APPENDIX B

A Review of Four Studies of
FM Receiver Adjacent-Channel Immunity

By

Dr. Raymond L. Pickholtz

Dr. Charles L. Jackson

November 1999

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Executive Summary

We were asked by the National Association of Broadcasters (NAB) to review four studies of the susceptibility of consumer FM receivers to adjacent-channel interference. These studies were sponsored or performed by the Office of Engineering and Technology (OET) of the Federal Communications Commission (FCC), the NAB, the National Lawyers Guild (NLG), and National Public Radio together with the Corporation for Public Broadcasting (CPB) and the Consumer Electronics Manufacturing Association (NPR et al.).

Each of these four studies examined the same technical question, but the studies are being used to support contradictory conclusions. Even so, there are great areas of agreement among the studies. The methods used to test receivers are quite similar. Every study reported that car radios out perform other FM broadcast receivers. When we reformatted the data from each study into a consistent format, we found the four sets of measured data to be quite consistent.

The significant differences among the studies were not in the measurements or in the performance of the radio receivers tested. Rather, the most important difference among the studies was the criterion used to decide whether the effects of an interfering signal on an adjacent channel caused harm to the desired signal. The difference among these studies lies in the definition of impaired reception. The NLG defined impaired reception to mean badly broken reception. The NAB used the same definition of impaired reception as had the FCC when it developed the FM service—that a broadcast service suffers from interference when it is degraded to the level many observers would characterize as slightly annoying. NPR et al. used a definition similar to that used by the NAB. The OET used a distortion measure that, while not as flawed as

that used by NLG, could bias the testing and required that an audio signal be substantially degraded to be counted as impaired.

Table 8 of our report is reproduced below. It compares the four reports and confirms that the differences among the studies arise from the definition of impairment and not the measurement process or the characteristics of the radios tested. Specifically, it shows that if the measurements of each study are interpreted consistently using the 50-dB criterion of harmful interference, each study predicts that the vast majority of receivers will fail when receiving interference at the interference level implied by the FCC's ratios.

TABLE 8—Percentage of Receivers Not Meeting FCC Ratios in the Four Reports and Using 50-dB Output SNR Criterion

Report	Criterion in SNR terms	Tested radios failing under authors' criterion	Tested radios failing under 50-dB SNR criterion
NPR et al.	45 dB	81% (13/16)	100% (16/16)
NLG	20–30 dB	27% (3/11)	73% (16/22)
OET	25–30 dB	10% (2/21)	79% (16.5/21)
NAB	50-dB or 5-dB degradation if receiver cannot reach 50 dB	79% (22/28)	79% (22/28)

Note: SNR = signal-to-noise ratio.

The results of these tests are no surprise. In radio engineering, as in most other engineering activities, there is always a tradeoff between cost and performance. It makes little economic sense to build radios that are capable of rejecting more adjacent-channel interference than those radios will actually experience in use. Consequently, we would expect to see radios engineered to perform reasonably well in the radio environment created under the FCC's rules. The FCC's rules set the adjacent-channel-interference environment, and radios are built to perform well in that environment. But, there is little or no point to building in better adjacent-channel protection than is needed.

All four studies made the mistake of reporting the results of tests of car radios along with other radios. Every report showed that car radios outperform other radios with respect to adjacent-channel interference rejection. In fact, car radios need this capability if they are to provide reasonable performance. At the very least, car radios should have been tested and reported separately. Including car radio performance in these studies provides misleading signals about the overall performance of receiving systems.

To sum up, decision makers should understand the tradeoff between added adjacent-channel interference and reduced performance of broadcast receivers. Listen to music at signal-to-noise ratios of 70, 60, 50, 40, and 30 dB. Consider the literature on subjective testing of audio systems, and consider consumer preferences. Finally, decide what quality of FM broadcast service the FCC's rules should protect.

