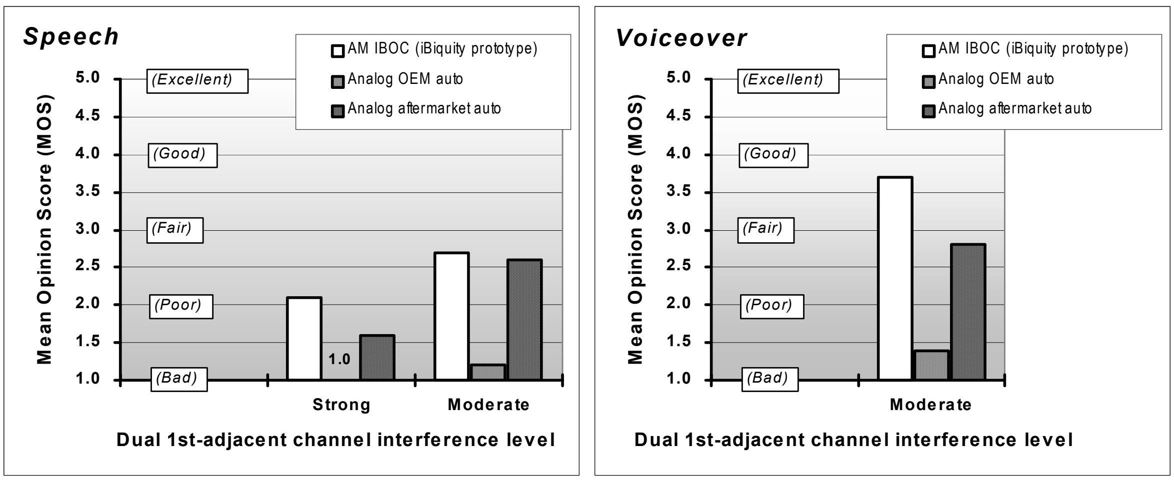

Figure 15. Comparison of AM IBOC and analog audio subjective evaluation field results with strong (0 to +3 dB D/U) and moderate (+8 to +15 dB D/U) dual 1st-adjacent channel interference

Note that for this field test data, only analog interferers were present (no hybrid IBOC interferers). The fact that only speech and voiceover data were obtained is a consequence of the fact that the field test stations that had 1st adjacent channel interferers were "talk" stations. It should also be noted that these interference conditions were found to exist at locations of weak desired signal level and consequently the field test performance results are more pessimistic than the lab test results, which were obtained under moderate desired signal levels. Furthermore, since these results were obtained using the commercial test sites that (as discussed above) were not using high fidelity audio program material, the quality differences between analog and AM IBOC are diminished.

Overall, these results demonstrate that AM IBOC is significantly more robust to single 1st adjacent channel interference than is existing analog AM, confirming very rugged performance at D/U ratios that are very unlikely to be experienced during the day within a station's allocation contour. These ratios might be experienced during night operation and will be station specific.

These results also demonstrate that AM IBOC is moderately more robust in the presence of dual 1st adjacent channel interference than is existing analog. There may be some stations that experience the D/U ratios at which blending to analog was found to occur (for dual 1st adjacent interferers) within their 0.5 mV/m daytime contours, limiting digital coverage under these conditions.

4.5.4 With 2nd adjacent channel interference

Laboratory tests of digital performance in the presence of single 2nd adjacent IBOC interferers established that the iBiquity AM IBOC system is extremely robust with respect to this type of interference. Figure 16 illustrates the subjective evaluation results for system performance near the enhanced to core (left graph) and core to analog (right graph) blend points, respectively. The core to analog graph in particular illustrates the robustness of AM IBOC compared to analog AM since at this operating point (-31 dB D/U) the IBOC audio quality is in the fair to good range while at the same operating point the two analog receivers tested have either failed (home hi-fi) or have audio quality in the bad to poor range (portable).

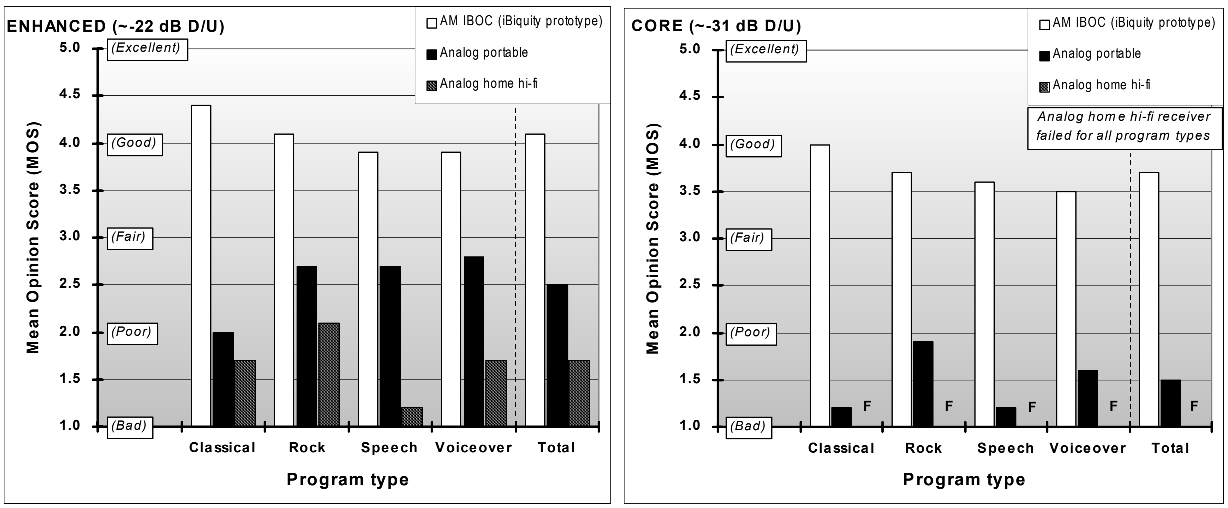

Figure 16. Comparison of AM IBOC and analog audio subjective evaluation results obtained in the laboratory with single 2nd-adjacent channel interference

The operating point at which this core-to-analog blend occurs (-31 dB D/U) would fall well outside an AM station's 5 mV/m contour. Note that ground wave allocations hold 2nd adjacent interferers to 5 mV/m at the 5 mV/m contour, corresponding to a 0 dB D/U at that contour.

For the dual 2nd adjacent channel lab tests, one interferer was fixed at a D/U of 0 dB while the other interferer's level was varied until the AM IBOC system audio blended progressively from enhanced digital to core digital to analog. These results (Figure 17) represent operation with the second interferer at approximately 25 dB D/U (enhanced to core, left graph) and 3 dB D/U (core to analog, right graph). Because the interference levels (of the individual 2nd adjacent interferers) are reduced compared to the single 2nd adjacent channel interference case (shown in Figure 16) the analog receiver performance in the dual interferer case is better by comparison.

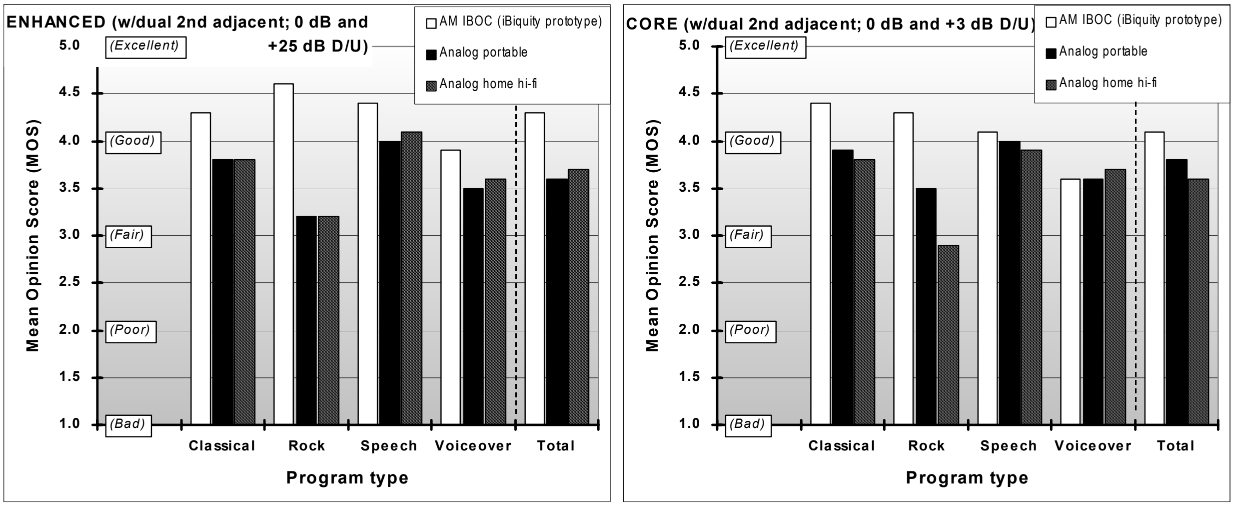

Figure 17. Comparison of AM IBOC and analog audio subjective evaluation results obtained in the laboratory with dual 2nd-adjacent channel interference

Tests were also done (in the field) on digital performance in the presence of single 2nd adjacent channel analog interferers for speech and voiceover program types (Figure 18).

