Advanced Television Systems Committee

Performance Assessment of the ATSC Transmission System, Equipment and Future Directions

Report of the ATSC Task Force on RF System Performance

Revision: 1.0
April 12, 2001

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Executive Summary

This report summarizes the technical findings of the Task Force on RF System Performance, created to study RF transmission performance issues concerning equipment complying with the ATSC A/53 standard. The sections that follow report the group's findings in the following areas: introduction and summary of the controversy that led to the formation of the ATSC Task Force on RF System Performance (Section 1); summary of the original transmission system requirements, industry interpretations of those requirements and current broadcasters requirements (Section 2); assessment of DTV RF propagation channels (Section 3); consumer DTV antennas and ease of reception issues (Section 4); DTV link budgets and sources of degradation (Section 5); analysis of 8-VSB system performance data (Section 6) and potential future improvements (Section 7). The conclusions of the Task Force are presented in Section 8 and the Task Force's recommendations to the ATSC are presented in Section 9.

The Task Force finds that the A/53 DTV transmission system and newer generation 8-VSB receivers largely meet the goals of outdoor reception by fixed receivers with 30 foot antenna height, in accordance with the FCC DTV planning factors. The group finds evidence that the goal of DTV replication of NTSC service where NTSC video quality is of ITU-R grade 3 or higher is largely met.

The Task Force finds that indoor reception of DTV with set-top antennas may be a service mode available only to a minority of viewers in some television markets, primarily due to insufficient RF field strength. Further advances in DTV receiver design, particularly in reducing the “multipath C/N penalty,” are expected to increase the percentages of outdoor and indoor sites that successfully receive DTV, but the group finds that expectations of widespread indoor reception are inconsistent with the DTV planning factors and link budget variables. The Task Force further concludes that reliable DTV service to receivers using fixed indoor antennas will be available over a wider area than to portable indoor receivers utilizing self-contained antennas. The group finds that reliable DTV service to pedestrian and mobile receivers poses a unique set of challenges that will be difficult to overcome in a single transmitter environment.

The Task Force recognizes that many aspects of the received signal quality are independent of the type of modulation employed. Most prominent of these are the antenna and RF propagation channel characteristics, which degrade RF signals in any transmission system. The importance of DTV link budgets and variables affecting link margin cannot be overstated. Broadcasters control some variables that affect link margin, such as transmitter antenna height and transmitter power up to the authorized maxima. Manufacturers control other variables, including transmitter linearity, receiver noise figure, receiver selectivity and dynamic range, and 8-VSB demodulation and equalization design choices. Consumers have, however, enormous influence on link margin through their selections of antenna type, mounting location and height, and antenna orientation.

The group understands that even transmitter and receiver hardware that is theoretically perfect and lossless in every respect will still be subject to transmission errors induced by thermal noise, and that a minimum carrier-to-noise (C/N) ratio necessary to achieve a suitably low bit error rate for DTV service must be delivered to the receiver. Clearly there will be some percentage of potential viewers who are unable to install an antenna and receiving system capable of providing the minimum C/N to overcome the "digital cliff" -- for example, those consumers who cannot achieve reliable indoor reception and are unable to install a rooftop antenna. The Task Force is unable to estimate how many potential viewers this may represent, nor how much different that number would be using theoretically perfect lossless equipment versus existing consumer equipment.

It is evident to the Task Force that to maximize the number of consumers capable of receiving DTV, the primary means by which link margin can be increased are: antenna and receiver improvements; increasing RF field strength throughout a DTV market -- either by using a more powerful single transmitter or by supplementing the high power transmitter with on-channel repeaters; and finally, by selecting a more favorable "digital cliff." This last method implies acceptance of a lower DTV transmission data rate, regardless of the modulation format used.

The principal recommendation of the Task Force to the Executive Committee is that the ATSC investigate enhancements to the DTV transmission system. The consensus of the group is that enhancements to the existing A/53 standard will more rapidly meet more of the requirements delineated in the Broadcasters' Requirements document [7] and provide more ubiquitous DTV services for American consumers than mere reliance on technological innovation of receivers based upon the existing A/53 standard. The group commends the ATSC Executive Committee for its prompt action in assigning this work to the T3/S9 specialist group. It is the expectation of the Task Force that the trade-offs of data rate vs. robustness for different types of DTV service will be revealed during the course of the T3/S9 activity.

The Task Force also recognizes the need for further testing and studies, and recommends development of criteria for definition, prediction and measurement of different levels of DTV service in various modes of reception.

1 Introduction

The ATSC[1] 8-VSB RF transmission system, described in the ATSC A/53 specification, was approved by the FCC in December 1996 for U.S. digital television terrestrial broadcasting [1]. By early 2001, over 180 DTV stations were on the air in 55 U.S. television markets.

As digital television stations began operations and real-world experiences grew, a potential concern arose over the ruggedness of consumer DTV receivers and of the transmission system. As stations came on the air, some experiences of receivability less than expected were encountered. The need for an assessment of DTV reception was determined in 1998 by the ATSC Implementation Subcommittee.

In March 2000, the ATSC Executive Committee approved the creation of a Task Force on RF System Performance, to “examine technical issues related to DTV RF system performance" and to "make recommendations expeditiously to the Executive Committee regarding potential ATSC technical initiatives.”

An Ad Hoc Group on VSB Performance was created within the RF Task Force, to examine the state of the art in 8-VSB transmission and reception equipment, to assess potential improvements in future transmission and receiver equipment, and to make recommendations to the RF Task Force, which would then make recommendations to the Executive Committee. Since its formation, the VSB Performance ad hoc group has also considered a number of potential modifications to the A/53 transmission subsystem that offer potential improvements in reception robustness and (if permitted) offer new service opportunities. This group consisted of representatives of several transmitter and receiver manufacturers, semiconductor manufacturers of 8-VSB demodulator chips, tuner manufacturers, independent consultants and broadcasters.

2 DTV Transmission System Requirements

2.1 Original Transmission System Requirements

The requirements developed during the ACATS process were to provide transmission robustness “Better than NTSC within the defined service area” [2]. These requirements were not intended to exclude any services currently delivered by the NTSC system. The focus was the delivery of HDTV at maximum data rate, which ended up being 19.39 Mbps.

The opinion of the Task Force is that there was a lack of specificity in defining “Better than NTSC…,” concerning the digital transmission system design. Further, a test suite was developed during the ACATS process to select a DTV transmission system. These test procedures may have been used by some manufacturers as receiver design goals.

2.2 Evolution of Transmission System Expectations and Industry Response

The Task Force understands that some in the industry interpreted the standard as intending to provide reliable HDTV reception at 19.39 Mbps to "fixed" receivers anywhere that NTSC reception of ITU-R Grade 3 quality is currently available, using antennae similar to those currently used for such NTSC reception. In this context, "HDTV" implies 1080i or 720p video formats that require the majority of the available 19.39 Mbps payload. The group fully appreciates that SDTV video formats are included in Table 3 of A/53, but recognizes that the fixed 19.39 Mbps data rate of the transmission standard was intended to provide for HDTV delivery. "Fixed receivers" implies television receivers that are normally kept in one location and connected to a suitable indoor or outdoor antenna. A "suitable" antenna, whether indoor or outdoor, was

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[1] Less commonly used acronyms are defined prior to their first use in this document.

defined to be one which provides the receiver with a dominant signal. In terms of propagation models, this definition implies Ricean multipath channel conditions.

Some thought that the A/53 transmission standard was not designed for and was not intended to imply reliable DTV reception under conditions different from those described in the preceding paragraph, although reliable reception is often possible under more adverse conditions. Specifically, there was no assumption that reliable DTV reception by "portable" receivers in arbitrary channel environments was expected. "Portable" implies a television receiver that can be moved from place to place, uses a self-contained or set-top receiving antenna, but remains stationary during operation. Reliable reception by portable receivers was assumed only when channel conditions are comparable to those experienced by fixed receivers, namely, Ricean channels. Also, there was no contemplation of a possible need for receiving DTV signals by mobile receivers in fast-moving vehicles or of provisions for implementing such reception.

The testing process used during the ACATS process compared DTV performance to NTSC performance at the CCIR Grade 3 (now ITU-R Grade 3) level of NTSC video quality and did not consider comparative performance under conditions in which NTSC quality was below Grade 3 [3]. Furthermore, static and dynamic multipath tests were conducted under conditions which are now understood to be more representative of rooftop antenna reception than of indoor set-top antenna reception in urban environments.

An industry understanding arose that the primary usage model for the DTV system was fixed receivers using antennas comparable to those currently in use for Grade 3 or higher NTSC service. For many consumers in both urban and rural areas, this implies a receiving antenna height of 30 feet.

On the subject of antennas for DTV reception, a “Digital Television Consumer Information” page on the FCC web site states that “DTV is intended to work with an outside TV antenna (as is today's analog TV service). If you have an outside antenna and it provides acceptable TV reception now on UHF channels (i.e., channels 14-69), it should also work for DTV. Also, if your indoor antenna is capable of receiving UHF television service now, you may also be able to receive DTV service with that antenna. Indoor DTV reception is affected by a number of factors that vary depending on local conditions.” [4]. A more recent DTV Frequently Asked Questions page on the FCC web site offers the following advice to consumers: "In general, dependable reception of DTV will require the same type of signal reception equipment that currently works to provide good quality reception of analog TV signals. If you now need a roof-top antenna in order to receive television, the same antenna generally will be needed to receive DTV reception" [5].

Even before the formation of the Broadcaster's Requirements ad hoc group within the RF Task Force, some manufacturers recognized the value to consumers in extending the capabilities of A/53 receivers to include more robust "portable" reception. Indeed, the inclusion of SDTV formats in Table 3 and the recognition that many consumers would use set-top box receivers to watch SDTV on their existing displays, including "portable" displays, has led receiver manufacturers and the general market semiconductor manufacturers that supply many of them with 8-VSB demodulator chips to extend the reception capabilities of the latest generation DTV receivers.

In the opinion of some of these manufacturers, the training signals provided in the Data Field Sync are inadequate in length needed for distant echoes and in repetition rate for dynamic multipath cancellation in many indoor reception environments. Some manufacturers have increased the length of their adaptive equalizers and employed additional equalizer algorithms beyond those of the Grand Alliance prototype receiver and beyond those suggested in ATSC document A/54, "Guide to the Use of the ATSC Digital Television Standard," to improve reception reliability in more difficult indoor environments [6]. Recognizing that the multipath ensembles specified in the ACATS test procedure, which have previously been the benchmark tests used by manufacturers and testing organizations, are inadequate for describing all reception environments, many of these manufacturers have tested their equipment with more difficult multipath ensembles and have engaged in field testing and/or RF signal captures, to better understand the reception environment so that further improvements in receiver technology can be made.

2.3 Current Requirements

The Broadcaster Requirements ad hoc group within the RF Task Force drafted a Broadcasters' Requirements document, agreed to by the Task Force in July 2000 [7]. This document represents the consensus[2] of participating broadcasters' opinions on the DTV transmission system requirements.

The Broadcaster Requirements document specifies a DTV transmission system which is "as easy, or easier, to receive from the consumer's point of view as the present analog system" under real-world signal conditions. It further states, "The system must provide excellent reliability for fixed position, portable, pedestrian and mobile receivers, assuming adequate signal level is available," and requires support for high data rate services up to the current A/53 data rate of 19.39 Mbps, with no fundamental changes to the DTV Table of Allotments. On-channel repeaters (boosters) must be supported to extend coverage or fill in poor coverage areas. Broadcasters further desire a multi-mode service, in which a more robust lower data rate mode can be transmitted along with the normal high data rate mode. Finally, the Broadcasters' Requirements document recommends voluntary industry receiver standards that ensure reception under some minimum set of signal conditions.

The Broadcasters' Requirements document "recognizes that physical realities may dictate compromise on one or more of the requirements" and that broadcasters are willing to prioritize their requirements once the trade-offs are better understood.

The Broadcasters’ Requirements document establishes four classes of DTV service as follows:

Fixed: Fixed means a television receiver that is normally kept in one location and connected to a suitable fixed indoor or outdoor antenna. Broadcasters require that all DTV receivers must operate with a high degree of reliability in a fixed position with no manual or user directed adjustment needed to the antenna.

Portable: Portable means a television receiver that can be moved from place to place, uses a self-contained receiving antenna, but remains essentially stationary during operation. For example, a receiver operating on a counter top in a kitchen would be considered portable, if it is not connected to an external antenna. Laptop computers and receivers used at a sports stadium are other examples.

Pedestrian: Pedestrian means operation while a television receiver is moving up to 5 kilometers per hour (3 mph). For example, a pedestrian receiver could be carried on a person while moving about or walking.

Mobile: Mobile means operation of a television receiver at speeds greater than 5 kilometers per hour. For example, a receiver in a moving automobile is considered mobile.

Consumer DTV antennas and their location and positioning are also discussed in the Broadcasters' Requirements document and are fundamental to the issue of 'ease of reception.' The issue of consumer intervention in antenna positioning is important. The ad hoc group recognizes that many broadcasters are concerned about the need for critical antenna positioning by consumers in order to achieve robust reception of A/53 standard DTV signals. This is particularly of concern in those markets where transmission towers of the various DTV stations are not co-located. Channel surfing, using picture-in-picture and recording one program while watching another all imply simultaneous reception of two channels. Many broadcasters think that today’s consumer expects to receive all local stations with one antenna position/orientation and with minimum intervention.

This requirement of no antenna re-positioning when channel surfing is set forth in the Broadcasters' Requirements document. In locations where antennas deliver adequate signal level to the receiver, broadcasters expect consumers to have reliable reception.

A "suitable antenna," whether indoor or outdoor, is defined as one which delivers sufficient signal power to the DTV receiver. The FCC has defined the minimum incident field strength for Longley-Rice LR(50,90) service contours as an incident field strength of 41dBµV/m (41 dBu). Note that the LR(50,90) contours imply that this field strength is available at the best 50% of the locations and 90% of the time within the

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[2] ATSC defines “consensus” as a “clear majority.”

contour. For the purpose of defining coverage, the FCC calculations assume a receiver antenna height of 30 feet Above Ground Level (AGL). The FCC Planning Factors are discussed further in the section on DTV Link Budgets.

3 Common RF Propagation Channel Characterizations

It is infeasible to consider DTV reception issues independently of the RF channel. This section presents two of the more common multipath propagation models, the Ricean and Rayleigh models, and discusses some RF propagation studies that have been published in the 1990s.

The Ricean and Rayleigh models are mathematical descriptions of multipath RF propagation that are useful for describing many but not all real-world terrestrial channels. The Ricean model provides a convenient mechanism for describing the severity of multipath in a RF channel, through the "K-factor." The Ricean K-factor is simply the ratio of the power in a main or desired signal path to the power in all other signal paths. The Rayleigh channel is shown in Appendix G to be a special case of Ricean fading in which there is no main path that is distinguishable from the other paths. As the K-factor tends toward zero, the channel approaches a Rayleigh fading distribution. As the K-factor tends toward infinity, the channel approaches a Gaussian (white noise) channel, free of multipath effects.

Elevating the receive antenna height above ground level reflectors tends to increase the K-factor.

The ACATS test procedures defined a set of multipath ensembles, A-G, that some engineers in the mid-1990s may have thought were representative of multipath channels encountered by outdoor antennas for DTV reception. As further experience with indoor and outdoor propagation has been gained by the industry, the need to supplement the ACATS test procedure ensembles to more adequately characterize reception environments has been recognized and the industry has responded to this recognition.

A number of RF propagation studies have noted the differences between RF propagation in indoor vs. outdoor and rural vs. urban environments, as well as the differences in RF propagation characteristics as a function of transmitter and receiver antenna heights above average terrain. Although some studies have been done at VHF and UHF frequencies, and some specifically for digital television transmission, the majority of studies have been done at the higher frequencies used for cellular telephony and PCS services. Measurements of RF propagation at frequencies higher than UHF and at low power and low transmitter antenna heights are not directly applicable to DTV, but are still useful for providing a general understanding of the issues involving RF propagation in various environments.

3.1 Multipath Propagation Parameters For Terrestrial DTV

In terms of placing bounds on the parameters in the Ricean propagation equation as it pertains to DTV channels, the recognition that Rayleigh channels do exist in some environments implies that there is no limit on the relative magnitudes of the various echo paths. The time-varying nature of RF propagation channels also implies that the relative magnitudes of various paths may change over time and a path which was dominant (the "desired" signal) at particular time may later become an undesired echo to be cancelled. This phenomenon has been observed in some DTV indoor reception field tests and analysis of RF data captures.

A 1992 study by NTIA measured channel impulse responses to characterize 6 MHz VHF and UHF outdoor channels in the San Francisco and Denver areas [8]. A digital signal was embedded in the VBI of an NTSC station’s signal and RF data captures were recorded from both a directional (log-periodic) and an omnidirectional receiver antenna at a height of 30 feet.

This study found Ricean K-factors that varied from less than 0.5 to over 30 when an omnidirectional antenna was used. The smallest K-factors were found in areas described as “urban, near a high-rise region” in San Francisco, Oakland and Denver and also at locations in Boulder described as “suburban activity center” areas. Somewhat larger K-factors were generally found in areas described as “urban, 3 to 5 story buildings” and the largest K-factors were found in areas described as “wooded residential,” “open residential,” “rural rough” and “rural flat.” The author states that generally, the K-factor is 2-4 dB worse at UHF than at VHF, although the data shows cases where the reverse is also true.

The maximum delay spread found with the omnidirectional antenna was less than 12 µs. It should be noted, however, that using the author's definition of delay spread, echoes of significant amplitude with substantially longer delays may have existed.8-VSB

This NTIA study also found that the use of a log-periodic antenna increased the K-factor by 1-5 dB but increased the multipath delay spread relative to the omnidirectional antenna.

It is also noteworthy that measurements were made in nearly the same sites in a wooded residential area in both summer and winter. Despite the absence of leaves on the trees, the winter measurements were very similar in both multipath amplitude and delay spread.

Placing bounds on the rates of phase changes (dynamics) in the echoes, and on the maximum echo delays is much more difficult than bounding the maximum echo amplitude. The rate of phase change is dependent upon the source of the echo. For example, tower and/or tree sway is a sub-Hz phenomenon and motion of people may cause echo dynamics of several Hz. Vehicular traffic may cause echoes with Doppler shifts in excess of 70 Hz. A 1990 study of airplane flutter measured echoes with Doppler shifts that increase in frequency and decrease in amplitude as the receiver distance from the airport increases [9]. Close to the airport, where echo amplitudes were most significant, Doppler shifts were below 40 Hz.

Accurate measurements of channel dynamics for DTV VHF and UHF channels require analysis of RF data captures. This work is still in its early stages, so the statistical distribution of echo phase dynamics in various types of channels is not known. Anecdotal evidence from DTV field testing suggests that echoes with the highest rates of phase change tend to be smaller in amplitude than echoes with lower rates of phase change.

When line-of-sight exists, the main path travels a shorter distance from the transmitter to the receiver than any of the echo paths. Most echoes are therefore post echoes, meaning simply that they are delayed in time relative to the dominant path. In near line-of-sight cases, in which the echo paths are scattered, diffracted or reflected at small angles, there may be significant pre-echoes. Pre- echoes are those which arrive prior to the dominant path (i.e., echoes which travel a physically shorter distance than the strongest signal).

In completely obstructed sites, there is no direct path -- only reflected, scattered and diffracted signals. Complete obstruction does not necessarily imply Rayleigh fading, since the most powerful reflection may in fact be substantially more powerful than all other reflections, producing a Ricean channel characteristic. Complete obstruction does, however, imply that pre-echoes of much longer delay relative to the "desired" signal (strongest reflection) may exist. Complete obstruction also implies that the optimum antenna position may have no particular relationship to the direction of the transmitting antenna. Finally, complete obstruction may also result in Rayleigh fading, in the case where a number of reflections of approximately equal amplitude arrive at the receiving antenna from a variety of directions. In this case, the distinction between pre-echoes and post-echoes becomes somewhat blurred, since any echo may become the dominant signal at any time. This implies a longer pre-echo span for some Rayleigh faded channels than is normally encountered in Ricean channels.

The statistical distribution of echo delays for the frequencies used for DTV in the U.S. has not been reliably determined, pending additional field tests and RF data captures. There have been field tests conducted in the Washington, D.C. area which have measured post-echoes of significant amplitude with delays as long as 37 µs and others have reported echo delays in excess of 60 µs in New York City. Evidence from DTV field testing suggests that for the majority of sites tested, echo delays span no more than 20-25 µs total pre and post-echoes. The DTV field testing experience, like the cellular experience, also indicates that in these cases, moving the receiver just a few feet can completely change the multipath characteristics and eliminate or greatly attenuate these extremely long echoes. It will take a great deal of additional testing to determine the number of consumers that are presented with echoes of substantially long delays.

In some DTV applications, a minimum echo delay span can be determined analytically. Studies of Digital On-Channel Repeaters ("Gap fillers") have indicated that in such retransmissions there could be pre-echoes with significant amplitudes and pre-echo delays in the 25 µs region [10].

In examining DTV reception, much of the focus has been on multipath echo amplitudes, rates of echo phase changes and echo delay spread. Another parameter that is even more fundamental to DTV reception is path loss, which directly determines the average power available to receivers in various reception environments. A variety of RF propagation models have been described in the literature, with varying degrees of experimental validation. The choice of a propagation model directly impacts link budget calculations.

The relative incidence of Rayleigh vs. Ricean channels for 'real world' consumer DTV reception has not yet been quantified by a statistically significant number of DTV field tests and RF data captures. Existing DTV field test evidence and RF propagation studies suggest that Rayleigh faded channels and low K-factor Ricean channels are not uncommon in urban environments, especially when indoor antennas are used.

Although the Task Force is unable to make a quantitative comparison between indoor and outdoor reception channels, a review of existing DTV field testing and RF propagation studies confirms that indoor reception with set-top antennas is generally characterized by weaker signals and more severe multipath than rooftop antenna reception.

4 DTV Link Budget and Sources of Degradation

This section addresses link budgets for outdoor and indoor reception. The analysis that follows focuses on indoor reception and finds that successful reception can only be expected in high field strength situations. This is inherent in any terrestrial television transmission system.

A consumer DTV link budget is statistical in nature. There are many random variables in the link budget that have mean values and distributions that are not well understood. Additional variability is added by the selection and placement of receiving antennas.

The group attempted to characterize the sources of degradation in the A/53 DTV communications link, so that future improvements might address some of the larger sources of this degradation. The group's investigation revealed that with typical DTV transmitters and higher quality DTV demodulators, the overall degradation is less than 0.5 dB in a theoretical Gaussian channel. This implies that path loss and the additional C/N required due to multipath and other real world reception site conditions are by far the largest link budget items[3]. The multipath component, based on laboratory testing, can range from a few tenths of a dB for a mild multipath channel to 12 or more dB for a severe multipath channel.

Given the uncertainty regarding channel characterization and statistical distribution of channels, as well as the relatively close agreement of existing equipment with theoretical performance in Gaussian channels, the Task Force determined that a detailed link budget is not within its resources at this time.

4.1 *FCC DTV Planning Factors*

The FCC's choices of the Longley-Rice propagation model, the assumed antenna gain and height, downlead loss, receiver noise figure, required C/N and other parameters may all be debated, but the Task Force understands that these choices were made to support spectrum planning and a definition of DTV "coverage" that is correlated with the definition of NTSC "coverage." The DTV Planning Factors, like the NTSC Planning Factors, are not a guarantee of "service" at any particular site or reception environment.

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[3] The terms C/N (carrier to noise ratio) and S/N (signal to noise ratio) are used interchangeably throughout this document.

The FCC Planning Factors for DTV reception, from FCC OET Bulletin 69, are repeated in Table 2 below [11].

Table 1: FCC Planning Factors For DTV

Planning Factor	Symbol	Low VHF	High VHF	UHF
Geometric mean frequency (MHz)	F	69	194	615
Dipole factor (dBm-dBu)	K_d	-111.8	-120.8	-130.8
Dipole factor adjustment	K_a	None	none	See text
Thermal noise (dBm)	N_t	-106.2	-106.2	-106.2
Antenna Gain (dB)	G	4	6	10
Downlead line loss (dB)	L	1	2	4
System noise figure (dB)	N_s	10	10	7
Required Carrier/Noise ratio (dB)	C/N	15	15	15

Note that the Dipole factor adjustment, K_a = 20 log[615/(channel mid-frequency)], is added to K_d. This factor equals 0 dB (no adjustment) at 615 MHz, approximately the mid-frequency of UHF channel 38.

Note that among the Planning Factors listed in Table 2, those that are variable and subject to consumer and manufacturer choices are Antenna Gain, Downlead Loss and System Noise Figure. All other losses associated with the reception system were included in these three parameters.