About the Authors

Raymond L. Pickholtz is a professor in and former chairman of the Department of Electrical Engineering and Computer Science at The George Washington University. In 1984, Dr. Pickholtz received the IEEE centennial medal. In 1987, he was elected Vice President and in 1990 and 1991 President of the IEEE Communications Society. He received the Donald W. McLellan Award in 1994. He is a fellow of the Institute of Electrical and Electronic Engineers (IEEE) and of the American Association for the Advancement of Science (AAAS). He was an editor of the *IEEE Transactions on Communications* and guest editor for several special issues. He is editor of the Telecommunication Series for Computer Science Press and of the *Journal of Telecommunications and Networks*. He has published scores of papers and holds six United States patents. Professor Pickholtz has authored or coauthored several papers on radio system performance in the presence of adjacent-channel interference.

Charles L. Jackson received his Ph.D. degree in electrical engineering fom the Massachusetts Institute of Technology. Dr. Jackson is a member of the IEEE, the Internet Society, the American Mathematical Society, and Sigma Xi. He is an adjunct professor of electrical engineering at the George Washington University, where he has taught a graduate course in mobile communications. From 1982 to 1988, he was an adjunct professor at Duke University. He is a member of the U.S. Department of Commerce's Spectrum Planning and Policy Advisory Committee (SPAC) and of the Federal Communications Commission's Technological Advisory Committee (TAC). He has written for professional journals and the general press, with articles appearing in publications ranging from *The IEEE Transactions on Computers* to *Scientific American* to *The St. Petersburg Times*.

1 Introduction and Overview

We were asked by the National Association of Broadcasters (NAB) to review four studies of the susceptibility of consumer FM receivers to adjacent-channel interference. Three of these studies were filed by parties in the comment round of pleadings in MM Docket 99-25. These three parties were the NAB, the National Lawyers Guild (NLG), and National Public Radio (NPR) together with the Corporation for Public Broadcasting (CPB) and the Consumer Electronics Manufacturing Association, collectively referred to as NPR et al. Two staff members in the Office of Engineering and Technology prepared the fourth study.[1]

Each of these four studies examined the same technical question, but the studies are being used to support contradictory conclusions. For example, CPB wrote, "The tests show that, in many situations, adding a new LPFM station by eliminating the 2^{nd} and 3^{rd} adjacent channel protections would significantly impair both the existing and the new stations."[2] In contrast, NLG wrote, "These results strongly indicate that, at least for Low Power FM stations of 100 watts ERP or less, regulation of second and third adjacencies should also be eliminated."[3] Obviously, CPB and NLG cannot both be right. Either some of the tests are flawed or someone is arguing improperly from the data.

The NAB requested that we review and compare these studies. They asked us—as experts who had not been previously involved with this proceeding and who had no involvement with the design or execution of these four studies—to perform a cross between a *Consumer Reports*

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1 *TRB 99-3 Interim Report*, July 19, 1999.
2 Comments of CPB, MM Docket 99-25, p. 16.
3 Comments of NLG, MM Docket 99-25, p. 19.

product evaluation and a book review. Based upon this general request from the NAB, we formulated our own specific directives:

- Examine and compare the studies, identifying the strengths and weaknesses of each;
- Comment on appropriate criteria for defining unacceptable interference and methods of interference measurement;
- Identify conclusions supported by all the studies;
- Identify conflicts among the conclusions of the various studies; and
- Offer our explanation for any conflicts identified in the step above and provide our opinion as to the likely correct conclusions.

This report presents the results from our undertaking the above five tasks. We begin by discussing briefly the role engineering can play in helping the Commission understand the implications of the decisions it will make in this docket. Next, we discuss how one measures the effects of interference. After that, we look at each of the four studies. Finally, we offer our conclusions.

2 Engineering Insights for Policymakers

Many important policy issues today depend upon scientific and technological factors that require specialized knowledge and training to fully understand or evaluate. This section considers briefly this general dilemma and then focuses on the specific concerns created by the four studies of adjacent-channel interference.

2.1 General Considerations

Science and engineering must contribute to the policy process when the policy in question involves a technical subject like radio broadcasting. Their most profound contribution is the creation of new ways of doing things or new alternatives. There would be no concern about funding childhood immunizations if immunization technology did not exist. Science and engineering can also illuminate the choices before policy makers. Congress, the FCC, the Environmental Protection Agency (EPA), judges, and state legislators face the problem of choosing policies the outcomes of which depend upon technical facts that the policy makers cannot be expected to master. Often, as in this case, policy makers face the problem of making policy choices based upon engineering or scientific studies they cannot replicate, verify, or sometimes, even fully understand. What should policy makers do when faced with incomprehensible, conflicting, ambiguous, or weak technical advice?