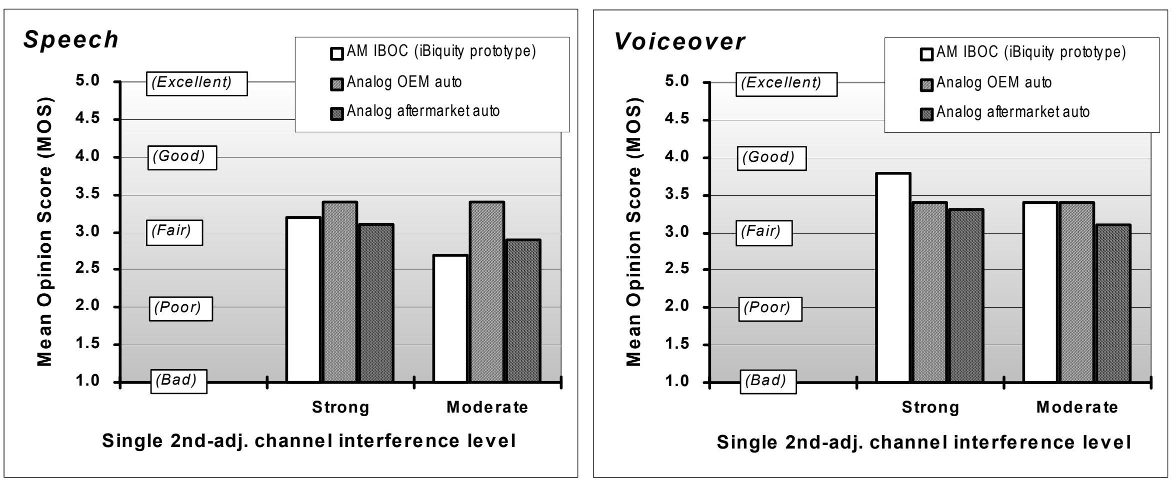

Figure 18. Comparison of AM IBOC and analog audio subjective evaluation field results with strong (-7 to -12 dB D/U) and moderate (+1 to -4 dB D/U) single 2nd-adjacent channel interference

As was true for the 1st adjacent channel case discussed above (Section 4.5.3), for 2nd adjacent channel field test data:

- only analog interferers were present (no hybrid IBOC interferers)
- only speech and voiceover data were obtained because the field test stations that had 2nd adjacent channel interferers were “talk” stations;
- the quality differences between analog and AM IBOC are diminished because the field test stations did not utilize high-fidelity audio program material;

- interference conditions were found to exist at locations of weak desired signal level and consequently the field test performance results do not exactly match the lab test results, which were obtained under moderate desired signal levels.

Overall, these results demonstrate that AM IBOC is significantly more robust to single 2nd adjacent channel interference than is existing analog AM, and moderately more robust in the presence of dual 2nd adjacent channel interference.

4.5.5 With 3rd adjacent channel interference

Laboratory tests of digital performance in the presence of a single 3rd adjacent IBOC interferer established that the iBiquity AM IBOC system is extremely robust with respect to this type of interference, and confirms that the 500 Hz guard band between 3rd adjacent IBOC primary digital sidebands (see Figure 4 and discussion in Section 3.1 above) is adequate.

Subjective evaluation results for this test are shown in Figure 19. Performance near the enhanced to core blend point is shown in the graph on the left. The graph on the right represents the audio performance of the core digital audio at the test bed operating limit since even when the D/U ratio was set to the laboratory test bed limit of -44 dB, the system did not experience any blending to analog.

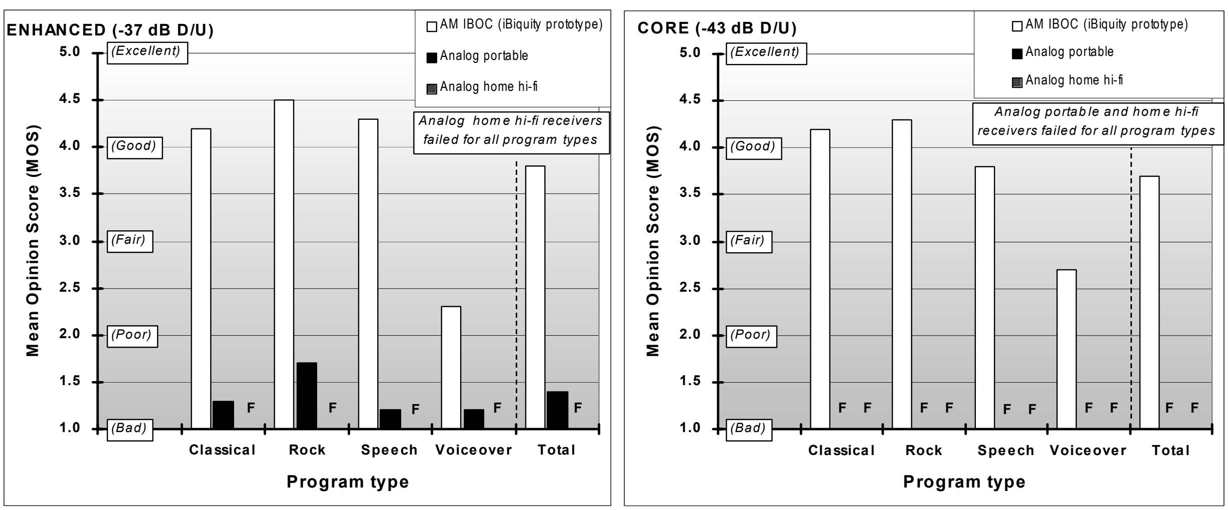

Figure 19. Comparison of AM IBOC and analog audio subjective evaluation results obtained in the laboratory with single 3rd-adjacent channel interference

4.5.6 Versus other types of interference

During field testing a number of additional interference scenarios were identified (Figure 20). In each of these cases the IBOC audio quality was equal to or better than that being experienced on the analog host signal that was being subjected to the same interference. Again, as in earlier field test results discussed above, the quality differences between analog and AM IBOC are diminished because the field test stations were not using high fidelity audio program material.

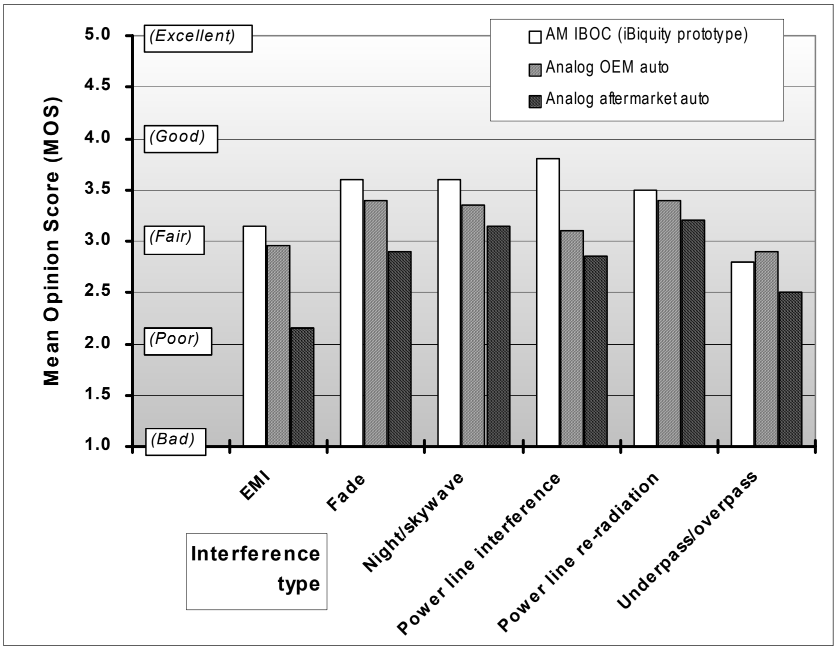

Figure 20. Comparison of AM IBOC and analog audio subjective evaluation results obtained in the field in the presence of various forms of interference

4.5.7 Versus broadcast antenna configuration

To test the performance and durability of iBiquity's AM IBOC system under different antenna configurations, field test stations were specifically selected to include both single-tower omni directional and multiple tower directional antenna configurations (basic information on the configurations tested is given in Table 4 above). In each case, no detrimental impact on IBOC performance or durability was observed due to the transmitting antenna system employed. The maps and field strength graphs included as Appendix D of the AM IBOC Test Data Report demonstrate comparable daytime and nighttime coverage independent of the type of antenna system. The field tests on these different transmission systems serve to demonstrate the flexibility of the AM IBOC system.

4.5.8 Comparison of measured digital to predicted analog coverage

iBiquity submitted a series of maps depicting the predicted coverage (both day and night) of four AM IBOC test stations[25] and the measured performance of each station's IBOC signal. This section of the EWG report contains a brief discussion of those maps as they pertain to comparing analog performance with digital performance within a station's coverage area.

For the iBiquity field test report submitted to the NRSC, audio samples and signal measurements were collected using receiving antennas that were placed relatively close to the ground, as would be the case with typical mobile, portable, and fixed receivers. Nominally, the receiving antenna height was

[25] Stations represent a variety of station classes, antenna configurations and potential interference scenarios. See Table 4 in Section 3.3 above.

approximately 2 meters (7 feet) above ground level. Signals were measured utilizing a calibrated spectrum analyzer connected to a calibrated sample feed from the antenna.

This signal strength information is depicted in a series of graphs submitted with the maps (Figure 21 and Figure 22). Each field intensity graph presents the data collected on one radial drive test and contains field strength of the desired signal and of the upper and lower first and second adjacent channels, plus the digital-vs.-blend mode of the received digital and the distance from the transmitter.

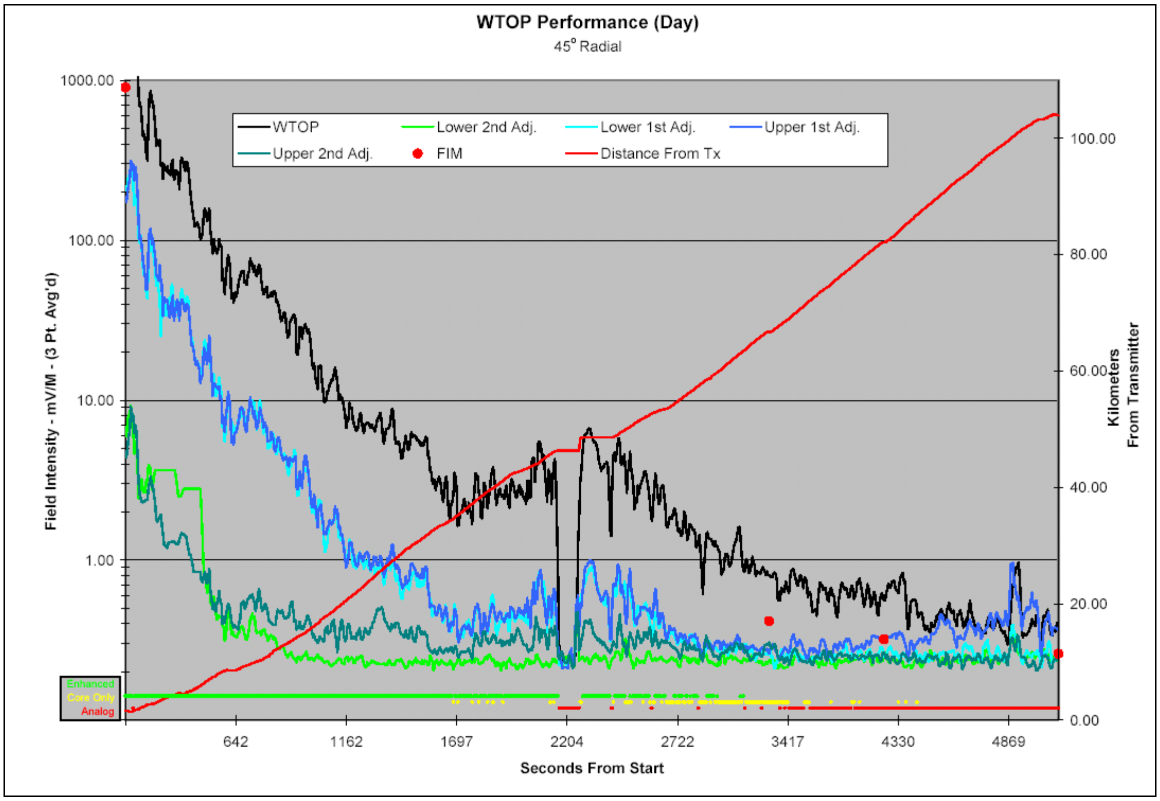

Figure 21. Field test signal strength graph, daytime (WTOP, 45º radial)