The defining field strengths that were predicted from the LR(50,90) curves in OET Bulletin 69 were determined by solving the following equation:

$$Field + K_d + K_a + G - L - N_t - N_s = C / N$$

Equation 1: Defining Field Strength

Substituting the UHF Planning Factors and solving for the field yields the following result:

$$Field - 130.8 + 0 + 10 - 4 + 106.2 - 7 = 15 \Rightarrow Field = 40.6 \text{ dBu}$$

4.2 Link Budget Considerations

The Task Force recognizes that some studies have measured the RF attenuation characteristics of various building construction materials and that other studies have measured outdoor to indoor multipath propagation, although not necessarily at DTV frequencies. The group recognizes the immense complexity of generating statistically reliable link budgets for either outdoor or indoor antenna reception in all DTV markets.

In the event that the ATSC, the FCC or another group chooses to generate statistically reliable link budgets for outdoor or indoor reception, the Task Force advises that these link budgets account not only for the reduced field strength at antenna elevations less than 30 feet, but also allow additional C/N margin for noise enhancement introduced by multipath channel equalization and for a variety of antenna gains available in consumer DTV antennas. The indoor antenna data discussed in Section 5, for example, indicates gains of up to 5 dB at some UHF frequencies, but losses approaching 30 dB at other UHF frequencies. The test data discussed in this report reveals static multipath conditions in which the required C/N exceeds 25 dB. Both of these factors increase the field strength required for reliable DTV reception.

Consider a hypothetical set-top antenna reception example in which severe multipath imposes a C/N requirement of 25 dB for reliable reception. Suppose also that the downlead loss is reduced to 1 dB and the antenna gain is 0 dB. Assume a system noise figure of 7 dB. For such an example, the link budget calculation provides the following required field strength:

$$Field = 25 + 130.8 - 0 - 0 + 1 - 106.2 + 7 = 57.6 \text{ dBu}$$

Note that for this hypothetical example, the field strength exceeds that used for DTV planning (41 dBu), although the reduction in field strength for reduced receiver antenna height, ground clutter, building attenuation and terrain sampling error has not been included in this example.

The required field strength is increased by approximately 12 dB due to reduction in receiver antenna height from 30 feet to 7.5 feet. The required field strength must be further increased to account for ground clutter and building attenuation. The building loss can exceed 20 dB. The MSTV/NAB test data showed a range of 8 to 12 dB for building attenuation [14]. Antenna/tuner/downlead mismatch, while variable, may require an additional 6 dB or more.

Adding 20 dB for building attenuation to the previous example yields a required field strength of **approximately 97 dBu** at 30 feet AGL. This is a 56 dB increase in field strength over the Planning Factor threshold. Using a building attenuation of 8 dB, but increasing the receiver noise figure to 10 dB, the required field strength is 88 dBu – still a 47 dB increase over the Planning Factor threshold.

It is clear that any link budget that estimates either a higher required C/N and/or a lower antenna gain has the effect of estimating a substantially smaller service area for indoor reception. Broadcasters will be unable to provide DTV service to those viewers who are unable or unwilling to install an antenna capable of providing the required field strength. This is true even if a theoretically perfect lossless receiver could be built and the C/N penalty due to multipath cancellation were zero.

5 Consumer DTV Antennas and 'Ease of Reception'

The subject of 'ease of reception' is closely coupled with consumer DTV antenna issues, so both will be addressed in this section.

The DTV coverage calculations were based upon field strength predictions at 30 feet above ground level. In general, it appears that the use of directional outdoor antennas secures the expected level of service at locations distant from the transmitter. There have been no corresponding calculations for indoor reception, which generally has reduced and variable field strengths. Broadcasters desire to continue to reach a broad section of the audience that uses simple indoor antennas. At the heart of the DTV reception controversy is the sometimes unreliable reception using small, simple antennas in the environments typically associated with receiving devices in indoor and portable applications.

A suitable antenna, whether indoor or outdoor, is defined to be one that provides the receiver with “sufficient” signal level. Broadcasters expect that so long as sufficient signal level is available at the receiver terminal, the DTV standard should enable reliable reception. The Task Force finds that there is no widely agreed upon definition of “sufficient” signal level. This topic was addressed in greater detail in Section 4on DTV Link Budgets. Regardless of how one defines “sufficient” signal level, broadcasters expect that consumers should be required to use directional antennas only when such directionality is required to ensure sufficient signal level to the receiver and that antenna positioning should not be required solely for reducing multipath echoes.

The Task Force recognizes that a variety of set-top antennas at different price and performance points exist on the market. The group observes that for many years there has been little incentive for advanced development of television receiving antennas, especially the indoor variety. Statistics provided to the group indicate two-third of households subscribe to cable, but a large percentage of receivers in cable and non-cable households use antennas. The apparent disparity is that many households have multiple receivers and the principal receiver is frequently connected to cable. Other receivers may rely upon outdoor or indoor antennas. Such usage may include tolerance of poor NTSC reception.

For optimum reception under adverse signal level and multipath conditions, more attention needs to be paid to the development of indoor and outdoor antennas that are intended for DTV reception.

5.1 Set-Top Antenna Performance

A characterization of the impedance mismatch (VSWR) vs. frequency of several representative models of set-top antennas was performed by a member of the ad hoc group[4]. These antennas display wide variation in the impedance match to the tuner versus frequency as shown in Table 1 and Table 2 of Appendix E. Impedance mismatch affects the RF power transfer from the antenna to the tuner, the noise figure of the receiver and, depending on the length of the antenna-to receiver cable, creates reflections between the antenna and tuner. These reflections affect the receiver in much the same manner as short delay multipath propagation. They create echoes (positive and negative) as well as linear (amplitude and phase) variations that may require compensation by the receiver.

A complete theoretical characterization of the degradations caused by the impedance mismatch between the antenna and the front-end of the receiver is provided in Appendix F.

Another characteristic of present-day antennas for indoor reception is that their gain varies with the angle of arrival (directional antennas). This property could be advantageous when pointing the antenna such as to reduce the effect of multipath. When simultaneous reception of two or more channels is desired, an omnidirectional antenna would be the preferred choice. Simultaneous reception of two or more channels is desired when a VCR is also connected to the downlead or when picture-in-picture (PIP) display is expected. Appendix E provides typical gain characteristics of present-day antennas.

The Task Force also conducted limited indoor reception tests with a particular dipole set-top antenna that was specifically designed to optimize VSWR across the UHF band [12]. From this limited testing, this antenna appears to offer improvements over the traditional bowties, loops and double bowtie reflectors used to date.

5.2 Industry Antenna Initiatives

Lack of standardization in advertising and specifications confuse consumers concerning which antennas are best or have advantages for a specific area. The Consumer Electronics Association (CEA) organized an R-5 (Antennas) committee to make such choices easier. At present, a system of color coded maps, retailer training and a web site “Antennaweb.org” are established for NTSC outdoor antennas. This work also describes use of mast-mounted amplifiers with antennas to aid weak signal areas. Many outdoor antennas already contain amplifiers. Such devices redress the downlead and splitter losses and provide impedance stabilization (VSWR). When compared to the FCC UHF planning factors, a system improvement of 3 to 6.9 dB is achieved [13]. Similar works are in progress for indoor antennas; and many models contain amplifiers that mitigate splitter losses, such as from VCRs, and stabilize VSWR.

In addition, R-5 and R-4 (CEA Video Systems Committee) have established a cooperative project for a “Smart Antenna” interface between a DTV receiver and electronically steered or otherwise adaptive antennas. Antenna positioning for DTV reception is often more difficult than for NTSC because picture quality gives little indication of optimum reception during manual antenna adjustment due to the “cliff effect.” There are, however, many signal qualities internally available in the digital receiver, such as equalizer tap energy and signal strength, which can be automatically applied to adjust and/or select an optimum antenna setting. For example, a pair of dipoles can be placed at right angles and the receiver can select the dipole giving the best signal for the channel received. The DTV system only requires the signal to noise or other interference to be consistently above a threshold for error free reception.

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[4] Antenna return loss data provided by Max Muterspaugh.

5.3 Consumer Ease Of Reception Issues

Despite the potential improvements offered by higher quality passive antennas or 'smart' active antennas, the Task Force acknowledges that an important issue is providing for robust reception using one of a variety of commonly available antennas that are capable of providing sufficient signal strength to the receiver. The opinion of the group is that undue requirements should not be placed on the consumer. The group expects that the typical consumer can select an antenna based primarily on geographic location.

The Task Force notes that a number of sites have been found where sufficient signal strength was present and no tested A/53 DTV receiver achieved satisfactory reception with tested indoor antennas. It is further noted that in some indoor test locations, an A/53 DTV signal is successfully received only if a directional antenna is carefully positioned.

The antenna positioning issue is important to 'ease of reception,' particularly in those markets where the transmission towers of all DTV stations are not co-located, yet provide sufficient signal level for reception. The ability to receive multiple DTV channels at the same time facilitates channel surfing, picture-in-picture display, and recording of one program while watching another. Accordingly, it is desirable for the consumer to be able to receive all stations with one position and orientation of the receiving antenna.

While simple antennas will provide reception in some locations, expecting a simple antenna to provide reception in all locations is unrealistic for any television system. The number of sites where simple antennas provide reliable reception can be expected to increase with advances in receiver design.

In locations where antenna positioning is required to achieve reliable reception, consumer 'ease of reception' benefits a great deal when DTV receivers provide feedback on signal strength and quality. The consumer gets such feedback today with NTSC reception, simply by examining changes in picture quality as the antenna is moved. The 'cliff effect' inherent in any digital modulation system provides only a 'picture/no picture' type of feedback, with substantial processing delay between the antenna movement and its resulting effect on the display. Some receivers provide a 'signal strength' on-screen display. Other receivers also provide a 'signal quality' display that includes information about the severity of the multipath characteristics, which often gives a better indication for antenna adjustment. Research is ongoing to optimize indicators for viewer use. This type of feedback to the consumer is valuable in any DTV system, not just 8-VSB.

Future 'smart' antennas offer the potential to completely automate antenna adjustment and make it invisible to the consumer. This is one potential long-term solution to the antenna positioning 'ease of reception' issue.

6 Analysis of 8-VSB Performance

6.1 Field Test Results

The performance of the 8-VSB transmission system in the field depends on a number of factors. This section attempts to organize them with respect both to requirements and to subsystem performance characteristics that are applicable to those requirements. After some summary observations of field test data, a section addressing the broadcasters’ requirements is presented. This is followed by sections assessing Transmitter and Receiver performance in general.

In the analysis that follows, the following service definitions are used:

Service Availability (SA): This is the percentage of total sites where reception was successful.

System Performance Index (SPI): This is the percentage of sites where sufficient field strength was measured and where reception was successful. Note that “sufficient field strength” has been defined differently by various testing groups and some groups have used C/N or C/(N+I) to define the threshold for a sufficient signal.

In the preparation of this section, the Task Force reviewed reports from several organizations that have conducted tests involving 8-VSB. General comments about these test reports and results follow. In the discussion that follows, measurements are described as “30 foot outdoor,” “6 foot outdoor,” and “indoor.” These terms refer to the location (outdoor vs. indoor) and height above Average Ground Level (AGL) of the receiver antenna. For indoor measurements, the antenna height is not normally specified, but is typically about 4 feet above floor level.

6.1.1 Broadcasters’ 8VSB/COFDM Project (MSTV/NAB Tests)

The 8-VSB/COFDM test project was designed to contrast the difference between 8-VSB and COFDM systems operating at the same average power levels, not to predict performance or coverage of either system [14]. The group considered only the 8-VSB performance data from this project.

The Washington/Baltimore tests involved four UHF DTV stations and included 185 outdoor sites and 44 indoor sites. Outdoor measurements were taken at 30 feet and 6 feet antenna heights AGL. The Cleveland tests involved one low VHF DTV station (channel 2) and a co-located NTSC station (channel 3). Ninety-eight outdoor sites and 22 indoor sites were tested. As in the Washington/Baltimore tests, the Cleveland outdoor measurements were taken at 30 feet and 6 feet antenna heights AGL.

Tests were performed primarily for comparison purposes and as such, outdoor sites were preferentially selected with emphasis on close-in sites (less than 10 miles from transmitters) and far out sites, near the edge of coverage. Indoor site selection was not statistically diverse. Sites were pre-qualified based on having adequate outdoor field strength. The homes were within 25 miles of the transmitters for Washington and Baltimore. The homes were within 30 miles of the transmitter in Cleveland. While efforts were made to have the sites be geographically diverse, this was not completely realized, as the indoor sites were homes of employees who volunteered. In order to stress each system, a number of previously identified difficult indoor reception sites were included. The number of sites is also quite small, so even if the selection had been a random sampling, extrapolation of the results would have a low confidence factor. Therefore, the performance percentages in this report cannot be projected to a full coverage area or used as representative of other service locations.

At 30 feet antenna height, 75% of all Washington/Baltimore sites had successful DTV reception (i.e., a SA of 75%). Among each of the four DTV stations, the lowest SA was 60% and the highest was 85%. The corresponding SPI values ranged from 56% to 89% across the four stations.[5]

When the outdoor antenna height was reduced to 6 feet, the overall SA dropped to 36%. Among each of the four DTV stations, the lowest SA at 6 feet was 24% and the highest was 47%. The corresponding SPI values at 6 feet ranged from 40% to 53% across the four stations.

Indoor reception had a SA of 32% among all sites in the Washington/Baltimore indoor tests when a highly directional set-top antenna was used. With a UHF bowtie antenna, the percentage of successful sites dropped to 30%. Among each of the four DTV stations, indoor SA using the better antenna varied from 15% to 42%. The corresponding indoor SPI values ranged from 41% to 70% across the four stations.

At 30 feet antenna height, 73% of all Cleveland sites had successful DTV reception (i.e., a SA of 73%). When the outdoor antenna height was reduced to 6 feet, the SA dropped to 28%. SPI data was not made available for the Cleveland outdoor tests.

Indoor reception had a SA of 26% of the Cleveland indoor sites, using a broadband VHF/UHF set-top antenna. SPI data was not made available for the Cleveland indoor tests.

The Cleveland tests provided an opportunity to study the extent to which DTV coverage replicates NTSC coverage. With an outdoor antenna at 30 feet AGL, 8-VSB was successfully received at 92% of the sites that had an NTSC picture quality of ITU-R grade 3 or higher. Sixty of the 98 sites had NTSC ITU-R ratings of 3 or higher.

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[5] SPI data provided by Victor Tawil of MSTV

For sites that had an NTSC picture quality below ITU-R grade 3, the success rate of 8-VSB was substantially reduced. There were 22 sites where the NTSC ITU-R grade was between 2 and 3. Of these, 5 sites (23%) had successful 8-VSB reception. There were 8 sites where the NTSC ITU-R grade was 1.5 or less. Of these, only one site (12.5%) had successful 8-VSB reception. The low numbers of these sub-grade 3 sites make statistical predictions unreliable, but the data suggest that the goal of replicating NTSC coverage at ITU-R grade 3 is largely met by DTV.

6.1.2 Communication Research Centre (CRC)

The Communications Research Centre (CRC) Canada carried out laboratory and field tests to evaluate the performance of ATSC 8-VSB receivers [15]. Laboratory tests were performed to characterize 8-VSB receivers from different manufacturers and from different generations. The tests also provided a way to quantify improvements made in the design of 8-VSB receivers since 1999. The field trial took place in Ottawa, using the CDTV transmitter with an average ERP of 30 kW. The DTV signal was broadcast on channel 67, while an NTSC signal on channel 65 was used for comparison. Outdoor measurements were taken with a 10 meter mast-mounted antenna at 46 sites. These sites were primarily suburban and covered radial distances from the transmitter of less than 9 km to more than 50 km.

The laboratory tests results showed that the earliest receivers tested in June 1999 were very sensitive to the phase of the echoes. The latest ones tested, however, in August 2000 were significantly less sensitive to the phase of the ghosts and had a wider (-2 to 40 μs) equalizer window. The CRC used the added white noise test method and reported a degradation of less than 0.3 dB between the robustness against random noise measured under controlled conditions in the laboratory and the measurements done at a calibration site (no multipath) in the field.

DTV reception was successful at 42 of the 46 sites (91%). CRC reported that 43 sites had sufficient field strength to support reception.

It is noteworthy that of the 42 sites that had successful DTV reception, only 31 of them (67%) had NTSC quality of ITU-R grade 3 or higher.

CRC reported that the C/N degradation relative to an AWGN channel was less than 3 dB for all sites except one site in downtown Ottawa, which had a degradation of 3.5 dB when dynamic multipath was present. At the four sites where DTV reception was not possible, the primary cause was weak signal, defined by CRC as a C/(N+I) of less than 20 dB.

Indoor testing was also conducted at 43 sites, using both active and passive set-top antennas. The antenna was mounted on a tripod at an elevation of about 5 feet and was placed near a window in each of the rooms where a TV might normally be located (living room, bedroom and kitchen). A site was rated *successful* if DTV could be received in at least one of these rooms and was only rated *unsuccessful* if DTV could not be received in any of them.

Using these criteria, 25 sites (58%) had reliable DTV reception using the active antenna and 23 sites were successful using the passive antenna. Five sites (12%) had *marginal* DTV reception with the active antenna, while 2 sites were marginal with the passive antenna. Finally, 13 sites (30%) had no DTV reception (the *unsuccessful* sites) with the active antenna, while 18 sites (42%) were unsuccessful with the passive antenna. The System Performance Index for indoor reception was 88% using the best antenna.

Of the 14 indoor sites that were unsuccessful with the active antenna, in one case the failure was attributed solely to low field strength. At 11 unsuccessful sites, the failure was attributed to a combination of low field strength and multipath, meaning that the C/N was less than 20 dB. At two failed sites, the failure was attributed solely to multipath, meaning that the C/N was greater than 20 dB but reception was not possible. A similar distribution of failure mechanisms was observed when the passive antenna was used.

6.1.3 Federal Communications Commission (FCC)

The FCC testing in the Washington/Baltimore area sought to evaluate reception using 30 foot and 7 foot outdoor antenna heights primarily for evaluating receiver improvements made since DTV receivers were first available [16]. Another goal was to confirm the field strength at 30 feet.

The FCC preliminary measurements reveal a 98% Service Availability at sites tested with the 30 foot antenna and a System Performance Index of 98-100%. For the bowtie at 7 feet, the Service Availability was also 98% and the System Performance Index was 86% for one DTV station and 90% for the other station tested.

Of the 51 sites, there were 13-14 sites where reception was not successful with the bowtie antenna at 7 feet. A highly directional set-top antenna was then used, achieving a System Performance Index of 57% for one station and 46% for the second station at these sites. In other words, the highly directional set-top antenna was able to provide successful reception at approximately half of the sites that were unsuccessful with the bowtie antenna.

The FCC measurements of C/N at threshold (Appendix A) provide an indication of the true C/N required for real-world reception, including the combined effects of the C/N degradation due to multipath and other interference mechanisms. This data also reveals the progress that has been made by receiver manufacturers in reducing the multipath C/N penalty.

In the 30 foot "coverage" measurements, the data reveals a spread in C/N threshold from the minimum Gaussian channel value (between 15 and 16 dB for all receivers tested) at the best sites to as much as 25 dB at the worst sites. Some of the newer generation receivers demonstrate a 2-3 dB improvement across all sites compared to first generation receivers. This was largely attributed to reduction of the multipath C/N penalty in newer receivers.

The 7 foot "coverage" measurements exhibit higher C/N thresholds, although the threshold of the best receiver is under 20 dB for the best 85% of the sites. The higher C/N thresholds at 7 feet AGL are consistent with more severe multipath channels (lower Ricean K-factors) at 7 feet than at 30 feet, as various propagation studies have measured.

The FCC test engineers also identified 11 sites they considered to be "high multipath, high signal strength" sites. In 30 foot mast measurements, the best receiver tested had a C/N threshold of under 25 dB for the best 85% of these sites. This receiver showed a 6-7 dB reduction in multipath C/N penalty compared to first generation receivers tested. More significantly, this receiver provided successful reception at **all** of these high multipath sites, where the first generation receivers were unsuccessful at more than one-third of these sites.

The 7 foot "high multipath" measurements did not exhibit a significantly higher multipath C/N penalty than the 30 foot "high multipath" measurements, except at the very worst sites. This supports the FCC characterization of these sites as "high multipath."

6.1.4 Brazilian Society of Television Engineering/Brazilian Association of Radio and TV Broadcasters (SET/ABERT)

The SET/ABERT tests conducted in Sao Paulo Brazil in 1999-2000, were designed to compare 8-VSB and two COFDM systems [17].

For 8-VSB 30 foot outdoor measurements, Service Availability was 64% and System Performance Index was 71%, based on 130 outdoor sites throughout the Sao Paulo area.

6.1.5 Early Field Tests (1995-1999)

Prior to 2000, the ATSC transmission system was field tested in 14 separate outdoor tests in 11 cities that included 2,905 sites. There were 8 indoor tests in 7 cities with a total of 333 locations. In general, outdoor testing was conducted with a mast-mounted directional receiver antenna at a height of 30 feet above average terrain. Indoor testing was conducted with various set-top antennas at an average height of approximately four feet above floor level.

These tests primarily employed the Grand Alliance prototype receiver. As Figure 1 indicates, this early 8-VSB receiver design still represents the bulk of the field test data collected to date. These early tests generally showed high SA and SPI values for outdoor reception – upwards of 80% SPI and 70% SA, depending upon the particular cities and stations. Indoor tests exhibited somewhat lower SA and SPI values, as expected, but still generally above 50%.

6.1.6 Field Test Results From Different Cities

The city with the largest number of field test sites is Washington, D.C., followed by Seattle. Figure 2 shows the accumulation of all outdoor field test data available to the ad hoc group – early as well as most recent – sorted by city. The two cities with the highest number of test sites have not only the highest number of failed sites, but the highest percentage of failed sites.

Figure 3 shows a similar accumulation of all indoor field test data available to the Task Force, sorted by city. The same sort of trend in number of failed sites and percentage of failed sites is revealed in the indoor data as in the outdoor data.

It is the opinion of the group that statistically significant geographical differences in DTV reception performance are expected, and Figures 2 and 3 suggest some of those differences. The group cautions that field test data from one or two cities cannot be extrapolated across all North American cities and that the heavy reliance upon data from the Washington, D.C. area may lead to overly pessimistic conclusions regarding DTV reception performance in other cities.