2.2 Engineering and the Decisions in MM Docket 99-25

In the case at hand, technologists can provide data and analysis that allow the policy makers to understand the tradeoffs, if any, in choosing among the alternative courses of action in this docket. Good engineering studies should assist informed choice in the political process. The fundamental issues are not so difficult or esoteric that a nontechnologist cannot master them with modest effort.

In the Notice of Proposed Rulemaking (NPRM) in this docket, the FCC articulated the specific question at hand. The Commission stated, "We seek comment and analysis on our tentative conclusion not to include 3rd-adjacent channel protection requirements for any LPFM service"[4] and "We also seek comment on the state of receiver technology and the ability of receivers to operate satisfactorily in the absence of 2nd-adjacent channel protection."[5] The theory needed to understand and explain the performance of receivers under adjacent-channel interference is well understood. Measurement of the performance of receivers suffering from adjacent-channel interference requires care and is a moderately exacting technical process. In fact, the studies we reviewed used similar test methods and test equipment. The studies differed in the way they measured and reported the impairments caused by interference and in the type and number of receivers tested. Before we review these studies, some background on measuring audio impairments would be helpful.

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4 NPRM, para. 45.

5 NPRM, para. 46.

3 Measuring Audio Impairments

Before reviewing the individual studies, we believe a quick review of the key technology—the measurement and characterization of the quality of audio system performance—is in order. This is hardly a new field. Investigators in the nineteenth century such as Rayleigh and Helmholtz conducted significant research on this topic.[6] Throughout this century, other investigators have extended their understanding. For example, in the 1930s scientists at Bell Labs tested the human response to sounds at various intensities and levels—leading to the Fletcher/Munson curves familiar to most audiophiles.[7] There is now an extensive literature on effects of noise and distortion on human perception of speech and music. Proper measurement of these effects is important in both the telephone industry and in broadcasting, as well as in sound recording and now the computer industry. We can draw on over a century of research and experience. Colleges teach courses in the subject (e.g., MIT's Subject 6.182 Psychoacoustics Project Laboratory, USC's EE 522 Immersive Audio Signal Processing). There exists a broad library of standards in this area—including many ITU-R standards. Recent years have seen an expansion of work in this area due to the need to perfect and verify the performance of audio compression techniques.[8] In this proceeding, it is radio interference we are looking at that *results* in audio imperfections.[9]

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6 Amazon.com ranks Helmholtz's book, *On the Sensations of Tone,* as number 35,154 in their sales rankings of more than 1.5 million titles. Not bad for a science book first published in 1863.

7 Fletcher, H., & Munson, W. A. (1933). "Loudness, its definition, measurement, and calculation," *Journal of the Acoustical Society of America*, 5, 82-108.

8 Speech compression is essential to modern digital wireless devices such as digital cellular phones. The more general audio compression is used in digital broadcasting (terrestrial digital

Examination of the literature and standards leads to a few conclusions. First, *subjective testing*—the use of a panel of listeners to compare and grade the performance of alternative systems—is the gold standard of audio system evaluation.[10] Second, although they may be the gold standard, subjective listening tests are, like gold, very expensive—requiring significant time and staff. Consequently, other objective test methods have been developed. These objective measurements may or may not be monotonically related to subjective quality, but they are close enough for many applications. A primary measurement used to assess the performance of analog broadcasting and recording systems is the audio or output *signal-to-noise* ratio (SNR). This ratio compares the energy in the desired signal with the energy in the obscuring or impairing noise signal. Often the SNR is calculated using a weighting procedure that attaches more weight to noise at the most easily heard frequencies and less weight to noise at frequencies that are less irritating. Informally speaking, SNR is a measure of the static that has been added to a signal.

Table 1 below shows SNR for some familiar audio systems. In this table, a higher number is better and SNR is reported in dB—a logarithmic measure that matches well with the human hearing process. A difference of about 3 dB in SNR is usually regarded as the smallest size

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television, digital audio broadcasting, DirecTV's service) as well as in consumer products such as MP3 players.

