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UHF Spectrum Study

Final Report

prepared by

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Table of Contents

I. Introduction

The IEEE 802.22 working group [1] has been working on the development of a Wireless Regional Area Network (WRAN) standard to provide fixed wireless broadband service in the broadcast television spectrum on television (TV) channels that are not being used for authorized or incumbent services. The IEEE802.22 WRAN will use cognitive radio principles (spectrum sensing and dynamic bandwidth management) to operate on the unused television channels without causing harmful interference to incumbent TV and other authorized devices such as wireless microphones. In the United States, the TV bands include the following portions of the VHF and UHF radio spectrum: 54-72 MHz, 76-88 MHz, 174-216 MHz and 470-806 MHz. More specifically, the WRAN is envisioned to operate in the U.S. in the frequency range of 54 MHz to 698 MHz (TV channels 2 to 51), with a possible extension to 47 – 910 MHz for international operation [1]. WRAN service will not be allowed to operate on Channel 37 that is used by radio astronomy and in the United States on Channels 14-20 that are used by public safety in some parts of the country. WRAN services will have to coexist with the following incumbent services

a) Commercial DTV broadcasters
b) Wireless Microphones
c) Other devices (e.g., some classes of mobile radio)

In October 2006, the FCC has issued a First Report and Order wherein it FCC agreed to allow *fixed* wireless access CR devices to operate in TV bands on a non-interfering basis [2]. The FFC has also issued a Further Notice of Proposed Rule Making to develop additional information to establish and clarify such rules [2].

The purpose of this project is to characterize the sensitivity of television and wireless microphone receivers to interference from WRAN transmitters. Since WRAN operation in the television bands will only be allowed in the United States after the analog to digital television transition is completed in February 17, 2009 [2], this study only evaluates the impact of WRAN interference into ATSC 8VSB digital television receivers. We do not consider analog NTSC receivers in our study. The goal of this study is to arrive at emission limits for WRAN operation that does not cause undue interference to ATSC/8VSB DTV services and analog FM wireless microphone services, as a function of frequency separation between the WRAN and such incumbent signals.

The systems being proposed for IEEE802.22 WRANs are based on IEEE802.16e OFDMA with single channel operation over 6 MHz in the U.S. (7 or 8 MHz in other parts of the world), using a scalable FFT design with possible FFT sizes of 512, 1024 and 2048. This project aims to characterize the interference from WRAN Customer Premise Equipment (CPE), which is limited to a transmit EIRP of 4 Watts (36 dBm) based on a conducted power of 1 Watt and a CPE antenna gain of 6 dBi (other combinations are also possible, as long as the maximum transmit EIRP of 4 Watts is not exceeded). More specifically, this project aims to test this limit and to find the threshold EIRP value that would cause undue interference as a function of frequency offset from the service being interfered to. This project also seeks to test the adequacy of the following emission requirements (sect. 15.1.7 of [1]) for adjacent channel operation and incumbent signal detection thresholds for TV and wireless microphone signals shown in Table 1. See section 5.4 of [1] for typical CPE installation requirements that apply to expected WRAN deployment conditions.

	If WRAN operates	
	First adjacent channel to wireless microphone	Second adjacent channel and beyond to TV or wireless microphone
WRAN first adjacent channel limit	4.8 μV/m	200 μV/m
WRAN second adjacent channel and beyond limit	4.8 μV/m	4.8 μV/m

Table 1 Emission levels (measured at 3 m in 120 kHz bandwidth), from [1]

I-A Objectives:

1. Characterize the interference sensitivity of UHF band receivers in commercial ATSC/8VSB DTV television sets and wireless microphones to IEEE 802.22 WRAN signals, hereafter referred to as ICAs (incumbent consumer appliances). The goal here is to determine emission limits for WRAN CPE operation that will not cause undue interference to incumbent services in the UHF band, as a function of frequency separation between the WRAN and incumbent signals. This will require a detailed evaluation of levels of harmful interference from broadband signals in adjacent (and co-channel) bands that would become noticeable in standard operation.

Important note: The 802.22 Functional Requirements Document [1] specifically precludes operation in an adjacent channel to an active TV channel. This study tests this assumption by evaluating the maximum power level at which a CPE can operate in an adjacent channel without undue interference to an active TV channel.

II. Grade A and Grade B Television Service

Analog NTSC television services in North America are deployed according to Grade A and Grade B iso-service contours [3]. These contours are calculated according to a specific procedure outlined in Section 73.684 of the FCC Rules and Regulations, and have been used since the 1950s. The numerical values associated with these contours are in units of electric field strength, in dB above 1 μV/m (abbreviated dBu) at a height of 30 feet above ground. To arrive at these contours, assumptions are required in terms of the receiver sensitivity, and the antenna gain and transmission line loss of the receiving system. Also, consideration is given to the statistical variation of the electric field strength with location and time, and the subjective nature of the picture quality. The NTSC Grade A contour is the outer geographic limit where the median field strength equals or exceeds that required to produce a picture which a median observer would classify as "acceptable" at least 90% of the time in the best 70% of the receiving locations within the contour. The NTSC Grade B contour is similarly defined, such that a median observer would classify as "acceptable" at least 90% of the time in the best 50% of the receiving locations within the contour. For DTV services, the "Grade B" service contour is calculated using the field strength that is predicted for 50% of the locations, 90% of the time in the service area. In the US, the defining field strengths for DTV service are 28 dBu (Channels 2-6), 36 dBu (Channels 7-13), and 41 dBu (Channels 14-69) [4]. At a weak desired input signal level (-68 dBm), the desired-to-undesired (D/U) ratio for DTV into DTV interference is 15.5 dB (co-channel), -33 dB (first upper and lower adjacent channel), -44 dB (second adjacent channel) [5]. In this study, we seek to establish similar values for WRAN into DTV interference.

As mentioned above the DTV "Grade B" service contour makes assumptions regarding the receiver sensitivity, antenna gains, cable losses, dipole factor, and other quantities. Once these values are specified, it is possible to translate the Grade B field strength into the corresponding input signal power level to the DTV receiver. For example, with a center frequency of 615 MHz, Chouinard [6] has provided the relationship in Table 2 between the field strength at Grade B and the input power to the DTV receiver:

FCC OET Bulletin 69	Frequency:	615 MHz
Grade B Contour	**DTV**	
Field Strength at Grade B	41.0	dB(uV/m)
PFD at Grade B	-104.8	dB(W/m^2)
RX Antenna gain	**12.15**	dBi
RX Antenna front-to-back	**14**	dB
RX Cable loss	**4**	dB
Noise Figure	**7**	dB
Omni Antenna Aperture	0.02	m^2
Power at input of RX	-83.9	dBm

Table 2: Power at the DTV receiver input at the Grade B contour.

For other channel frequencies, the input power to the DTV receiver can be similarly calculated. For example, the input signal power level for a DTV receiver operating at the Grade B value on a channel with mid-frequency 539 MHz is -85 dBm.

Alternatively, the FCC OET Bulletin 69 [4] provides the planning factors for DTV reception shown in Table 3. The Grade B signal strength values of 28 dBu (Low VHF), 36 dBu (High VHF), and 41 dBu (UHF) satisfy the equation

$$\text{Field} + K_d + K_a + G - L - N_t - N_s = C/N$$

The above values can also be used to specify Grade B input signal levels. For example, UHF frequencies we have $C = N_t + N_s + C/N = -84.2$ dBm. Note that Chouinard's calculation further reduces this value by the Dipole adjustment factor.