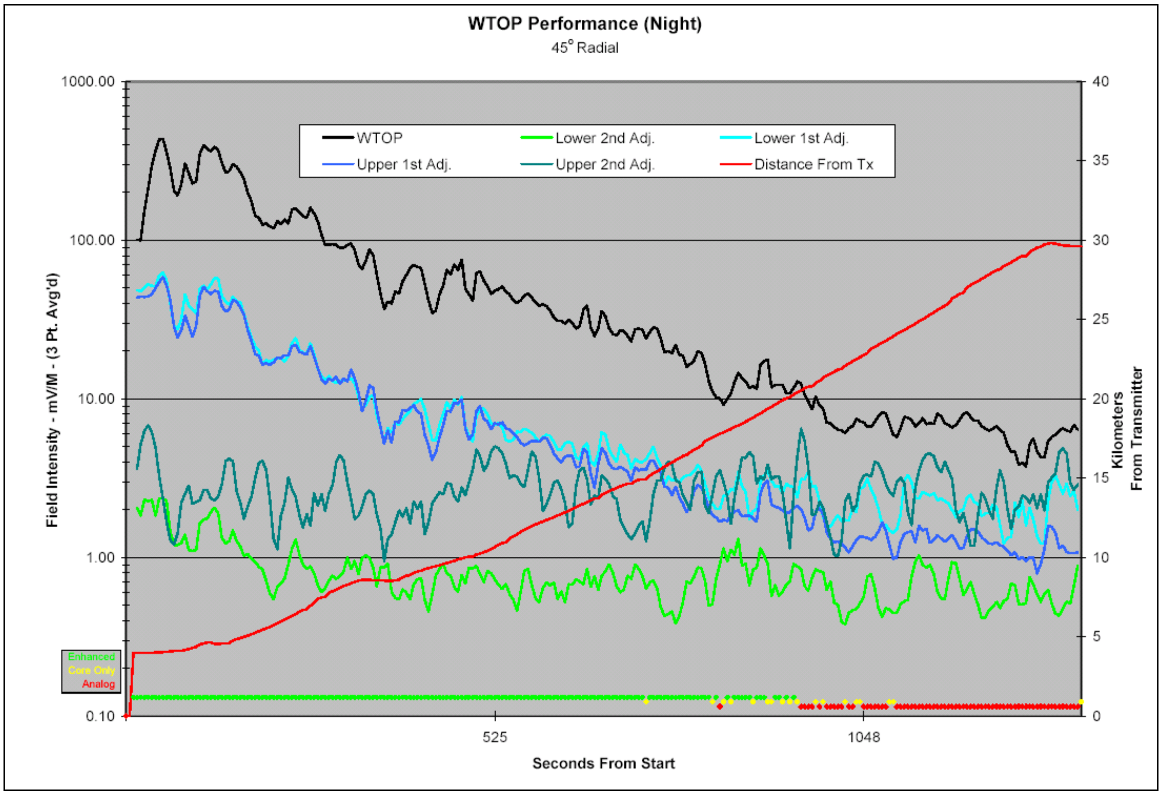

Figure 22. Field test signal strength graph, nighttime (WTOP, 45º radial)

Using this information it is possible to approximate the signal level at which the AM IBOC signal is blending from enhanced to core and from core to analog (Figure 23) for each station tested. These plots confirm that the audio quality transition from enhanced digital to core digital to analog is (in part, at least) a function of signal strength, since for a given test station the average signal strength corresponding to the enhanced-core transition is always greater than it is for the core-analog transition. They also show that on average these transitions occur at higher signal levels (i.e. closer to the transmitter) during the nighttime than during the daytime.

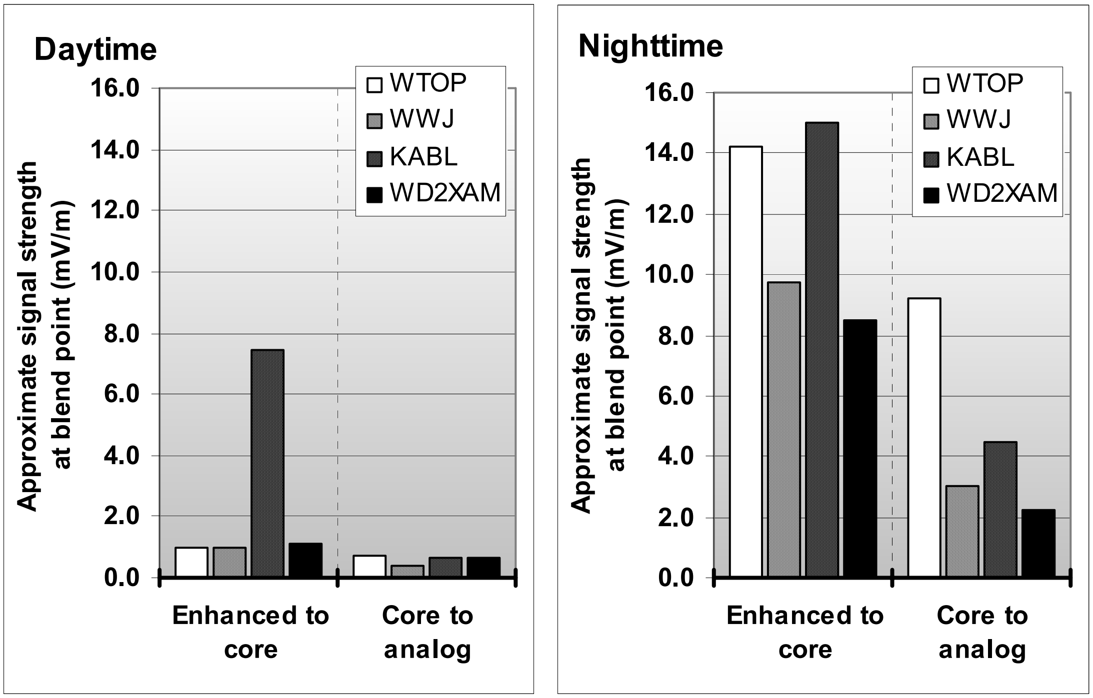

Figure 23. Approximate signal strength at blend points for field test stations (for each station, results averaged over all test radials)

The test station coverage maps contained in the report each show either a 2 mV/m (daytime) or the nighttime interference free (NIF) contour overlaid to enable a comparison between predicted analog signal strength and actual digital IBOC reception (Figure 24 and Figure 25). The predicted signal strength information in these maps was generated with ComStudy software and appears as an overlay on each map, permitting the map reader to compare the predicted analog signal strength with digital performance.

The digital reception data included in these coverage maps appear as sets of "worm trails" on the maps. The data were taken from mobile tests in which the test vehicle was driven on roads that generally radiate from the transmitter sites of the test stations. The data from which the worm trails were generated is presented on the signal strength graphs that accompany the maps. The worm trails indicate one of two conditions; either the digital signal was being received reliably (shown in gray – corresponds to either enhanced or core digital audio), or the receiver had blended to analog (shown in black). No information was given to indicate what the quality of the blended-to-analog signal was. Hence, the digital reception radial drive test maps indicate positively where digital reception was reliable, but give no direct comparative information on the quality of the analog coverage of the station.

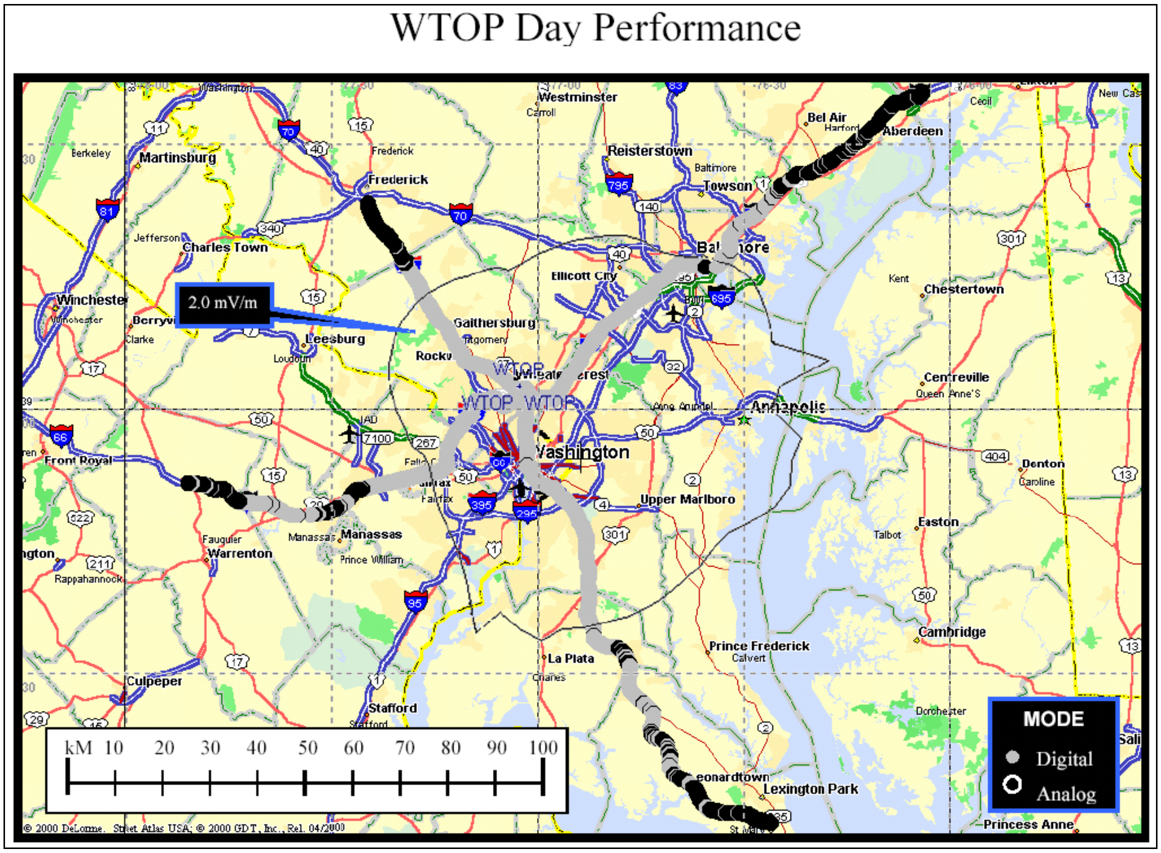

Figure 24. Coverage map including IBOC digital coverage (on radials) and 2 mV/m contour

