Technical Report ITTC-FY2007- 44910-01

Quantifying the Impact of Unlicensed Devices on Digital TV Receivers

Study Commissioned by New America Foundation

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31 January 2007

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Abstract

This report presents the preliminary results from a feasibility study regarding the operation of secondary spectrum users within unused television spectrum. It has been hypothesized that television spectrum is underutilized, making it a candidate for dynamic spectrum access. The feasibility of using this spectrum for enabling secondary transmissions is assessed in this work, with a focus on the possibility of unlicensed devices interfering with digital TV reception. Specifically, we investigate the critical operating parameters for developing the technical rules for device operation in bands adjacent to a digital television transmission.

1. Introduction

The growing demand for wireless services and applications shows no sign of slowing down. However, the current *command-and-control* regulatory structure for licensing spectrum has been unable to cope with the drastic growth demands of the wireless industry. This has given rise to an 'artificial scarcity' of usable spectrum, resulting in spectrum license price levels that are prohibitively expensive, preventing many small to medium size businesses from entering the wireless market. Numerous studies have thus begun to examine how licensed spectrum is actually used, with the goal of not only re-thinking the spectrum licensing regime but also opening certain underutilized 'prime' spectrum to unlicensed and licensed secondary usage. It has been shown that several spectral bands, including the television spectrum, are underutilized [1].

There has been regulatory and legislative activity that could allow new wireless devices to access TV band *white space* on a per market basis. This approach, called *dynamic spectrum access* (DSA), allows unlicensed devices to transmit in parts of the spectrum unoccupied by the licensed signals. On June 28, 2006, the Senate Commerce Committee adopted 'The Advanced Telecommunications and Opportunity Reform Act of 2006' (S. 2686), which built upon the May 2004 Federal Communications Commission (FCC) Notice of Proposed Rulemaking (NPRM) [2] allowing unlicensed devices to utilize unused spectrum in the TV band. This legislation requires the FCC to continue with rule making procedures governing the opening of TV channels 2-51 (54 MHz - 698 MHz) for use by wireless broadband services and other DSA enabled devices. The FCC proposal also includes the reallocation of TV channels 52 - 69 (698 MHz to 806 MHz) to public safety communications as well as for auction. The NPRM specifies that any devices certified to use TV *white spaces* should use agile or cognitive radio technology in a dynamic spectrum access (DSA) configuration, such that these devices would not interfere with primary rights holders, namely television broadcasters.

In a DSA approach, the "secondary" users must not cause any 'harmful interference' to the primary users as well as the other unlicensed users sharing the same portion of the spectrum. Since primary users hold exclusive rights to the spectrum, it is not their responsibility to mitigate any additional interference caused by unlicensed or secondary device operation. These devices will have to periodically sense spectrum to detect primary or secondary user transmissions, and should be able to adapt to the varying spectrum conditions for mutual interference avoidance [3].

The availability of the underutilized TV spectrum is not disputed. Two technical issues remain for the regulatory and business communities. The regulatory community must determine the technical rules that devices must use that access this spectrum in order to prevent harmful interference to the primary devices (i.e. DTV receivers). Additionally, the device manufacturing community must determine if devices can be made cost effectively while meeting both the technical rules as well as operate in the RF environment created by the broadcasting of DTV signals.

The primary technical rules that are of particular interest to the Federal Communications Commission are the emission and the out-of-band emissions (OOBE). The device manufacturers must comply with these rules through the selection of appropriate modulation, amplifier, and filter characteristics in both the transmitter and receiver chains. The expected RF environment also has a direct impact on the receiver characteristics and thus must be well understood.

In this report, we present a feasibility study of devices performing DSA in underutilized television bands when television signals are present. The impact of transmissions on the video quality of digital television signals is determined for several scenarios. This will provide the basis to determine the emission levels that DTV receivers can tolerate.

2. Background

Substantial research effort has been aimed at the utilization of vacant portions of the TV spectrum using DSA techniques. A new standard IEEE 802.22 focuses on reuse of the vacant TV spectrum without causing any harmful interference to the primary users [4]. Some of the important issues that have been addressed include the feature detection of TV signals [5], collaborative sensing for improved detection capabilities [6], detection of the presence of receivers in the vicinity of the unlicensed device [7], and effective methods for unlicensed spectrum access in the TV band [8].

Even though it has been proposed that these methods are effective in avoiding harmful interference to TV receivers, there is still a debate on whether devices can operate within the underutilized spectrum without causing interference. There are many who claim that the unlicensed devices will cause harmful interference to the primary users [9], while others argue that DSA can be done in a transparent manner [10] and can be safely implemented using the latest radio technology communications techniques [11]. Proponents of the DSA approach favor the TV bands for DSA for several reasons: There is substantial amount of unused spectrum available for DSA and, in addition, the propagation properties in these frequency ranges, such as low propagation attenuation, are beneficial for long range mobile and line-of-sight (LOS) communications [8]. Moreover, the fixed channel allocations resulting in deterministic usage patterns in these bands are favorable for accurate spectrum sensing [12].

However, there are challenges for enabling the use of these bands. The secondary device might potentially cause interference to the primary users in case the spectrum sensing fails to identify the presence of the primary user or there is significant out-of-band power leakage from the secondary transmissions that can slip into the primary user bands.

To provide input to these debates and assess the challenges to DSA, the feasibility of unlicensed device operation in the TV spectrum needs to be studied. This feasibility study of secondary user access in the TV spectrum requires the evaluation of the impact of secondary user transmissions over TV receivers.

Interference caused by the unlicensed devices to the TV receivers needs to be evaluated. It should be ensured whether an enabling technology for operation conforms to regulations on limiting the interference to a certain level. The need for a standardized procedure to measure the effects of interference on the TV signals has been stressed in [15]. The interference levels which can be considered *harmful*[1] vary with the TV receiver technology and the secondary device technology. Therefore, a standard procedure for testing the interference-limiting capabilities of devices should be devised for various spectrum environments and different scenarios.