Planning Factor	Symbol	Low VHF	High VHF	UHF
Geometric mean frequency (MHz)	F	69	194	615
Dipole factor (dBm-dBu)	K_d	-118.8	-120.8	-130.8
Dipole factor adjustment	K_a	none	none	See comment
Thermal noise (dBm)	N_t	-106.2	-106.2	-106.2
Antenna gain (dBd)	G	4	6	10
Downlead line loss (dB)	L	1	2	4
System noise figure (dB)	N_s	10	10	7
Required carrier to noise ratio (dB)	C/N	15	15	15

Comment: For UHF frequencies, the Dipole adjustment factor is 20log [615/ (channel mid-frequency in MHz)].

Table 3: Planning factors for DTV reception, from [4].

III. DTV Interference Testing

Figure 1 shows our experimental arrangement for DTV interference testing. The losses through the combiner, splitter, cables, and 50 to 75 ohm impedance matching circuit were carefully measured to ensure proper control of input signal levels to the DTV receiver. The WRAN signal was set to have the parameters shown in Table 4.

WRAN Physical Layer Parameters	
Software:Agilent Signal Studio for 802.16 WiMAX (Model: N7615A/B, Version 1.8.2.0)	
Parameter	Value
Bandwidth	5MHz
FFT Size	2048 point
Frame Duration	10ms
Uplink Duration	9.9ms
Downlink Duration	0.1ms
Symbol Rolloff	10%
Cyclic Prefix	1/8

Table 4: Physical layer parameters of the WRAN interfering signals.

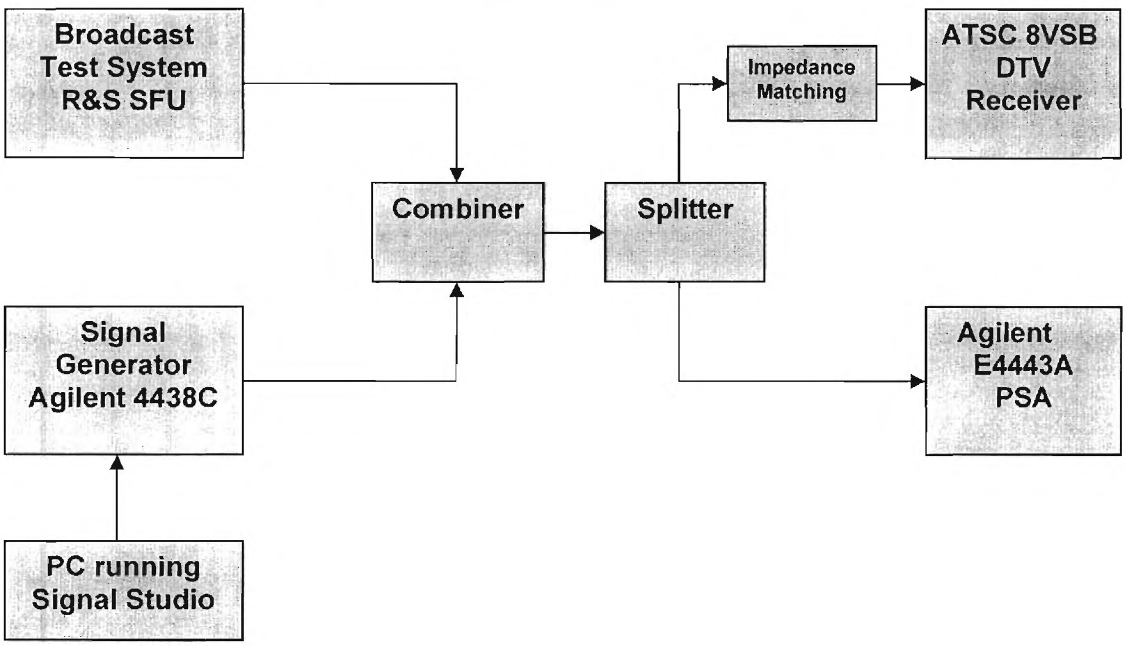

Figure 1: Equipment connections for DTV interference testing

DTV Interference Testing – Key Instrument Specification

Name	Specification
DTV signal Generator	Rohde and Schwarz, SFU
Agilent Signal Generator	Model No. 4438C
Agilent High Performance Spectrum Analyzer	Model No. 4443A
PC	Dell
Agilent Signal Studio for WiMax	Version N7615A/B
ATSC 8VSB Receiver	Sharp Model # 27SC26B
ATSC 8VSB Receiver	Magnavox 27MT6005D

III.-A Taboo Channel Rejection Threshold

In the first series of tests, a DTV test signal was placed in channel *N* at 539 MHz at input levels of -53 dBm (moderate), -68 dBm (weak), -76 dBm, and -84 dBm (Grade B). Note that we were not able to perform testing at the -20 dBm (strong) desired DTV signal level, because the Agilent 4438C WRAN signal generator reached saturation at these levels. However, the strong signal levels are not important in the context of WRAN deployments. Also, the DTV receivers were observed to have a very sharp noise-limited performance threshold close to the Grade B contour receiver input signal level of -84 dBm. For the Sharp 27SC26B receiver, a high quality DTV image and audio was present so long as the desired DTV signal level was above -83.5 dBm. However, reducing the DTV input signal just 0.1 dB below -83.5 dBm, resulted in a total loss of image and audio. Hence, we were only able to perform D/U testing at an input level of -83.5 dBm, which is 0.5 dB above the value specified by the Grade B contour. For the Magnavox 27MT6005D receiver, the noise-limited performance threshold was slightly softer. A high quality DTV image and audio was present so long as the desired DTV signal level was above -84.3 dBm and the image is completely gone at -84.9 dBm.

The WRAN signal was placed in channels $N+i$, $i=1, \ldots, 15$. The power of the WRAN signal was increased in steps of 0.1 dB to determine the taboo channel rejection threshold, or threshold desired-to-undesired (D/U) ratio, equal to the power of the desired DTV signal power at the DTV receiver input (in dBm) minus the power of the WRAN signal in channel $N+i$ (in dBm). This taboo channel D/U ratio (in dB) will be negative. The Sharp 27SC26B receiver has a very sharp taboo channel rejection threshold. The DTV receiver was observed to generate high quality video and audio when a WRAN signal is present as long as the D/U is greater than the taboo channel rejection threshold; however, if the WRAN signal power is such that the D/U is 0.1 dB below the taboo channel rejection threshold the DTV image and audio is completely lost. Similar to the noise-limited performance threshold, the Magnavox 27MT6005D receiver exhibited a 0.6 dB transition region from a high quality signal to no signal at all. In any case, however, the taboo channel rejection threshold is sharp and subjective performance testing is not needed. We only need to record the taboo channel rejection thresholds, defined here as the smallest (most negative) D/U value such that a high quality image and video is present.

We also recorded the WRAN signal power that was present in the DTV desired signal pass band, when the WRAN signal was operating at the taboo channel rejection threshold. This will give a measure of the C/N_I, where C is the desired DTV signal power operating in channel N, and N_I is the in-band noise power due to the WRAN signal operating in channel $N+i$. The purpose of this measurement is to ensure that the DTV receiver performance is being limited by the WRAN signal power in the taboo channel (i.e., the DTV receive filtering) rather than the WRAN signal power that is present in the DTV receiver pass band (i.e., the WRAN out-of-band emissions).