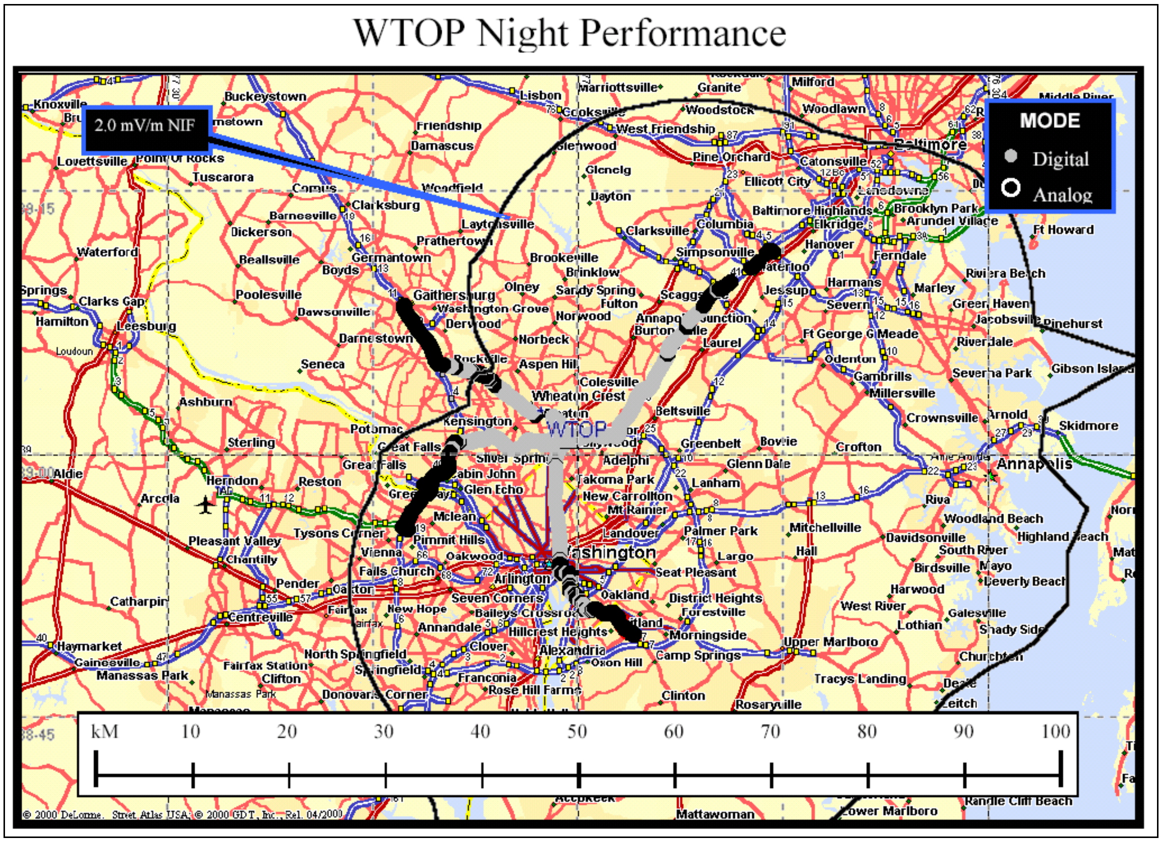

Figure 25. Coverage map including IBOC digital coverage (on radials) and NIF contour

The Evaluation Working Group found the iBiquity maps to be very helpful as a means of geographically comparing digital and analog performance of these IBOC stations. Typically, the digital IBOC signal is extremely reliable wherever there is enough signal strength to support analog reception. When interference conditions impair analog signals significantly within the protected contour, there is no reason to expect the digital coverage to overcome the impact of this interference. At night, the test results indicate that the digital coverage is impacted to a greater extent by interference than is the analog.

During the day, outside the 2 mV/m contours it is commonly understood that stations may have some additional coverage that is limited by factors such as interference, ground conductivity, and distance. The digital IBOC signals appear to provide coverage generally in areas where the analog signal strength is at useable levels. The stations may be subjected to interference from adjacent channels in some locations.

The four maps submitted by iBiquity represent a variety of station classes and interference scenarios (see Table 4 above). While these test stations provide a good cross section of various conditions, they of course represent a very small percentage of the AM stations in the U.S. and cannot be employed as the only means of verifying IBOC digital service area. The general association among the maps, between predicted analog signal strength and measured digital performance, does suggest that careful generalizations can be made about digital coverage area to the degree they are supported by lab test data. This data is discussed elsewhere in this Section.

4.5.9 Findings – service area

NRSC test results indicate that the hybrid AM IBOC digital coverage during the daytime is comparable to analog coverage along radial routes tested. Due to AM IBOC's improved resistance to various types of interference (*e.g.*, co- and adjacent channel, impulse noise, power lines), AM IBOC service may be available in areas where analog service is currently of unacceptable quality due to such interference. At night, digital coverage fell short of the predicted nighttime interference-free (NIF) contours and the system had blended to analog before reaching this contour. In general, these results demonstrate that adjacent channel interference experienced by the test stations during night operation restricts digital coverage.

4.5.10 Findings – durability

NRSC test results demonstrate that the iBiquity hybrid AM IBOC system, compared to analog AM, is substantially more robust under impulse noise and co- and adjacent channel interference conditions.

4.6 Criterion 4 – Acquisition performance

Table 11 lists the test result pertaining to acquisition performance of the iBiquity AM IBOC system.

Table 11. AM IBOC test results pertaining to acquisition performance

TEST NO. (PROCEDURES)	OBJECTIVE DATA	SUBJECTIVE DATA	ANALOG BENCHMARK	RESULTS / COMMENTS
Lab – F.1 – IBOC acquisition	Appendix I: - Table 5-7, pg. 29	n/a	Acquisition time of analog receiver	IBOC receiver acquisition time – 300 msec; mode - analog

The iBiquity AM IBOC system is designed such that an IBOC receiver will initially acquire an AM channel utilizing the analog portion of the hybrid AM IBOC signal. Once the digital portion of the signal is fully acquired (takes a few seconds), the receiver will then blend from analog audio to digital audio. Consequently, an IBOC receiver has the same acquisition performance as an analog radio. This was confirmed by NRSC lab test F.1, where the acquisition time was measured to be 300 msec.

4.6.1 Findings

The acquisition performance of the iBiquity hybrid AM IBOC system is identical to that of an analog AM radio since, by design, an IBOC receiver initially acquires the analog portion of the hybrid AM IBOC signal.

4.7 Criterion 5 – Auxiliary data capacity

According to the system specification, the iBiquity AM IBOC system operating in hybrid mode supports transmission of an auxiliary data stream along with the main channel audio data stream with a capacity as shown in Table 12.[26] This system feature was not tested by the NRSC. Since existing AM analog services do not support the broadcast of auxiliary data, this represents a new capability for the AM broadcast service.

Table 12. Auxiliary data capacity of the iBiquity AM IBOC system - data rates include 2-3 kbps average rate for opportunistic data[27]

Operating mode	With 36 kbps main channel audio (stereo)	With 20 kbps main channel audio (mono)
Hybrid	0.4 kbps	16.4 kbps

4.7.1 Findings

The iBiquity hybrid AM IBOC system design incorporates an auxiliary data transmission feature with a minimum capacity of 0.4 kbps. This system feature was not tested by the NRSC. Since existing AM analog services do not support the broadcast of auxiliary data, this represents a new capability for the AM broadcast service.

4.8 Criterion 6 – Behavior as signal degrades

This criterion pertains to how an IBOC receiver generally behaves as the received signal becomes weak (due to blockage or distance from the transmitter), or encounters severe degradation due to interference (*e.g.*, strong adjacent channels) compared to how an analog receiver would behave under similar conditions. Table 13 lists the test results pertaining to behavior as signal degrades of the iBiquity AM IBOC system.

Table 13. AM IBOC test results pertaining to behavior as signal degrades

TEST NO. (PROCEDURES)	OBJECTIVE DATA	SUBJECTIVE DATA	ANALOG BENCHMARK	RESULTS / COMMENTS
Field – Performance at blend (NRSC procedures as amended by Steering Committee)	n/a	Appendix G, pg. 2	Audio quality of host analog signal (recorded simultaneously with IBOC audio)	IBOC audio cuts containing blends (enhanced to core, core to analog) were tested Subjective results: Audio quality of IBOC with blends either significantly better (enhanced to core) or similar (core to analog) to corresponding analog

Fundamentally, by virtue of the AM IBOC system's blending feature (enhanced digital to core digital and core digital to analog), an AM IBOC receiver behaves similar to an analog receiver as the signal weakens or otherwise approaches the outer limits of a reception area. This behavior differs from that of other digital broadcast systems which, under similar conditions, exhibit the so-called "cliff effect," whereby the signal transitions from a high-quality digital signal to muting. iBiquity has indicated to the NRSC that the blending points of the system have been placed such that they will occur prior to the point

[26] See AM IBOC Test Data Report, Appendix A.
[27] See AM IBOC Test Data Report, main report, pg. 18, and Appendix A.

where the received digital audio would start experiencing undesirable, audible artifacts (“clicks,” “pops,” etc.) due to signal degradation. According to iBiquity, these points are established (within the receiver) by monitoring the block error rate (BLER, which increases with increasing signal degradation) as well as the overall error statistics of the received signal.