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[1] Interference levels that impact the operation of the TV receivers to such an extent that the received TV signal is severely degraded.

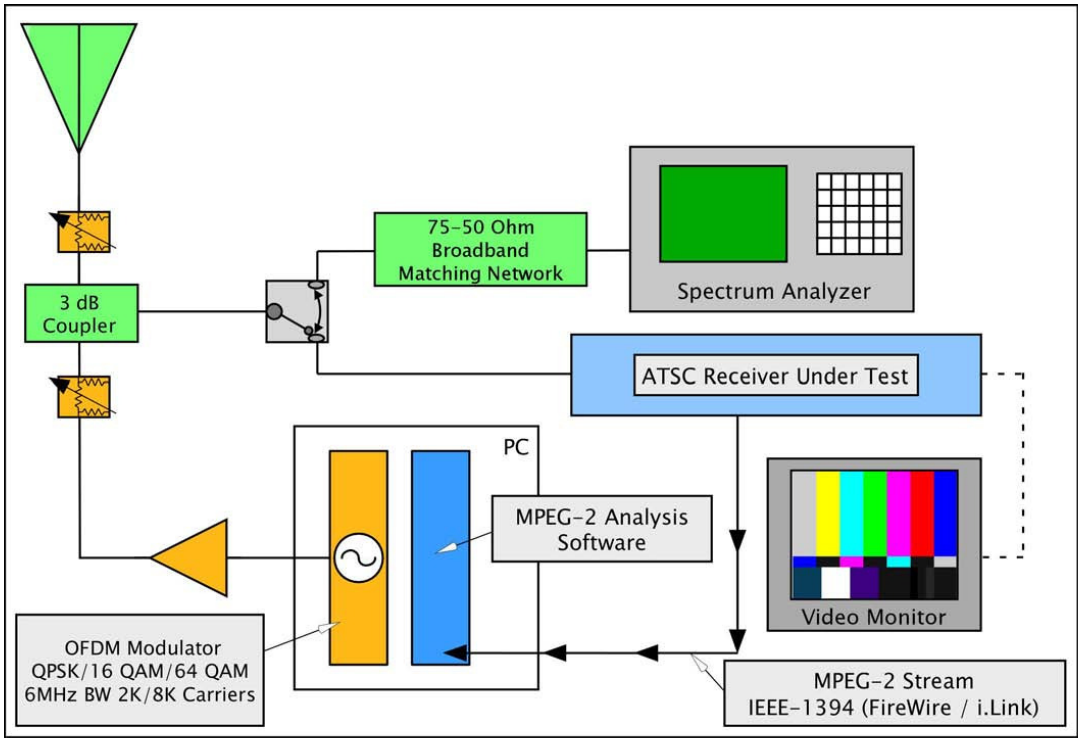


Fig. 1 - KU Unlicensed Device Emulator and Testbed (KUUDET)

An investigation studying the operation of public safety transmissions in television, when both digital and analog television signals were present, was conducted in [16]. Although several insights were obtained regarding the interaction between licensed and unlicensed transmissions, the investigation did not quantify the impact on the video quality of the television signal nor the effects of operating unlicensed devices at close distances to television transmitters.

3. KU Unlicensed Device Emulator and Testbed

The KU Unlicensed Device Emulator and Testbed (KUUDET), shown in Fig. 1, is currently configured to simulate a Secondary Device (SD) operating in the 54 MHz to 806 MHz frequency range using OFDM modulation. U-D emulation is accomplished using a desktop computer equipped with a modestly priced PCI form factor DVB-T modulator, which is capable of QPSK, 16 QAM, and 64 QAM, 2000 or 8000 carriers, and various code rates and guard intervals, with a 6 MHz transmit bandwidth. The RF output level can be software controlled over a 31.5 dB range. Additional RF amplification and step attenuation are inserted into the U-D transmit chain as required in support of specific test parameters. The U-D output and the feed from a roof-mounted consumer grade directional TV antenna are fed into a 3 dB coupler, and the combined output is switched between a spectrum analyzer and the DTV (ATSC) receiver under test.

In the case of DTV receivers equipped with an IEEE-1394 (FireWire / i.Link) output, the KUUDET has the additional capability of MPEG-2 transport stream statistics analysis, which provides more precise DTV channel performance testing. Tests to date have focused on the effects of U-D transmissions on consumer grade DTV receivers.

Although performance of the KUUDET has exceeded expectations, system enhancements are planned, and will include the addition of an 8-VSB (DTV/ATSC) modulated programmable signal source and a PCI form factor OFDM receiver, providing support for a greater range of U-D and DTV experiments.

4. Types of Interference

When wireless transmissions operate in close proximity to each other in the frequency domain, there exists the potential for these signals to interact. This interaction can negatively impact the ability of a receiver to perfectly recover the desired signal. By characterizing the spectral characteristics of the signals located within a frequency range of interest, it is possible to classify the type of interference expected at the receiver. Five types of interference that could exist between a primary DTV signal and a secondary transmission in a dynamic spectrum access network are shown in Fig. 2.

The differences between each of these types of interference are based on the relative spacing between the two transmissions, and their relative transmission power levels. For instance, when the DTV signal spectrum is located at channel n, and the secondary transmission is also located at the same channel, this is referred to *co-channel interference*. In this scenario, the desired DTV channel would be severely corrupted by Secondary Device operation due to its inability to resolve the two signals. Another type of interference can occur if the secondary signal is located in an adjacent channel, such as channel $n+1$. In this case, the DTV signal may experience *adjacent channel interference* from the secondary signal since the transmitted spectrum of the latter may not be totally confined to its allocated band. Note that as the amplitude level of the secondary transmission is increased, so does the amount of out-of-band radiation that could interfere with the DTV signal.