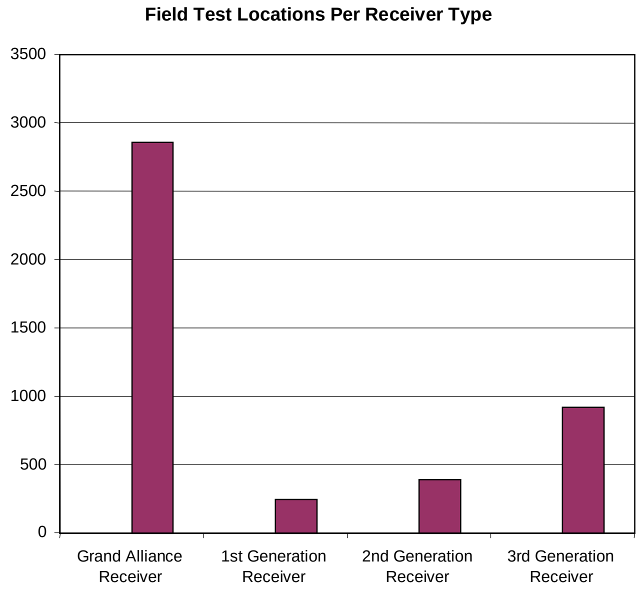

Figure 1: Number of Test Sites vs. Receiver Generation

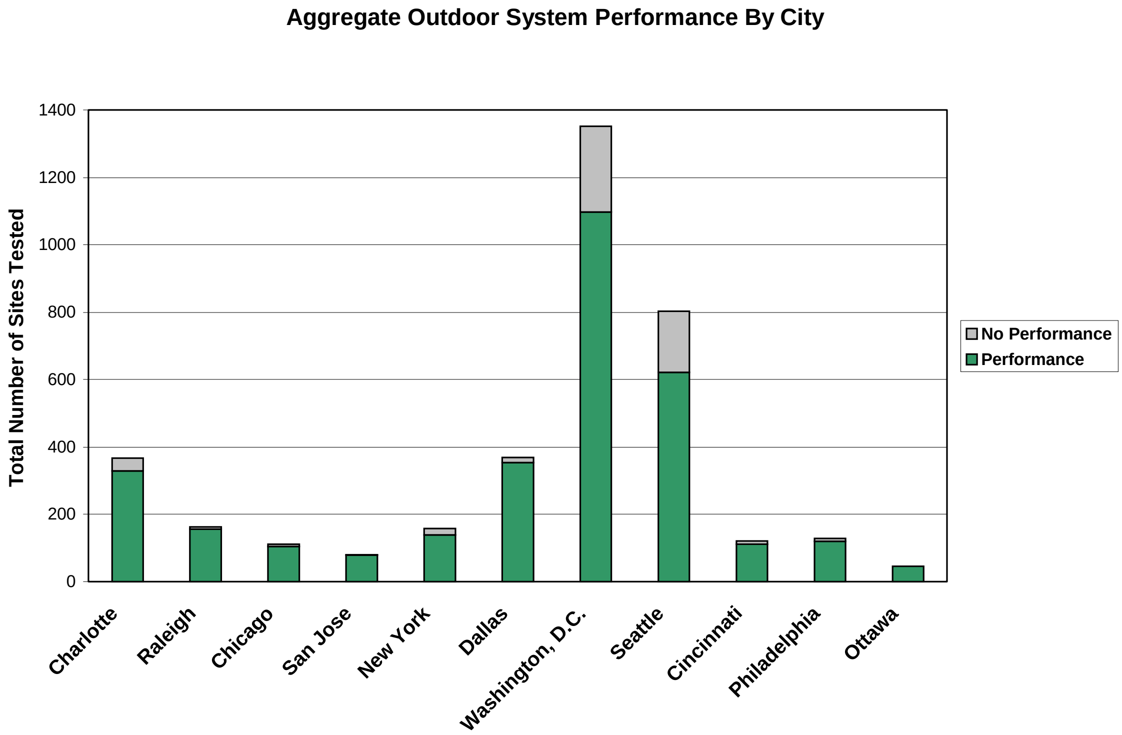

Figure 2: Aggregate Outdoor Performance By City

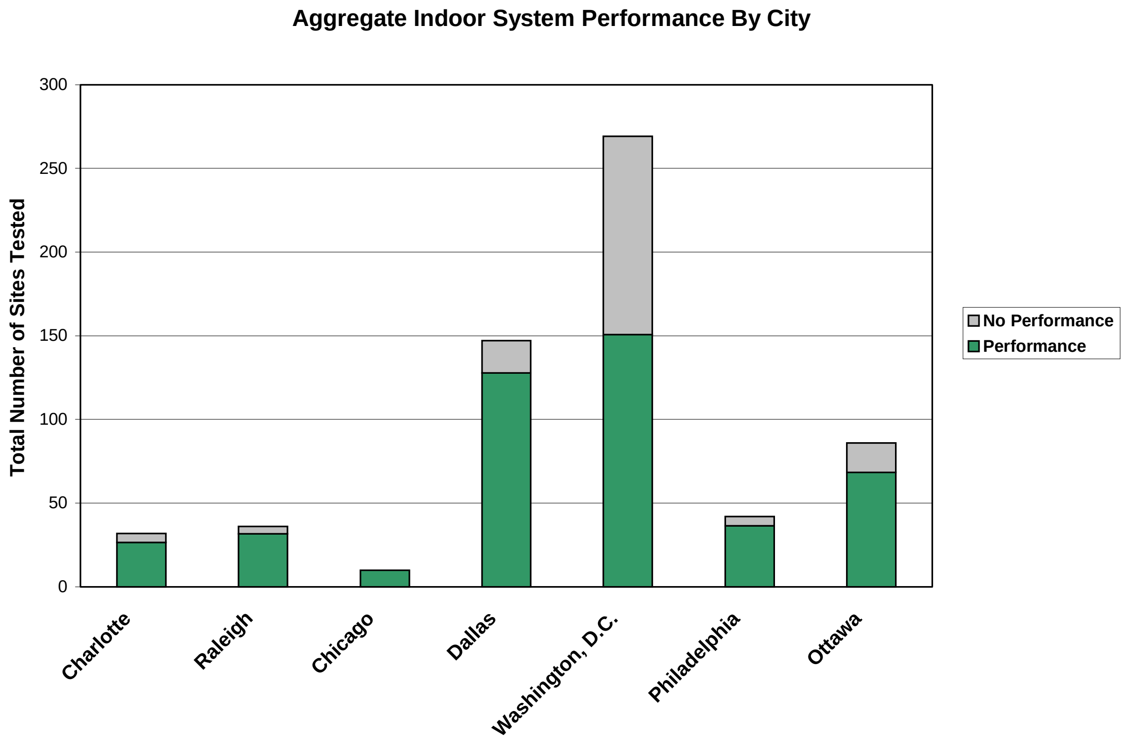

Figure 3: Aggregate Indoor Performance By City

6.2 VSB Performance Relative to Broadcaster Requirements

This section addresses the analysis of 8-VSB performance in relation to the Broadcaster Requirements document developed by the Task Force [7]. These requirements are presented below.

6.2.1 Allocations for DTV and DTV Allotment Table

One of the broadcasters' requirements was that there should be no fundamental changes in the DTV Table of Allotments. In general, the ATSC transmission system as currently implemented correlates with this table, which was designed to provide NTSC replication at allocated power and interference levels.

The 6th Report & Order states:

> "In fact, during the transition period, over 50% of all existing broadcasters would receive a DTV allotment that fully replicates their existing service area, and more than 93% would receive an allotment that replicates at least 95% of their existing service area. We also believe that the DTV Table meets our objective of minimizing new interference to NTSC service. For example, 98 to 99% of all NTSC stations will receive less than 10% new interference (in terms of both area and population served) from DTV operations"[6].

The field test and laboratory data studied by the Task Force indicates that 8-VSB as currently implemented provides the desired coverage and interference protection in accordance with the Table of Allotments. The group notes, however, that the TV spectrum is not yet fully loaded and the full effects of interference are not necessarily evident in existing field test data.

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[6] FCC 97115, 6th Report and Order , section 206. Note the FCC usage of service area is different than the definition adopted by this report..

6.2.2 Fixed Reception

Fixed reception is distinguished from other kinds of reception by the Broadcasters' Requirements document [7]. Fixed reception means a television receiver that is normally kept in one location and connected to a suitable fixed indoor or outdoor antenna. Broadcasters believe all DTV receivers must operate with a high degree of reliability in a fixed position without manual adjustment of the antenna.

6.2.2.1 Fixed Reception Using an Outdoor Antenna

The initial 8-VSB system implementations varied in performance, with some broadcast facilities and some receivers either introducing degradations or being unable to accommodate variations normally present with a fixed outdoor antenna. The field test data presented in this report, however, demonstrate a high level of service availability for outdoor antennas. Note that the outdoor System Performance Index approaches but does equal 100%, because there are some sites where "adequate field strength" is available, but reception is not possible. The group hypothesizes that this may simply be a manifestation of the multipath C/N penalty or other interfering signals. The opinion of the group is that "adequate field strength" must be determined within the context of a link budget appropriate to each reception scenario.

The Task Force notes that the LR(50,90) calculations and associated Planning Factors do not support ubiquitous DTV service within the DTV contour, even when outdoor antennas are used. The Planning Factors predict a field strength availability to the best 50% of sites, 90% of the time, based upon terrain effects but excluding buildings and other man-made structures. The Planning Factors for NTSC were based upon F(50,50) calculations, with the knowledge that at locations and times where the predicted field strength is not met, the NTSC reception is increasingly degraded [18]. The 'digital cliff' effect means that for DTV, at the locations and times where the required field strength is not met there will be no service.

The group also recognizes deficiencies in the current coverage prediction methods that indicate optimistic predictions of coverage. This has also been reported in the technical literature [19]. Some field tests [20] and [21] have also reported a measured threshold of 50 dBu instead of the 41 dBu used in the Planning Factors.

The MSTV/NAB results indicate that DTV service is available wherever NTSC is available at ITU-R grade 3 or higher picture quality [14]. The CRC data also indicates that DTV service is available at many sites where NTSC quality is below grade 3. Based on available data, the group concludes that the goal of DTV service replicating NTSC service at the ITU-R grade 3 level has largely been achieved for fixed reception with outdoor antennas.

6.2.2.2 Fixed Reception Using an Indoor Antenna

Building attenuation and field strength reduction at antenna heights lower than 30 feet result in very weak signals for many indoor sites [7]. Nearly half of all indoor reception failures in the MSTV/NAB tests were due simply to insufficient signal strength.

The System Performance Index of DTV using indoor antennas is generally lower than the SPI using outdoor antennas. As with NTSC, this is not unexpected because indoor reception is affected by the more severe multipath environment created by antenna height reduction, and both exterior and interior reflections.

The severity of the indoor weak-signal and multipath environment also affects the number of sites that can receive NTSC at grade 3 or higher quality. The CRC tests found that among the indoor sites that received DTV (92%), only 67% had grade 3 or better NTSC.

The group's understanding that multipath is usually more severe indoors than outdoors leads to a conclusion that the C/N requirement due to multipath effects at some of these indoor sites was significantly higher than at the outdoor sites. This is simply another way of stating that "adequate field strength" for indoor reception may need to be greater than for outdoor reception, due to lower K-factors in

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[7] Table 12 and 13 of the VSB/COFDM Project report show indoor signal strengths 14.8 to 17.8 dB below 30 foot outdoor measurements, and 7.4 to 12 dB below 6 foot outdoor measurements.

many indoor sites. The group recognizes that site selection was not entirely random for these various tests. In some cases the NTSC and DTV transmitter antennas were not co-located. The FCC DTV Planning Factors and DTV system design are predicated on replication of NTSC at ITU-R grade 3 or higher. The data studied by the group demonstrates a high success rate of DTV reception in the cities tested, at sites where NTSC was grade 3 or better.

It is recognized that antenna positioning (location and orientation) for DTV reception is more difficult than for NTSC reception. There are two components to this difficulty. One is the on/off nature of DTV reception, which is exacerbated by digital processing delays and lack of indicators to aid in correct antenna placement and orientation. This is an expected result of the digital cliff effect. The second component is the need to position and orient the antenna for sufficient signal strength and tolerable multipath.

Newer DTV receivers have demonstrated improved capability for tolerating multipath, and can thus be expected to accommodate a wider range of antenna orientation, simplifying ease of use for the viewer. Further improvements such as electronically steerable “smart” antennas and antenna orientation feedback to the viewer are discussed in Section 7 of this report.

6.2.3 Portable Reception

6.2.3.1 Portable Reception Outdoors

Portable reception outdoors is bounded by fixed outdoor measurements near ground level (i.e., six and seven foot antenna height data). The field strength at this height is approximately 12-16 dB lower than at 30 feet. Signal power delivered to the receiver is further limited by poorer antenna directivity, lower antenna gain and constrained positioning, although it does not suffer from the building attenuation experienced in fixed indoor reception. More severe (lower K-factor) channels result from the constraints on antenna type and position. These constraints significantly limit the service area for portable outdoor reception of the existing 8-VSB signal. At the time of these tests, there were no portable DTV products available. The FCC and MSTV/NAB tests, however, included outdoor measurements near ground level to simulate outdoor portable reception. Outdoor portable reception using a directional antenna may achieve similar SA and SPI values to these test results. Outdoor portable reception using an omnidirectional antenna can expected to have a lower SA due to reduced signal power, and can also be expected to have a lower SPI. The FCC outdoor SPI was 85% at 6 feet antenna height and the SA was 98% (check this). The MSTV/NAB outdoor SPI at 6 feet antenna height varied from 40% to 53% across the four DTV stations in the Washington/Baltimore area.

The vertical polarization of typical omnidirectional receiving antennas exacerbates the low signal strength problem for these receivers. The potential benefits of circularly or elliptically polarized transmitter and/or receiver antennas to address this problem are discussed in Section 7.

6.2.3.2 Portable Reception Indoors

Portable indoor reception is bounded by fixed indoor reception. As noted in the section on Portable Reception Outdoors, the field strength is substantially reduced due to lower antenna height. The field strength is further reduced by building attenuation, as in the case of Fixed Indoor reception. Portable indoor reception is further limited by poorer antenna directivity, lower antenna gain and constrained positioning. These constraints result in a requirement to tolerate more severe (lower K-factor) Ricean channels and lower signal levels, compared to fixed indoor reception.

There have been no formal field tests of portable indoor DTV reception, but some fixed indoor tests are more indicative than others of the expected performance of portable indoor reception. For example, the MSTV/NAB indoor site selection procedure for indoor fixed reception more closely approximated portable indoor reception than the CRC indoor site selection procedure. This difference is reflected in the higher System Performance Index of the CRC results as compared to the MSTV/NAB results.

The group recognizes that there is a range of products and antenna types that may fall in the “portable” category. For example, a portable television set or computer may incorporate a bowtie or other directional antenna. In this case, the performance of portable indoor reception can be expected to be similar to that of fixed indoor reception, subject to the constraint of receiver location only. At the other extreme, a hand-held portable receiver may incorporate an omnidirectional monopole antenna, requiring higher strength and providing less multipath rejection. The SA and SPI of a portable receiver utilizing a directional antenna can be expected to approach the values obtained in the MSTV/NAB tests. The SA will be lower when using an omnidirectional antenna, due to the reduced signal strength. The SPI of a portable utilizing an omnidirectional antenna can also be expected to be lower.

The vertical polarization of typical omnidirectional receiving antennas exacerbates the low signal strength problem for these receivers. The potential benefits of circularly or elliptically polarized transmitter and/or receiver antennas to address this problem are discussed in Section 7.

6.2.4 Pedestrian Reception

Although there are no field test measurements of pedestrian reception, the group examined existing laboratory data and concluded that there is no significant effect due to Doppler shift, per se, at pedestrian speeds.

Pedestrian reception, however, will be affected by spatial signal level variations encountered as the receiver is moved. This is a form of dynamic multipath that arises from sudden interruptions or additions in multipath signals. This type of dynamic multipath is similar to that experienced in a portable or fixed receiver when the field is discontinuously modified (for example, blocking the dominant signal path through a window).

The fundamental distinction between pedestrian and portable reception is that in pedestrian reception, motion through the field increases the likelihood that such discontinuities will occur.

6.2.5 Mobile Reception

A major challenge would be providing adequate field strength at all reception sites, so as to overcome abrupt changes in the spatial field, as discussed in the previous section on pedestrian service. Mobile reception was not a consideration when the DTV system was designed and the FCC planned the allocations. Numerous trade-offs were made that emphasize maximum data rate to fixed receivers from a single primary transmitter.

The existing laboratory data from SET/ABERT, MSTV/NAB and others show improvements of newer DTV receivers in tolerating strong echoes at higher Doppler frequencies. Analysis of multipath in the mobile environment indicates that further improvements are necessary.

Mobile service could be improved by increased C/N margin, longer interleaving depths to accommodate momentary signal fades, faster AGC response and more robust acquisition loops. The various system trade-offs, such as reducing data rate to increase C/N margin, required to support reliable mobile service are beyond the scope of this document.

6.2.6 System Throughput

8-VSB is optimized for maximum data capacity within the television channel. (19.39 Mbps in 6 MHz).

6.2.7 Multi-Mode Operation

The existing ATSC transmission standard provides a single RF transmission mode. The broadcasters' requirement for a multi-mode service is a subject of the T3/S9 consideration of enhancements to the transmission standard.

6.2.8 On-Channel Repeaters and Boosters

The ATSC Task Force on RF System Performance has established that the use of Digital On-Channel Repeaters (DOCR) and "boosters," is a priority for digital television service[8]. DOCR and booster facilities will extend and fill in service areas in much the same way as translators are used in NTSC service. However, with the doubling of the number of television stations, coupled with the reduction in core channels[9], on-channel systems will be needed to take advantage of the frequency reuse made possible through digital transmission and reception technology.

The Advanced Television Technology Center (ATTC) put a temporary DOCR on the air in Charles Town, West Virginia in 1999[10]. Results show that with proper design and isolation, the percentage of successful sites increased. SET/ABERT also tested the benefits of DOCR in a shadowed area of Sao Paulo. In 30 foot outdoor measurements at 46 sites, their results showed an increase in Service Availability from 23% to 85% of the sites in the weak-signal area targeted by the booster. Areas in which the main transmitter and booster signals overlapped also showed an increase in SA, from 27% to 45% of sites. Other studies of DOCR applications have supported the benefits of their use[11].

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[8] Broadcasters' Requirements document

[9] FCC, Fifth and Sixth Reports and Orders, MM Docket 87-268,both adopted April 3, 1997, amended by the Memorandum Opinion and Order on Reconsideration of the Sixth Report and Order, adopted February 17, 1998.

[10] On-Channel Repeaters for Digital Television Implementation and Field Testing; ATTC; Presented to NAB 1999

[11] National Translator Association, Annual Meeting, May 2000, Medford, Oregon

It is expected that future DOCR and booster implementations will take advantage of improvements in receiver technology allowing for a greater variety of successful situations. Further improvements in receiver support for DOCR and boosters are discussed in Section 7.

6.3 Other Performance Results

6.3.1 DTV Transmitter Performance

Many DTV transmitters are calibrated for an equivalent C/N, as measured by the Error Vector Magnitude (EVM), of 27 dB. Other items that can affect EVM are things such as transmission line VSWR and Group Delay. Most transmitters equalize to the flange; therefore, it is a general system requirement that the transmission line and antenna be adjusted as required to minimize VSWR across the 6 MHz channel. Some transmitter manufacturers have noted that a carefully tuned DTV transmitter can achieve 30-35 dB without requiring extraordinary efforts.

Concerns were raised about the amount of jitter on the clock and data inputs to the 8-VSB modulator and the adequacy of the SMPTE-310 jitter specification of 2 ns peak to peak [22]. The group concluded that a Studio-Transmitter Link (STL) that meets SMPTE-310 causes minimal degradation to the DTV link budget, and the anecdotal evidence reported of jitter problems in the field are the result of STLs which exceed the SMPTE-310 jitter specification.

CRC reported a degradation of less than 0.3 dB between Gaussian noise threshold measured under controlled conditions in the laboratory and the measurements done at a calibration site (no multipath) in the field.

The conclusion of the group is that transmitters conforming to current requirements contribute minimally to link budget degradation.

6.3.2 DTV Receiver Performance

Laboratory interference tests of Analog TV into DTV, DTV into Analog TV, and DTV into DTV have demonstrated that some receivers are not compliant with the FCC planning factors for D/U ratios. For example, the FCC Planning Factors assume a lower NTSC into DTV D/U ratio of -48 dB. In the MSTV/NAB tests, a value of -34.5 dB was reported. Similar results were reported by SET/ABERT and others.

Although different receivers exhibit different interference rejection performance, theopinion of the Task Force is that no significant DTV receiver innovations are needed to avoid unexpected interference to or from existing NTSC or DTV transmissions. Compliance with D/U ratios assumed by the Planning Factors is an issue of RF filtering and other performance trade-offs in the DTV receiver.

The results of impulse noise testing in the laboratory are not easily correlated to real world reception. Some field test results have reported impulse noise, particularly on low VHF channels. Field tests in Charlotte showed that DTV reception is robust against impulse noise. The group’s opinion is that further data is needed to quantify the significance of impulse noise in practical consumer reception environments, particularly as it is one of many impairments with which DTV receivers must cope..

Laboratory tests of receiver sensitivity demonstrate that some receivers do not meet the FCC Planning Factors for Noise Figure. The Task Force is aware that some DTV tuners have a Noise Figure greater than the 7 dB assumed in the UHF Planning Factors. Such receivers will require a higher gain antenna or a low-noise preamplifier to achieve reliable reception in weak signal areas.

In strong signal areas, RF overload may be an issue if a high-gain antenna or preamplifier is used, but this is generally a much simpler problem to solve. The problem can be solved by padding the antenna end of the downlead, which also helps reduce VSWR. Signal overload may be solved in some cases by simply substituting a lower gain, lower directivity antenna with good VSWR.

In the area of multipath interference, substantial progress has been made by receiver manufacturers in improving the strength of echoes tolerated, the echo dynamics (Doppler shift) tolerated, the delay spread of post-echoes tolerated and in reducing the multipath C/N penalty of recent A/53-compliant receivers and demodulator chips, compared to first generation products.

7 Future 8-VSB Performance Improvements

7.1 Future 8-VSB Receiver Improvements Through "Technological Innovation"

This section discusses receiver improvements achievable simply through advancements in technology, without requiring changes to the A/53 standard. Each major receiver subsystem is considered.

7.1.1 DTV Tuners

Revision of channel allotments will eventually result in a fully occupied spectrum in the TV broadcasting bands. Until the transition to DTV broadcasting is completed, the spectrum will include NTSC transmissions at relatively high power levels compared to DTV transmissions. Thusfar, the only experience with a fully occupied spectrum has been in cablecasting, where the power levels of the channels are uniform and there are no interfering signals except for other TV signals. It is difficult to be certain just how much general improvement may be needed in tuner design so over-the-air transmissions will be satisfactorily received in the future. Techniques for making such general improvement are, however, already known to tuner designers.

A variety of DTV tuners currently exist in the market for OEMs of A/53 receivers. Some DTV tuners currently available utilize a double-conversion architecture to convert VHF or UHF channels to a first IF signal above the UHF reception band and then to a second IF signal having a 44 MHz center frequency. Plural-conversion tuners are less susceptible than single-conversion tuners to interference from signals in "taboo" channels, particularly those containing image frequencies of the channel selected for reception. This is important for achieving satisfactory reception with the revised channel allotments.

Some manufacturers offer single-conversion DTV tuners for converting directly to IF signal having a 44 MHz center frequency. They are less expensive to manufacture than plural-conversion tuners. Since a single-conversion tuner contains only one oscillator, typically it exhibits less phase noise than plural-conversion tuners.

Designing DTV tuners for off-the-air reception involves a series of compromises to achieve acceptable performance over a wide range of received signal strengths. These compromises are similar to those made in designing tuners for off-the-air NTSC reception. All DTV tuners must be capable of providing linear output signals with C/(N+I) in excess of the 15 dB threshold value that VSB-8 needs at the data slicer in order for a Gaussian channel to be successfully received. In the real world the reception channel is likely to be Ricean or Rayleigh in nature, so the DTV tuner must deliver linear output signals with substantially higher C/(N+I) in order to accommodate loss of C/N in the filtering used for channel equalization and multipath suppression. C/(N+I) as much 30 dB may be necessary for satisfactory reception of a Rayleigh channel. Such C/(N+) is achieved only when the RF signal is received with sufficient strength, but is not so strong as to overload the tuner.

Adjacent channel interference (ACI) is caused by a strong adjacent channel overloading an RF amplifier or mixer in the tuner. There are nearly 400 upper or lower first adjacent channels in the DTV allotments, increasing the likelihood that ACI will be a problem. Biasing of the initial stage in the tuner so as to minimize overloading by a strong adjacent channel is not optimal biasing for reducing noise figure, however. The noise figure in a DTV tuner designed for off-the-air reception is apt to be around 10 dB, not counting the effects of echoes or loss in a downlead from an outside antenna.

This is substantially higher than the noise figure of 2 dB or so for a RF amplifier specifically designed for receiving only weak signals. Experts in the group recommend that a low-noise-figure RF amplifier be used as an auxiliary pre-amplifier for a current DTV receiver, when signal strength is low. Inclusion of a signal strength indicator in future DTV receiver designs would facilitate detection of such circumstances. Another potential improvement is incorporation of means for the receiver to exert automatic control of a remotely located low-noise amplifier.

Tuner input impedance is an area in which significant improvements are possible. It has been anecdotally reported that prior to mid-2000 measurements of about a dozen receivers from different manufacturers revealed that most of the receivers had a poor return loss, only slightly greater than 10 dB, and many were even poorer, with less than 10 dB return loss. In most cases the reactive component was capacitive and was about half the magnitude of the real component. In most, but not all cases, the real component of the tuner impedance was closer to 50 ohms than to 75 ohms. It was reported that rarely was the impedance match optimal for the tuned channel and typically the best match was on a channel different than that to which the DTV set was tuned.

7.1.2 IF Processing

The IF processing includes all IF filtering and amplification from the first converter output of the tuner to the analog-to-digital converter (ADC) input. Typically, the IF filter that principally determines channel selectivity is a Surface Acoustic Wave (SAW) filter with a flat passband, a constant group delay within the passband, and a 3 dB bandwidth of approximately 6 MHz centered near 44 MHz. Some earlier DTV receiver designs establish the Nyquist roll-off by IF filtering with somewhat narrower bandwidth SAW filters. As compared to the SAW filter in an NTSC receiver, the SAW filter in a DTV receiver requires more fingers on both transducers to obtain the flatter passband and the steeper skirt slopes for similar adjacent channel suppression. This requires a larger substrate and packaging, so cost is somewhat higher. Current SAW filter designs can suppress triple transient echoes (TTE) about 50 dB with some 15dB insertion loss. Acoustic delay is around 1.5 microseconds, so TTE exhibits about 3 microseconds delay. TTE is well within equalization range and also is too low in amplitude to affect data slicing significantly.