As part of the NRSC evaluation, audio recordings were obtained in the field at the point where the AM IBOC receiver was blending such that the blend process was captured; consequently, this audio is a combination of enhanced digital and core digital, or core digital and analog, and the blending between the (respective) two. These recordings were then compared subjectively to recordings made on analog automotive receivers at the same time under the same conditions and the results of these evaluations are shown in Figure 26.

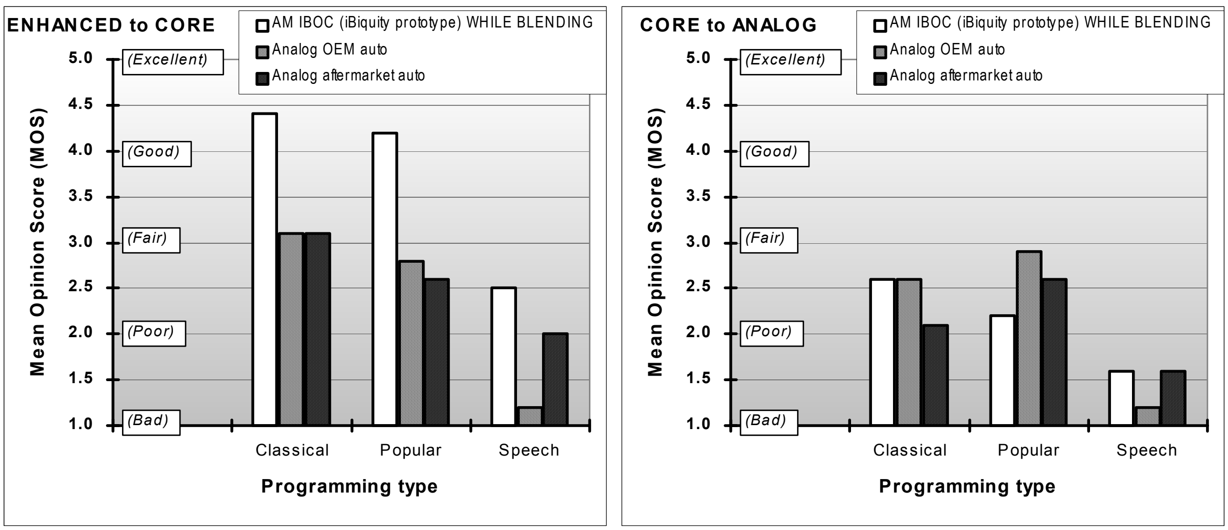

Figure 26. Comparison of AM IBOC and analog audio subjective evaluation field results at “blend to analog” operating point

These results demonstrate both that the AM IBOC audio during the blend process is perceived to have either significantly better audio quality (enhanced to core) or similar audio quality (core to analog) as does the analog audio. Note that in the core to analog blend results (graph on the right in Figure 26), the audio quality of the AM IBOC receiver indicated is a combination of the quality of the core digital receiver and the analog receiver sections of the AM IBOC receiver; since this analog receiver section has not been optimized for good audio performance (discussed earlier in Section 3.1 above) these results are likely poorer than would be found in a more refined, commercial implementation of an AM IBOC receiver.

4.8.1 Findings

NRSC testing has demonstrated that the iBiquity prototype hybrid AM IBOC receiver’s audio during the blend process is perceived to have either significantly better audio quality (enhanced to core) or similar audio quality (core to analog) as does the analog audio.

4.9 Criterion 7 – Stereo separation

The AM IBOC system offers listeners two-channel stereo audio, unlike the vast majority of analog AM receivers and radio broadcasts presently available, which only support mono audio. Stereo audio is supported by the enhanced digital audio mode of the AM IBOC system (the mode tested by the NRSC) such that when all 36 kbps of the digital audio data stream are received acceptably, stereo audio will be available. Under degraded reception conditions where the receiver is operating in either the core digital or analog audio modes, mono audio will be available. Table 14 lists the test results pertaining to the stereo separation of the iBiquity AM IBOC system.

Table 14. AM IBOC test results pertaining to stereo separation

TEST NO. (PROCEDURES)	OBJECTIVE DATA	SUBJECTIVE DATA	ANALOG BENCHMARK	RESULTS / COMMENTS
Lab – Stereo separation (not in test procedure)	Appendix K: Table 4-3, pg. 6	Appendix K: Table 4-4, pg. 7	n/a	Objective results: L→R and R→L separation >100 dB using 1 kHz and 4 kHz tones Subjective results: indicate full stereo when backed off 4, 6 dB from enh→core blend point

These results indicate that when the AM IBOC receiver is operating in stereo mode in an AWGN channel, it offers exceptionally good stereo separation.

4.9.1 Findings

AM IBOC receivers are expected to exhibit superior stereo separation compared to analog AM receivers (the vast majority of which offer no stereo capability at all) when reception conditions allow for the AM IBOC receiver to make full use of the enhanced digital audio data stream.

4.10 Criterion 8 – Flexibility

Appendix A of the AM IBOC Test Data Report, the "IBOC AM Transmission Specification," documents a number of features of the AM IBOC system that should provide significant flexibility for both broadcasters and receiver manufacturers, including:

- Modes of operation: four modes of operation are described—two hybrid modes and two all-digital modes—offering significant opportunities for individualizing the broadcast signal to specific needs and for future improvements in system performance. Only one of the hybrid modes (mode MA1) has been tested by the NRSC.

- Audio coding rate: the bit rate used for transmission of the main channel audio signal can be varied, allowing for re-allocation of the digital payload based on a broadcaster's particular requirements. NRSC testing of the AM IBOC system was done with the audio coding rate fixed at 36 kbps, however some of the test results (those obtained when the receiver was operating in the "core" digital mode) are applicable to when the system is operated with only 20 kbps audio.

- Auxiliary data rate: (this is discussed in Section 4.7 above in greater detail) the AM IBOC system supports transmission of an auxiliary data stream along with the main channel audio bit stream. The actual amount of auxiliary data transmitted can be decreased or increased in conjunction with a corresponding increase or decrease in the audio coding rate. This system feature was not tested by the NRSC.

- On-channel repeaters: the use of OFDM modulation in the AM IBOC system allows on-channel digital repeaters to fill areas of desired coverage where signal losses due to terrain and/or shadowing are severe. This system feature was not tested by the NRSC.

4.10.1 Findings

There are a significant number of features in the iBiquity AM IBOC system that should provide for system flexibility and should offer broadcasters and receiver manufacturers opportunities to customize services and equipment for their particular goals, and offer the possibility of performance improvements in the future. None of these features (except for establishing the subjective audio quality of both 36 kbps and 20 kbps audio) were tested by the NRSC.

4.11 Criterion 9 – Host analog signal impact

Table 15 lists the test results from the AM IBOC Test Data Report that pertain to host analog signal impact of iBiquity's AM IBOC system.

Table 15. AM IBOC test results pertaining to host analog signal impact

TEST NO. (PROCEDURES)	OBJECTIVE DATA	SUBJECTIVE DATA	RESULTS / COMMENTS
Lab – H.1, H.2 - IBOC ➔ host analog (main channel audio)	Appendix B: - Table 9, pg. 40 (Delphi) - Table 7, pg. 38 (Pioneer) - Table 10, pg. 41 (Sony) - Table 8, pg. 39 (Technics)	Appendix G, pg. 11	Objective: Delphi: host analog unaffected by addition of IBOC Pioneer: addition of IBOC degraded host analog S/N by about 6 dB Sony: addition of IBOC degraded host analog S/N by about 7 dB Technics: addition of IBOC degraded host analog S/N by about 9 dB Subjective: Delphi: results with and without IBOC nearly identical Pioneer: addition of IBOC degraded host analog from excellent/good to good/fair for speech Sony: addition of IBOC degraded host analog from good to fair/poor for all programming Technics: addition of IBOC degraded host analog from excellent/good to good/fair for speech
Field – C.1 – host compatibility (main channel audio)	Appendix D1: - Pg. 1 (WTOP locations) - Pg. 2 (WWJ locations) - Pg. 3 (KABL locations) - Pg. 4 (WD2XAM locations)	Appendix G, pg. 7	Objective: no conclusions – location identification only Subjective: Delphi: results with and without IBOC nearly identical Pioneer: addition of IBOC degraded host analog

TEST NO. (PROCEDURES)	OBJECTIVE DATA	SUBJECTIVE DATA	RESULTS / COMMENTS
	- Pg. 4 (WD2XAM locations)		from good to fair for speech/voiceover Sony: addition of IBOC degraded host analog from good to fair/poor for speech/voiceover Technics: addition of IBOC degraded host analog from good/fair to fair for speech/voiceover

The design of the AM IBOC system (see Figure 1) is such that its addition to an AM broadcast signal will cause a reduction in the host analog signal-to-noise performance at the receiver. Within the passband of an analog AM receiver the digital reference carriers are at 181.7 Hz above and below the analog carrier, and the tertiary OFDM carriers extend from 363.4 Hz to 4,723.8 Hz above and below the analog carrier. These carriers occupy the same spectrum as the analog AM signal and are modulated in a form that is designed to cancel interference to the host analog signal. The effectiveness of this cancellation depends on the linearity of the RF channel and the linearity of the receiver. If the passband of the receiver extends beyond 5,000 Hz, the receiver will detect the higher power secondary digital carriers that extend from 5,087 Hz to 9,448 Hz above and below the AM carrier frequency.

The AM IBOC Test Data Report indicates that the power level for the secondary carriers and the IBOC Data Service carriers can be set at a power spectral density of -43 or -37 dB per subcarrier relative to the total power of the unmodulated analog AM carrier.[28] The final level for the tertiary carriers has not yet been announced.[29] It is important to note that, in the NRSC tests, host compatibility performance was measured with the secondary carriers set at -44 dB per subcarrier relative to the total power of the unmodulated analog AM carrier,[30] and the tertiary carriers set at an average value of -47.8 dB. The *total* sideband power of each sideband with respect to the analog carrier, as verbally reported by iBiquity to the NRSC, is listed in Table 3. Changes in the power levels for any of these carriers would cause the host compatibility characteristics of the system to differ from the NRSC test results reported in the AM IBOC Test Data Report.

The laboratory and field test results, summarized in Table 15, indicate that, except for one of the two automobile receivers, which was unaffected by the addition of the IBOC signal, all of the radios tested had the reception of the host analog signal degraded to some degree by the addition of the IBOC signal. The reception of the host analog signal on the other automobile receiver went from "good" to "fair," as did the reception on the home hi fi receiver. Reception on the portable receiver went from "good" to "fair-to-poor." During the testing of its FM IBOC system (which was the subject of Part 1 of this report), iBiquity found that for speech programming listeners would not be motivated to stop listening unless the audio quality was worse than "fair-to-poor."[31] Based on this information, it appears that none of the degradation expected to be caused to the host analog signal by the IBOC digital signal will be sufficient to impact listening.