The testing results are shown in Tables 5 to 8 for the Sharp 27SC26B receiver. Note that the in-band WRAN power measurements inn the cases where the desired signal input level is -53 and -68 dBm and the WRAN signal is located at channels *N*+3 and *N*+4 are unreliable. The values in question are shown in bold font in Tables 1 and 2. The measured values were corrupted by some inter-modulation products that were internally generated by the Agilent PSA. Hence, the reported SNR values for a WRAN signal operating in these channels are lower than actual (or pessimistic). The corresponding taboo channel rejection thresholds (D/U values) are still reliable.

Tables 9 to 12 show our testing results for the Magnavox 27MT6005D receiver. However, for this receiver we only show the taboo channel rejection thresholds and we did not calculate the corresponding in-band SNR values when a WRAN signal is operating in an adjacent channel at a level equal to the taboo channel rejection threshold.

Input Level (-53dBm) Moderate Desired						
CH	WRAN Signal Power (dBm)	DTV Signal Power (dBm)	D/U (dB)	WRAN (inband) (dBm)	DTV (inband) (dBm)	SNR (inband) (dB)
N+1	-13.30	-53.00	-39.70	-76.30	-53.00	23.30
N+2	-10.20	-53.00	-42.80	-77.30	-53.00	24.30
N+3	-6.60	-53.00	-46.40	**-68.80**	-53.00	**15.80**
N+4	-5.20	-53.00	-47.80	**-68.20**	-53.00	**15.20**
N+5	-2.80	-53.00	-50.20	-69.40	-53.00	16.40
N+6		-53.00			-53.00	
N+7		-53.00			-53.00	
N+8		-53.00			-53.00	
N+9		-53.00			-53.00	
N+10		-53.00			-53.00	
N+11		-53.00			-53.00	
N+12		-53.00			-53.00	
N+13		-53.00			-53.00	
N+14		-53.00			-53.00	
N+15		-53.00			-53.00	

Table 5: Threshold D/U and in-band SNR (C/N_I) for a moderate desired DTV input signal level for Sharp 27SC26B receiver.

Input Level (-68dBm) Weak Desired						
CH	WRAN Signal Power (dBm)	DTV Signal Power (dBm)	D/U (dB)	WRAN (inband) (dBm)	DTV (inband) (dBm)	SNR (inband) (dB)
N+1	-29.40	-68.00	-38.60	-91.50	-68.00	23.50
N+2	-26.50	-68.00	-41.50	-92.70	-68.00	24.70
N+3	-22.80	-68.00	-45.20	**-84.90**	-68.00	**16.90**
N+4	-21.50	-68.00	-46.50	**-83.50**	-68.00	**15.50**
N+5	-18.80	-68.00	-49.20	-84.80	-68.00	16.80
N+6	-18.00	-68.00	-50.00	-84.00	-68.00	16.00
N+7	-19.60	-68.00	-48.40	-85.10	-68.00	17.10
N+8	-18.40	-68.00	-49.60	-83.70	-68.00	15.70
N+9	-18.20	-68.00	-49.80	-83.90	-68.00	15.90
N+10	-17.60	-68.00	-50.40	-83.50	-68.00	15.50
N+11	-17.60	-68.00	-50.40	-83.50	-68.00	15.50
N+12	-17.60	-68.00	-50.40	-83.30	-68.00	15.30
N+13	-17.60	-68.00	-50.40	-83.30	-68.00	15.30
N+14	-17.90	-68.00	-50.10	-82.50	-68.00	14.50
N+15	-22.40	-68.00	-45.60	-81.50	-68.00	13.50

Table 6: Threshold D/U and in-band SNR (C/N_I) for a weak desired DTV input signal level for Sharp 27SC26B receiver.

Input Level (-76dBm)						
CH	WRAN Signal Power (dBm)	DTV Signal Power (dBm)	D/U (dB)	WRAN (inband) (dBm)	DTV (inband) (dBm)	SNR (inband) (dB)
N+1	-41.40	-76.00	-34.60	-101.10	-76.00	25.10
N+2	-37.40	-76.00	-38.60	-100.80	-76.00	24.80
N+3	-32.10	-76.00	-43.90	-99.70	-76.00	23.70
N+4	-29.10	-76.00	-46.90	-96.70	-76.00	20.70
N+5	-26.90	-76.00	-49.10	-93.70	-76.00	17.70
N+6	-26.90	-76.00	-49.10	-93.30	-76.00	17.30
N+7	-27.10	-76.00	-48.90	-92.90	-76.00	16.90
N+8	-27.10	-76.00	-48.90	-92.90	-76.00	16.90
N+9	-26.90	-76.00	-49.10	-92.80	-76.00	16.80
N+10	-26.80	-76.00	-49.20	-93.20	-76.00	17.20
N+11	-26.80	-76.00	-49.20	-93.60	-76.00	17.60
N+12	-26.80	-76.00	-49.20	-93.60	-76.00	17.60
N+13	-26.80	-76.00	-49.20	-93.80	-76.00	17.80
N+14	-26.80	-76.00	-49.20	-93.80	-76.00	17.80
N+15	-30.10	-76.00	-45.90	**-88.70**	-69.30	**19.40**

Table 7: Threshold D/U and in-band SNR (C/N_I) for a desired DTV input signal level of -76 dBm for Sharp 27SC26B receiver.

Input Level (-83.5dBm) Grade B Desired						
CH	WRAN Signal Power (dBm)	DTV Signal Power (dBm)	D/U (dB)	WRAN (inband) (dBm)	DTV (inband) (dBm)	SNR (inband) (dB)
N+1	-51.9	-83.5	-31.6	-103.8	-83.5	20.3
N+2	-49.8	-83.5	-33.7	-102.8	-83.5	19.3
N+3	-49.3	-83.5	-34.2	-102.6	-83.5	19.1
N+4	-48.3	-83.5	-35.2	-101.6	-83.5	18.1
N+5	-47	-83.5	-36.5	-101	-83.5	17.5
N+6	-46.8	-83.5	-36.7	-101.5	-83.5	18
N+7	-46.8	-83.5	-36.7	-101.6	-83.5	18.1
N+8	-46.8	-83.5	-36.7	-101.1	-83.5	17.6
N+9	-46.7	-83.5	-36.8	-100.9	-83.5	17.4
N+10	-46.5	-83.5	-37	-100.9	-83.5	17.4
N+11	-46.3	-83.5	-37.2	-100.9	-83.5	17.4
N+12	-46.3	-83.5	-37.2	-101	-83.5	17.5
N+13	-46.3	-83.5	-37.2	-101.2	-83.5	17.7
N+14	-46.3	-83.5	-37.2	-102.1	-83.5	18.6
N+15	-52.1	-83.5	-31.4	-100.7	-83.5	17.2

Table 8: Threshold D/U and in-band SNR (C/N_I) for a Grade B desired DTV input signal level of -83.5 dBm for Sharp 27SC26B receiver.