The IF processing also includes fixed and variable gain amplifiers to (a) make up for the losses of the SAW filter and (b) provide Automatic Gain Control (AGC) at weak signal levels. In some designs, the IF signal from the IF processing is demodulated in the analog regime and the resulting baseband signal digitized by an analog-to-digital converter (ADC). In most newer designs, the IF signal is digitized by an ADC and is then demodulated in the digital regime. Preferably, the IF processing regulates the IF signal voltage so the full dynamic range of the ADC can be exploited and the full number of bits resolution available from the ADC is secured. For a modern ADC, this voltage is typically between 0.5 and 1.0 Vpp. Thus, the IF dynamic range requirements for DTV receivers differ little from those for NTSC receivers.

7.1.3 Analog-to-Digital Conversion (ADC) and Digital Demodulation

Most current designs for A/53 receivers to be sold in commerce utilize either 8-bit or 10-bit analog-to-digital converters, followed by purely digital demodulation of the 8-VSB signal to baseband I and Q components. The use of 10-bit-resolution ADCs allows more dynamic range for coping with multipath fading and ACI than 8-bit converters. The group recognizes that additional performance gains can be achieved using 12-bit or higher resolution ADCs, presuming these become economical for consumer receivers. The 12-phase trellis coding lends itself to polyphase analog-to-digital conversion, with an oversampling ADC in each phase to gain extra bits of resolution, reducing the quantizing noise.

Many recent designs for A/53 receivers employ bandpass subsampling of the 44 MHz IF. Beyond an increase in ADC precision, very little performance improvement may be necessary in the bandpass sampling and digital demodulation subsystems. The conversion of 8-VSB signals to double-sideband AM signals prior to demodulation, which suppresses quadrature-phase echoes and helps stabilize carrier synchronization loops, has recently come into use. The procedure may simplify some types of channel equalization.

7.1.4 Automatic Gain Control

Because of the importance of automatic gain control (AGC) to the proper operation of a DTV receiver, AGC is considered as a separate topic in this part of this document.

The AGC circuitry regulating gain in the analog portions of a DTV receiver typically encompasses the tuner, the IF processing and a portion of the demodulator. One purpose of such AGC circuitry is to assure that the full dynamic range of the analog-to-digital converter is exploited, to maximize the actual bit-resolution of the digitized DTV signal. Besides a DTV receiver having AGC circuitry regulating gain in its analog portions, the DTV receiver customarily has AGC circuitry regulating gain in its digital portions, so the equalized baseband DTV signal is scaled appropriately for data slicing. This is done to minimize the dynamic range required of digital multipliers employed in the equalizer.

Analysis of DTV field test data has revealed the need for rapid AGC response times to adapt to broadband ("flat") fading conditions. A closed-loop bandwidth of at least 75 Hz has been suggested for the AGC loop(s) in a home DTV receiver. A mobile receiver will require a higher closed-loop bandwidth, perhaps 200 Hz, in its AGC loop(s). Some manufacturers have indicated that their early prototypes had slower AGC, and that this limitation has been corrected in the latest model consumer receivers or those that will soon be on the market.

As in NTSC television receivers, it is customary to employ "delayed" AGC in DTV receivers. This technique must be carefully implemented for optimum receiver performance. Delayed AGC maintains the tuner at maximum gain, where it has the best noise figure, under weak signal conditions. As the input RF signal level increases above the minimum, all AGC is performed by the IF processing. When the IF processing gain approaches its minimum, the tuner gain is reduced to accommodate any further increase in RF input level. Accordingly, the tuner noise figure is degraded only when the signal is moderately strong and there is substantial C/N margin – i.e., at an operating point where the tuner noise figure is less important to receiver performance. The 'crossover' point at which the tuner takes over the AGC function from the IF processing must be selected not only for noise figure optimization, but also based on receiver overload (AM/AM nonlinearity) and cross-modulation considerations.

The preferred 'crossover' point for delayed AGC in a DTV receiver differs from 'crossover' point preferred in an NTSC receiver. In an NTSC receiver, keeping noise in the video more than 40 dB below average luma is subjectively more important than maintaining the best linearity of video signals, so the RF amplifier stage gain is cut back only when mixer overload is imminent. In a DTV receiver, linearity of the data modulation is critical to accurate data slicing. As long as the signal-to-noise ratio is maintained above threshold, the signal-to-noise requirements are less stringent than for an NTSC receiver. Accordingly, in a DTV receiver it is preferred to begin reduction of RF amplifier gain at a lower-strength input signal than is done in an NTSC receiver. This also reduces the likelihood of ACI in the DTV receiver.

Cross-modulation products may be generated in a mixer when strong adjacent or taboo channels are present and are excessively amplified. As an alternative to delayed AGC for DTV signals, the RF & IF sections may utilize separate AGC systems. In such designs, in order to prevent interfering signals being excessively amplified by the RF amplifier, so as to overload the mixer, the RF AGC is derived from the mixer output signal and is amplified wideband.

7.1.5 Carrier Synchronization

Many A/53 receivers rely to some extent upon the 8-VSB pilot for carrier synchronization, and some do not use it at all. Sole reliance upon the pilot is problematic for robust carrier synchronization in dynamic multipath channels with severe fading, since frequency-selective fades will sweep through the pilot frequency. Since most consumer receivers utilize fully digital processing techniques, pilot tracking loops are typically implemented on-chip with digital phase locked loops (DPLLs), rather than with external analog PLLs, as was done in early A/53 prototypes.

Improving carrier synchronization is the subject of substantial research by 8-VSB receiver designers and it is likely that some of the approaches being considered have not been disclosed to the industry at large. The group recognizes that carrier synchronization in multipath channels is a significant performance issue and that alternatives to purely pilot-based synchronization do exist and are reported to be used in some recent A/53 receiver designs. Besides pilot tracking loops, decision-directed techniques for suppressed carrier recovery, commonly used in QAM and QPSK systems, are well known. Some A/53 receivers now use fractional equalizers or complex synchronous equalizers. These equalizers provide better tracking of the carrier than can be achieved using the real-only synchronous equalizers of early 8-VSB receiver designs.

Each method of carrier phase and frequency detection is theoretically subject to failure under certain multipath conditions, but a combination of techniques will reduce the likelihood of complete carrier synchronization failure in any particular real-world reception condition. The rapid changes in reception conditions that will be encountered by mobile receivers in fast-moving vehicles present particularly difficult challenges to maintaining carrier synchronization.

7.1.6 Symbol Timing Synchronization

Symbol timing synchronization, like carrier synchronization, is another area of active research by receiver manufacturers. Early A/53 receivers relied exclusively upon the Data Segment Synchronization (DSS) sequence, which is provided in the A/53 framing structure for this purpose. Newer receivers have either supplemented or replaced the DSS-based methods with band edge detection, spectral bright line detection or other techniques designed to improve timing synchronization robustness in the presence of dynamic multipath.

As in the case of carrier synchronization, each method of symbol timing phase and frequency detection is theoretically subject to failure under certain multipath conditions. However, a combination of techniques will reduce the likelihood of complete symbol timing synchronization failure in any particular real-world reception condition. The rapid changes in reception conditions that will be encountered by mobile receivers in fast-moving vehicles present particularly difficult challenges to maintaining symbol synchronization.

7.1.7 Adaptive Equalization

Several manufacturers have attempted to address severe Ricean (low K-factor) channels and Rayleigh faded channels, in the interest of improving indoor reception robustness in urban environments. By the end of 2000, several manufacturers had implemented adaptive equalizers that can cancel multipath echoes from 5-6 µs pre-echo delay to over 40 µs post-echo delay at amplitudes reaching 0 dB attenuation for single echoes at particular echo delays. They had also implemented a variety of equalizer algorithms which track echo dynamics out to 5-20 Hz, but with exponentially decreasing echo amplitude tolerance as echo dynamics increase in frequency. The benefits of these improvements relative to first generation receivers were clearly demonstrated in laboratory and field tests, but these improvements did not assure robust reception in some severe Ricean and Rayleigh channels that exist in the real world. Moreover, the positioning of the antenna was critical to maintaining satisfactory reception of DTV signals, presenting an ease-of-use issue in markets where not all DTV signals emanate from the same transmission antenna site.

Some members of the group suggested that the pre-echo range of adaptive equalizers should be increased. They thought this could be particularly important in ameliorating the critical antenna positioning sometimes necessary in Rayleigh faded channels, in which any echo may appear as the dominant path and echoes with arbitrary delays, up to the maximum echo delay spread, may appear as either pre-echoes or post-echoes. Longer pre-echo support will also extend the benefits of DOCR, as discussed in Section 6.

Besides increasing the ranges of pre-echo advance and post-echo delay that can be accommodated by A/53 receivers, designers now recognize that strong echoes, with amplitudes as large as or even slightly larger than the desired signal, must be tolerated to secure reception in many indoor reception environments. Laboratory data indicate that a single echo at or near 0 dB relative amplitude could be cancelled by some receivers available at end of year 2000, but these receivers are incapable of separating a useful principal signal from echo ensembles that include multiple strong echoes characteristic of Rayleigh channels. Solving the Rayleigh channel problem requires additional techniques not disclosed to the Task Force. Individual members of the group have asserted that the Rayleigh channel problem is solvable.

Some Task Force members have reported excellent simulation results for severe Ricean channels using Discrete Fourier Transform (DFT) techniques to measure echoes and to use these measurements for initializing the adaptive equalizer. In order to initialize or re-initialize adaptive equalizer filter coefficients, these methods require measurements of the echo phases at times that known symbol sequences are transmitted. Reportedly, it is difficult to extract sufficiently accurate echo phase measurements from the existing Data Field Sync (DFS) reference signal for channels with echo delay spreads that are a large percentage of the DFS duration and it is impossible to extract this information for channels with echo delay spreads that exceed the duration of the DFS.

Receivers available in 2000 lock to and track the dominant path, and they re-acquire the channel if a previously undesired echo becomes the new dominant path. From a practical implementation viewpoint, it may be better for receivers to tolerate echoes greater than 0 dB and avoid re-locking during transient echo conditions. If, however, a signal weaker than the strongest one is chosen as the principal signal, the somewhat lower C/N of that principal signal is the best that will be achieved. The exact trade-offs are implementation issues for receiver manufacturers.

Manufacturers have also recognized that receiver capability to track higher-frequency echo dynamics is important for practical mobile reception. Additional industry experience with field testing and RF data captures will better define the requisite tracking frequency requirements and their statistical significance to determining broadcasting coverage. Existing 8-VSB equalizer designs show an exponential decrease in tolerable echo amplitude as a function of Doppler shift. Other techniques for tracking higher frequency dynamics are being developed, as indicated by the following simulation results of a next generation 8-VSB receiver chip[12]. After decaying from an echo tolerance of 0 dBc at 0 Hz to -3 dBc at 5 Hz, the receiver is able to tolerate a single 4 µs post-echo at -3dBc out to 40 Hz, with a very gradual decrease in echo amplitude tolerance out to 80 Hz.

From this and other data, including the group's understanding of multipath dynamics for fixed and portable receivers, some group members say that the issue of tracking time-varying echoes is largely solved for fixed and portable receivers in most environments. The group expects that tracking echo dynamics in DTV receivers in fast-moving vehicles during mobile reception will be more difficult. There is ongoing research on equalizing Rayleigh and severe Ricean channels. Methods to cope with the strong echoes, lower K-factors and higher frequency dynamics are sought which do not require inordinately high C/N ratios. The Task Force notes that the laboratory and field test data summarized in Section 6 and in the Appendices indicates C/N requirements in excess of 25 dB for some low K-factor channels that are in fact receivable by existing 8-VSB receivers.

Some simulations show that this extreme increase in required C/N is not inherent in the 8-VSB system, at least for static multipath channels, and noise enhancement can be avoided by directly calculating the equalizer coefficients based on correlating long blocks of data. Some group members share the opinion that a C/N requirement of 25 dB should suffice even with Doppler frequencies above 5 Hz for a single 0 dB echo. Sparse equalization is another technique that is being used to reduce noise enhancement. The group notes that the DTV Planning Factors make no allowance for C/N degradation caused by multipath.

Coping with higher-frequency dynamic multipath encountered in mobile reception will require integrated circuits considerably more complex than currently used in A/53 receivers.

7.1.8 Antennas with Electronically Steered Directional Sensitivity

There is current investigation into "smart" antennas that electronically combine the responses of two similar component antennas to achieve an overall directional antenna response that can be redirected subject to electrical control signals. These control signals will be supplied from a DTV receiver especially equipped to optimize the directionality of the overall antenna response. The receiver will perform the optimization based on a variety of data including AGC, C/(N+I), and equalizer tap weights. CEA has formed an R4 "WG4 Antenna/DTV Interface" committee to investigate and set voluntary standards for a DTV to "smart" antenna interface, as well as an R5 "Antenna" Committee considering "smart" antenna issues.

These "smart" antennas are expected to contribute to ease of reception of 8-VSB signals, especially in markets where DTV signals are received from different broadcast antenna locations. More rapid changes between channels received from different directions is possible. The directionality of a "smart" antenna could be adjusted automatically by the receiver or manually by remote control. The directionality of an

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[12] NXT2002 simulated performance, provided by Nxtwave Communications

outdoor “smart” antenna can be changed almost instantly; there is no wait for the slewing of an electromechanical antenna rotor.

The responses of the two similar component antennas can be simultaneously combined in different ways to support concurrent reception of TV channels received from different directions. The concurrent reception can be by a single TV receiver with picture-in-picture capability or can be by different receivers in the household.

7.1.9 Antenna (Spatial) Diversity

Antenna or Spatial Diversity is a technique long used in digital communication systems to combat the effects of multipath interference, but which thusfar has not been used to any extent in DTV reception. A spatial diversity receiver employs two or more antennas, and two or more component receivers or significant portions of receivers. The antennas are positioned to be affected differently by multipath signals, so any notches in the frequency spectra of their respective responses can be filled in when they are combined with each other. The diversity receiver may simply select the best signal, or may intelligently combine the signals from two or more antennas prior to decoding.

To achieve sufficient de-correlation between the multipath characteristics ‘’seen” by each antenna, the antennas usually are physically separated by at least one-quarter of the RF wavelength. Other ways of achieving spatial diversity are also being explored. Antenna diversity is most likely to be used in mobile applications. Insofar as portable receivers or fixed receivers with indoor or outdoor antennas are concerned, antenna diversity tends to be impractical for low VHF channels, but is quite manageable for UHF channels.

7.1.10 Polarization Diversity

Polarization diversity concerns the simultaneous transmission, reception, or both transmission and reception of a signal in two orthogonal RF polarizations. Such techniques have long been used to improve reception in various communication systems, and a transmission technique of this sort was proposed for DTV in a 1996 paper presented at the NAB Engineering Conference [23]. This paper reports that the frequency-selective fading caused by multipath is uncorrelated between the Vertical (V) and Horizontal (H) polarization components of a Circular Polarization (CP) wave. The multipath nulls in the H component are not at the same frequencies or depths as those in the V component. By using a CP receiver antenna, deep nulls in one polarization component are substantially filled in by the other polarization component of a received CP signal. Improvement in multipath fading was also observed using Elliptical Polarization (EP). The benefits of CP and EP were achieved without increasing transmitter output power in either case. The present FCC Rules do not prohibit CP or EP for DTV broadcasting.

One Task Force member has experimented with a pair of log-periodic indoor UHF antennas respectively arranged to receive H and V components of DTV signal transmissions. Although the transmitted DTV signal is horizontally polarized, de-polarization is caused by reflections — e.g., as occur when the signal passes through dense foliage. Nearly the same total power in the channel from the V as from the H antenna was observed at a number of sites where there is no line-of-sight path. When the H and V signals were combined in a simple passive power combiner, the gain ripple observed on a spectrum analyzer could be made much smaller than with just the H plane antenna response alone, despite the DTV signal being horizontally polarized when transmitted. It is speculated that CP or EP might benefit a receiver that experiences Rayleigh fading, since the vector combination of the independently faded H and V components may make Rayleigh channels more Ricean.

7.1.11 Changing Overall Receiver Layout

High VSWR in the downlead connection to the DTV receiver from an outside antenna raises the noise floor of the receiver, as well as reducing the signal power available to it. These effects significantly increase receiver noise figure (see Appendix E). It is difficult to optimize VSWR for different DTV signals with diverse channel frequency allocations, especially when the down-lead connection is driven directly from a wideband outside antenna designed to receive signals over as many as four octaves.

It has been proposed that the DTV receiver be reconfigured so front-end tuner and IF amplifier sections are located outdoors with the antenna connected directly to the front-end tuner through a balun, and the IF amplifier sections driving the downlead connected to a further IF amplifier section in the indoor receiver apparatus. The downlead is terminated in characteristic impedance for the IF signal, which prevents echoes in that connection no matter which DTV channel is selected for reception. A demodulator follows the further IF amplifier section in the indoor receiver apparatus. Channel-tuning remote-control signals are transmitted from the indoor receiver apparatus to the outdoor tuner. Frequency multiplexing can be used to transmit these remote-control signals and operating power to the outdoor tuner via the downlead.

In this proposal, plural outdoor tuners facilitate picture-in-picture (PIP) displays, receiving different displays on different monitors, or recording a channel other than the one currently being watched. The tuners are arranged to drive a shared down-lead connection with different-frequency IF signals. There is a reduction of the number of 6-MHz channels at which the down-lead connection must be terminated with its characteristic impedance in order to prevent echoes, compared to supplying the down-lead connection RF DTV signals that have not been converted in frequency. A lossy transmission line with the same characteristic impedance as the downlead is preferred for terminating the indoor end of the downlead over a broad band of frequencies. A high-input-impedance buffer amplifier with neutralization is preferred for extracting the IF signals from the indoor end of the downlead.

Reconfiguration of the DTV receiver to suit an outdoor antenna would create an additional class of DTV receiver than that used with an indoor antenna and does not help with problems of indoor antenna reception. Additional liability issues of weather-resistance, safety against lightning, proper installation, et cetera arise for the manufacturer of the outdoor tuner.

7.2 Future 8-VSB Receiver Improvements Through Changes to the A/53 Standard

The Task Force has discussed several proposals for enhancements to the A/53 standard. It is beyond the scope of this report to rigorously analyze the proposals. The T3/S9 committee has issued a Request For Proposals (RFP) for VSB enhancements and will evaluate the proposals in 2001.

8 Conclusions

8.1 DTV Transmission System Design Parameters

Much of the discussion within the Task Force focused on the requirements of the DTV transmission system – original requirements, industry interpretations of those requirements and current broadcasters' requirements. The original requirements for the DTV system were to provide robustness "better than NTSC."

The FCC DTV Planning Factors were selected to plan for replication of NTSC reception. The Planning Factors are variables in a link budget, but not a complete link budget. There are several link budget variables not included in the Planning Factors.

The evidence gathered by the Task Force suggests that the transmission system was not specifically designed for or evaluated for any particular level of "service" to fixed receivers using indoor antennas, portable receivers using self-contained antennas, and pedestrian or mobile receivers. The group understands that reliable reception in these other service modes is sometimes possible, but the DTV Planning Factors did not anticipate these other service modes.

The expectation of many broadcasters was that wherever there is acceptable NTSC reception to the viewer, DTV reception would be available if the broadcasters transmitted per the allocation plan. Some broadcasters believe that expectation has not been met. The group concludes that a perceived failure of DTV to replicate NTSC coverage is largely a matter of mistaking "coverage" for "service" and of unrealistic expectations of DTV "service" replicating NTSC "service" at arbitrarily low levels of NTSC picture quality.

The Task Force finds ample evidence, particularly in the recent data from the FCC tests, MSTV/NAB tests and CRC tests, that the ATSC transmission standard and FCC DTV Table of Allotments largely fulfills the goal of "replication of NTSC coverage," where such coverage is measured at 30 feet AGL – for DTV as it is for NTSC – and where the comparison between DTV and NTSC is made at an NTSC picture quality of ITU-R grade 3 or higher. Concerns have been raised, however, that the low VHF Planning Factors may be inadequate.

8.2 Assessment of Existing 8-VSB Receiver Implementations

The group concludes that the performance of current 8-VSB receivers largely fulfills the original goals envisioned for the DTV transmission standard and encompassed by the FCC Table of Allotments.

The Task Force concludes that more recently designed receivers demonstrate significant improvements in multipath tolerance compared to first-generation receivers. The group also notes that improvements have been made in other areas of receiver design, including the RF front end design, the AGC and other tracking loops. The group further notes that newer receivers exceed the performance of the original Grand Alliance reference receiver in several areas, including length of echoes, amplitude and dynamic rate of change of echoes. Increased pre-echo capability will be valuable in supporting DOCR and indoor reception, and the group is aware of industry efforts addressing these needs.

These and future improvements are expected to help meet broadcasters' requirements for other service modes beyond those for which the system was originally planned.

The group also notes that more recent designs better integrate the analog and digital portions of the receiver, resulting in improved overall system design.

8.3 Fixed Reception Using Outdoor Antennas

The group concludes that 8-VSB as implemented per A/53 largely fulfills the goals of providing DTV service to fixed receivers via outdoor rooftop antennas.

8.4 Fixed Reception Using Indoor Antennas

The group concludes that any DTV service using indoor antennas is among the more difficult of the broadcasters' requirements to meet, primarily due to insufficient signal power.

The group calculates that a link budget for indoor reception requires substantial additional margin, perhaps 47 dB, compared to outdoor reception at the edge of the DTV contour. Indoor reception is therefore limited to a much smaller contour than outdoor reception, as is the case with NTSC grade 3 reception. Fixed DTV reception using indoor antennas that offer degrees of freedom in gain, placement and orientation will have the highest Service Availability of all indoor reception modes.

8.5 Portable Reception

To the extent that portables may use monopole antennas, the link budget calculation is more pessimistic than for fixed receivers. The consensus of the group is that indoor reception by portables with monopole antennas will be supportable only over a limited portion of a broadcaster's DTV service area, as is the case with NTSC.

8.6 Pedestrian Reception

The issues for pedestrian receivers are similar to those of portable receivers using monopoles, and the Doppler shift dynamics on multipath echoes are not a significant problem for pedestrian receivers.

Pedestrian receivers will receive substantially higher field strengths outdoors than indoors. As with portable reception, the opinion of the group is that reception by pedestrian receivers will be supportable only over a limited portion of the broadcaster's service area.

The motion of pedestrian receivers will subject them to abruptly changing spatial field conditions, which differentiates this class of service from portable reception and may further reduce the service area.

8.7 Mobile Reception

Mobile reception is similar to pedestrian reception, with the addition of higher Doppler rates on received signals. As with pedestrian reception, the primary difficulty in achieving reliable mobile service is the abrupt spatial field variations (i.e., dropouts in signal strength and abrupt changes in multipath characteristics).

The problem of dropouts is not particularly associated with single-carrier modulation. This problem may be addressed by changing modulation parameters to increase C/N margin (e.g., by reducing data rate), by increasing interleaving depth, employing stronger forward error correction coding or receiver antenna diversity. The group hypothesizes that reliable mobile DTV service may require multiple transmitters to minimize the likelihood of abrupt spatial field variations in the received DTV signal.

9 Recommendations

9.1 Transmission System Enhancements

The Task Force recommends that the ATSC investigate enhancements to the A/53 transmission standard if it is the intention of the ATSC to meet most or all of the stated requirements in the Broadcaster Requirements document [7]. The consensus of the ad hoc group is that some form of enhancements to the existing A/53 standard would more rapidly meet these requirements and provide more ubiquitous DTV services for American consumers than relying solely on technological innovation of receivers based upon the existing A/53 standard.

The group recommends in particular that the ATSC study the potential of including a more robust audio mode as a potential enhancement.

9.2 Need For Further Testing And Studies

Some field tests have reported a measured threshold of 50 dBu instead of the 41 dBu used in the Planning Factors. The cause of this discrepancy should be investigated.

The potential benefits of Polarization Diversity, Spatial Diversity and electronically steerable antennas should also be investigated.

It is the opinion of the Task Force that a clear and acceptable definition of DTV service, particularly indoor, does not exist at this time and that DTV service and NTSC coverage are not universally related. Further, the group notes that the Planning Factors and the propagation channel (AWGN) used by the FCC to develop the channel allocation table are of limited use for predicting real-world service.

The group notes that it is difficult to compare DTV to NTSC at any specific NTSC video quality, due to the all-or-nothing nature of DTV.

The Task Force recommends development of criteria for definition of applications for DTV service in various modes of reception, and observes that the distribution of errors over time is critical in assessing service. It is therefore recommended, for the benefit of future studies, that a working group be established within the ATSC to address specific subjects essential to the implementation of Broadcasters' Requirements in [7]: Definition, Prediction and Measurement of DTV coverage and service.