[28] AM IBOC Test Data Report, Appendix A, p. 26.
[29] AM IBOC Test Data Report, Appendix A, p. 26.
[30] Note that the measured value is slightly different (1 dB lower) than the specified value.
[31] iBiquity Digital Corporation, *Report to the National Radio Systems Committee, FM IBOC DAB Laboratory and Field Testing,* August, 2001 ("FM IBOC Test Data Report"), Appendix J, p. 2.

4.11.1 Findings

For the conditions tested, the AM IBOC system has little effect on the host analog signal. The amount of interference to the host analog signal is receiver dependent. The narrow bandwidth automobile receivers were found to be the least sensitive to the digital signal. The wider bandwidth hi fi and portable radios were found to be more sensitive to the digital signal. Each receiver's frequency and phase response symmetry plays a part in its host compatibility.

The test results suggest that, although the introduction of AM IBOC will be noticeable to some listeners of the host analog station using certain analog receivers, these listeners are not expected to find their audio quality sufficiently degraded to impact listening.

4.12 Criterion 10 - Non-host analog signal impact

Table 16 lists the test results pertaining to the non-host analog signal impact of the iBiquity AM IBOC system.

Table 16. AM IBOC test results pertaining to non-host analog signal impact

TEST NO. (PROCEDURES)	OBJECTIVE DATA	SUBJECTIVE DATA	RESULTS / COMMENTS
Lab – E.1, E.4 - IBOC ➜ analog (main channel audio), single 1st adj.	Appendix B: - Table 9, pg. 40 (Delphi) - Table 7, pg. 38 (Pioneer) - Table 10, pg. 41 (Sony) - Table 8, pg. 39 (Technics)	Appendix G, pg. 12	Objective: Delphi: analog unaffected by addition of IBOC to 1st adjacent interferer at 0, +15 and +30 dB D/U Pioneer: analog unaffected by addition of IBOC to 1st adjacent interferer at 0, +15 and +30 dB D/U Sony: analog S/N degraded by 4 dB when IBOC added to upper 1st adjacent interferer at 0 and +15 dB D/U, but addition of IBOC to lower 1st adjacent interferer at these D/U ratios actually improved analog S/N by about 1 dB; addition of IBOC had essentially no impact at +30 dB D/U Technics: analog S/N degraded by about 4 dB when IBOC added to upper 1st adjacent interferer at 0 and +15 dB D/U, and by about 3 dB at the +30 dB D/U, but addition of IBOC to lower 1st adjacent interferer actually improved analog S/N by about 2 dB and 0, +15 and +30 dB D/U Subjective: Delphi (10 kHz undesired analog audio): speech and voiceover programming was unaffected at +30 dB D/U; and went from “good-to-fair” to “fair-to-poor” for speech, and “good” to “fair” for voiceover, with addition of IBOC to 1st adjacent interferer at +15 dB D/U Pioneer (10 kHz undesired analog audio): speech and voiceover programming was unaffected at +30 dB D/U; and went from “good” to “fair-to-poor” for speech and voiceover with addition of IBOC to 1st adjacent interferer at +15 dB D/U Sony (10 kHz undesired analog audio): speech and voiceover programming was unaffected at +30 dB D/U; and went from “fair” to “poor” for speech and

			voiceover with addition of IBOC to 1st adjacent interferer at +15 dB D/U Technics (10 kHz undesired analog audio): speech and voiceover programming was unaffected at +30 dB D/U; and went from "good" to "fair-to-poor" for speech and voiceover with addition of IBOC to 1st adjacent interferer at +15 dB D/U
Lab – E.2, E.5 - IBOC ➜ analog (main channel audio), single 2nd adj.	Appendix B: - Table 9, pg. 40 (Delphi) - Table 7, pg. 38 (Pioneer) - Table 10, pg. 41 (Sony) - Table 8, pg. 39 (Technics)	Appendix G, pg. 13	Objective: Delphi: desired analog unaffected by addition of IBOC to 2nd adjacent interferer Pioneer: desired analog unaffected by addition of IBOC to 2nd adjacent interferer, except that at 0 dB D/U addition of IBOC to lower 2nd adjacent degraded desired S/N ratio by about 7 dB Sony: desired analog unaffected by addition of IBOC to 2nd adjacent interferer at +30 and +15 dB D/U, except that at +15 dB D/U addition of IBOC to lower 2nd adjacent degraded desired S/N by 5 dB; at 0 dB D/U addition of IBOC degraded S/N by about 10 dB for the upper 2nd adjacent case, and about 20 dB for the lower 2nd adjacent case Technics: desired analog unaffected by addition of IBOC to 2nd adjacent interferer at +30 and +15 dB D/U, except that at +15 dB D/U addition of IBOC to lower 2nd adjacent degraded desired S/N by 3 dB; at 0 dB D/U addition of IBOC degraded S/N by about 10 dB for the upper 2nd adjacent case, and about 15 dB for the lower 2nd adjacent case Subjective: Delphi (10 kHz undesired analog audio): speech and voiceover programming was unaffected by the addition of IBOC to a 2nd adjacent interferer at +30, +15 and 0 dB D/U, and was in the "good-to-fair" range in all cases Pioneer (10 kHz undesired analog audio): speech and voiceover programming was unaffected by addition of IBOC to 2nd adjacent interferer at +30 and +15 dB D/U, and was in the "good-to-fair" range in all cases; at 0 dB D/U addition of IBOC sent audio quality from "good" to "fair-to-poor" Sony (10 kHz undesired analog audio): speech and voiceover programming was unaffected by addition of IBOC to 2nd adjacent interferer at +30 dB D/U, and was in the "good-to-fair" range in all cases; at +15 dB D/U addition of IBOC sent audio quality from "good-to-fair" to "fair-to-poor;" at 0 dB D/U addition of IBOC sent audio quality from "good-to-fair" to "poor-to-bad" Technics (10 kHz undesired analog audio): speech and voiceover programming was only slightly affected at +30 and +15 dB D/U and was in the "good-to-fair" range in all cases; at 0 dB D/U addition of IBOC sent audio quality from "good" to "poor"
Lab – E.3, - IBOC ➜ analog (analog main channel audio), single 3rd adj.	Appendix B: - Table 9, pg. 40 (Delphi) - Table 7, pg. 38 (Pioneer) - Table 10, pg. 41 (Sony)	Not in test plan	Objective: Delphi, Pioneer, Sony, Technics: desired analog unaffected by addition of IBOC to 3rd adjacent interferer

	- Table 8, pg. 39 (Technics)		
Field – C.2 – 1st adjacent compatibility	Appendix D1: - Pg. 1 (WTOP locations) - Pg. 2 (WWJ locations) - Pg. 3 (KABL locations) - Pg. 4 (WD2XAM locations)	Appendix G, pp. 8-9	Objective: no conclusions – location identification only Subjective: Delphi (5 kHz undesired analog audio): speech programming unaffected by addition of IBOC to 1st adjacent interferer, though quality was "poor" at 10 dB D/U and "fair-to-poor" at 13-16 dB D/U; voiceover programming went from "fair-to-poor" to "poor-to-bad," and popular music went from "fair" to "poor" over the 13-16 dB D/U range Delphi (10 kHz undesired analog audio): speech programming went from "good-to-fair" to "fair" with addition of IBOC to 1st adjacent interferer at 13-16 dB D/U Pioneer (5 kHz undesired analog audio): speech programming unaffected by addition of IBOC to 1st adjacent interferer at 10 dB D/U though quality was "poor-to-bad;" at 13-16 dB D/U speech went from "fair" to "fair-to-poor;" voiceover programming was unchanged at "poor-to-bad," and popular music went from "fair-to-poor" to "poor-to-bad" Pioneer (10 kHz undesired analog audio): speech programming went from "good-to-fair" to "fair" with addition of IBOC to 1st adjacent interferer at 13-16 dB D/U Sony (5 kHz undesired analog audio): with 1st adjacent interference at 10-16 dB D/U, speech, voiceover and popular music were all "poor-to-bad" whether or not IBOC was on the first adjacent interferer Sony (10 kHz undesired analog audio): speech programming remained unchanged at "poor" with addition of IBOC to 1st adjacent interferer at 13-16 dB D/U Technics (5 kHz undesired analog audio): with 1st adjacent interference at 10-16 dB D/U, speech, voiceover and popular music were all "poor-to-bad" whether or not IBOC was on the first adjacent interferer Technics (10 kHz undesired analog audio): speech programming went from "fair-to-poor" to "poor" with addition of IBOC to 1st adjacent interferer at 13-16 dB D/U
Field – 2nd adjacent compatibility (not in test procedure)	Appendix D1: - Pg. 1 (WTOP locations) - Pg. 2 (WWJ locations) - Pg. 3 (KABL locations) - Pg. 4 (WD2XAM locations)	Appendix G, pg. 10	Objective: no conclusions – location identification only Subjective: Delphi (10 kHz undesired analog audio): addition of IBOC to 2nd adjacent interferer had no impact, quality was "poor-to-bad" at 9-10 dB D/U for gospel music, and "fair" for speech, with IBOC on and off; speech was "good" at 16 dB D/U with IBOC on and off Pioneer (10 kHz undesired analog audio): addition of IBOC to 2nd adjacent interferer had no impact, quality was "poor-to-bad" at 9-10 dB D/U for gospel music, and "fair" for speech, with IBOC on and off; speech was "good" at 16 dB D/U with IBOC on and off Sony (10 kHz undesired analog audio): addition of

			IBOC to 2nd adjacent interferer had no impact, quality was "poor-to-bad" at 9-10 dB D/U for gospel music and speech, "fair-to-poor" at 16-21 dB D/U for speech Technics (10 kHz undesired analog audio): addition of IBOC to 2nd adjacent interferer had no impact, quality was "fair" at 9-21 dB D/U for speech

4.12.1 Co-channel compatibility

Introduction of hybrid AM IBOC should not cause additional co-channel interference to AM reception. This is due to the fact that the power level of the analog portion of an interfering IBOC signal is significantly greater than the power level of the IBOC digital sidebands, and also to the fact that the analog portion of the interferer is frequency coincident with the analog portion of the desired signal. Because this performance is dictated by design, the NRSC test procedures did not include tests for co-channel compatibility.