Input Level (-53dBm) Moderate Desired

CH	WRAN Generator (dBm)	DTV Generator (dBm)	D/U (dB)
N+1	-12.60	-53.00	-40.40
N+2	-9.40	-53.00	-43.60
N+3	-5.70	-53.00	-47.30
N+4	-4.30	-53.00	-48.70
N+5	-4.30	-53.00	-48.70
N+6	-2.70	-53.00	-50.30
N+7	-12.40	-53.00	-40.60
N+8	-3.70	-53.00	-49.30
N+9	-3.10	-53.00	-49.90
N+10	-2.40	-53.00	-50.60
N+11		-53.00	
N+12		-53.00	
N+13		-53.00	
N+14		-53.00	
N+15	-6.60	-53.00	-46.40

Table 9: Threshold D/U for a moderate desired DTV input signal level for Magnavox 27MT6005D receiver.

Input Level (-68dBm) Weak Desired			
CH	WRAN Generator (dBm)	DTV Generator (dBm)	D/U (dB)
N+1	-25.50	-68.00	-42.50
N+2	-24.90	-68.00	-43.10
N+3	-22.00	-68.00	-46.00
N+4	-20.10	-68.00	-47.90
N+5	-17.70	-68.00	-50.30
N+6	-17.40	-68.00	-50.60
N+7	-18.40	-68.00	-49.60
N+8	-18.00	-68.00	-50.00
N+9	-17.80	-68.00	-50.20
N+10	-17.40	-68.00	-50.60
N+11	-17.50	-68.00	-50.50
N+12	-17.50	-68.00	-50.50
N+13	-17.50	-68.00	-50.50
N+14	-18.40	-68.00	-49.60
N+15	-22.50	-68.00	-45.50

Table 10: Threshold D/U for a weak desired DTV input signal level for Magnavox 27MT6005D receiver.

Input Level (-76dBm)

CH	WRAN Generator (dBm)	DTV Generator (dBm)	D/U (dB)
N+1	-33.80	-76.00	-42.20
N+2	-33.50	-76.00	-42.50
N+3	-29.90	-76.00	-46.10
N+4	-28.10	-76.00	-47.90
N+5	-26.80	-76.00	-49.20
N+6	-26.80	-76.00	-49.20
N+7	-26.80	-76.00	-49.20
N+8	-26.80	-76.00	-49.20
N+9	-26.80	-76.00	-49.20
N+10	-26.80	-76.00	-49.20
N+11	-26.80	-76.00	-49.20
N+12	-26.80	-76.00	-49.20
N+13	-26.80	-76.00	-49.20
N+14	-26.80	-76.00	-49.20
N+15	-29.40	-76.00	-46.60

Table 11: Threshold D/U for a desired DTV input signal level of -76 dBm for Magnavox 27MT6005D receiver.

Input Level (-84 dBm) Grade B			
CH	WRAN Generator (dBm)	DTV Generator (dBm)	D/U (dB)
N+1	-50.3	-84	-33.7
N+2	-50.3	-84	-33.7
N+3	-49.4	-84	-34.6
N+4	-47.3	-84	-36.7
N+5	-47.2	-84	-36.8
N+6	-47.2	-84	-36.8
N+7	-45.7	-84	-38.3
N+8	-45.6	-84	-38.4
N+9	-45.8	-84	-38.2
N+10	-45.8	-84	-38.2
N+11	-46.8	-84	-37.2
N+12	-45.8	-84	-38.2
N+13	-44.8	-84	-39.2
N+14	-46.2	-84	-37.8
N+15	-52.5	-83.5	-31

Table 12: Threshold D/U for a Grade B desired DTV input signal level of -83.5 dBm for Magnavox 27MT6005D receiver.

III.-B Co-Channel Rejection Threshold

At very low DTV input signal levels, such as at the Grade-B service contour, the internal DTV receiver noise power (N2) will strongly affect signal reception in the absence of interference. It is therefore desirable to know N2 to make accurate estimates of performance degradation due to co-channel or other in-band interference. In practice, it is not possible to measure this internal noise source, N2. However, it is possible to infer N2 from a series of measurements external to the receiver. Once N2 is determined for a specific television, one can determine how much WRAN co-channel interference can be tolerated by the DTV receiver. Several tests were conducted to determine N2 and consequently, the amount of WRAN interference tolerable at the receiver input.

Approach

The overall approach is shown in Figure 2 where C is the DTV desired input signal, N1 is the external noise and N2 is the internal receiver noise. For high C and N1 levels, N2 is "swamped out" and a constant overall C/(N1+N2) ~ C/N1 called ("SNR_{reqd}") can be maintained by setting C/N1 to a threshold value such that the DTV receiver produces a stable picture, yet any reduction in C/N1 causes picture degradation. Once the SNR_{reqd} is determined, N2 can be determined by varying C/N1 while keeping C/(N1+N2) at the threshold operating point.

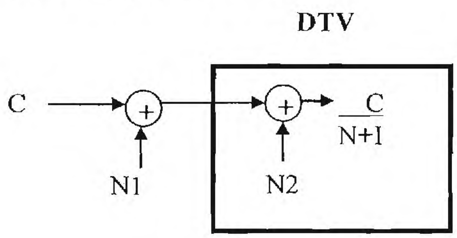

Figure 2 Noise Injection Method

$$C(\frac{N1+N2}{C}) - C(\frac{N1}{C}) = N2$$

$$C(\frac{1}{\frac{C}{N1+N2}}) - C(\frac{1}{\frac{C}{N1}}) = N2$$

$$\frac{10^{\frac{C_{dB}}{10}}}{10^{\frac{SNRreqd_{dB}}{10}}} - \frac{10^{\frac{C_{dB}}{10}}}{10^{\frac{C/N1_{dB}}{10}}} = N2$$

$$10^{\frac{C_{db}-SNR_{reqddB}}{10}} - 10^{\frac{C_{db}-C/N1_{dB}}{10}} = N2 \_\_\_\_(1)$$

Noise

This method for determining N2 by using noise injection is suggested by the above analysis. The final equation shows that N2 can be determined by measurable quantities C, C/N1 and SNR_{reqd}.

The SNR_{reqd} was determined by adjusting the signal power to the relatively strong level of -40 dBm and increasing N1 to a level at which a 0.1 dB further increase would result in noticeable picture or audio quality degradation. Therefore, N1 yielded the lowest C/N1 that would produce acceptable DTV service.

C and N1 were then adjusted to very low desired signal input power levels at which the internal noise source N2 would dominate the total SNR and require a substantial increase in C/N1 to ensure the TV provides an acceptable video and audio quality.

Thus, the variation in C/N1 would reveal the value of N2 – the TV receiver internal noise power. The measured values in (1) and the derived values of N2 are plotted in Figure 3. The values of N2 determined by (1) are about -96 dBm in low DTV desired signal input conditions such as Grade B.