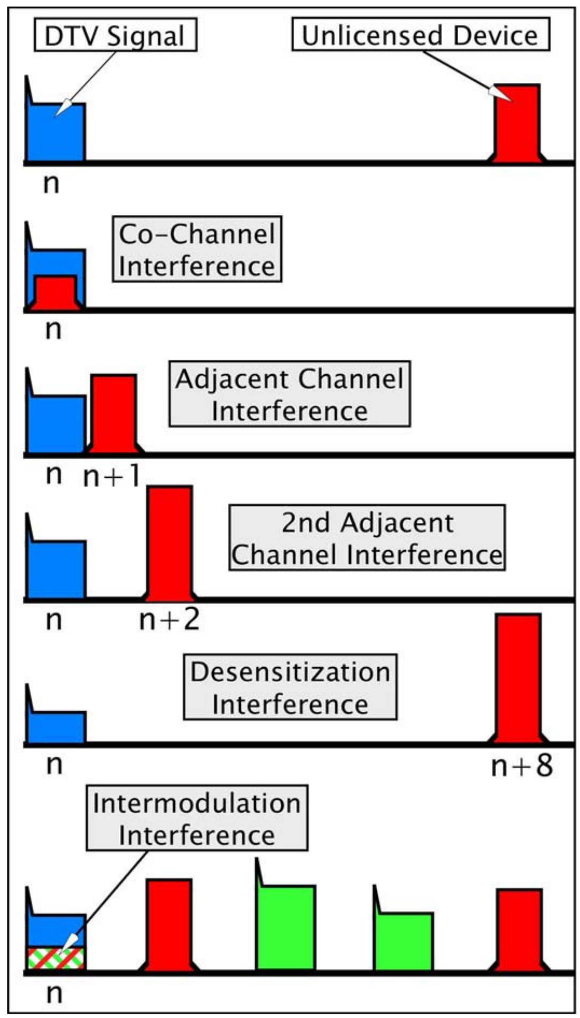


Fig. 2 - Types of DTV Receiver Interference

If the secondary signal is located further way from the DTV signal, such as the second adjacent channel, the impact of adjacent channel interference is substantially reduced, relative to secondary signals operating closer to the DTV signal, given the same power levels. However, if the power level of the secondary signal is increased, it is possible that some out-of-band radiation may interfere with the DTV signal. In fact, when the secondary signal is substantially stronger than the DTV signal and is located within the vicinity of a desired frequency, *desensitization interference* can potentially occur. In this scenario, the secondary signal overloads the receiver, inhibiting its ability to fully recover the desired DTV signal.

Receiver *intermodulation interference* occurs when two or more signals are present within the same frequency range, that are mixed in a receiver RF amplifier or mixer stage during non-linear operation, producing a signal that interferes with a desired signal. Consequently, these receiver-generated signals could prevent the display of the content of a desired DTV channel.

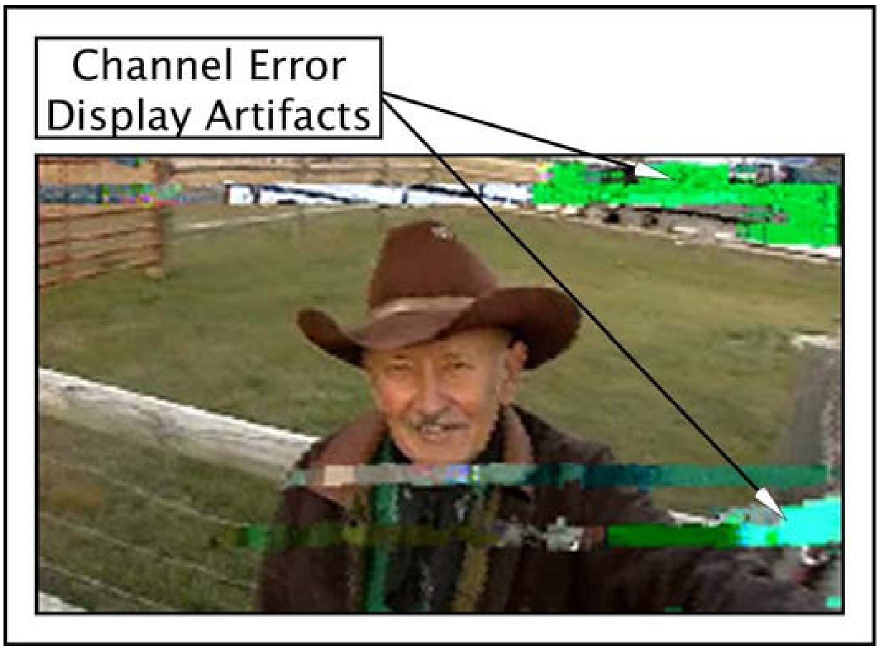


Fig. 3 - Displayed Effects of DTV Channel Errors

The visible effects of DTV receiver interference can range from mild error artifacts to complete loss of channel content display. Fig. 3 is an example of moderate display errors.

5. Initial Observations

Initial experiments reveal that a relatively high U-D channel power level is required before the output negatively impacts a DTV test receiver. The spectrum analyzer plot in Fig. 4 represents the U-D Emulator output level required to create displayed errors in a desired DTV channel with the emulator tuned two channels away.

Initial adjacent channel and co-channel measurements are illustrated in the Appendix. Shown are the U-D transmit levels (in dBm / 5.38 MHz BW) required to cause visible impairments to the DTV reception when the desired DTV signal is at the indicated level (most commonly in these tests, at the ATSC A/74 "Weak Desired" -68 dBm / 5.38 MHz) level. The ATSC Recommended Practice: Receiver Performance Guidelines A/74 document [19] was used as a reference to develop test procedures, as there is not yet a standard for non-TV (ATSC/NTSC) signals. Three receivers were tested: (1) a 1999-vintage ATSC set-top tuner, (2) a recently manufactured midrange LCD digital TV, and (3) a recently manufactured but relatively inexpensive ATSC set-top tuner.