4.12.2 1st-adjacent channel compatibility

Because the IBOC digital sidebands of an AM station share spectrum with the analog signal of a 1st adjacent AM station, 1st adjacent channel compatibility is a significant issue for AM IBOC (see Figure 2). The digital OFDM carriers that make up an undesired 1st adjacent AM IBOC station's primary sidebands start on the opposite side of the desired station's carrier from the undesired station and extend from 356 Hz to 4,717 Hz above or below the desired carrier. Thus, these undesired primary sidebands are superimposed on one side of the desired station's analog signal. Because the digital signal is in the same spectrum as the desired audio signal, the interference will affect all AM analog receivers, regardless of how narrow their passbands might be. The level of digital interference is primarily dependent on the D/U ratio.

Both the laboratory and the field test results, summarized in Table 16, indicate that some listeners will notice the addition of an IBOC signal to a station that is 1st adjacent to one to which they listen. Table 17 further summarizes the results for speech programming.

Table 17: Summary of 1st Adjacent Compatibility Test Results

	1	2	3	4	5
Receiver type	10 dB D/U Field D - Speech No IBOC / IBOC (ACR-MOS)	13, 15, 16 dB D/U Field U - 5 kHz filtered D - Speech No IBOC / IBOC (ACR-MOS)	13, 15, 16 dB D/U Field U - 10 kHz filtered D - Speech No IBOC / IBOC (ACR-MOS)	15 dB D/U Lab U - 10 kHz filtered D - Speech No IBOC / IBOC (ACR-MOS)	15 dB D/U Lab Objective Analog-to-analog No IBOC Upper / Lower S/N (dB)
OEM auto	2.0 / 1.7	2.5 / 2.3	3.5 / 2.9	3.3 / 2.5	28 / 29
Aftermarket auto	1.6 / 1.6	3.0 / 2.4	3.7 / 3.0	3.8 / 2.2	27 / 28
Portable	1.65 / 1.6	1.8 / 1.7	2.0 / 2.0	3.2 / 2.1	26 / 29
Hi fi	1.4 / 1.3	2.1 / 1.7	2.4 / 2.1	3.9 / 2.3	26 / 27
High-low spread	0.6 / 0.4	1.2 / 0.6	1.5 / 0.8	0.7 / 0.4	2 / 2

The field test results indicate that AM listeners using automobile receivers are likely to find that the quality of their audio goes from "good-to-fair" to "fair" when a first adjacent station begins IBOC transmissions and the 1st adjacent station's signal is 15 dB weaker than the signal of the station they are listening to. Listeners using home hi fi receivers are likely to find that their audio goes from "fair-to-poor" to "poor" at the 15 dB D/U point, and listeners using portable radios are likely to find that their audio remains unchanged at "poor" at the 15 dB D/U point. The daytime protected contour for AM stations with respect to 1st adjacent channel stations is the 0.5 mV/m contour.[32] Because the FCC rules allow an interfering 1st adjacent station's field strength to be as high as 6 dB below the field strength of a desired station at the desired station's protected contour,[33] the +15 dB D/U point occurs inside the desired station's 0.5 mV/m protected contour.

For the 13, 15 and 16 dB D/U points the field test results with the 5 kHz filter on the undesired analog signal are summarized in column 2 of Table 17, and the same results with the 10 kHz filter on the undesired analog signal are summarized in column 3. Except for one borderline data point with the hi fi receiver, the automobile receivers were the only ones that produced listenable audio with or without IBOC present under these conditions. The laboratory and field test results for the automobile radios were nearly identical under the 10 kHz filtered condition (columns 3 and 4). The hi fi and portable receivers did not perform nearly as well in the field as they did in the lab, probably due to the increased complexity of the RF environment in the field.

At the 10 dB D/U point, column 1 in Table 17 shows that listeners subjectively rated the AM audio with 1st adjacent IBOC interference to be very close in quality to the analog AM audio with 1st adjacent analog interference, and that in all cases the audio was at or below the unlistenable point (2.3 MOS for speech) discussed above.[34] The desired signal field intensity for these tests varied from 0.4 to 1.2 mV/m.[35] Since the daytime protected contour for an AM station is the 0.5 mV/m contour, and since AM stations are supposed to be protected from 1st adjacent channel interference by at least a +6 dB D/U ratio at their protected contours, this data suggests that AM stations do not receive adequate protection from 1st adjacent channel analog interference today. There is 1st adjacent analog-to-analog interference today inside the protected contour, and there will be 1st adjacent channel IBOC-to-analog interference inside the protected contour should AM IBOC be introduced.

During the testing of its FM IBOC system, iBiquity found that, for speech programming, at least half of all listeners would not be motivated to stop listening unless the audio quality was worse than "fair-to-poor."[36] Based on this information, it appears that only the home hi fi receiver would be pushed from the listenable range into the unlistenable range by the introduction of IBOC at the 15 dB D/U level. At the 10 dB D/U level (farther away from the transmitter, but still inside the protected contour) analog audio quality is unacceptable in the presence of both analog and IBOC 1st adjacent channel interference. At the 30 dB D/U level (closer to the transmitter, and well inside the protected contour) analog audio quality is very listenable whether the 1st adjacent interferer is analog or IBOC.

It should be noted that the wideband analog interfering signal used for the analog-to-analog 1st adjacent compatibility tests was more representative of a radio station with music programming than one with speech programming, even though the trend in analog AM radio broadcasting has been toward speech programming. Also, because of potential interference to the OFDM secondary sidebands from the host analog signal of an IBOC station, the analog transmitter audio bandwidth is limited to something less than 5 kHz. At 5 kHz, the filter is at least 40 dB down. The spectral response of this filter is more representative of talk programming than the filter used for the analog-to-analog reference tests. The narrower filter also has the advantage of filtering out processor artifacts. With the analog modulation

32 47 CFR Section 73.182.
33 47 CFR Section 73.37.
34 For further discussion of the interference levels used in the AM IBOC compatibility tests see Appendix H.
35 See February 4, 2002 iBiquity memo to NRSC DAB EWG.
36 FM IBOC Test Data Report, Appendix J, p. 2.

limited to less than 5 kHz, the interference measured for the digital-to-analog tests in Table 18 is from the primary digital sidebands of the 1st adjacent IBOC signal. The S/N measurement spread for the digital interference at the 0 dB D/U varied from 12 dB to 15 dB for all four receivers. It is clear that analog receiver selectivity has very little to do with the receiver's sensitivity to 1st adjacent digital interference. It can also be seen that the characteristics of the undesired host program modulation have little to do with interference to the desired analog signal because there is little difference in S/N (2 dB) between the wideband and narrowband receivers' test results. At the lower interference levels (15 dB D/U and 30 dB D/U) the test results showed that the AM IBOC signal had little impact on a first adjacent analog signal.

Table 18: 1st Adjacent Laboratory Compatibility

Xetron Laboratory Tests WQP S/N at 0 dB D/U		
	Upper No IBOC/IBOC (dB)	Lower No IBOC/IBOC (dB)
Delphi	14.9/13.9	14.6/14.2
Pioneer	14.3/12.6	13.3/13.5
Technics	15.4/11.8	12.6/14.5
Sony	15.5/11.5	11.5/12.8

The laboratory compatibility tests conducted for the NRSC used only three D/U ratios, 0 dB, 15 dB and 30 dB. Additional objective compatibility tests conducted by Xetron for iBiquity are reported in the Clark Report.[37] The interfering 1st adjacent signals for these tests were advanced in 3 dB steps from -24 dB to +45 dB D/U. Two of the four NRSC radios (the OEM auto and the portable radio) were used for this test, which found that with the interfering signal level reduced by 9 dB, the WQP S/N for both receivers improved by 9 dB.[38] The NRSC tests found that, at +15 dB D/U, all four receivers were in the 28 dB WQP S/N range.[39] Thus, it seems reasonable to assume that all of the receivers tested would be at 35 dB WQP S/N at approximately the +22 dB D/U point, at 30 dB WQP S/N at approximately the +17 dB D/U point, etc.

4.12.2.1 Subjective laboratory tests

Subjective 1st adjacent tests were digitally recorded at the Xetron laboratory and evaluated by Dynastat. The undesired audio for the subjective recordings was the "Shania" cut. The undesired audio channel was NRSC preemphasized, 10 kHz low-pass filtered, and processed. The tests were recorded at the same D/U levels as the objective tests, 0 dB, 15 dB, and 30 dB. At the 0 dB D/U all of the MOS ratings were in the 1.2 ("poor-to-bad") range with the IBOC on, and for the reference tests the analog MOS rated between 1.6 and 1.9 ("poor-to-bad"). The interference was significantly reduced at the +15 dB D/U.

Overall conclusions about 1st adjacent compatibility of the AM IBOC system are that the interference caused by the introduction of the IBOC signal is predominantly determined by the D/U ratio.

[37] *Study of Present Analog Signal-to-Noise Ratios in the AM Band and the Changes that Could Result with the Introduction of IBOC Digital Radio Signals*, Glen Clark & Associates, January, 2002 ("Clark Report").
[38] Clark Report, Appendix C.
[39] AM IBOC Test Data Report, Appendix B, pp. 38-41.

Around the 10 dB D/U point (inside the protected contour) today's AM radios are unable to provide audio quality that would satisfy at least half of all listeners. At the 15 dB D/U point (farther inside the protected contour) today's automobile radios provide listenable audio, and would not be significantly affected by the introduction of IBOC; however, today's hi fi receivers do provide listenable audio that would become unlistenable with the introduction of IBOC. At the 15 dB D/U point portable radios appear to provide unlistenable audio with or without IBOC. Farther inside the protected service area, at the 30 dB D/U point, all radios appear to provide listenable audio with or without IBOC.

The Committee's findings are borne out by anecdotal observations made by Clear Channel Communications and C. Crane Company. Clear Channel described AM IBOC compatibility observations made in Frederick, Maryland on February 20, 2002, in cooperation with iBiquity. Clear Channel raised concerns about a potential greater impact of AM IBOC on analog AM reception than is indicated by the data in the AM IBOC Test Data Report.[40] C. Crane Company expressed concerns about the impact of potential AM IBOC interference on listeners distant from AM stations.[41]

4.12.3 2^nd^-adjacent channel compatibility

The IBOC digital sidebands of an AM station also share spectrum with the analog signal of a 2nd adjacent AM station (see Figure 3), though to a lesser extent than with a 1st adjacent station. Therefore, 2nd adjacent channel compatibility is also a significant issue for AM IBOC. Both the laboratory and field test results, summarized in Table 16, indicate that most listeners will not notice the addition of an IBOC signal to a station that is 2nd adjacent to one to which they listen. However, the data does seem to suggest that out at the point of prohibited overlap (0 dB D/U for the 2nd adjacent case[42]) there may be some impact. For example, the portable radio's audio quality was "good-to-fair" without IBOC, and "poor-to-bad" with IBOC when tested under these conditions.