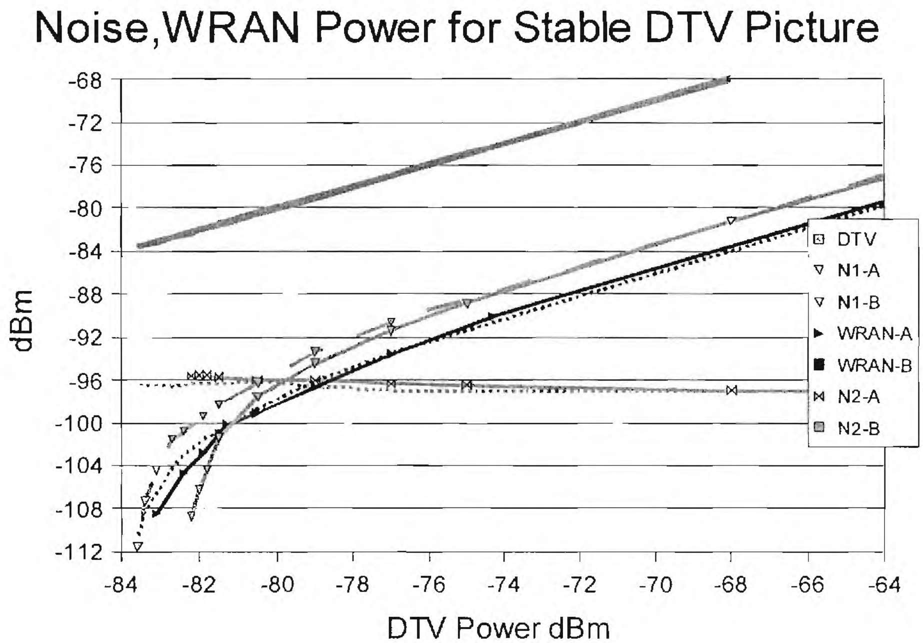

Figure 3: Noise and WRAN co-channel power limits required for maintaining a stable DTV image; A = Sharp 27SC26B receiver, B = Magnavox 27MT6005D receiver.

Interference

Additional testing of the DTV receivers with co-channel WRAN signals (and no noise) revealed the SNR_{reqd} ratio must exceed 15.6 dB, even for strong DTV signals. This increase of 2.4 dB over that obtained with Gaussian noise confirms that the structure of the co-channel interference affects the maximum interference power tolerated by the DTV receiver. More importantly, it shows that WRAN's OFDM in-band interference cannot be treated as a source with equivalent Gaussian noise power. For weak DTV signal and interference levels, the internal receiver noise N2 dominates the undesired in-band energy. Under these conditions, the minimum SNR required by DTV receivers A and B were 13.2 dB, 12.7 dB, respectively.

The maximum tolerable WRAN interfering power can now be determined by the analysis shown here. For example, in the strong signal case of C = - 40 dBm and a SNR_{reqd} of 13.2 dB, equation (2) indicates the WRAN interference must not exceed -53 dBm. Plotting (2) yields the curves shown in Figure 4. The individual DTV receiver internal noise powers N2-A,-B are shown as the horizontal red lines.

$$\left(\frac{C}{N2+I}\right) \geq SNR_{reqddB}$$

$$\frac{10^{C/10}}{10^{SNRreqd/10}} - 10^{N2/10} = 10^{I/10}$$

$$10\log_{10}\left(\frac{10^{C/10}}{10^{SNRreqd/10}} - 10^{N2/10}\right) \geq I_{WRANdBm}$$

$$10\log_{10}\left(\frac{10^{C/10}}{10^{SNRreqd/10}} - 10^{-9.6}\right) \geq I_{WRANdBm} \quad \_\_(2)$$

The dashed lines are extrapolations assuming that the WRAN and N2 act like noise on the DTV signal at low (Grade B) signal levels. The lines intersect at the Grade-B DTV signal power abscissa and N2 ordinate indicating that to maintain a 13.2 dB SINR at the Grade B contour, no additional degradation beyond the internal receiver power can be tolerated. Note that when the WRAN signal dominates the noise+interference, the maximum allowed WRAN power will follow a curve below the presented WRANmax curves shown due to the larger $SINR_{reqd}$.

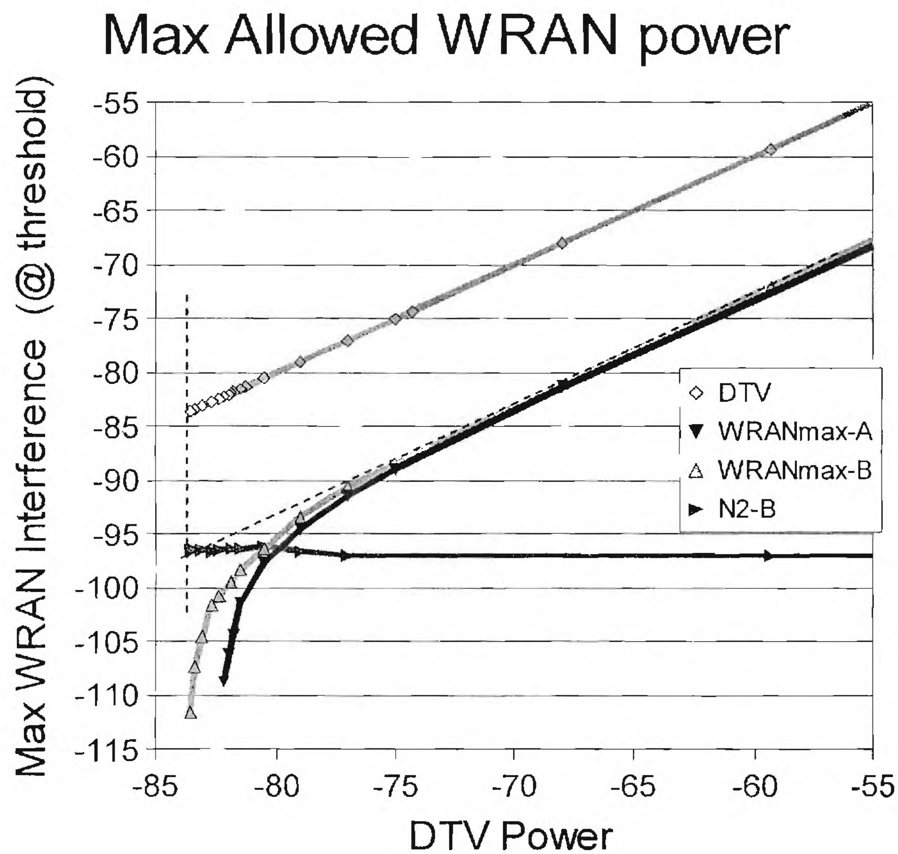

Figure 4: SNR and SINR required for maintaining a stable DTV image; A = Sharp 27SC26B receiver, B = Magnavox 27MT6005D receiver.

Further Work

This approach described in this paper can be used to generate higher fidelity performance estimates for TV receivers, particularly at Grade B contours.

Additional experiments should be conducted to determine the reason for the different DTV receiver performance due to the structure of interference (noise vs WRAN signal). Although the Central Limit Theorem suggests the multi-carrier OFDM WRAN signal should appear as a Gaussian noise source, the large peak-to-average ratios found in OFDM signals, may degrade SNR as would a noise source at a higher power level, thus leading to a required SIR 2.4 dB higher than the required SNR for acceptable DTV service.

IV. Wireless Microphone Interference Testing

Wireless microphone testing is somewhat simpler, because we do not have to determine taboo channel rejection ratios. We only need to determine the co-channel protection ratio. This is simply the ratio of the desired signal power measured in a 200 KHz bandwidth to the interfering signal power in the same 200 KHz bandwidth that is generated from a WRAN signal operating in the first or second adjacent channel. However, because the wireless microphone uses analog FM modulation the co-channel protection ratio is "subjective" and not clearly defined. Hence, our methodology is to test the performance of the wireless microphone at various desired signal input levels and WRAN power levels by using audio recordings of a sample audio waveform. Each listener can then decide on what they perceive to be the required co-channel protection ratio.