The group recognizes a need in the industry for more data on RF propagation channels and their impacts on the C/N requirement for DTV service. The group recognizes that RF data captures have significant benefit and recommends that RF data captures be incorporated in field tests.

Appendix A: FCC Preliminary Test Results

This data represents 51 sites in the Washington/Baltimore area. Of these 51 sites, 11 were categorized by the FCC engineers as "high signal strength, high multipath" sites.

Station	Antenna	# of Sites	Tx HAAT	SA	SPI
WUSA (34)	Log Periodic on Mast	51	254	98%	100%
WUSA (34)	Bowtie on Tripod	40	254	98%	90%
WUSA (34)	Silver Sensor on Tripod	14	254	93%*	57%*
WUSA (34)	Total for BT &SS onTripod	50	254	98%	86%
WRC(48)	Log Periodic on Mast	51	242	98%	98%
WRC(48)	Bowtie on Tripod	42	242	98%	86%
WRC(48)	Silver Sensor on Tripod	13	242	92%*	46%*
WRC(48)	Total for BT &SS onTripod	50	242	98%	84%

Table 2: Summary of FCC Preliminary Results

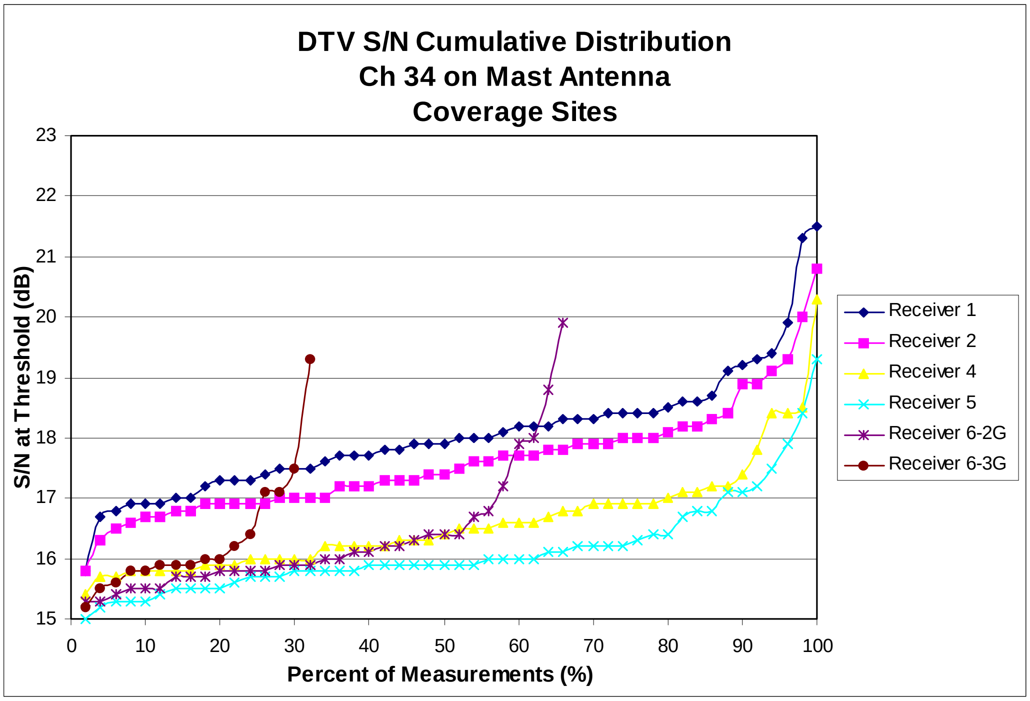

Figure 4: S/N at Threshold; Ch 34, Mast Antenna

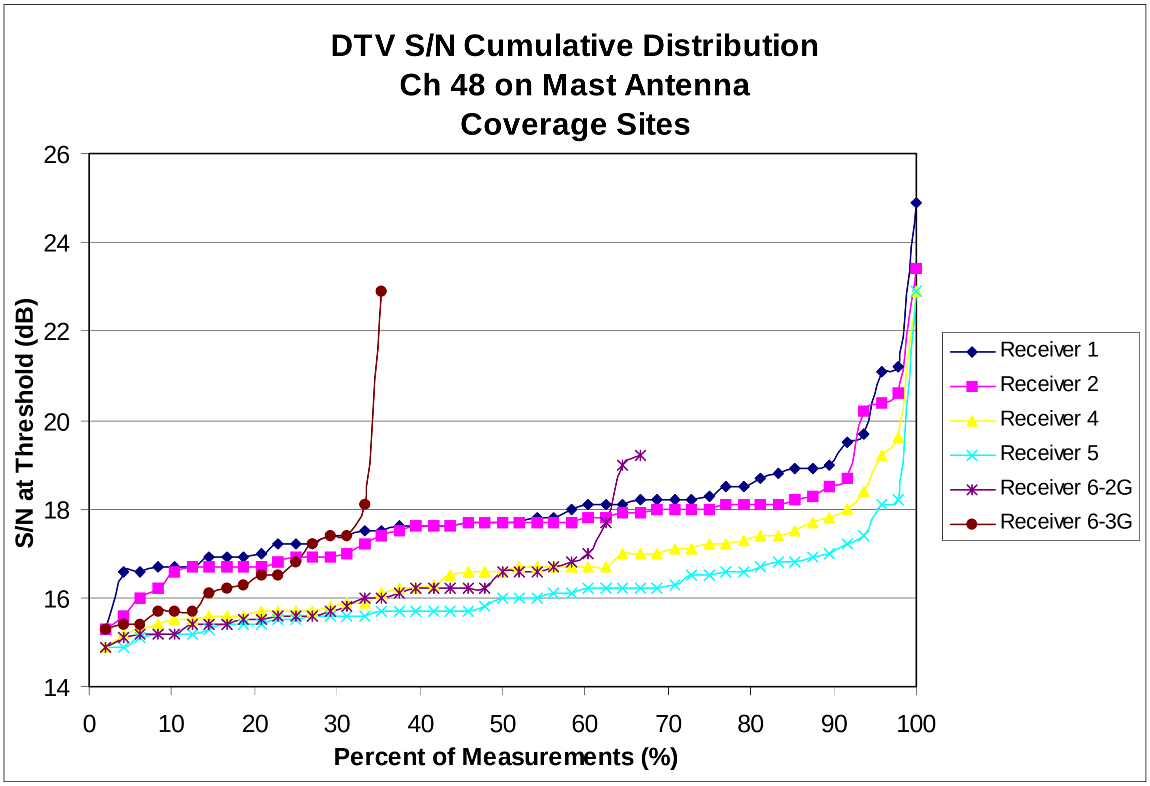

Figure 5: S/N at Threshold; Ch 48, Mast Antenna

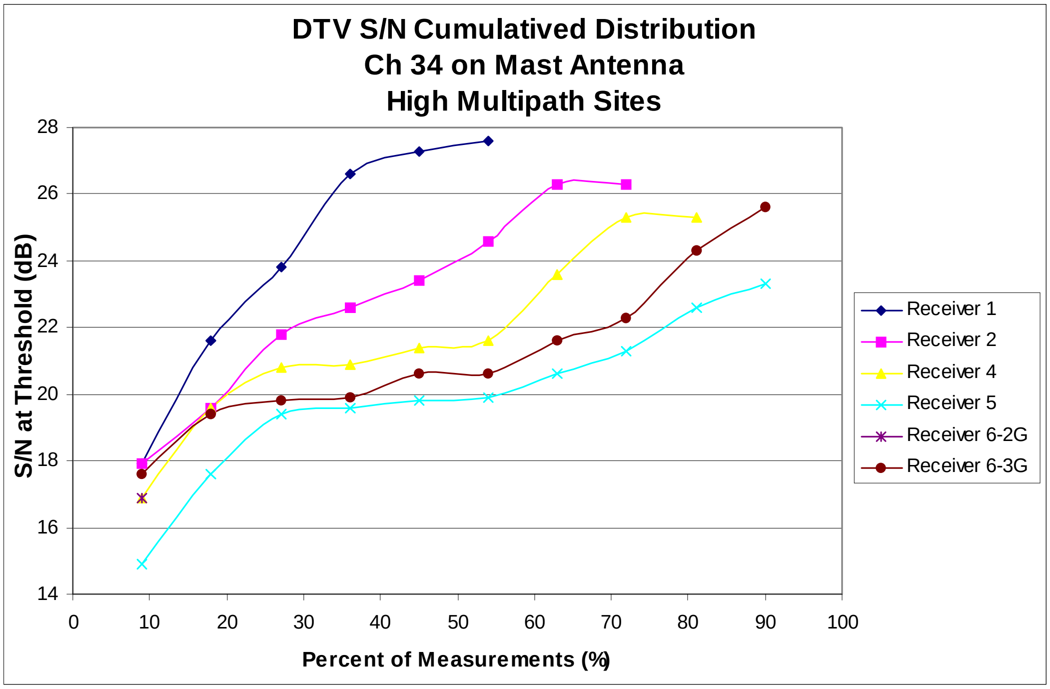

Figure 6: S/N at Threshold; Ch 34, Mast Antenna, High Multipath

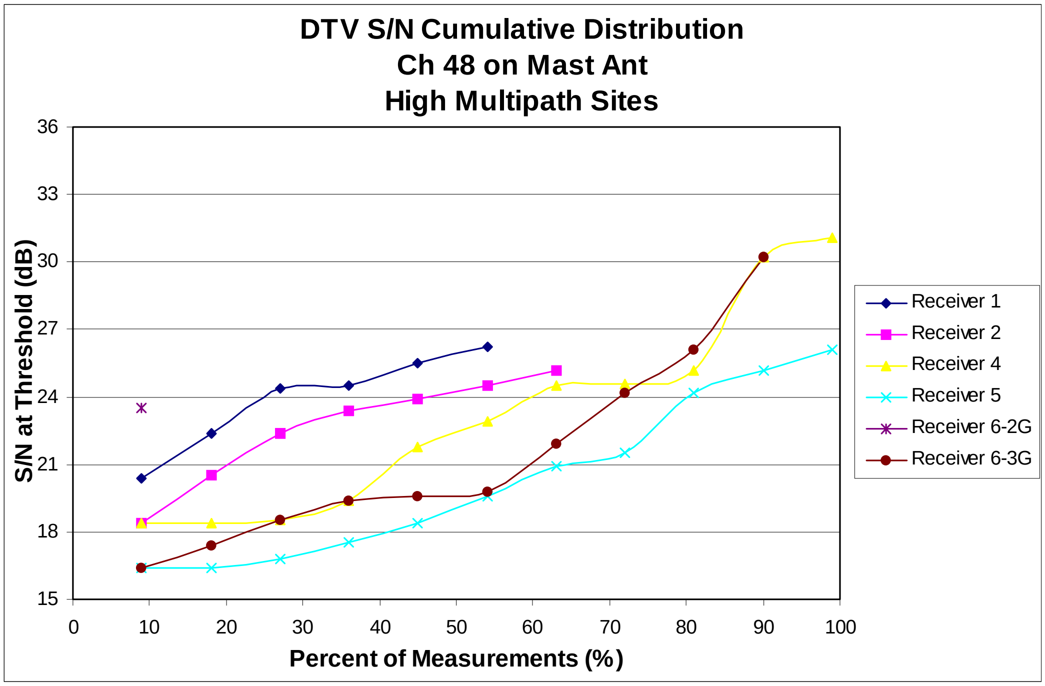

Figure 7: S/N at Threshold; Ch 48, Mast Antenna, High Multipath

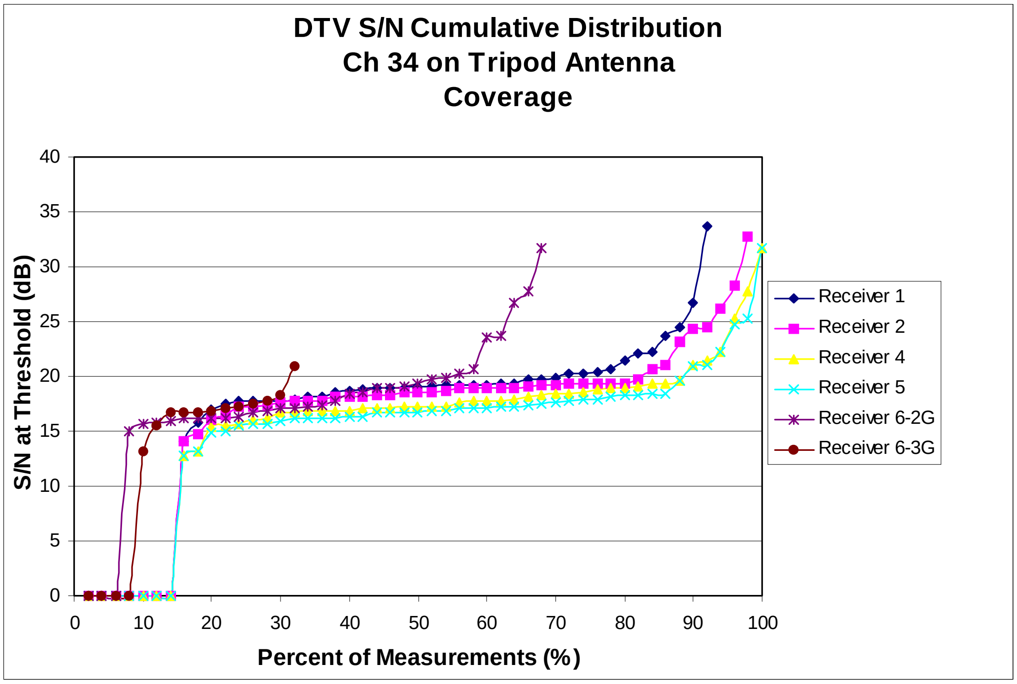

Figure 8: S/N at Threshold; Ch 34, Tripod Antenna

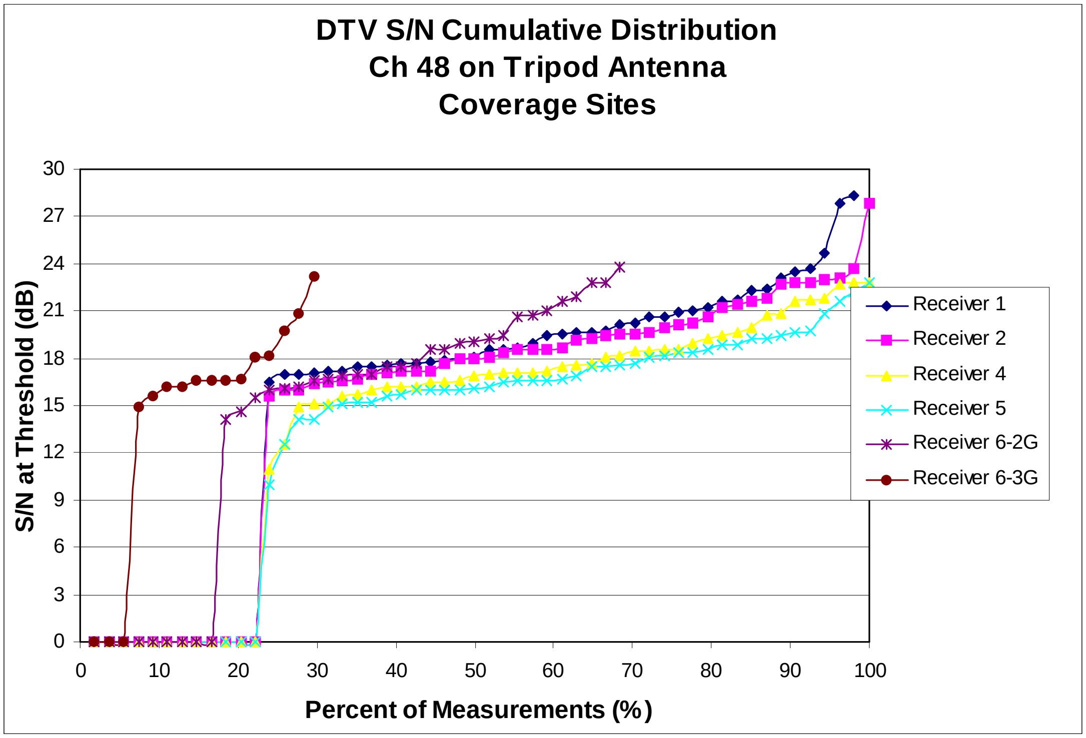

Figure 9: S/N at Threshold; Ch 48, Tripod Antenna

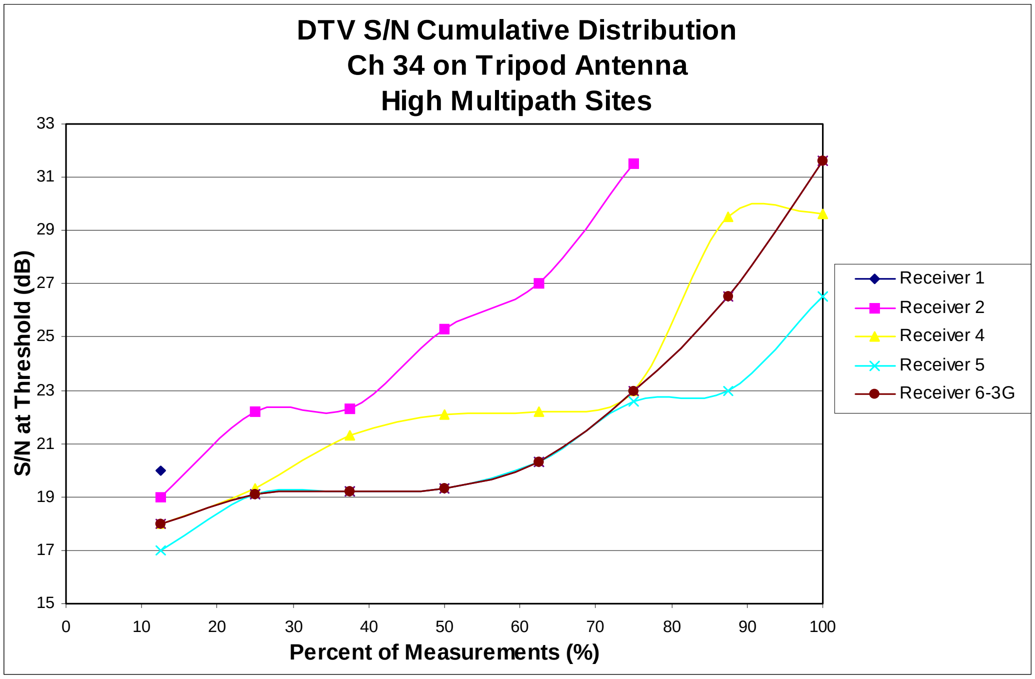

Figure 10: S/N at Threshold; Ch 34, Tripod Antenna, High Multipath

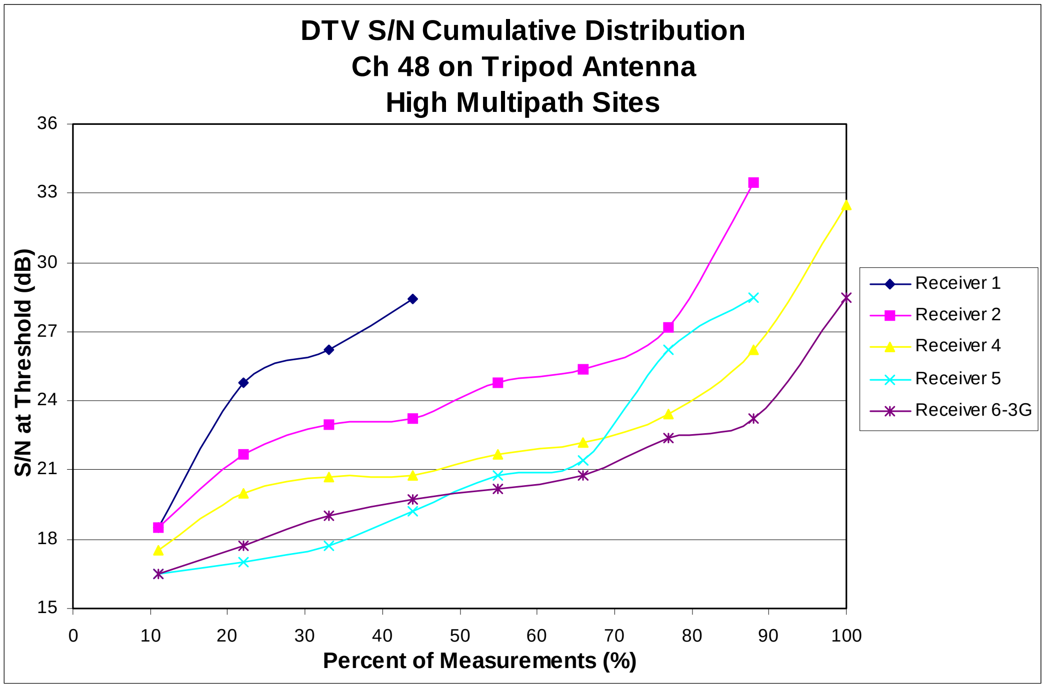

Figure 11: S/N at Threshold; Ch 48, Tripod Antenna, High Multipath

Appendix B: MSTV/NAB Test Results

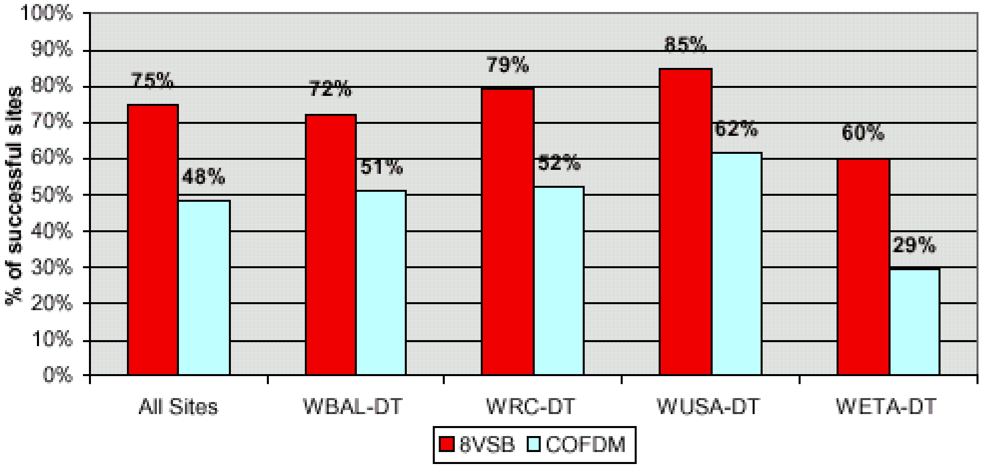

Figure 12: Washington/Baltimore Reception Statistics, 30 Foot Outdoor Antenna

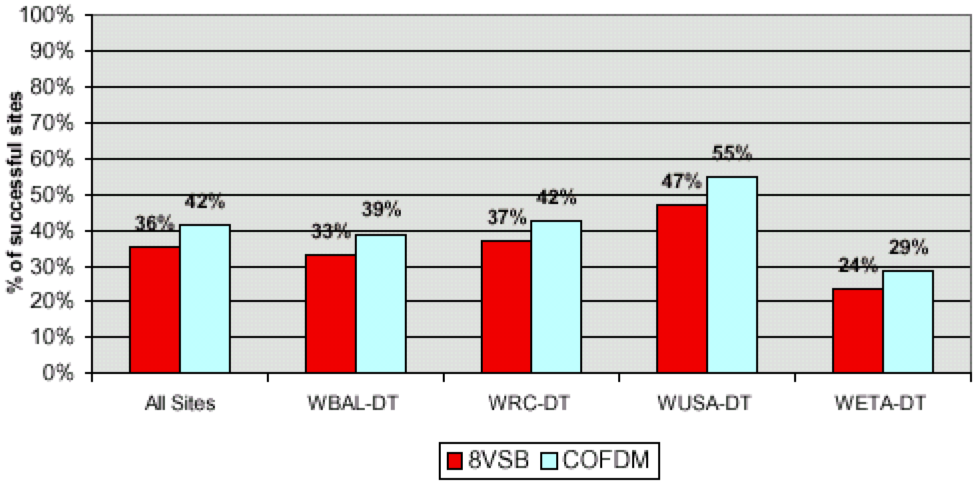

Figure 13: Washington/Baltimore Reception Statistics, 6 Foot Outdoor Antenna

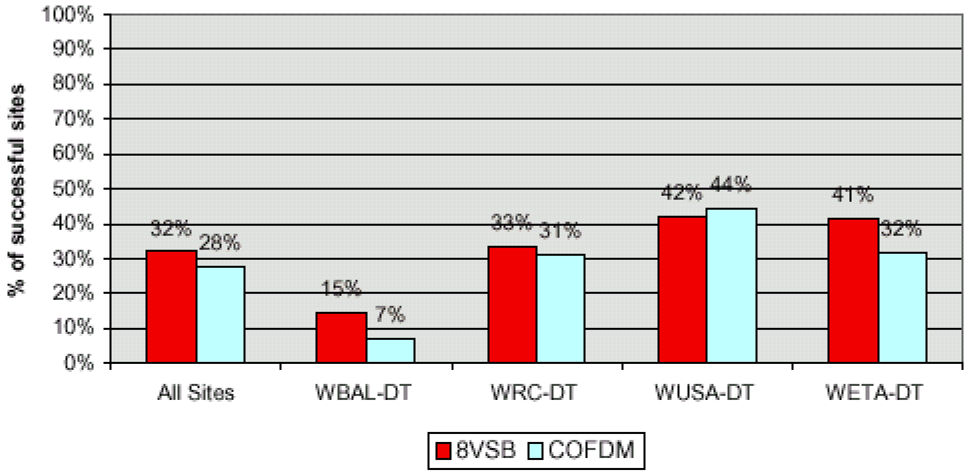

Figure 14: Washington/Baltimore Reception Statistics, Indoor UHF Directional Antenna