9 The Audio Engineering Society maintains a web site at http://www.aes.org/ that contains many pointers to the literature on audio system measurement. Other useful web sites are those of the Acoustical Society of America, http://asa.aip.org, and the European Broadcasting Union, http://www.ebu.ch/.

10 It may seem strange to some that engineers rank a subjective test as the highest performance standard. Despite stereotypes, engineers actually have normal endowments of common sense and they recognize that the proper measure of a system designed to serve consumers is the consumer reaction to that system.

difference a typical observer will notice. Thus, there is not much difference in the typical subjective evaluation of the performance of two audio systems—one operating with 40-dB SNR and the other with 43-dB SNR. However, there is a big difference between a system operating with 40-dB SNR and one operating with 60-dB SNR.

TABLE 1—Signal-to-Noise Ratio for some Familiar Audio Systems

System	Approximate SNR
Compact disc	100 dB
Sony Walkman digital audio tape	Better than 87 dB
FM broadcasting (best conditions)	60–80 dB
Consumer audio taping equipment[11]	60 dB
Telephone call	30-50 dB

A second measure of audio system performance is *harmonic distortion*. Harmonic distortion is most often used to measure the performance of audio devices such as amplifiers or recording systems. It is a measure of how accurately an audio system reproduces the input signal. Harmonic distortion is often used to characterize the performance of amplifiers. It is caused by nonlinearity in the amplification chain that creates frequency components that are harmonics of the original frequencies (integer multiples of the original frequencies, also called overtones). If the output signal from an amplifier is the same as the input signal, except bigger, then there is no distortion. With music or pure tones, distortion can be noticed by the presence of overtones. For example, if a real-world amplifier has as input a 1,000-Hz tone, the output will consist primarily of a 1,000-Hz tone, but tones at 2,000 and 3,000 Hz (and other frequencies) will also be present

11 For example, the Sony TC-KE500S.

in the amplifier output. These unintended overtones produced by the amplifier are called harmonic distortion. It is hard for the human ear to hear harmonic distortion. The human ear's response to a 2,000-Hz tone is reduced when a strong signal is also present at 1,000 Hz. Similarly, people often think they hear a sound at 2,000 Hz when they only hear a sound at 1,000 Hz.[12] Most music sources, such as a piano or violin note, contain overtones that are only slightly modified by the overtones created by distortion.

Hence, given both the reaction of the human hearing system and the content of most music, harmonic distortion is harder to hear than unrelated noise.[13] It is generally accepted that harmonic distortion has to rise to about 1 to 2% before people find it objectionable.[14] Some people would find 1% harmonic distortion hard to notice.[15] The nonlinearities in the signal processing chain that cause harmonic distortion also cause intermodulation distortion that produces other, unintended frequency components. The usual test procedures for audio

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12 See, for example, A. Gersho, "Advances in speech and audio compression," *Proceedings of The IEEE*, vol. 82, pp. 900-918, June 1994. P. Noll, "Wideband speech and audio coding," *IEEE Communication Magazine*, vol. 26, pp. 34-44, November 1993. J. J. N. Jayant and Y. Shoham, "Coding of wideband speech," *Speech Communication*, vol. 11, pp. 127-138, 1992.

13 It is easier to hear someone cough at an orchestra concert than to tell that one of the violinists is playing an octave high. Indeed, everybody in the audience can hear the person coughing, but only audience members with unusual musical acuity will notice that one violin is an octave high.

14 See H.F. Olson, *Elements of Acoustical Engineering*, Van Nostrand, New York, 1947 as quoted in Electronics Engineers' Handbook, 2nd Edition, Donald G. Fink and Donald Christiansen, eds., McGraw-Hill, 1982, at pp. 19-18.

15 While engineers are good, they are not perfect. Engineers often use different units to measure SNR and harmonic distortion. Although SNR is normally measured as a power ratio and expressed in dB, harmonic distortion is often measured as a voltage ratio and expressed in percent. This notational difference makes it harder for the nonexpert to keep track of what is going on in the four studies we consider. This confusion adds an unintended shell-game element to reading the engineering studies in this docket.

equipment use the measure of total harmonic distortion plus noise (THD+N) as shorthand for all nonlinear impairments.