It is important to note that no additional filtering was applied to the output of the OFDM modulator, which produced significant undesirable spurious signal levels. The measurements detailed in this report indicate the performance achievable with filtering comparable to that of the OFDM modulator card used in the KUUDET.

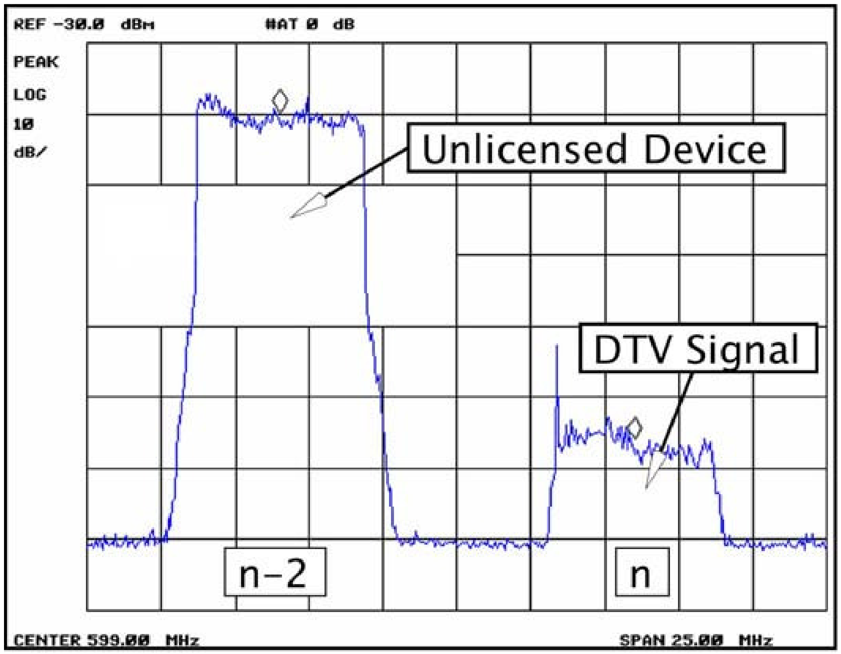
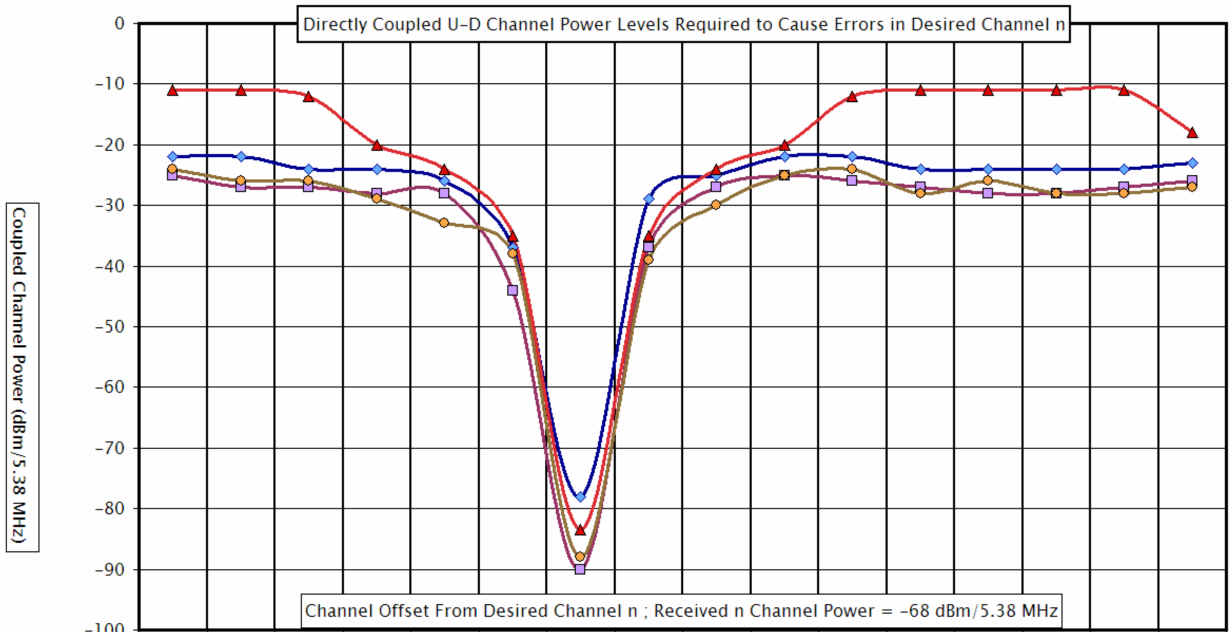


Fig. 4 - Spectrum of input to DTV receiver

TV band devices with more effective output filtering would potentially be capable of transmitting at higher power levels, without inducing negative effects into a desired DTV signal, than those reported in the measurements contained in the Appendix, with the exception of a co-channel situation.

A summary of the results is shown in Fig. 5. This is a plot of the results for the three receivers (individually reported in the Appendix, sections A.2, A.5, and A.8) versus the A/74 threshold. In this test series, the desired DTV signal was set to a -68 dBm / 5.38 MHz level, which corresponds to the A/74 "Weak Desired" level. Each receiver was tested at the channel offsets shown (e.g., n+2), and the U-D power levels that caused visible errors were recorded. These levels are shown in the plot versus the recommended A/74 profile, as well as in the table below. The Receiver #1 (1999-vintage set-top box) measurements are the purple squares, the Receiver #2 (LCD DTV) measurements are the blue diamonds, and the Receiver #3 (recent but inexpensive set-top box) measurements are the yellow circles. The A/74 profile is shown with red triangles.



	n-10	n-8	n-5	n-3	n-2	n-1	n=0	n+1	n+2	n+3	n+4	n+6	n+8	n+9	n+10	n+15
Receiver #1	-25	-27	-27	-28	-28	-44	-90	-37	-27	-25	-26	-27	-28	-28	-27	-26
Receiver #2	-22	-22	-24	-24	-26	-37	-78	-29	-25	-22	-22	-24	-24	-24	-24	-23
Receiver #3	-24	-26	-26	-29	-33	-38	-88	-39	-30	-25	-24	-28	-26	-28	-28	-27
ATSC A/74	-11	-11	-12	-20	-24	-35	-83.5	-35	-24	-20	-12	-11	-11	-11	-11	-18

Fig. 5 - Example initial DTV receiver measurement results

The Appendix displays the measurement results individually and in various formats for clarity.