Using the experimental configuration in Figure 5, we have corrupted a wireless microphone signal at 733 MHz with a 5 MHz WRAN signal with a center frequency of 737 MHz, corresponding to first adjacent channel operation and 743 MHz corresponding to second adjacent channel operation. Note that the center frequency of the wireless microphone is toward the edge of the 728-734 MHz TV channel. The wireless microphone is dependent upon the desired signal input power. We have tested two levels, -76 dBm and -95 dBm. The -76 dBm level corresponds to the "preferred minimum signal level [7], whereas the -95 dBm level corresponds to the noise limited performance threshold. The results of our wireless microphone testing are summarized in Tables 13 and 14 for first and second adjacent channel operation, respectively. In these tables, the D/U ratio is the power of the desired wireless microphone signal to the WRAN signal power operating in the first or second adjacent channel. This is similar to the D/U values for DTV receivers, although the wireless microphones have no minimum D/U performance specifications. The SNR value is equal to the co-channel protection ratio, equal to the dB ratio of the power of the wireless microphone signal in 200 kHz to the WRAN signal power in the 200 kHz wireless microphone pass band.

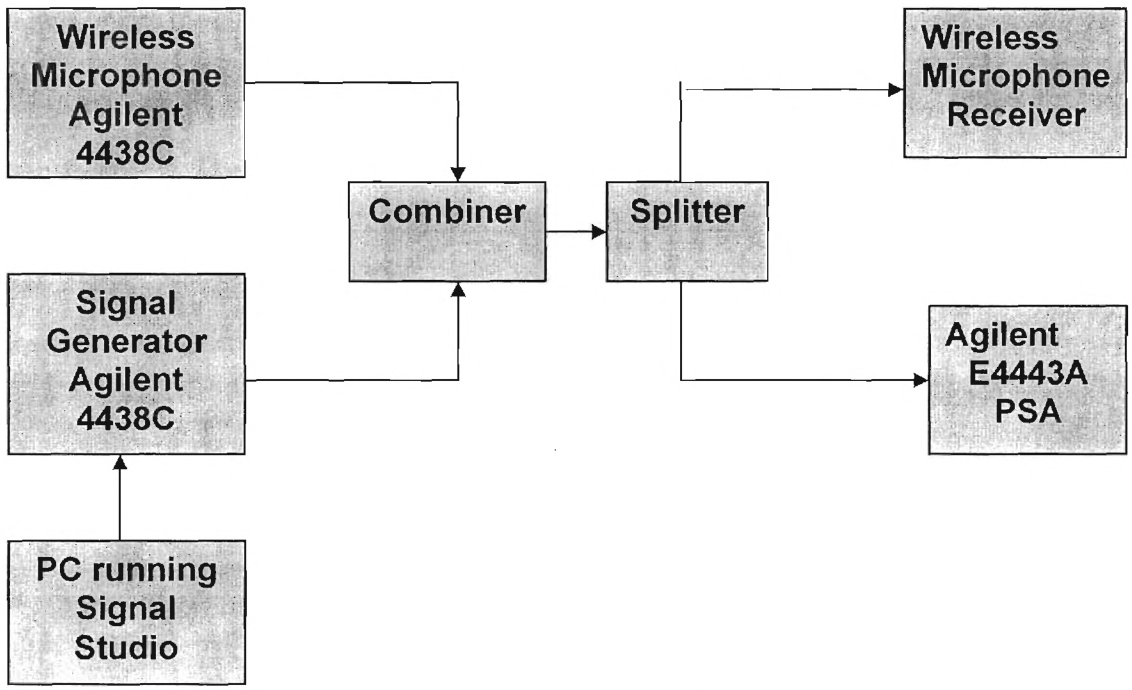

Figure 5: Equipment connections for wireless microphone interference testing

Wireless Microphone Testing – Key Instrument Specification

Name	Specification
Agilent Signal Generator	Model No. 4438C
Agilent High Performance Spectrum Analyzer	Model No. 4443A
PC	Dell
Agilent Signal Studio for WiMax	Version N7615A/B
Audio-Technica Wireless Mic System	Frequency (733MHz), Max Power 50mW

	Wireless Mic Power (	AN Power(SigG	D/U	ireless Mic Pow	WRAN power	SNR	Audio File
WRAN in Channel	(dBm)	(dBm)	(dB)	(200KHz) (dBm	(200KHz) (dB	(dB)	
N-1 (725MHz)	-76	-11.9	-64.1	-76.1	-93.2	17.1	No Signal
N-1 (725MHz)	-76	-12.1	-63.9	-76.1	-93.8	17.7	
N-1 (725MHz)	-76	-13.1	-62.9	-76.1	-94.4	18.3	
N-1 (725MHz)	-76	-14.1	-61.9	-76.1	-95.3	19.2	
N-1 (725MHz)	-76	-15.1	-60.9	-76.1	-96.6	20.5	
N-1 (725MHz)	-76	-16.1	-59.9	-76.1	-97.5	21.4	
N-1 (725MHz)	-76	-17.1	-58.9	-76.1	-98.8	22.7	
N-1 (725MHz)	-76	-18.1	-57.9	-76.1	-100.1	24	
N-1 (725MHz)	-76	-19.1	-56.9	-76.1	-101.2	25.1	
N-1 (725MHz)	-76	-20.1	-55.9	-76.1	-102.1	26	
N-1 (725MHz)	-76	-21.1	-54.9	-76.1	-102.9	26.8	
N-1 (725MHz)	-76	-22.1	-53.9	-76.1	-103.5	27.4	
N-1 (725MHz)	-76	-23.1	-52.9	-76.1	-104.4	28.3	
N-2(719MHz)	-76	-4.4	-71.6	-76.1	-87.7	11.6	No Signal
N-2(719MHz)	-76	-4.5	-71.5	-76.1	-88.2	12.1	
N-2(719MHz)	-76	-5.6	-70.4	-76.1	-89.1	13	
N-2(719MHz)	-76	-6.6	-69.4	-76.1	-89.9	13.8	
N-2(719MHz)	-76	-7.6	-68.4	-76.1	-90.5	14.4	
N-2(719MHz)	-76	-8.6	-67.4	-76.1	-90.9	14.8	
N-2(719MHz)	-76	-9.6	-66.4	-76.1	-91.8	15.7	
N-2(719MHz)	-76	-10.6	-65.4	-76.1	-92.3	16.2	
N-2(719MHz)	-76	-11.6	-64.4	-76.1	-93.05	16.95	
N-2(719MHz)	-76	-12.6	-63.4	-76.1	-94.2	18.1	
N-2(719MHz)	-76	-13.6	-62.4	-76.1	-95.6	19.5	
N-2(719MHz)	-76	-14.6	-61.4	-76.1	-96.2	20.1	
N-2(719MHz)	-76	-15.6	-60.4	-76.1	-97.3	21.2	
N-2(719MHz)	-76	-16.6	-59.4	-76.1	-97.9	21.8	
N-2(719MHz)	-76	-17.6	-58.4	-76.1	-98.2	22.1	

Table 13: Sample audio files for Audio-Technica wireless microphone under different in–band SNR values (otherwise known as microphone reception protection ratio) with first adjacent channel WRAN operation.