Although it may be possible, albeit rare, for interference to drive the signal into the nonlinear region and cause harmonic distortion, that is not usually the principal concern when considering the effects of interference. Interference is best treated as a different, extraneous source of additive noise. Thus, we measure its effects by considering the signal-to-noise plus interference ratio (SNIR). The *noise* we refer to here is due to thermal, environmental, or receiver noise that we cannot overcome and is not the interference from like signals residing in a co- or adjacent channel. The interference of concern here is external and produced by other emissions in the radio spectrum by other than the desired transmitter. It is what can be controlled by regulation. It is therefore our considered opinion that the deleterious effects caused by this interference must be measured. Other undesirable effects, inherent in the imperfections in the signal chain may also be present, but they are a red herring when the objective is to determine whether controllable external additional emissions such as second and third adjacent channel interference should be permitted to degrade expected reception quality.

SNR and SNIR and harmonic distortion can be easily and quickly measured by modern test equipment. One could measure all of these quantities on 10 audio systems in much less time and at much lower cost than it would take to conduct subjective listening tests of those same audio systems. In some of its rules, the FCC uses audio SNR as a criterion of system performance and requires equipment to meet minimum SNR levels.[16]

16 See, for example, 47 CFR 80.961(b).

4 The Proper Standard for Measuring Interference Effects

We believe that the audio output SNIR (often called SNR and measured in the same fashion) is the appropriate measure in this context.[17] We note that it is often used for such comparisons. The ITU-R, and before it the CCIR, recommended that measurement of the degradation of SNR by the interfering signal be used in this situation. Three of the four studies we review (NAB, NLG, and NPR et al.) measured and reported the effects of interference on SNR. The measuring process for determining harmonic distortion does not measure all the extraneous energy delivered in the output signal; rather there is a hole of no measurement around the test tone. In most circumstances, this hole would not be disabling, but it may alter some measurements. Distortion, specifically harmonic distortion, is normally used to measure the accuracy of the reproduction of a signal rather than the presence of extraneous signals.

The FCC and the broadcast industry have long used SNR as a measure of system performance. For example, in 1979, the FCC authorized the CPB/NPR satellite interconnection system. In the order, the FCC stated, "NPR states that the satellite interconnection system has been designed to provide a minimum end-to-end channel performance that satisfies all requirements for radio broadcasting transmissions set forth in the Commission's Rules and Regulations. Specifically, the public radio satellite interconnection is designed to provide a subjective signal-to-noise ratio greater than 65 dB."[18]

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17 For the rest of this report we use SNR to refer to SNIR in order to make our notation consistent with that used by NAB, NLG, and NPR et al.

18 70 FCC 2d 1858 (footnote omitted).

The comments in this proceeding by the AFCCE and the NAB contain histories of the development of the FCC's FM technical standards. Those histories show quite convincingly that the FCC designed the FM broadcast service to permit broadcasters to deliver signals good enough to permit reasonably priced receivers to provide a 50-dB SNR output signal. We note that in 1949 the FCC's NPRM in Docket No. 9407 stated, "The laboratory tests were based upon a 50 decibel rejection of the undesired signal. . . ."[19]

We also note that receiver manufacturers measure and report SNR and harmonic distortion separately. Figure 1 below is an excerpt from the data sheet for the Denon DRA-375RD receiver. Notice that this data sheet reports both an SNR (82 dB mono, 78 dB stereo) representing the output SNR ratio under ideal conditions and the level of total harmonic distortion (0.1% mono, 0.15% stereo). If the energy measured in the 0.1% harmonic number were noise instead of distortion, then the SNR would be only 60 dB. It is well known that 0.1% harmonic distortion is imperceptible to most observers but that almost all observers can tell the difference between 82-dB SNR and 60-dB SNR. Denon, like other hi-fi manufacturers, reports these measurements separately because they measure separate aspects of the performance of receiving systems. If the energy created by harmonic distortion were measured as noise, then there would be no reported difference in the performance of 80-dB and 60-dB SNR FM receivers with 0.1% harmonic distortion.

19 14 FR 4986. (F.R. Doc. 49-6556. Filed, Aug. 11, 1949, 8:48 a.m.)