The preliminary experimental results from this limited number of test receivers indicate that the proposed U-D operation in the television band can be accomplished without significant impact upon DTV receivers in the vicinity. Experiments are ongoing and will be reported in the future.

6. Conclusion

In this report, we have presented a feasibility study of secondary transmissions into the TV spectrum, and our preliminary experimental results support the claim that properly implemented secondary transmission in the television band is possible without significant impact upon DTV reception. Our hope is that this study, and future results from the continuing work at The University of Kansas in this subject area, will be of value in regulatory discussions concerning spectrum policy decisions that will ultimately define access to a valuable national asset, the TV band spectrum.

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Appendix A – Experimental Results

This appendix includes measurement results for three receivers, two set-top ATSC tuners and one LCD digital TV. Receiver performance was primarily measured using a -68 dBm/5.38 MHz desired signal level to allow comparison to the "Weak Desired" profile suggested by ATSC A/74. Also included are results at low DTV signal levels.

The measurement results appear in five groups:

1. Results for Receiver #1 1999 Set-top ATSC Tuner: -68 dBm/5.38 MHz Test (A.1, A.2, A.3)
   The results for Receiver #1 are displayed in three ways – (a) a table showing the power levels with the U-D signal at different channel offsets from the desired DTV signal, with the levels shown as power over the 5.38 MHz channel as well as per Hz, (b) a figure showing these same results versus the A/74 profile, and (c) a figure showing the same measurements represented as desired / undesired signal power ratios to allow easier comparison to A/74.

2. Results for Receiver #2 LCD DTV: -68 dBm/5.38 MHz Test (A.4, A.5, A.6)
   The results for Receiver #2 are displayed in three ways – (a) a table showing the power levels with the U-D signal at different channel offsets from the desired DTV signal, with the levels shown as power over the 5.38 MHz channel as well as per Hz, (b) a figure showing these same results versus the A/74 profile, and (c) a figure showing the same measurements represented as desired / undesired signal power ratios to allow easier comparison to A/74.

3. Results for Receiver #3 Set-top ATSC Tuner: -68 dBm/5.38 MHz Test (A.7, A.8, A.9)
   The results for Receiver #3 are displayed in three ways – (a) a table showing the power levels with the U-D signal at different channel offsets from the desired DTV signal, with the levels shown as power over the 5.38 MHz channel as well as per Hz, (b) a figure showing these same results versus the A/74 profile, and (c) a figure showing the same measurements represented as desired / undesired signal power ratios to allow easier comparison to A/74.

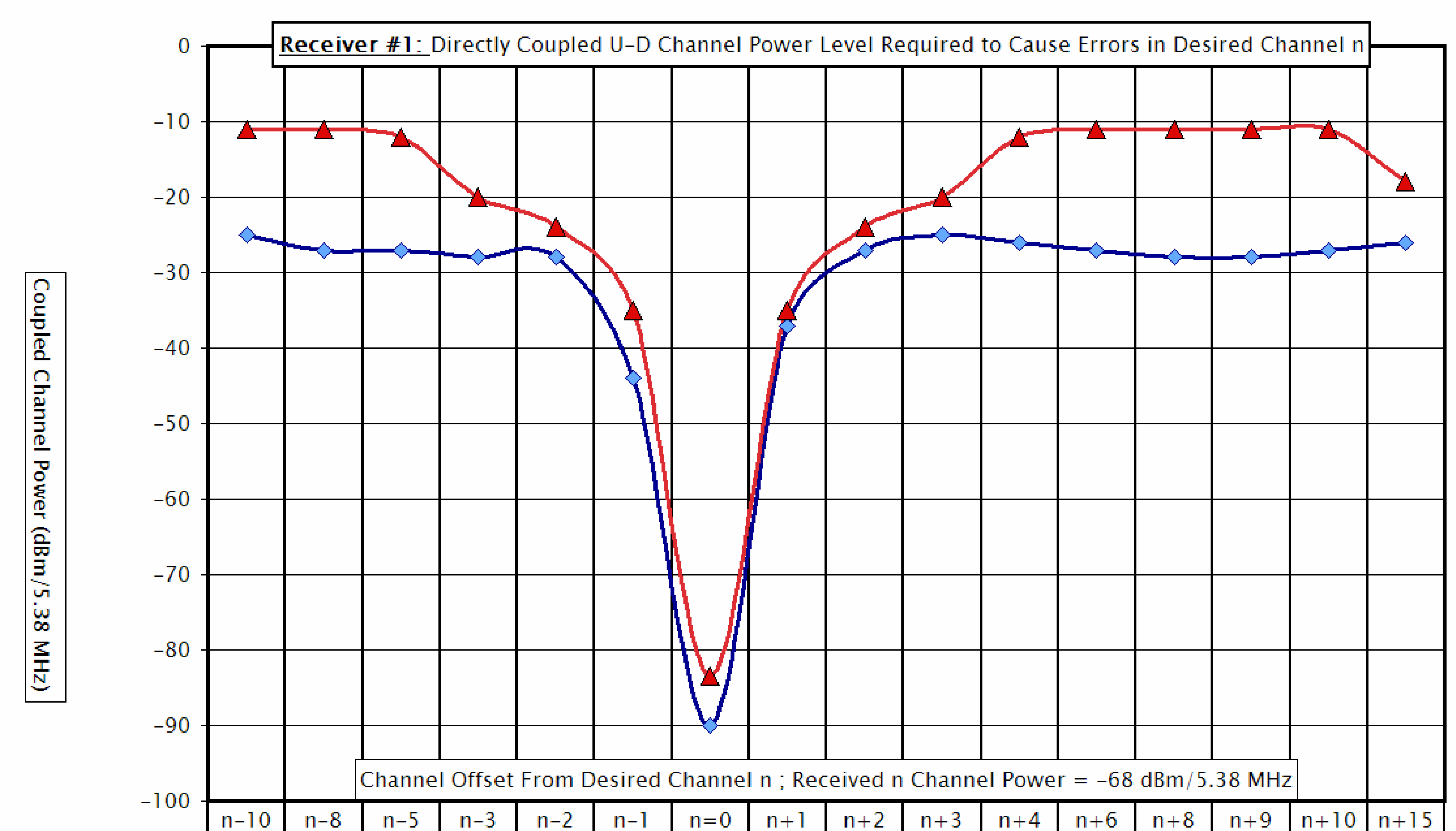
4. Summary for Receivers #1, #2, and #3 ATSC A/74 "Weak Desired" -68 dBm/5.38 MHz Tests (A.10)
   This is a summary plot of the results for the three receivers (A.2, A.5, and A.8) versus the A/74 threshold.