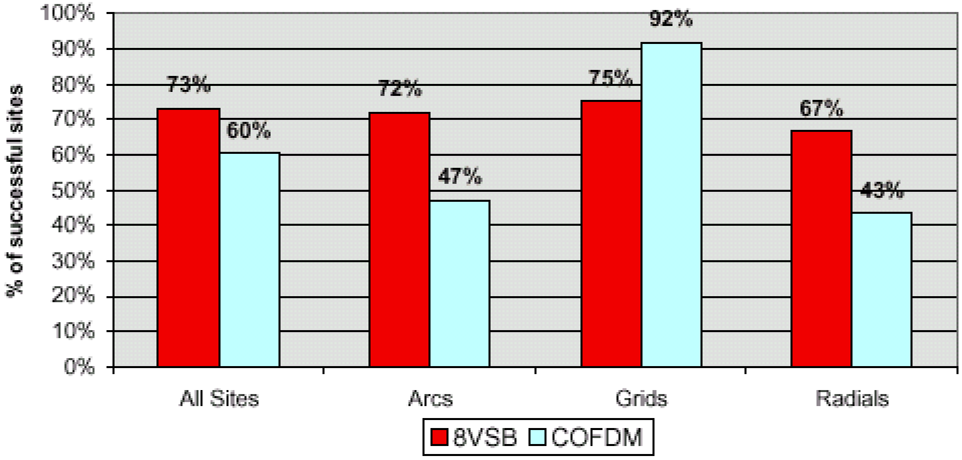

Figure 15: Cleveland Reception Statistics, 30 Foot Outdoor Antenna

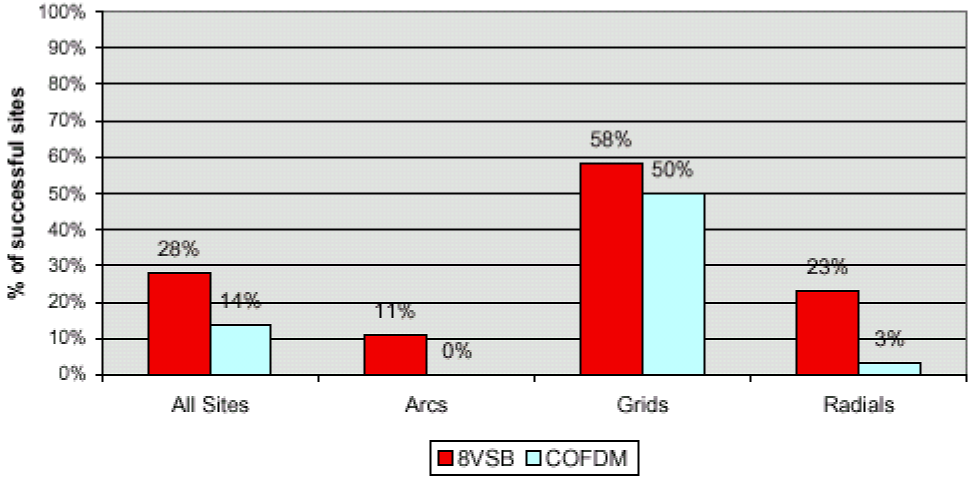

Figure 16: Cleveland Reception Statistics, 6 Foot Outdoor Antenna

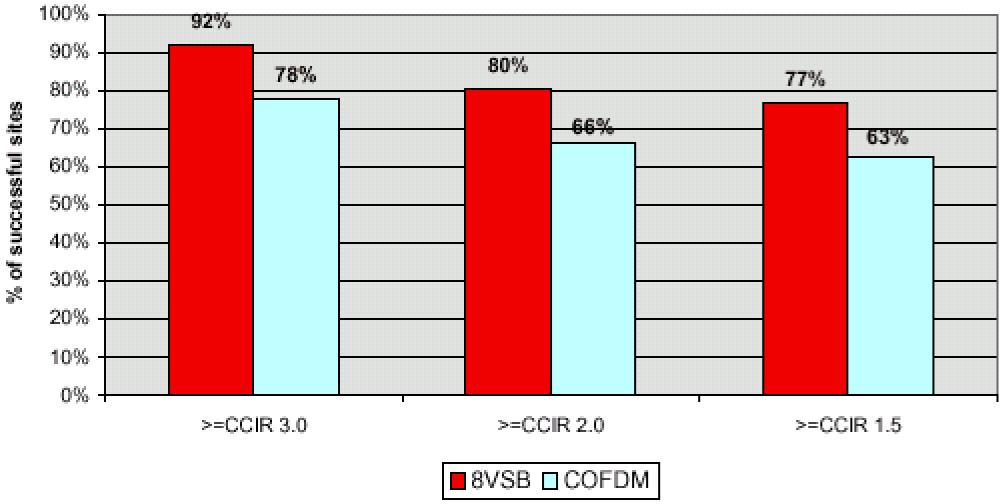

Figure 17: DTV Reception vs. NTSC Quality

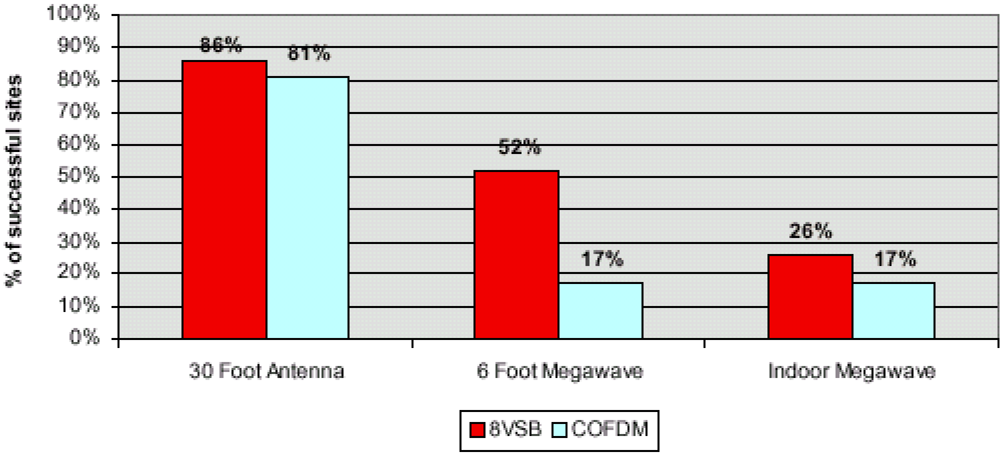

Figure 18: Cleveland Reception Statistics, Indoor VHF/UHF Antenna

Appendix C: CRC Test Results

Laboratory Tests

Confirmed multipath performance improvements in newer A/53 receivers.

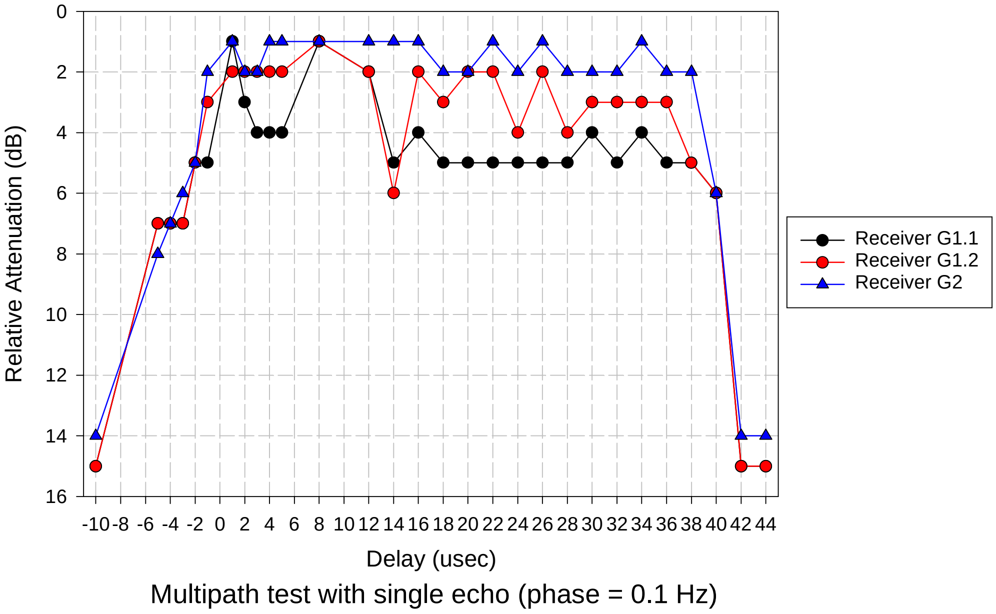

Figure 19: Quasi-Static Multipath Performance

Field Tests

Number of Sites	NTSC Rating	DTV Margin
22	4-4.5	>15 dB
9	3-3.5	>9dB
10	1-2.5	<9dB
1	2.5	16 dB
4	1-1.5	No DTV

Figure 20: DTV Outdoor Reception vs. NTSC Quality

	Active Antenna	Passive Antenna	NTSC Rating
Reliable DTV	25/43 (58%)	23/43 (53%)	1.5 to 4.5
Sensitive DTV	5/43 (12%)	2/43 (5%)	0.5 to 3
No DTV	13/43 (30%)	18/43 (42%)	0.5 to 3

Figure 21: DTV Indoor Reception vs. NTSC Quality

Appendix D: SET/ABERT Test Results

Laboratory Tests

DTV Into Analog TV Interference

The following table from SET/ABERT indicates the average protection ratios of A/53 DTV transmissions into PAL-M reception at ITU-R Grade 3 quality reception for co-channel, adjacent channel and “taboo” channel interference. These figures are generally applicable to NTSC reception, due to the close similarity between PAL-M and NTSC in all respects except the color encoding method.

The interference-free desired-to-undesired (D/U) ratio is the minimum ratio in dB between the power of the desired signal (PAL-M in these tests) and the power of the unwanted DTV signal; the lower the value, the more interference tolerated by the PAL-M receivers.

Table 3: DTV Into Analog TV Interference

Interference-Free D/U Ratios – ITU -R 3			
Interference		Frequency Off-Set (MHz)	Average Value of Interference -free Ratio (dB)
Interference Name	**Number of Channels Offset**		
Co-channel	0	0	32.34
Lower Adjacent	-1	-6	-12.71
Upper Adjacent	+1	+6	-13.19
Local Oscillator	-7	-42	-25.85
Local Oscillator	+7	+42	-25.94
IF Beat Frequency	-8	-48	-26.10
IF Beat Frequency	+8	+48	-26.69
Audio Image Frequency	+14	+84	-24.67
Video Image Frequency	+15	+90	-22.99

Analog TV Into DTV Interference

The following table from SET/ABERT indicates the average protection ratios of PAL-M transmissions into A/53 DTV receivers for co-channel, adjacent channel and “taboo” channel interference. These figures are also applicable to NTSC into DTV interference.

The interference-free ratio is the minimum ratio in dB between the power of the desired DTV signal and the power of the unwanted analog TV signal (PAL-M in these tests); the lower the value, the more interference tolerated by the DTV receivers. The criterion used for degradation of DTV reception was a BER of $3x10^{-6}$ measured at the MPEG-2 Transport Stream output. This is the commonly accepted Threshold Of Visibility (TOV) error rate criterion that has been in use since the ACATS process.

Table 4: Analog TV Into DTV Interference

PAL-M System Interference on the Digital Systems Co-channel and Upper and Lower Adjacent Channels			
Interference	Audio	Chip P	Chip T
Co-channel	Stereo	5.45	7.03
Lower Adj.	Mono	-33.30	-33.28
Lower Adj.	Stereo	-33.30	-33.54
Lower Adj.	Stereo +SAP	-32.70	-32.08
Upper Adj.	Stereo	-40.00	-37.84

DTV Into DTV Interference

The following table from SET/ABERT indicates the protection ratios of A/53 DTV into DTV for co-channel, adjacent channel and “taboo” channel interference.

The interference-free ratio is the minimum ratio in dB between the power of the desired DTV signal and the power of the undesired DTV signal; the lower the value, the more interference tolerated. The criterion used for degradation of DTV reception was a BER of $3x10^{-6}$ measured at the MPEG-2 Transport Stream output.

Table 5: DTV Into DTV Interference

Interference between Digital Systems Conditions: Co-channel and Upper and Lower Channels		
Interference	Chip P	Chip T
Co-channel	15.0	15.1
Adjacent Lower	-27.0	-27.7
Adjacent Upper	-27.0	-28.1

Resistance To Impulse Noise

There are no standardized laboratory procedures for generating impulse noise. It is, however, generally recognized that impulse noise from electrical appliances, auto ignitions, and electrical transmission lines is characterized by bursts of high energy, short duration impulses, and that these bursts are often periodic.

In the SET/ABERT tests, impulse noise was simulated in the laboratory by adding gated white noise to the desired DTV signal. The amplitude of the noise, the duration of the gating window and the frequency of repetition of the gate were adjustable parameters. The repetition rate was increased from 12.5 Hz to 100 Hz and back to 12.5 Hz during a 30 second measurement cycle.

The interference is measured by assessing the Carrier/Noise Equivalent (C/Neq) parameter, which is the ratio in dB between the power of the desired signal and the power of the equivalent noise signal without the gating window; the lower the value, the better the DTV receiver tolerates the interference.

Two criteria were used to evaluate performance. Criteria 1 had a constant DTV signal level steady and constant window length. The amplitude of the noise within the window was increased until the system threshold was reached, determined by the TOV error rate of $3x10^{-6}$, for a test duration of two minutes. Criteria 2 had a constant DTV signal level steady and constant noise amplitude, set at 5 dB above the average DTV signal level. The width of the gating window was increased until the TOV error rate was reached.

Using these criteria, the following results were obtained for various A/53 receivers.

Table 6: Resistance To Impulse Noise – Criterion 1

	Resistance to Impulse Noise (C/Neq) – Criterion 1									
Window size (μs)	50	100	200	300	400	500	600	700	800	900
ATSC- Chip P	-20.1	-12.9	-0.9	1.0	1.5	1.8	2.1	2.3	2.5	2.6
ATSC – Chip T	-12.8	-10.0	-1.5	0.8	1.3	1.7	1.9	2.0	2.2	2.3
ATSC - Chip S	NF	-11.4*	-1.6	0.9	1.6	1.9	2.1	2.3	2.4	2.5
ATSC - Chip A[1]	-20.1	-10.4	-1.8	0.9	1.5	1.9	2.1	2.3	2.5	2.6

*Window value: 120µs

[1] The ATSC Chip U performed similarly to Chip A.

Table 7: Resistance To Impulse Noise – Criterion 2

Criterion 2	
System and Configuration	**Window Size (µs)**
ATSC - Chip P	160
ATSC - Chip T	160
ATSC - Chip S	170
ATSC - Chip A	170
ATSC - Chip U	175

Static Multipath Interference

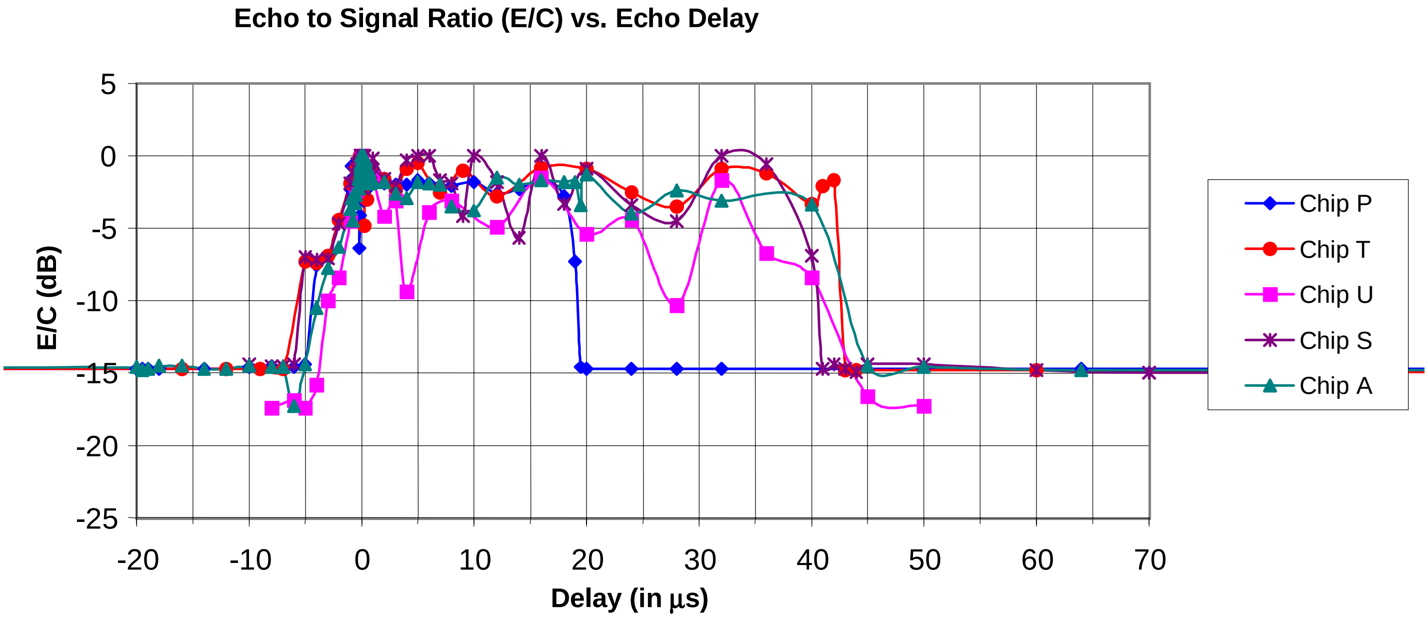

Figure 22: Static Multipath Interference – E/C vs. Echo Delay

The SET/ABERT test procedures included extensive testing of DTV receiver performance in static multipath environments. The laboratory tests included single echo tests and ensemble echo tests. The ensembles are limited to a total of six paths, as is usually the case in tests performed in U.S. labs. The SET/ABERT tests, however, included multipath ensembles that were intended to represent severe Ricean to Rayleigh channel conditions, as may be found in certain indoor reception environments.

The graph of single echo to signal vs. echo delay reveals some of the differences in the latest 8-VSB receiver chips relative to the Chip P baseline. The newer chips have an equalizer post-echo span of at least 40 µs, although the pre-echo span is still limited to 5 µs or less. The newer chips exhibit more variability in the maximum tolerable echo amplitude, depending upon the echo delay, but demonstrate an ability to tolerate stronger echoes at particular delays. Note that one of the new chips is able to tolerate 0 dB echoes at certain delays.

The “noise penalty” of multipath cancellation was also measured by SET/ABERT for single pre-echoes and single post-echoes. The data for the Chip P receiver and one of the new chips is presented in the following graphs.

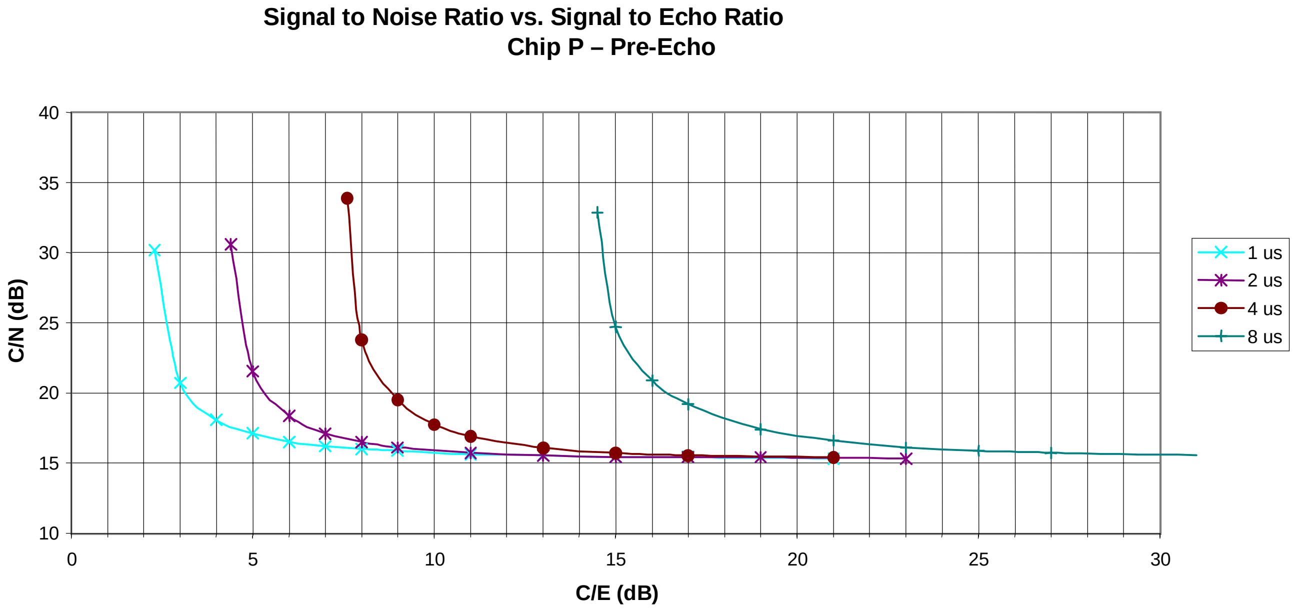

Figure 23: Static Multipath Interference – C/N vs. C/E (Chip P Pre-Echo)

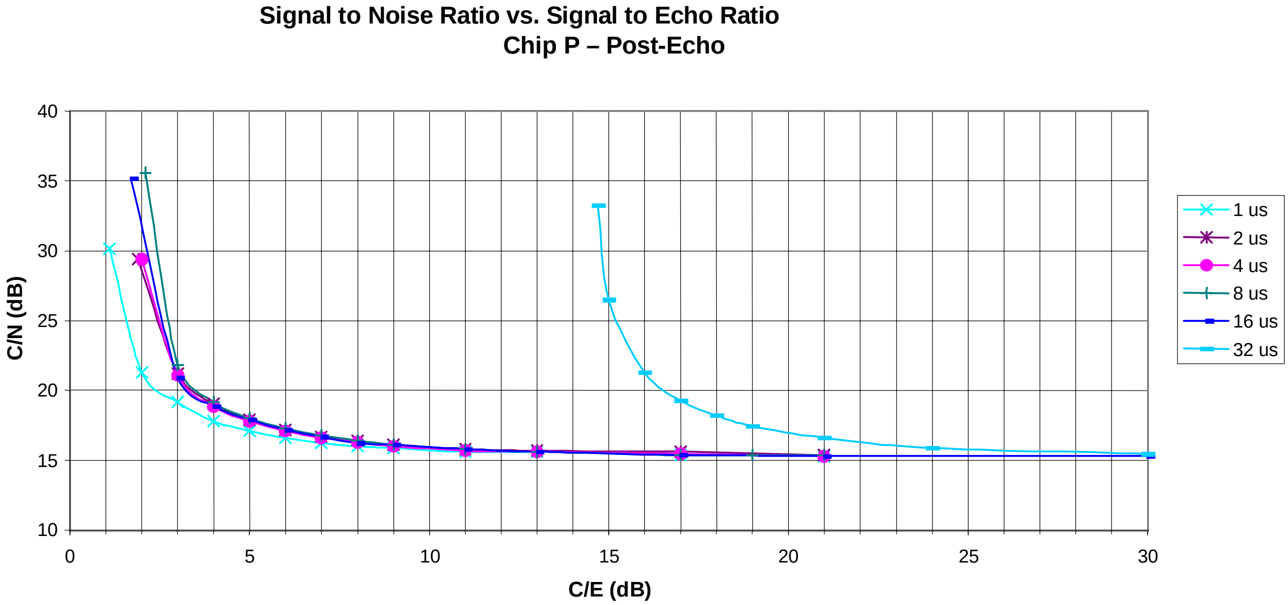

Figure 24: Static Multipath Interference – C/N vs. C/E (Chip P Post-Echo)