The AM IBOC primary digital sidebands start at 5,283 Hz and extend to 9,635 Hz from the desired 2nd adjacent analog carrier. If the frequency response of the desired receiver extends beyond 5,000 Hz, the receiver will detect the 2nd adjacent digital signal. Because the frequency response of the AM receiver determines its sensitivity to the 2nd adjacent digital carriers, this interference is receiver dependent. The objectives of the 2nd adjacent compatibility tests were to measure any interference change with the introduction of IBOC by comparing each receiver's analog-to-analog S/N performance with digital-to-analog S/N. The desired signal did not have digital sidebands.

Because the RF bandwidth of each AM receiver is determined by measuring the receiver audio frequency response, audio frequency response measurements were made as part of the receiver characterization tests for the NRSC's AM IBOC testing (see Appendix D for the receiver characterization results). Table 19, lines 1, 2 and 3 summarize the audio frequency response measurements made at 2 kHz, 4 kHz and 8 kHz. The 0 dB reference audio level was at 1 kHz. The maximum audio frequency response variation between receivers at 8 kHz was 39 dB (see line 3 of Table 19). It is clear from the data on line 3 that the auto radios are more selective (have narrower passbands) than hi fi and portable radios.

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[40] See Statement of Jeff Littlejohn, Senior VP Engineering Services, Clear Channel Communications, Regarding AM IBOC Field observations, Presented to the National Radio Systems Committee, DAB Subcommittee, Evaluation Working Group, March 6, 2002.
[41] See Bob Crane memo to the NRSC, March 15, 2002.
[42] 47 CFR Section 73.37.

Table 19: 2nd Adjacent Compatibility as a Function of Receiver Bandwidth

Line	Test Description	Delphi Auto Xetron (dB)	Pioneer Auto ATTC (dB)	Technics HiFi ATTC (dB)	Sony Portable - (dB)
1	Audio Frequency Response at 2 kHz	-4.0	-4.0	-3.0	-4
2	Audio Frequency Response at 4 kHz	-18	-15	-17	-11
3	Audio Frequency Response at 8 kHz	-66	-63	-52	-27
4	Upper/Lower A-to-A 2nd Adj. S/N at 0.0 dB D/U	45/45	46/46	47/47	41/40
5	Upper/Lower D-to-A 2nd Adj. S/N at 0.0 dB D/U	44/44	43/38	38/33	30/22*
6	Upper/Lower Difference Between A-to-A and D-to-A S/N	1/1	3/8	9/14	11/18
		MOS	MOS	MOS	MOS
7	Subjective IBOC off (Total) 0 dB D/U	(U) 3.5	(L) 3.7	(L) 3.7	(L) 3.2
8	Subjective IBOC on (Total) 0 dB D/U	(U) 3.4	(L) 2.8	(L) 2.0	(L) 1.5
*Measured at –2 dB and +2 dB D/U and averaged, S/N was 22 dB					

Table 19, line 4 shows a summary of the results of the 2nd adjacent analog-to-analog objective reference tests at the 0 dB D/U. Line 5 shows the digital-to-analog results. Line 6 shows the S/N degradation caused by the addition of the 2nd adjacent IBOC interferer. It is clear from the test data on line 4 that the receivers are not adversely affected by the 2nd adjacent analog interference at 0 dB D/U. The data on lines 5 and 6 show that the wideband receivers (hi fi and portable) are affected by the 2nd adjacent IBOC interference.

The subjective test results on line 7 indicate that the audio was very listenable in the analog-to-analog interference situation. The total ACR-MOS ratings for the analog-to-analog tests varied from 3.2 to 3.7 ("good-to-fair") for all four receivers. Adding the 2nd adjacent IBOC signal caused the ACR-MOS to range from 1.5 ("poor-to-bad") to 3.4 ("good-to-fair"). The wideband radios had the lowest subjective audio quality ratings.

As discussed in Section 4.12.2, the analog undesired signal modulated with audio extended to 10 kHz may overstate the effect of analog-to-analog 1st adjacent interference. With the 2nd adjacent channels separated by 20 kHz and the widest band receiver frequency response down 27 dB at 8 kHz,[43] there is little chance of interference caused by frequency overlap in the 2nd adjacent analog-to-analog case. The test data on line 4 of Table 19 shows that receiver bandwidth has little to do with 2nd adjacent analog interference. Thus, the wideband undesired modulating signal for the 2nd adjacent analog-to-analog tests did not affect the 2nd adjacent test results.

The additional tests in the Clark Report were conducted using the OEM auto and portable receivers. Because there are cases where the 2nd adjacent undesired signal can exceed the desired, it will be necessary to use the extended data for interference analysis. At a D/U of -15 dB the OEM auto S/N for the analog-to-analog test was 45 dB, and with digital the S/N was 28 dB. At a D/U of -15 dB the portable S/N for the analog-to-analog test was less than 29 dB with lower 2nd adjacent interference, and 37 dB with upper 2nd adjacent interference. S/N levels for intermediate D/U ratios can be determined using the data found in the Clark Report.

[43] See Table 19, line 3, under the Sony receiver column.

The 2nd adjacent field tests were conducted at D/U ratios of 9-10 dB, 16 dB, and 21 dB. For the laboratory digital-to-analog compatibility 15 dB D/U test, the lowest measured S/N was on the lower adjacent channel for the portable radio, 35 dB WQP. The extended tests measured the S/N for the Delphi and portable radios at a D/U of 9 dB. There was no detectable interference to the Delphi at 9 dB D/U, and the worst-case side of the portable radio measured 28 dB WQP S/N.

The 2nd adjacent field tests were limited to three D/U ratios of 9-10 dB, 16 dB, and 21 dB. Columns 1, 2 and 3 of Table 20 summarize the field test results for the three D/U ratios. Only speech assessment data is used for all of the subjective comparisons. Columns 4, 5 and 6 summarize the laboratory subjective and objective test data at the 15 dB D/U ratio.

With the minor exception of the portable receiver in column 2, at the three field test D/U ratios there is little interference from the digital signal (columns 1, 2 and 3). The laboratory subjective tests confirm the digital interference to the wideband portable receiver (column 4). The high level of interference to the hi fi receiver indicated by the subjective results from the laboratory was not confirmed in the field, and the amount of interference from IBOC to the hi fi receiver indicated by the subjective results from the laboratory was not confirmed by the objective results from the laboratory. The laboratory digital subjective interference to the Hi-Fi radio was not confirmed by the objective tests.

Table 20: Summary of 2nd Adjacent Compatibility Test Results

	1	2	3	4	5	6
Receiver type	9-10 dB D/U Field D - Speech No IBOC/IBOC (ACR-MOS)	16 dB D/U Field D - Speech No IBOC/IBOC (ACR-MOS)	21 dB D/U Field D - Speech No IBOC/IBOC (ACR-MOS)	15 dB D/U Lab D - Speech No IBOC/IBOC (ACR-MOS)	15 dB D/U Lab Objective IBOC off S/N (dB) Upper/Lower	15 dB D/U Lab Objective IBOC on S/N (dB) Upper/Lower
OEM auto	2.8/2.7	3.7/3.8	2.1/3.2	3.4/3.4	45/45	45/45
Aftermarket auto	2.7/2.8	3.9/3.9	3.2/3.4	3.7/2.5	46/46	46/45
Portable	1.7/1.8	2.8/2.2	2.6/2.6	3.4/1.4	41/41	39/35
Hi fi	2.8/2.6	3.5/3.1	2.9/3.0	3.9/2.1	48/48	47/46

Overall, AM IBOC compatibility with analog AM is receiver and D/U dependent. At the D/U ratios tested, narrowband receivers are not sensitive to AM IBOC interference. However, the data in the Clark Report suggest that, at lower and negative D/U ratios wideband hi fi and portable radios will experience interference from the AM IBOC signal.

4.12.4 3rd-adjacent channel compatibility

Laboratory tests were the only type collected for 3rd adjacent channel situations, and the results indicate that the addition of an IBOC signal to a 3rd adjacent channel station will have no impact on a desired station's analog reception.

4.12.5 Findings

These findings are based on the test results that were collected during the NRSC testing process, using the four receivers selected for this purpose.[44]

[44] For more information about the receiver selection, see Section 3.4 and Appendix D.

The introduction of AM IBOC is not expected to have any impact on the level of co-channel interference due to the design of the AM IBOC system. Co-channel compatibility was not tested by the NRSC.

Overall conclusions about 1st adjacent compatibility of the AM IBOC system are that the interference caused by the introduction of the IBOC signal is predominantly determined by the D/U ratio. Current FCC allocation rules permit 6 dB D/U ratios at an AM station's daytime protected contour.[45] At the 10 dB D/U point, all AM radios tested, when receiving speech programming, are unable to provide audio quality that would satisfy at least half of all listeners whether or not an interfering first adjacent station is broadcasting the AM IBOC signal. At the 15 dB D/U point existing automobile radios provide listenable audio, and would not be significantly affected by the introduction of IBOC; however, today's hi fi receivers do provide listenable audio that would become unlistenable with the introduction of IBOC. At the same 15 dB D/U point portable radios appear to provide unlistenable audio with or without IBOC. At the 30 dB D/U point, all radios appear to provide listenable audio with or without IBOC.

The data indicate that 2nd adjacent interference from AM IBOC will be receiver and D/U dependent. At the D/U ratios tested, narrowband (typically automobile) receivers are not sensitive to AM IBOC interference, though hi fi and portable receivers (*i.e.,* wideband receivers) will experience interference at the 0 dB D/U ratio, and at negative D/U ratios. Current FCC allocation rules permit 0 dB D/U ratios at an AM station's 5 mV/m groundwave contour.[46]

AM IBOC is not expected to have an impact on the amount of 3rd adjacent channel interference in the AM band, and the test results confirm this.

[45] 47 CFR Section 73.37.
[46] 47 CFR Section 73.37.

NRSC Document Improvement Proposal

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