Wireless Mic Power (		AN Power(Sig(	D/U	reless Mic Pov	WRAN power	SNR	Audio File
RAN in Chann	(dBm)	(dBm)	(dB)	**(200KHz)** (dBr	**(200KHz)** (dBr	(dB)	
N-1 (725MHz)	-95	-26.2	-68.8	-95.2	-105.5	10.3	No Signal
N-1 (725MHz)	-95	-26.6	-68.4	-95.2	-106.1	10.9	
N-1 (725MHz)	-95	-27.6	-67.4	-95.2	-106.8	11.6	
N-1 (725MHz)	-95	-28.6	-66.4	-95.2	-107.1	11.9	
N-1 (725MHz)	-95	-29.6	-65.4	-95.2	-107.5	12.3	
N-1 (725MHz)	-95	-30.6	-64.4	-95.2	-108.1	12.9	
N-1 (725MHz)	-95	-31.6	-63.4	-95.2	-108.9	13.7	
N-1 (725MHz)	-95	-32.6	-62.4	-95.2	-109.7	14.5	
N-1 (725MHz)	-95	-33.6	-61.4	-95.2	-110.4	15.2	
N-1 (725MHz)	-95	-34.6	-60.4	-95.2	-110.9	15.7	
N-1 (725MHz)	-95	-35.6	-59.4	-95.2	-111.6	16.4	
N-2(719MHz)	-95	-26.2	-68.8	-95.2	-106.8	11.6	No Signal
N-2(719MHz)	-95	-26.6	-68.4	-95.2	-107.1	11.9	
N-2(719MHz)	-95	-27.6	-67.4	-95.2	-107.3	12.1	
N-2(719MHz)	-95	-28.6	-66.4	-95.2	-107.6	12.4	
N-2(719MHz)	-95	-29.6	-65.4	-95.2	-107.6	12.4	
N-2(719MHz)	-95	-30.6	-64.4	-95.2	-107.8	12.6	
N-2(719MHz)	-95	-31.6	-63.4	-95.2	-107.8	12.6	
N-2(719MHz)	-95	-32.6	-62.4	-95.2	-107.9	12.7	
N-2(719MHz)	-95	-33.6	-61.4	-95.2	-108.1	12.9	
N-2(719MHz)	-95	-34.6	-60.4	-95.2	-109.3	14.1	
N-2(719MHz)	-95	-35.6	-59.4	-95.2	-110	14.8	

Table 14: Sample audio files for Audio-Technica wireless microphone under different in–band SNR values (otherwise known as microphone reception protection ratio) with second adjacent channel WRAN operation.

V. Analysis of Test Results

V-A. DTV Interference Testing

The maximum allowable CPE transmit power depends directly on the taboo channel rejection thresholds for a given DTV input signal level. The DTV receivers that we have tested exhibited a noise-limited performance threshold right at the Grade B contour input signal level. In our testing, the Grade B input signal level was -84 dBm. For the Sharp 27SC26B and Magnavox 27MT6005D receivers, the image and audio are either degraded or completely lost for input signal levels less than -83.5 dBm and -84.3 dBm, respectively. At the Grade B contour, the median field strength will equal or exceed the Grade B value. This means that the input signal level to the receiver will be less than -84 dBm in half the cases observed, i.e., DTV receiver that we tested will not display video and audio in half the cases even with a non-degraded (no multi-path) signal and no interference (thermal noise only).

The taboo channel rejection thresholds, or D/Us, will directly determine the maximum allowable WRAN CPE transmit power, as described by Chouniard [6]. The spread sheets in Tables 15 and 16 give a brief summary of the required calculation for the Sharp 27SC26B and Magnavox 27MT6005D receivers, respectively. Note that the very small allowed maximum CPE transmit EIRP is due to the small D/U values at the noise limited Grade B contour. We also note that the D/U values that we have obtained at the Grade B contour are significantly larger than those predicted by Chouinard tests [8]. However, this result is expected given the fact that the DTV receivers we have tested exhibit a noise limited performance threshold right at the desired signal input level (-84 dBm) specified by the Grade B value.

For the results in Table 15 and 16, we assume the following values:

Maximum permitted CPE EIRP	4 Watts
	6 dBW
Min. distance between CPE and DTV RX	10 m
Field strength at min. dist. in 6 MHz:	120.8 dB(uV/m)

Channel	D/U at noise-limited contour (-84 dBm) (dB)	DTV noise-limited contour field strength dB(uV/m)	DTV RX Antenna discrimination (dB)	Polarization discrimination (dB)	Max field strength at DTV RX dB(uV/m)	Min. dist. between CPE antenna and DTV RX antenna (m)	CPE transmit antenna discrimination (dB)	Maximum CPE transmit EIRP (dBW)	Maximum CPE transmit EIRP (W)
N	15.6	41.0	14.0	0.0	39.4	10	16.0	-59.4	0.0000
N±1	-31.6	41.0	14.0	0.0	86.6	10	16.0	-12.2	0.0601
N±1	-31.6	41.0	0.0	0.0	72.6	10	0.0	-42.2	0.0001
N±2	-33.7	41.0	0.0	14.0	88.7	10	0.0	-26.1	0.0025
N±3	-34.2	41.0	0.0	14.0	89.2	10	0.0	-25.6	0.0027
N±4	-35.2	41.0	0.0	14.0	90.2	10	0.0	-24.6	0.0035
N±5	-36.5	41.0	0.0	14.0	91.5	10	0.0	-23.3	0.0047
N±6	-36.7	41.0	0.0	14.0	91.7	10	0.0	-23.1	0.0049
N±7	-36.7	41.0	0.0	14.0	91.7	10	0.0	-23.1	0.0049
N±8	-36.7	41.0	0.0	14.0	91.7	10	0.0	-23.1	0.0049
N±9	-36.8	41.0	0.0	14.0	91.8	10	0.0	-23.0	0.0050
N±10	-37.0	41.0	0.0	14.0	92.0	10	0.0	-22.8	0.0052
N±11	-37.2	41.0	0.0	14.0	92.2	10	0.0	-22.6	0.0055
N±12	-37.2	41.0	0.0	14.0	92.2	10	0.0	-22.6	0.0055
N±13	-37.2	41.0	0.0	14.0	92.2	10	0.0	-22.6	0.0055
N±14	-37.2	41.0	0.0	14.0	92.2	10	0.0	-22.6	0.0055
N±15	-31.4	41.0	0.0	14.0	86.4	10	0.0	-28.4	0.0014

Table 15: Limits on maximum transmitted CPE power with the Sharp 27SC26B receiver. Table adapted from Chouinard [6] with measured WRAN into DTV co-channel interference rejection thresholds.