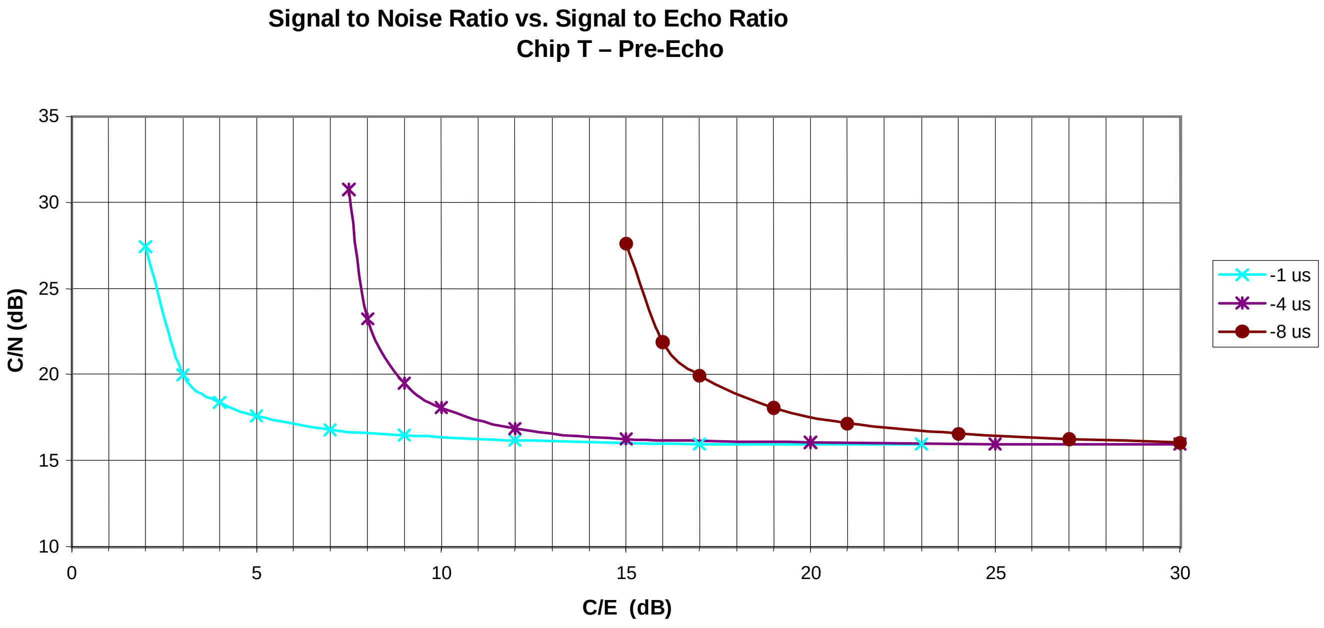

Figure 25: Static Multipath Interference – C/N vs. C/E (Chip T Pre-Echo)

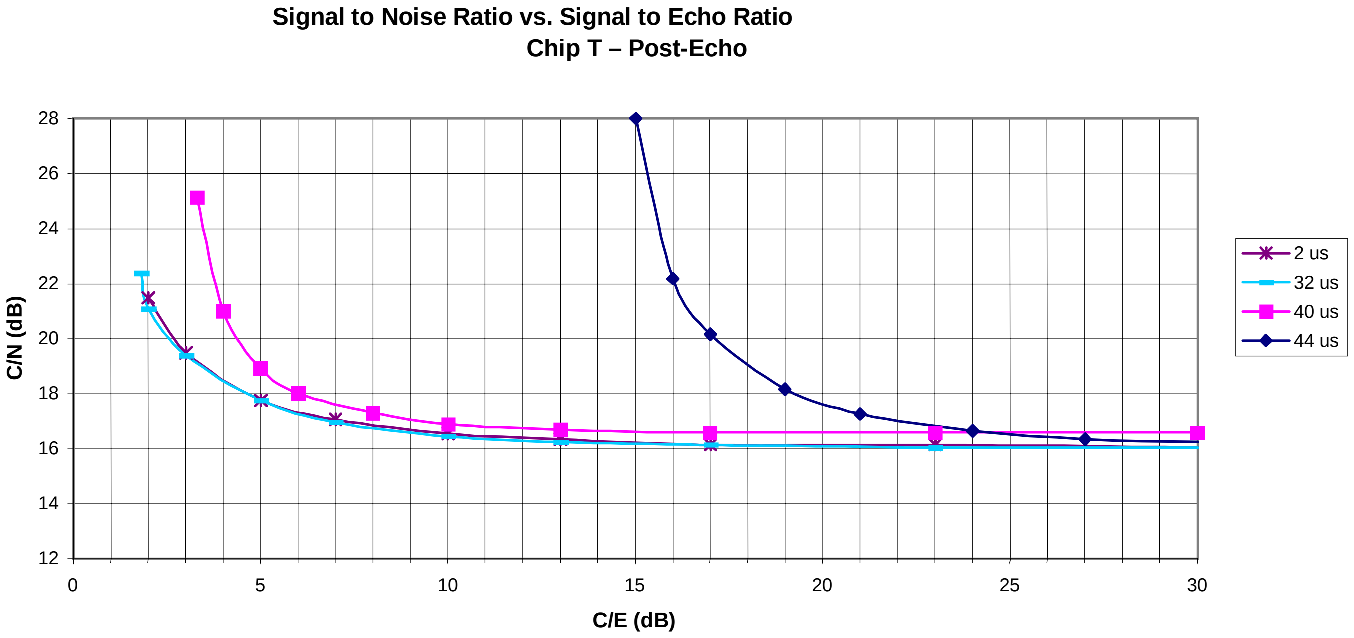

Figure 26: Static Multipath Interference – C/N vs. C/E (Chip T Post-Echo)

For the multipath ensemble tests, SET/ABERT defined the following ensembles.

Table 8: Static Multipath Channel A

Channel A	Signal	Relative Amplitude	Amplitude (dB)	Delay (μs)
E	0	1.0	0.0	0.00
C	1	0.2045	-13.8	0.15
H	2	0.1548	-16.2	2.22
O	3	0.1790	-14.9	3.05
E	4	0.2078	-13.6	5.86
S	5	0.1509	-16.4	5.93

Table 9: Static Multipath Channel B

Channel B	Signal	Relative Amplitude	Amplitude (dB)	Delay (μs)
E	0	1.0000	0.0	0.00
C	1	0.2512	-12.0	0.30
H	2	0.6310	-4.0	3.50
O	3	0.4467	-7.0	4.40
E	4	0.1778	-15.0	9.50
S	5	0.0794	-22.0	12.70

Table 10: Static Multipath Channel C

Channel C	Signal	Relative Amplitude	Amplitude (dB)	Delay (μs)
E	0	0.7263	-2.8	0.000
C	1	1.0000	0.0	0.089
H	2	0.6457	-3.8	0.419
O	3	0.9848	-0.1	1.506
E	4	0.7456	-2.5	2.322
S	5	0.8616	-1.3	2.799

Table 11: Static Multipath Channel D

Channel D	Signal	Relative Amplitude	Amplitude (dB)	Delay (μs)
E	0	0.9846	-0.1	0.15
C	1	0.6456	-3.8	0.63
H	2	0.7453	-2.6	2.22
O	3	0.8613	-1.3	3.05
E	4	1.0000	0.0	5.86
S	5	0.7265	-2.8	5.93

Table 12: Static Multipath Channel SFN

Channel SFN	Signal	Relative Amplitude	Amplitude (dB)	Delay (μs)
ECHOES	0	1.0000	0.0	0.00
	1	1.0000	0.0	1.00
	2	1.0000	0.0	2.00

No attempt is made to assess the relative occurrence of each type of channel in the real world, but the channels can be loosely described as follows:

Channel A represents an outdoor rooftop antenna or attic-mounted indoor antenna channel. It has a Ricean K-factor of 6.11.

Channel B is based on a data capture from a set-top antenna in a Baltimore, MD apartment and has a Ricean K-factor of 1.43.

Channel C represents a Rayleigh faded indoor channel with primarily post-echoes. This channel has a Ricean K-factor of 0.31.

Channel D represents a Rayleigh faded indoor channel with primarily pre-echoes. This channel also has a Ricean K-factor of 0.31.

Channel SFN represents an idealized model of a three transmitter single frequency network. In this model, equal power signals are received from each transmitter within a delay spread of 2 microseconds. This channel has a Ricean K-factor of 0.50.

By comparison, the Grand Alliance ensembles A-G each has a Ricean K-factor of 5.69 – slightly more echo energy than Channel A in the SET/ABERT tests.

Of the A/53 receivers tested, all were successful in receiving the Channel A ensemble and none could receive any of the other ensembles. The Chip P receiver had the lowest C/N threshold for receiving Channel A, 15.8 dB. The newer receivers all required at least an additional 1 dB to receive Channel A.

Of the five multipath ensembles in the SET/ABERT tests, only one had echo delays which exceeded the range of the equalizers in the A/53 receivers tested. This was Channel D, which had long pre-echoes.

Dynamic Multipath Interference

The SET/ABERT tests also examined the effect of Doppler shift on maximum echo amplitude tolerance of a single echo. In the real world, echoes will be subject to Doppler shifts when they are reflected off of moving objects. The non-symmetrical results for positive and negative Doppler are unexplained and are thought to be an artifact of the test procedure. It has been tested for Chip T that the more positive result is correct for both negative and positive Doppler.

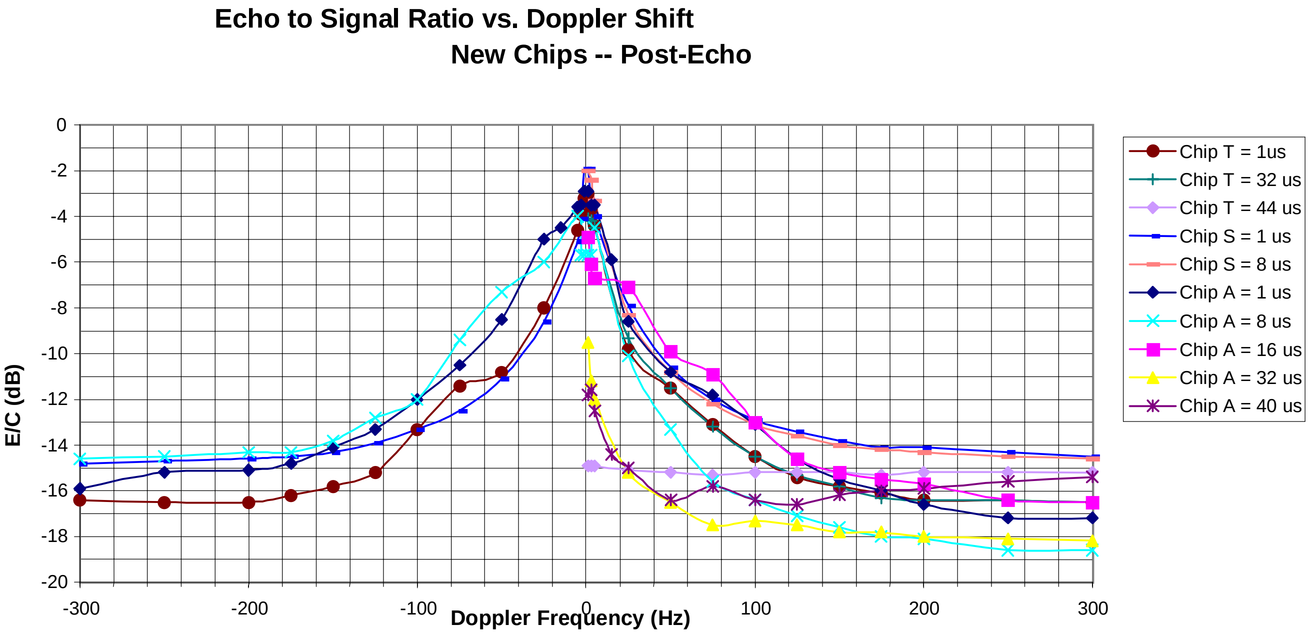

Figure 27: Dynamic Multipath Interference – E/C vs. Doppler Shift (New Chips, Post-Echo)

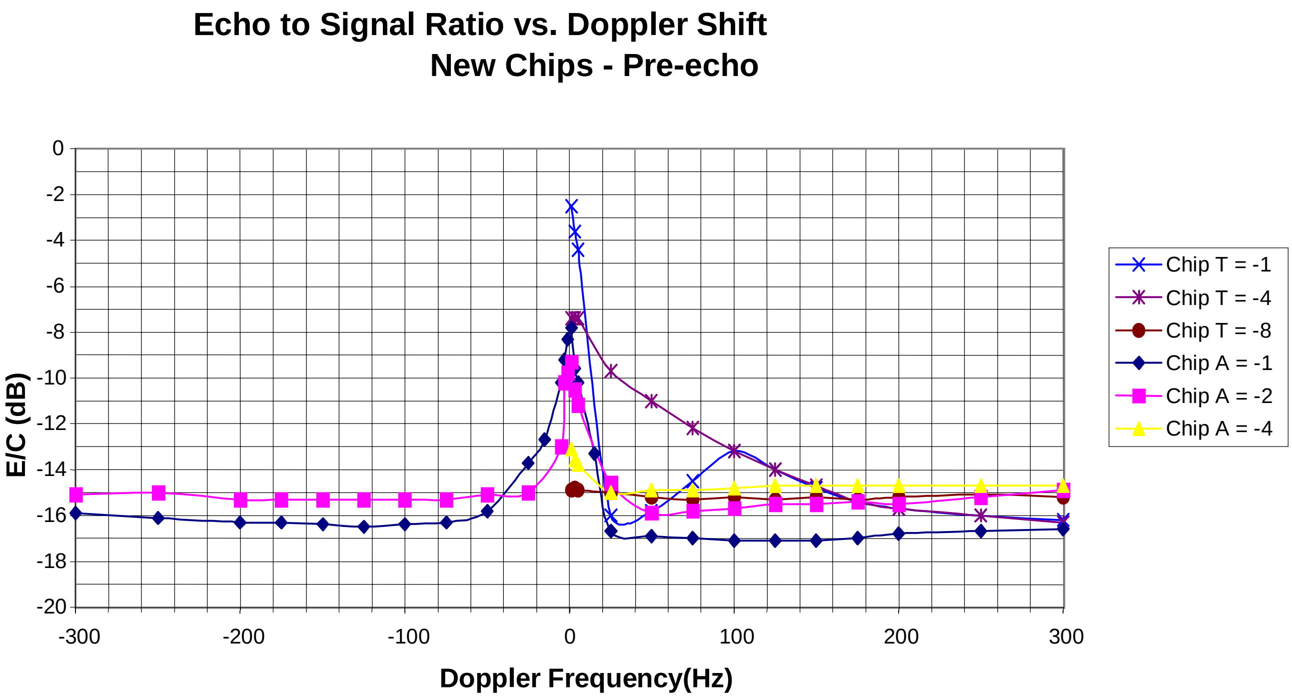

Figure 28: Dynamic Multipath Interference – E/C vs. Doppler Shift (New Chips, Pre-Echo)

Receiver Sensitivity and Dynamic Range

The SET/ABERT tests and various tests in the U.S. have demonstrated some degree of variability in receiver sensitivity and dynamic range. In general, consumer DTV receivers are capable of reception in Gaussian noise channels at RF input levels below –80 dBm.

The maximum RF input level for which consumer DTV receivers achieve reception has been measured to be greater than 0 dBm for a variety of receivers with which the group is familiar. These results were obtained from the tests of various manufacturers. Maximum RF input level was not tested by SET/ABERT.

Gaussian Noise C/N Threshold

The C/N threshold for reliable reception in Gaussian noise is an important parameter for assessing receiver optimization and degradation induced by various sources within the link. It also, of course, is a primary factor in determining signal “coverage,” although not necessarily “receivability.”

The theoretical C/N threshold for the A/53 transmission system has previously been simulated to be 14.8 dB. The value of 15.0 dB is frequently reported as a practical limit, allowing 0.2 dB implementation loss due to non-idealities in the transmitter and receiver. The SET/ABERT tests measured a C/N threshold of 14.5 dB for the Chip P receiver, based on the TOV BER criterion of $3x10^{-6}$. One member of the Task Force notes that his company’s private 8-VSB receiver tests also demonstrated a C/N threshold of 14.5 dB is achievable[13].

---

[13] Private communication from Frank Eory

Some of the prototype receivers tested by SET/ABERT were within 0.2 to 0.3 dB of the Chip P receiver, which implies that a threshold of 15.0 dB is achievable in consumer DTV receivers without requiring ‘extraordinary’ measures.

Appendix E: Ricean and Rayleigh Fading Models

Ricean Fading

RF propagation at typical DTV transmitter antenna heights and with rooftop or attic-mounted receiver antennas frequently can be characterized by Ricean fading. The Ricean model for RF propagation is characterized by a dominant path, due to the presence of a line-of-sight or nearly line of sight path between the transmitting and the receiving antenna. Ricean fading is described by the following equation:

$$y(t) = \frac{\rho_0 x(t) + \sum_{i=1}^{N} \rho_i e^{-j\theta_i} x(t - \tau_i)}{\sqrt{\sum_{i=0}^{N} \rho_i^2}}$$

Equation 1 : Ricean Fading

Where:

ρ_0 represents the attenuation of the dominant path, where $\rho_0 > \rho_l$ for i=1,2,…n. ρ_i represents the attenuation of the i^{th} echo path

N is the total number of echoes

θ_i represents the phase shift of the ith path relative to the dominant path

τ_i represents the delay shift of the ith path relative to the dominant path, τ_l

x(t) represents the transmitted signal

y(t) represents the received signal

Note that pre-echoes may be accommodated by including negative values of τ_i, the delay.

A Ricean K-factor can be defined as the ratio of the power in the dominant path to the total power of all the echo paths, as follows:

$$K = \frac{\rho_0^{\ 2}}{\sum_{i=1}^{N} \rho_i^2}$$

Equation 2: Ricean K-Factor

Rayleigh Fading

When K approaches zero, the channel is said to have a Rayleigh fading characteristic. The most salient distinction between the Ricean (K > 0) channel and the Rayleigh channel is that the Rayleigh channel has no dominant path. The Rayleigh fading channel is mathematically described as follows:

$$y(t) = \frac{\sum_{i=1}^{N} \rho_i e^{-j\theta_i} x(t - \tau_i)}{\sqrt{\sum_{i=1}^{N} \rho_i^2}}$$

Equation 3: Rayleigh Fading

Where τ_i can assume positive or negative values.

Ongoing DTV field tests and existing RF propagation studies reveal that some indoor reception environments and most mobile reception environments can be characterized by Rayleigh fading. Real-world channels are generally characterized by 'dynamic multipath,' in which ρ_i , θ_i or τ_i are functions of time and depend upon the relative motion between the receiver and environmental obstacles that can reflect, diffract or scatter the RF signal.

Appendix F: Set-Top Antenna Performance

In reviewing the accompanying antenna plots and data, the performance differences are apparent. Units A and B are typical of those included with 20” or smaller NTSC receivers. The gain is less than that of a resonant dipole, there is little directivity and the VSWR is poor. Units C and D offer some improvement in gain, a unidirectional pattern and better VSWR. Unit E offers further improvements in gain, directivity and VSWR while maintaining a small (12x12x6”) size. In addition, a moderate gain amplifier can be incorporated to improve VSWR and also overcome the insertion loss of the downlead or of a VCR.

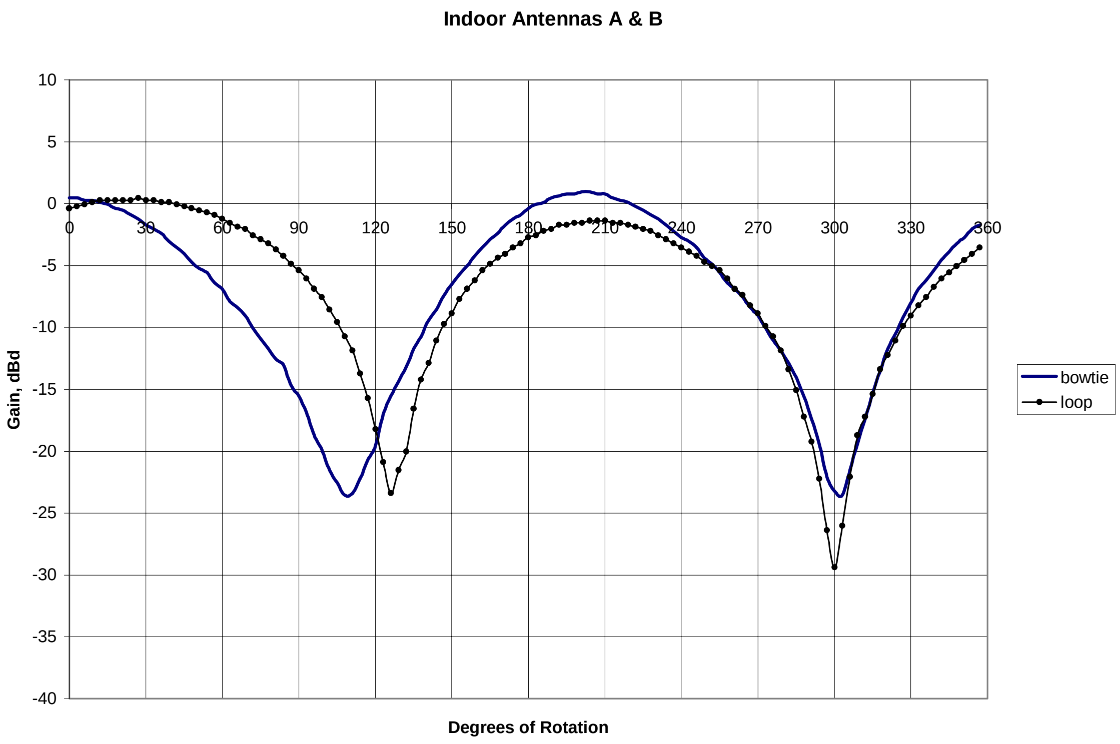

Figure 29: Indoor Antennas A & B Gain

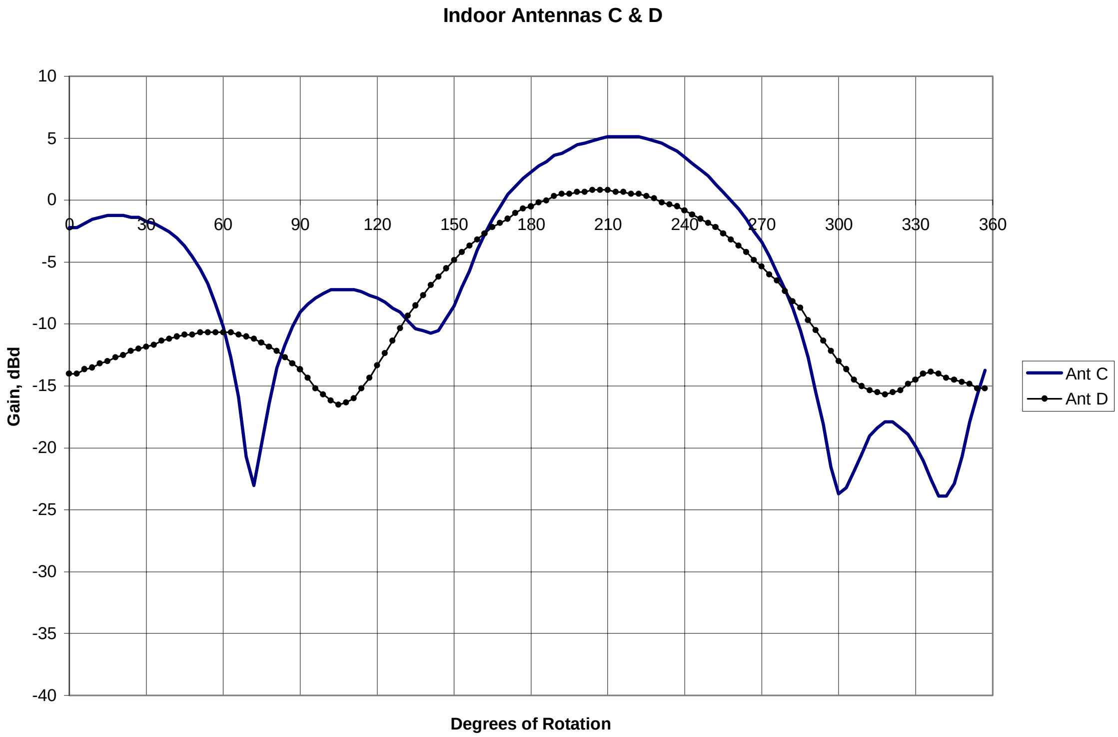

Figure 30: Indoor Antennas C & D Gain

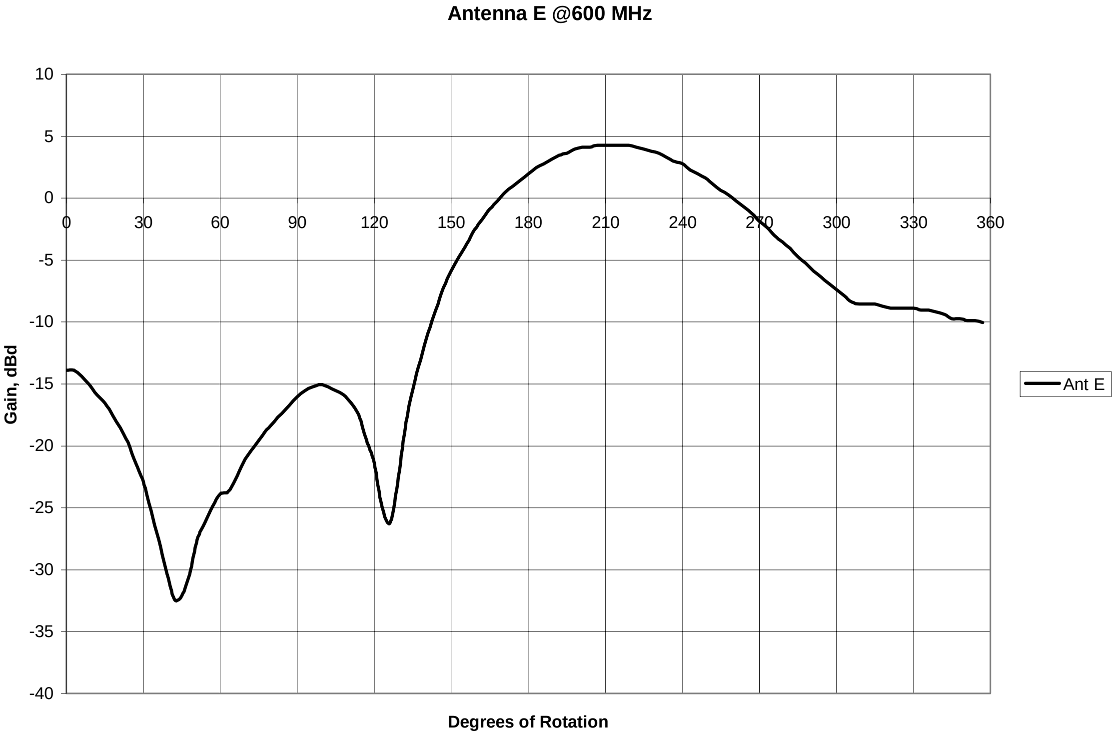

Figure 31: Indoor Antenna E Gain

Table 13: Indoor Antenna VSWR vs. Frequency

Antenna	480 MHz	520 MHz	600 MHz	652MHz	704 MHz	796 MHz
Bowtie A	3.5 : 1	3.5	3.2	2.8	2.0	1.3
Loop B	5.9	4.2	4.9	.1	2.6	11
C	8.6	6.7	2.6	1.4	1.7	3.0
D	2.7	2.7	3.6	3.6	4.2	2.9
E	1.5	2.2	2.2	2.1	2.0	2.6

Earlier measurements of 61 indoor and outdoor consumer antennas show an even larger variation in VSWR [24].