[illegible]	[illegible]
Tuning frequency range	87.5 - 108 MHz
Usable sensitivity	0.9 µV (10.3 dBf)
S/N 50 dB sensitivity (µV at 75 ohms)	Mono : 1.6 µV (15.3 dBf) Stereo : 23 µV (38.5 dBf)
Signal-to-noise ratio (A weighting)	Mono : 82 dB, Stereo : 76 dB
Total harmonic distortion	Mono : 0.1%, Stereo : 0.15%
Capture ratio	1.5 dB
AM suppression	50 dB
Image rejection	42 dB
Effective selectivity	55 dB (± 400 kHz)
Frequency response	30 Hz - 15 kHz, -0.2, -1.5 dB
Stereo separation	40 dB (1 kHz)

Figure 1. Denon data sheet excerpt.

There is still a question of what changes in SNR constitute unacceptable interference. We return to this point in more detail later. Note that the ITU-R in Recommendation 641 defines the interfering level to be that level of interference that degrades receiver performance to the 50-dB SNR level. This ITU-R level is not overly demanding—for example, it is much lower than audiophile standards or CD quality. It is a big step below the performance capabilities of the Denon receiver shown above.

5 Examination of the Four Studies

In this section, we consider each of the four studies. All four studies addressed the FCC's two questions regarding their tentative conclusion not to include 3rd-adjacent-channel protection requirements for any low-power FM service and on the state of receiver technology and the ability of receivers to operate satisfactorily in the absence of 2nd-adjacent-channel protection. All four studies used the same essential approach—the engineers obtained several consumer FM broadcast receivers and tested the performance of those receivers in the presence of interfering signals. None of the studies examined the economics of receiver manufacturing or the various tradeoffs (cost, receiver size, etc.) associated with improving the resistance of consumer receivers to interference from signals on the 2^{nd}- and 3^{rd}-adjacent channels. None of the studies explained why automobile receivers should be expected to outperform the FCC ratios.

Beyond this essential similarity, the four studies vary greatly—many of the differences appear to be consequences of limitations on the time and resources available for the studies rather than of positions of the sponsors of the studies. However, some of the differences do appear to reflect the position of the sponsoring party. Specifically, the NLG and OET studies use relatively poor measures of receiver performance—ones not supported by traditional engineering practice or accepted standards—that have the consequence of minimizing the observed effects of interference. Even so, all four studies show that some current receivers suffer interference at the signal levels currently embodied in the FCC rules. The studies differ on the proportion of receivers that suffer such interference. The NAB study showed 22 of 28 receivers (79%) failing to provide acceptable performance when subjected to an interfering signal right at the FCC's limits. The OET study showed only 2 of 21 receivers (10%) failing to meet their 3% added-distortion criterion in the presence of 2nd-adjacent-channel interference at the FCC limit and 6 of the 21 (20%) failed to meet the 1% added-distortion criterion.[20] Three of the 11 (27%) receivers tested by the NLG study failed (by its definition) with a 2nd-adjacent channel signal at the FCC limit. A full 13 of 16 (81%) receivers tested in the NPR et al. study were driven below the 45-dB SNR operating point before the interfering signal rose to the FCC's limit.[21]

5.1 OET Study

William H. Inglis and David L. Means prepared the OET study dated July 19, 1999.[22] They tested 21 receivers for resistance to interfering signals on the 2nd- and 3rd-adjacent channels. The interference criteria the OET team used was a 1% or 3% increase in distortion—by which they meant the quantity of total harmonic distortion plus noise (THD+N) as measured by an Audio Precision System One.[23] They measured the levels of adjacent-channel signal necessary to degrade receiver performance to one of two levels—a 1% increase in THD+N and a 3% increase in THD+N.

We believe that such increases in THD+N are inappropriate criteria for determining the onset of interference. Harmonic distortion can arise from many subsystems in the receiver. Yet, the base level of THD+N defines the results of the OET test. Consider two receivers, alike in every way, except that the first has an audio output stage that generates 1.0% harmonic distortion and the second has an output stage that generates 0.1% harmonic distortion. The harmonic distortion in

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20 See OET report p. 31 and Table 2.

21 NPR et al., p. 4, Chart # 6 2nd Adj D/U with 45 dB Audio S/N

22 *Second and Third Adjacent Channel Interference Study of FM Broadcast Receivers*, Project TRB-99-3, Interim Report, FCC/OET TRB-99-1, July 19, 1999.