5. Results for Threshold Test: Desired Signal +3dB above "Error Free Threshold" of Receivers #1, #2, #3 (A.11)
   This plot is similar to A.10, but reports results with the DTV signal level at 3 dB above the error-free threshold – the level at which the receiver fails to receive properly – rather than at the A/74 "Weak Desired" level of -68 dBm/5.38 MHz.

A.1. Receiver #1 1999 Set-top ATSC Tuner: -68 dBm/5.38 MHz Test

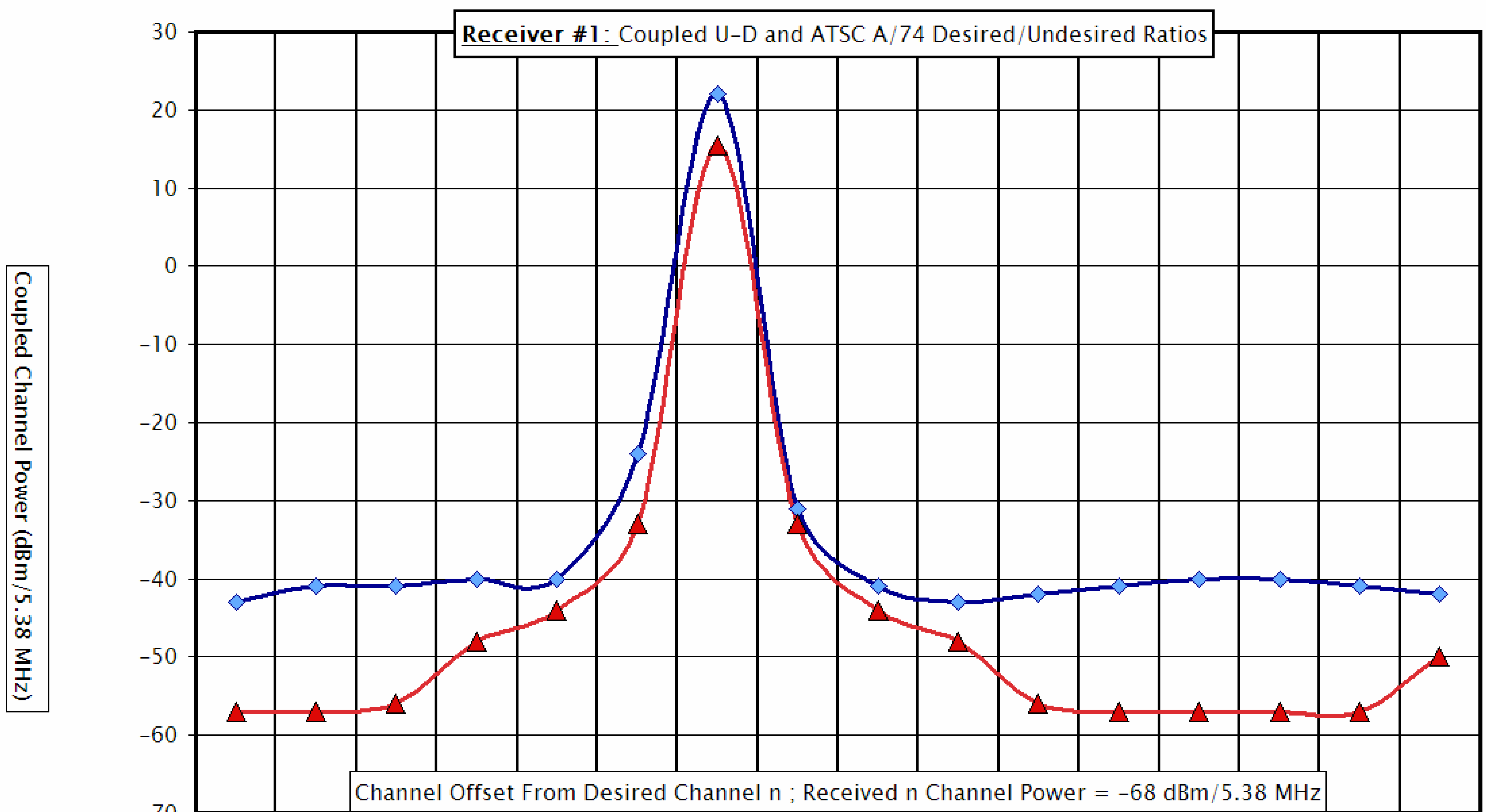
Receiver #1 Set-top ATSC Receiver (1999 Vintage)				20-Nov-06				
KMCI CH 36 605 MHz								
Channel Power		-68 dBm/5.38 MHz		-130 dBm/Hz				
CH 36 Offset	-10	-8	-5	-3	-2	-1	0 (Co-channel)	+1
U-D Channel Number f0	CH 26 545 MHz	CH 28 557 MHz	CH 31 575 MHz	CH 33 587 MHz	CH 34 593 MHz	CH 35 599 MHz	CH 36 605 MHz	CH 37 611 MHz
U-D Channel Power/5.38 MHz	-25 dBm	-27 dBm	-27 dBm	-28 dBm	-28 dBm	-44 dBm	-90 dBm	-37 dBm
	-92 dBm/Hz	-94 dBm/Hz	-94 dBm/Hz	-95 dBm/Hz	-95 dBm/Hz	-111 dBm/Hz		-104 dBm/Hz
CH 36 Offset	+2	+3	+5	+6	+8	+9	+10	+15
U-D Channel Number f0	CH 38 617 MHz	CH 39 623 MHz	CH 41 635 MHz	CH 42 641 MHz	CH 44 653 MHz	CH 45 659 MHz	CH 46 665 MHz	CH 51 695 MHz
U-D Channel Power/5.38 MHz	-27 dBm	-25 dBm	-26 dBm	-27 dBm	-28 dBm	-28 dBm	-27 dBm	-26 dBm
	-94 dBm/Hz	-92 dBm/Hz	-93 dBm/Hz	-94 dBm/Hz	-95 dBm/Hz	-95 dBm/Hz	-94 dBm/Hz	-93 dBm/Hz