Channel	D/U at noise-limited contour (-84 dBm) (dB)	DTV noise-limited contour field strength dB(uV/m)	DTV RX Antenna discrimination (dB)	Polarization discrimination (dB)	Max field strength at DTV RX dB(uV/m)	Min. dist. between CPE antenna and DTV RX antenna (m)	CPE transmit antenna discrimination (dB)	Maximum CPE transmit EIRP (dBW)	Maximum CPE transmit EIRP (W)
N±1	-33.7	41.0	14.0	0.0	88.7	10	16.0	-10.1	0.0975
N±1	-33.7	41.0	0.0	0.0	74.7	10	0.0	-40.1	0.0001
N±2	-33.7	41.0	0.0	14.0	88.7	10	0.0	-26.1	0.0025
N±3	-34.6	41.0	0.0	14.0	89.6	10	0.0	-25.2	0.0030
N±4	-36.7	41.0	0.0	14.0	91.7	10	0.0	-23.1	0.0049
N±5	-36.8	41.0	0.0	14.0	91.8	10	0.0	-23.0	0.0050
N±6	-36.8	41.0	0.0	14.0	91.8	10	0.0	-23.0	0.0050
N±7	-38.3	41.0	0.0	14.0	93.3	10	0.0	-21.5	0.0071
N±8	-38.4	41.0	0.0	14.0	93.4	10	0.0	-21.4	0.0072
N±9	-38.2	41.0	0.0	14.0	93.2	10	0.0	-21.6	0.0069
N±10	-38.2	41.0	0.0	14.0	93.2	10	0.0	-21.6	0.0069
N±11	-37.2	41.0	0.0	14.0	92.2	10	0.0	-22.6	0.0055
N±12	-38.2	41.0	0.0	14.0	93.2	10	0.0	-21.6	0.0069
N±13	-39.2	41.0	0.0	14.0	94.2	10	0.0	-20.6	0.0087
N±14	-37.8	41.0	0.0	14.0	92.8	10	0.0	-22.0	0.0063
N±15	-31.0	41.0	0.0	14.0	86.0	10	0.0	-28.8	0.0013

Table 16: Limits on maximum transmitted CPE power with the Magnavox 27MT6005D receiver. Table adapted from Chouinard [6] with measured WRAN into DTV co-channel interference rejection thresholds.

The out-of-band emissions requirements for WRAN signals can be determined from the DTV co-channel rejection thresholds. Our results in Figure 4 show that the co-channel protection threshold is about 15.6 dB so long as the desired signal input level is greater than the weak level of -68 dBm. However, as the desired signal input level decreases further, the internal noise (at level -96 dBm) in either of the DTV receivers we have tested causes a large increase in the required SIR, $SINR_{reqd}$. In fact, the allowable WRAN power exhibit asymptotes at input levels of -83.5 and -84.3 dBm for the Sharp 27SC26B and Magnavox 27MT6005D receivers. The implication is that at the Grade B input signal level (-84 dBm) very little if any WRAN interference can be tolerated.

As shown in Chouinard's reference model [6], this co-channel rejection threshold essentially determines the out-of-band emission requirements of the WRAN signal. According to Chouinard's analysis, the limit on out-of-band emission is calculated according to:

41 dBu – 15.1 dB (required SIR) – 5.9 dB (desensitization) = 20 dBu

34.0 dB(uV/m)
14.0 dB antenna X-pol discrimination
20.0 dB(uV/m) in 6 MHz at 10 m
13.4 dB(uV/m) in 120 kHz at 3 m
4.7 uV/m in 120 kHz at 3 m
2.94 dB(uV/m) in 120 kHz at 10 m

Our results in Figure 4 shows that the required SIR is 15.6 dB at weak input signal levels (-68 dBm). However, at the Grade B input level of -84 dBm, the desensitization is large due to the asymptotes at -83.5 and -84.3 dBm for the Sharp 27SC26B and Magnavox 27MT6005D receivers.

V-B. Wireless Microphone Interference Testing

The required co-channel protection ratio for wireless microphones also places a limitation on the maximum CPE transmit power. From Chouinard's analysis [6], we have the following. Note that our results show that the required SNR at the -95 dBm desired signal input level is about 15 dB rather than the 20 dB used by Chouinard in his analysis. This value is determined from subjective listening tests. The reader of this report can listen to the audio samples provided in Tables 13 and 14 and determine their own co-channel protection ratio. Afterwards, they can open and enter the corresponding co-channel rejection ratio into the Table 17 below.

Maximum CPE EIRP:	6.0	dBW	Reach: 30.7 km
	4.0	Watts	
CPE Antenna HAAT:	10.0	m	
CPE Transmit Power:	0.0	dBW	1.005 Watts
Power Flux Density at 1 m from CPE:	-5.0	dBW/m^2	in 6 MHz

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Wireless microphone transmission

Max: 250 mW at UHF, 50 mW at VHF

Transmit power:	**10**	dBm	Typical: 10-50 mW	
Antenna gain:	**-10**	dBi	Typical: -2 to -6 dBi	
Cable loss:	**0**	dB		
Transmit EIRP:	-30	dBW		
Power Flux Density at 1 m from the microphone:	-41.0	dBW/m^2		
Typical microphone fading due to body absorption:	**26.8**	dB	Body absorption and multipath fade allowance: 20-30 dB (less when diversity antennas are used)	
Wireless microphone coverage range	**100**	m		
Power Flux Density at microphone receiver:	-107.8	dBW/m^2		Distance at which the wireless microphone is protected from the WRAN CPE
Power at microphone receiver:	-94.8	dBm	(for 30 dB audio SINAI	
Microphone reception protection ratio (D/U):	**15.0**	dB		
Allowed maximum level of interfering power flux density at microphone receiver:	-122.8	dBW/m^2	in 200 kHz	
Allowed maximum interfering field strength	20.8	dB(uV/m)	in 120 kHz 17.8 dB	1.3 m
Allowed maximum interfering field strength	37.8	dB(uV/m)	in 6 MHz	
Part 15.209(a) level corrected for bandwidth:	2.2	dBW/m^2	in 200 kHz	
Minimum distance from Part 15.209(a) devices:	5341344.2	m	Free Space	

Wireless microphone receiver dynamic range

Wireless microphone receiver threshold:	**-98.0**	dBm	Mute level: -95 to -105 dB
Wireless microphone receiver antenna gain:	**0.0**	dBi	
Wireless microphone receiver cable loss:	**0.0**	dB	
Wireless microphone receiver antenna aperture:	0.02	m^2	
Minimum Power-flux-density at receiver:	-145.0	dBW/m^2	
Dynamic range of the wireless microphone receiver (shortest distance= 3m):	94.5	dB	

Table 17: Impact of co-channel protection ratio on distance at which the wireless microphone is protected from the WRAN CPE. Table adapted from Chouinard [6] with measured WRAN into DTV co-channel interference rejection thresholds.

VI. References

[1] IEEE 802.22 Functional Requirements Document (IEEE 802.22-05/0007r46). See section 5.

[2] FCC First Report and Order and Further Notice of Proposed Rule Making, FCC-06-156, October 12, 2006.

[3] R. A. O'Conner, "Understanding Television's Grade A and Grade B Service Contours," *IEEE Transactions on Broadcasting*, Vol. 47, No. 3, pp. 309-314, September 2001.

[4] The Federal Communications Commission (FCC), "Longley-Rice Methodology for Evaluating TV Coverage and Interference" OET Bulletin No. 69, July 2, 1997.

[5] Advanced Television Systems Committee (ATSC), "ATSC Recommended Practice: Receiver Performance Guidelines," *Doc. A/74*, June 18, 2004.

[6] G. Chouinard, "WRAN Reference Model," IEEE P802.22 Wireless RANs, doc.: IEEE 802.22-04/0002r15, January 2007.

[7] E. Reihl, "Wireless Microphone Characteristics," IEEE P802.22 Wireless RANs, doc.: IEEE 802.22-06/0070r0, May 2006.

[8] G. Chouinard, "DTV D/U's and the WRAN EIRP Profile," IEEE P802.22 Wireless RANs, doc.: IEEE 802.22-05/0073r0, August 2005