Table 14: Indoor and Outdoor Antenna VSWR Summary

Max. VSWR	Number of Antennas
2	22
2 to 3	20
3 to 4	10
4 to 5	6
5 to 10	3

Appendix G: DTV Coverage and Service Prediction, Measurement and Performance Indices

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The intent of this memo is to outline potential improvements in the modeling, methods and procedures now in use for prediction and measurement of DTV service. It is also the intent of this memo to serve as the basis for further discussion by specialist groups within the ATSC.

The need to review the methods and procedures now in use is highlighted by the various field tests conducted in the US and elsewhere. It is now clear that methods used to predict the replication of NTSC service were idealized and, for the most part, not validated.

In the US, the ATSC is the only organization presently in a position to effectively direct and moderate the discussion relative to the wireless transmission and reception of DTV.

Subjects for reassessment and potential improvements are:

Threshold SNR[14]

Threshold SNR of 15.2 dB, achieved in a laboratory for an AWGN channel, is a benchmark that cannot generally be realized with consumer-grade receivers operating in real-world conditions. Channels with multipath distortion and/or interference will require higher SNR threshold level.

For example, the FCC coverage prediction stipulates that the DTV receiver will provide service at a signal level as low as –84 dBm with SNR=15.2 dB. Such capability has not been demonstrated even for an AWGN channel, much less for real-world channels. In fact, the noise floor of the test setups being used in field tests may have been higher than –84 dBm. The consumer-grade receiver minimum signal level is rated <-78 dBm.

An implementation margin is needed for realistic predictions of coverage and service.

Propagation Loss and Statistics

Calculations show that the LR (Longley-Rice) model predicts coverage well beyond the Radio Horizon and well beyond the NTSC contours for receivers with an outdoor antenna 30’ HAG. This observation is borne out by calculations for TV stations in flat and mountainous terrain and for UHF and VHF channels.

Analysis of data collected in Washington DC (WHD) and in New York (WCBS) have confirmed the observation that the available signal may be significantly below that predicted especially within the predicted coverage area.

Even a less reliable prediction can be expected from the Longley-Rice model for an outdoor antenna 6’ HAG. In fact, the commonly assumed loss due to antenna height reduction is 20Log[6/30]=-14dB.

The LR model allows for adjustable parameters such as ground clutter, percent confidence level and percentage of time/location availability. At present, ground clutter is not included, the confidence level was set at 50% and the time/location availability is set at 90/50. The values of these parameters would be

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[14] The authors recognize that some prefer the acronym CNR (or C/N) when referenced to the input of the receiver and SNR (or S/N) when referenced to the output of the equalizer. In this paper, SNR will be used throughout because the classic “carrier” is missing in 8-VSB modulation. Consideration should be given to using the nomenclature $S/N]_{BB}$ at baseband and $S/N]_{RF}$ at RF in the future.

adjusted as part of the validation process. The problem is that the model has not been validated for TV broadcasting: not for coverage or service, either inside the Radio Horizon or beyond the Radio Horizon.

Receiver/Antenna Model for Coverage Planning

A realistic model would include the effect of impedance mismatch between the antenna and the input to the receiver. The mismatch results in lower antenna gain, added signal loss, change in the receiver's Noise Figure[15] and in added equalization loss. Preliminary calculations indicate that the overall effect may be a significant and unaccounted-for loss in the SNR margin is shown in Addendum B.

A realistic model should be based on proper characterization of the noise level. For outdoor antennas, and especially in the VHF range, sky temperature is the predominant source of noise[16] in the absence of man-made noise. At present, the assumed source of noise is thermal shot noise at room temperature. Because the maximum sky temperature at channel 2 is close to 30,000^{0}K, the assumption of thermal noise at room temperature (290^{0}K) would result in gross underestimation of the required minimum signal level as shown in Addendum A.

Although setting the ideal receiver's performance in an AWGN channel is a valuable benchmark, such benchmark is of limited use for practical service planning. With a realistic model, the Threshold SNR may not be 15.2 dB and the minimum detectable signal would be significantly higher than called for in current specifications.

It is of interest to note that complete characterization and calibration of receivers for real-world testing has not been made available. For example, the Effective Noise Figure and Threshold SNR at input levels below –68 dBm are unknowns. The field test method now in use is based on an equipment setup that does not simulate the receiver called-for by the FCC or any available consumer-grade receivers.

Clearly the practical modeling of receivers for outdoor, indoor, pedestrian and mobile applications is desirable.

Minimum Signal Level

Field tests, including the MSTV's VSB/COFDM Project, have shown that the minimum decodable signal levels are well above those planned for. In the UHF band, that "field strength" level is near 50 dBu compared with the specified value of 41 dBu. For VHF channel 2, that "field strength" is at least 40 dBu compared with the specified value of 28 dBu.

The discrepancy has not been explained. In the UHF band the discrepancy is probably due to a combination of incorrect Threshold SNR, impedance mismatches between the antenna and the receiver's input and error in calculating the "field strength." In the VHF band, the missing sky temperature factor would be an additional contributor to the discrepancies cited.

Field Test Sampling Statistics

Proper statistical sampling is a prerequisite if the data are to be validly projected as representative of the area in question. For coverage estimation, the sample should be representative of the predicted service contour area. For service estimation, the sample should be representative of the population inside the F(50,90) contour.

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[15] The specified Noise Figure is based on measurement with a noise source whose input resistance is constant, either 50Ω or 75Ω. The actual Noise Figure will vary with the source's impedance.

[16] The effect of man-made obstructions on indoor antennas has not been quantified.

For example, testing at 10 indoor locations in downtown NYC, with successful (100%) reception, is of little value to broadcasters. Similarly, testing at 100 outdoor locations in the suburbs, with successful (100%) reception, cannot serve as a basis for coverage or service determination.

For coverage estimation, the sample must be weighted for (separate) areas inside and beyond the Radio Horizon bounded by the predicted service contour.

For service estimation, the sample must be weighted for (separate) populations inside and (separate) population beyond the Radio Horizon. At least inside the Radio Horizon, the sample should be representative of (separate) metropolitan, suburban and rural populations.

Field Test Setup

In all documented measurements to date, the "White Noise Added" technique was used. This masks the effect of the impedance mismatch between the antenna and tuner and entirely masks the receiver's Noise Figure. This technique would also mask the Sky Noise present at VHF.

The AWGN noise injected at all locations to determine the SNR margin is not representative of real-world propagation channels (Ricean and Rayleigh). For example, injecting AWGN during indoor testing where reception is subject to human movement, vehicles, tree sway etc. would not provide the desired margin for the environment being tested. The difference could be significant. As a result, places where SNR margin (AWGN)=> 0 dB would now be classified as locations with good reception. However, such a conclusion would not apply to locations with consumer-grade receivers.

Further, the Pass/Fail approach used to date does not answer the question of why is there a failure. For example, the most recent MSTV/NAB test shows that 60% of the failed sites with outdoor antenna at 30' HAG met the minimum SNR. Why then did they fail?

SNR and "Field Strength[17]" Measurement via Spectrum Integration

When the received power is measured by integrating the power spectrum curve (sometimes segments thereof) as displayed on a spectrum analyzer, the result may contain an error of unknown magnitude.

The integrated power is not just the Desired Signal power. It includes all multipath, interference, (man-made), and thermal noise, and sky noise and residual transmitter signal impairments. For example, theoretically a pair of equal and asymmetric echoes, one of positive amplitude and positive delay relative to the main signal and one of negative amplitude and negative delay relative to the main signal, will not show any distortion of the power spectrum. They will create group delay, which can affect decoding. Thus, in a Rayleigh channel, a pair of such echoes with magnitude close to the magnitude of the primary signal would measure SNR $\approx \infty$ (excluding thermal noise) when using the spectrum integration technique whereas in reality, the SNR = 0. There may be other combinations that would yield a flat spectrum.

While in a Ricean channel the integration of the distorted spectrum may average out to the "correct" value, it is not clear that the same would apply to indoor Rayleigh spectra.

The integration method is relatively inexpensive. Whether it compares favorably, in most environments, with more sophisticated instruments available from Rohde & Schwartz, Tektronix and HP has not, to the writers' knowledge, been determined. It remains to be evaluated. One approach that could help identify and rectify the problems cited is to use an appropriate form of diversity reception for the spectrum integration method.

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[17] Field strength is defined and measured at a single wavelength and the usage of this term for wide-band signals without carrier is misleading.

The “field strength” is calculated from the measured total (multipath, noise etc.) received power assuming the gain of the antenna is known. Calibration of the antenna’s gain by comparing it to a “tuned” reference dipole is also a source of uncertainty as the antenna gain may be affected by its local surroundings. How the dipole could be tuned and its gain and directivity at the measured frequency established except when measured on a calibrated range is not explained in any of the test procedures. In fact, the characteristics of the test and reference antennas do not apply to indoor environments.

Coverage Definition

Coverage describes the statistical availability of the signal power to the receiver within the station’s F(50,90) contour.

> ***Coverage Index*** = % of sampled locations with incident “field strength” (or power flux density) ≥ minimum “field strength” (or power flux density) required for reception at 30’ HAG.

The minimum “field strengths” are specified by the FCC as 41 dBu for UHF channels, 36 dBu for channels 7-13 and 28 dBu for channels 2-6.

The measurement of coverage is subject to proper sampling (Section E) and the calculation is subject to the FCC’s choice of propagation model. The Coverage Index assumes an AWGN channel and Log-normal distribution. The median signal and standard deviation should be specified.

Locations subject to heavy multipath and/or interference should be avoided as the would-be errors in the statistical distribution and the measurement itself may be hard to quantify.

Service Definition

Fixed Outdoor Service describes the statistical availability of reliable DTV reception anywhere and anytime within the station’s protected contour and on a set equipped with a directional outdoor antenna connected through only a downlead cable to a consumer-grade receiver.

Fixed Indoor Service describes the statistical availability of reliable DTV reception anywhere and anytime within the station’s protected contour and on a set equipped with a portable indoor antenna connected through only a downlead cable to a consumer-grade receiver.

> ***Fixed Service Index*** = % of sampled locations where reception without impairments for ≥ X minutes has been possible.

The measurement of service is subject to proper sampling.

It is important to emphasize that service measurements must be made from the point of view of the consumer. Therefore, the location and rotation of antenna must be limited. The height and gain of the antennas may be arbitrary, but must be specified. The choice of receiver manufacturer is also arbitrary, so long as the receiver is compliant with certain performance parameter values, which are either specified or implied in the FCC Planning Factors for DTV.

System Performance Definition

System performance describes the expected rather than actual service at the sampled locations where the incident “field strength” (or power density) ≥ minimum required “field strength” (or power density) specified for reception at 30’ AG.

> ***System Performance Index*** = % of sampled locations where the minimum “field strength” (or power density) required for reception at 30’ AG was met and reception, indoor and (separate) outdoor without impairments for ≥ X minutes has been possible.

Thus, a system performance index can be assigned to both indoor and outdoor reception subject to coverage confirmation at the sites tested.

The calculation of the System Performance Index is subject to measurements performed in accordance with the requirements outlined. Substitution of SNR for the “field strength” would not provide an adequate measure for the reasons cited above.

ADDENDUM A: SNR Loss Due to Sky Temperature

The FCC receiver model assumes the thermal noise generator to be Johnson's noise at 290^0K for all channels. In fact, for outdoor antennas and VHF channels the sky temperature may generate the predominant noise. The maximum sky temperature and the related loss in SNR (relative to 290^0K) is shown below.

Channel	Sky Temp T_S - ^{0}K	SNR Loss dB
2	29977	6.86
3	23694	6.01
4	19134	5.28
5	13921	4.28
6	11721	3.79
7	2091	0.75
8	1933	0.68
9	1792	0.62
10	1665	0.57
11	1551	0.52
12	1447	0.48
13	1353	0.44
UHF	208	-0.05 to -.12

ADDENDUM B: Derivation of Noise Figure and Group Delay Parameters Due to Impedance Mismatch

The factory-specified Noise Figure is based on a matched source-generator measurement. The Effective Noise Figure, accounting for the mismatch at the antenna and at the receiver's front-end, may be 6 dB higher (or more) than the 7 dB for UHF channels in the FCC's Planning Factors. The Effective Noise Figure may be defined as[18]:

$$F_{EFF}=F_0+10\mathrm{Log}(\Delta F)+10\mathrm{Log}(\Delta L)\ \ \mathrm{dB}$$

Where:

F_0 = Factory noise figure measured with matched impedance noise source.

ΔF = Change in F_0 due to the antenna impedance mismatch.

ΔL = Increase in the power transfer loss due to the antenna impedance mismatch.

The equalizer may exact an additional penalty on the effective noise figure due to the antenna/tuner mismatch. The equalizer penalty is a nonlinear function and must be determined experimentally.

For a straight section of line with length x and a propagation constant $\gamma=\alpha+j\beta$, the added power loss, ΔL, due to mismatched impedance is:

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[18] The equations in this appendix are from a paper to be published by O. Bendov, Dielectric Communications.

$$\Delta L = \frac{\left(1-\left|\Gamma_A\right|^2\right)\left(1-\left|\Gamma_R\right|^2\right)}{\left|1-e^{-2\gamma x}\Gamma_A\Gamma_R\right|^2}$$

Where Γ_A and Γ_R are, respectively, the reflection coefficients of the antenna and the receiver and $\gamma=\alpha+j\beta$. The real part of the propagation constant, α, is the attenuation and the imaginary part of the propagation constant is $\beta=2\pi/\lambda g$ where λg is the wavelength in the propagation medium.

The total group delay variation due to the impedance mismatch between the antenna and the front-end of the receiver is given by:

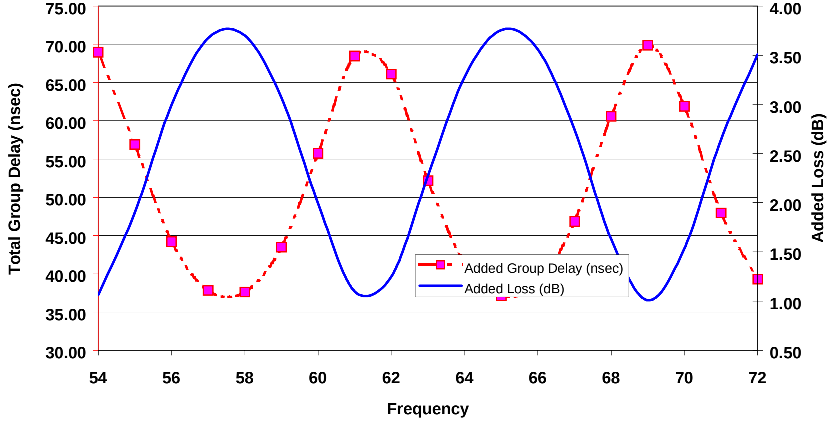
$$\frac{d\Phi}{d\omega} = \frac{x}{v}\left[1-2\left|\Gamma_A\right|\left|\Gamma_R\right|e^{-2\alpha x}\,\frac{\left|\Gamma_A\right|\left|\Gamma_R\right|e^{-2\alpha x}-Cos(-2\beta x+\Psi)}{1+\left|\Gamma_A\right|^2\left|\Gamma_R\right|^2e^{-4\alpha x}-2\left|\Gamma_A\right|\left|\Gamma_R\right|e^{-2\alpha x}Cos(-2\beta x+\Psi)}\right]$$

Where:

$$\Gamma_A\Gamma_R = \left|\Gamma_A\right|\left|\Gamma_R\right|e^{j\Psi}$$

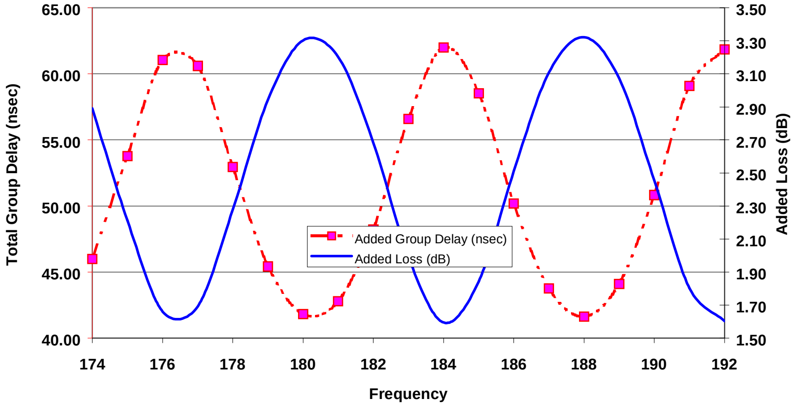
and V = phase velocity.

The effects of a typical impedance mismatch between the antenna and tuner on the added loss and group delay are shown below. For channel 2-6, the added loss may be 3.5 dB and the Group Delay ±15 nsec. For channel 7-13, the added loss may be 3.3 dB and the Group Delay ±12 nsec. For UHF channels, the added loss may be 2.8 dB and the Group Delay ±5 nsec.



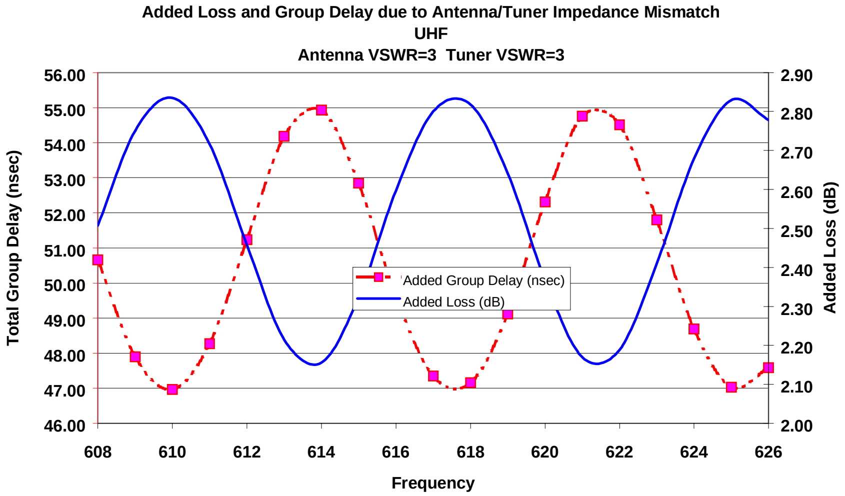
Added Loss and Group Delay due to Antenna/Tuner Impedance Mismatch
Channels 2-4
Antenna VSWR=3 Tuner VSWR=3

	Antenna/Tuner Downlead Parameters	
Nominal Attenuation:	2.00	dB/100'
Relative Velocity of Propagation:	0.78	to the speed of light
Length of Downlead:	50.00	Feet



Added Loss and Group Delay due to Antenna/Tuner Impedance Mismatch
Channels 7-9
Antenna VSWR=3 Tuner VSWR=3

	Antenna/Tuner Downlead Parameters	
Nominal Attenuation:	4.00	dB/100'
Relative Velocity of Propagation:	0.78	to the speed of light
Length of Downlead:	50.00	Feet



	Antenna/Tuner Downlead Parameters	
Nominal Attenuation:	8.00	dB/100'
Relative Velocity of Propagation:	0.78	to the speed of light
Length of Downlead:	50.00	Feet

The relationship between the spot noise figure and the source admittance can be expressed as[19]:

$$F(Y_S) = F_{OPT} + R_N \operatorname{Re}(Y_{OPT}) \frac{|Y_S - Y_{OPT}|^2}{\operatorname{Re}(Y_S)\operatorname{Re}(Y_{OPT})}$$

Where:

Y_S= Source admittance.

F_{OPT}= Minimum noise figure.

Y_{OPT}= Optimum source admittance at which minimum noise figure is obtained.

R_N= A constant which determines the rate of deterioration in noise figure for $Y \neq Y_{OPT}$.

The difference in spot noise figure between unmatched and matched source can be expressed as:

$$\Delta F = \frac{4R_N \operatorname{Re}(Y_{OPT})}{(1-|\Gamma|_S^2)(1-|\Gamma|_{OPT}^2)}\left\{\left[|\Gamma|_{OPT}^2 + |\Gamma|_S^2 - 2|\Gamma|_S|\Gamma|_{OPT} Cos(\phi_{OPT} - \phi_S)\right] - |\Gamma|_{OPT}^2\left(1-|\Gamma|_S^2\right)\right\}$$

$$\operatorname{Re}(Y_{OPT}) = Y_0 \frac{1-|\Gamma|_{OPT}^2}{1+|\Gamma|_{OPT}^2 + 2|\Gamma|_{OPT} Cos\phi_{OPT}}$$

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[19] “Noise Characterization of Linear Twoports in Terms of Invariant Parameters,” J. Lange, IEEE Journal of Solid-State Circuits, Vol. SC-2, NO.2, pp.37-40, June 1967.

Where:

Γ_{OPT}, Γ_S are respectively the optimum (minimum noise figure) reflection coefficient and measured reflection coefficient of the front-end.

The dependence of the effective noise figure on the mismatch is not bounded by an upper limit. Increased mismatch would result in increased noise figure and eventually cause a loss of service. This effect is of particular importance when Hi-Q antennas such as loops and monopoles are combined with tuners that exhibit high mismatch relative to the designed input impedance of 75 ohms.

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