A.2. Receiver #1 1999 Set-top ATSC Tuner: -68 dBm/5.38 MHz Test



	n-10	n-8	n-5	n-3	n-2	n-1	n=0	n+1	n+2	n+3	n+4	n+6	n+8	n+9	n+10	n+15
Receiver #1	-25	-27	-27	-28	-28	-44	-90	-37	-27	-25	-26	-27	-28	-28	-27	-26
ATSC A/74	-11	-11	-12	-20	-24	-35	-83.5	-35	-24	-20	-12	-11	-11	-11	-11	-18

A.3. Receiver #1 1999 Set-top ATSC Tuner: -68 dBm/5.38 MHz Test

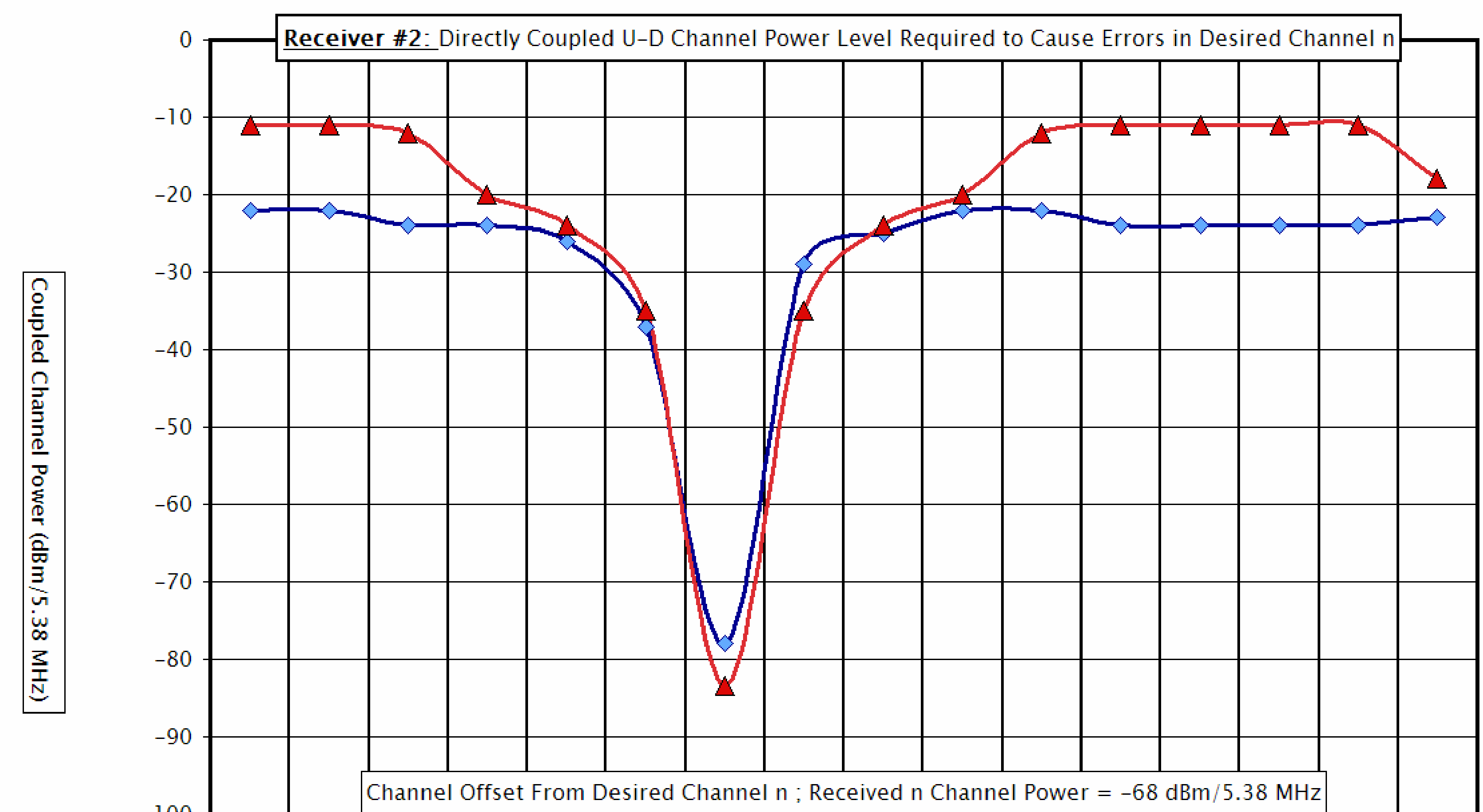


	n-10	n-8	n-5	n-3	n-2	n-1	n=0	n+1	n+2	n+3	n+4	n+6	n+8	n+9	n+10	n+15
Receiver #1	-43	-41	-41	-40	-40	-24	22	-31	-41	-43	-42	-41	-40	-40	-41	-42
ATSC A/74	-57	-57	-56	-48	-44	-33	15.5	-33	-44	-48	-56	-57	-57	-57	-57	-50

A.4. Receiver #2 LCD DTV: -68 dBm/5.38 MHz Test

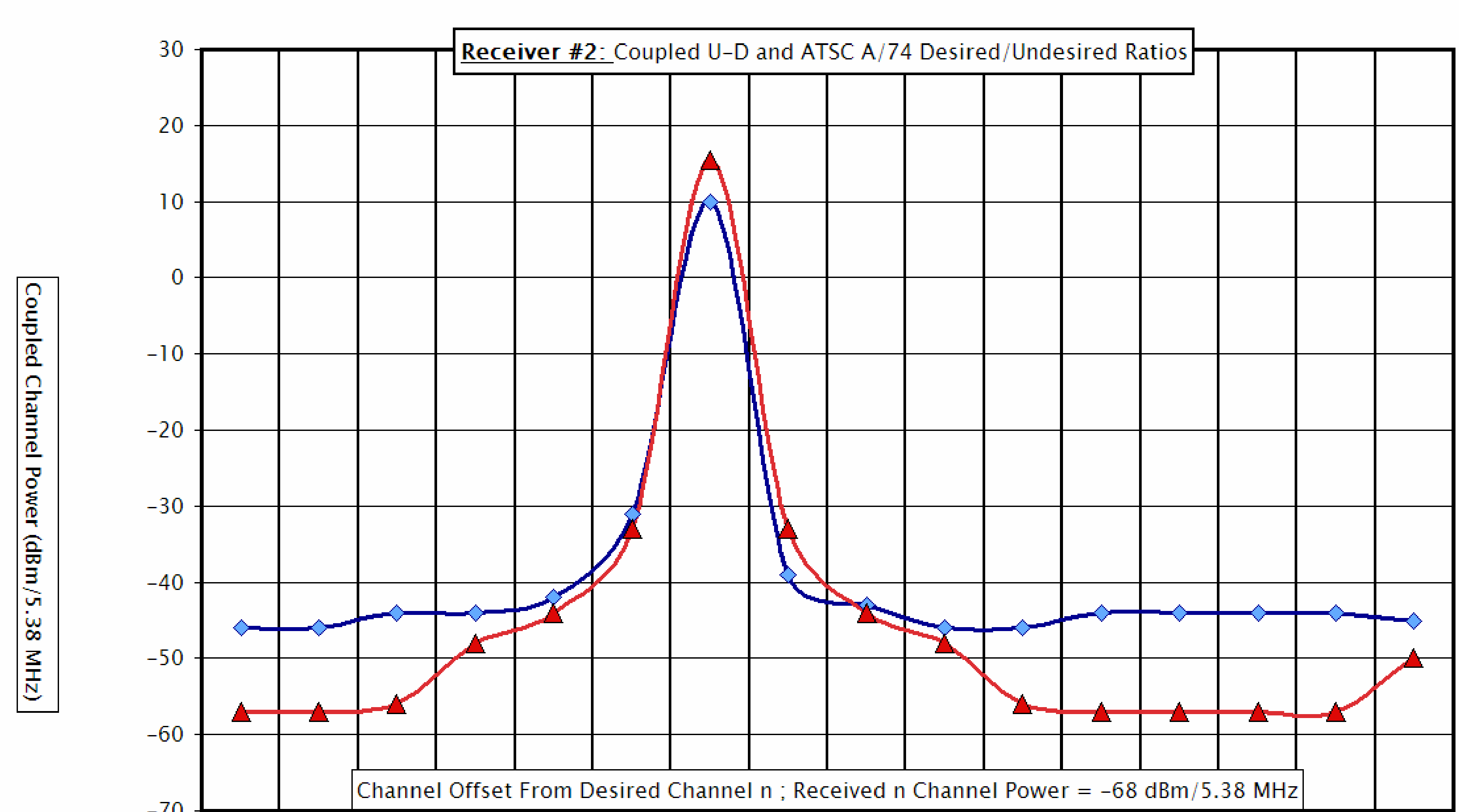
Receiver #2 LCD DTV				20-Nov-06				
	KMCI CH 36 605 MHz							
Channel Power		-68 dBm/5.38 MHz		-130 dBm/Hz				
CH 36 Offset	-10	-8	-5	-3	-2	-1	0 (Co-channel)	+1
U-D Channel Number f0	CH 26 545 MHz	CH 28 557 MHz	CH 31 575 MHz	CH 33 587 MHz	CH 34 593 MHz	CH 35 599 MHz	CH 36 605 MHz	CH 37 611 MHz
U-D Channel Power/5.38 MHz	-22 dBm	-22 dBm	-24 dBm	-24 dBm	-26 dBm	-35 dBm	-83 dBm	-29 dBm
	-89 dBm/Hz	-89 dBm/Hz	-91 dBm/Hz	-91 dBm/Hz	-93 dBm/Hz	-104 dBm/Hz		-97 dBm/Hz
CH 36 Offset	+2	+8	+5	+6	+8	+9	+10	+15
U-D Channel Number f0	CH 38 617 MHz	CH 39 623 MHz	CH 41 635 MHz	CH 42 641 MHz	CH 44 653 MHz	CH 45 659 MHz	CH 46 665 MHz	CH 51 695 MHz
U-D Channel Power/5.38 MHz	-25 dBm	-22 dBm	-22 dBm	-24 dBm	-24 dBm	-24 dBm	-24 dBm	-23 dBm
	-92 dBm/Hz	-89 dBm/Hz	-89 dBm/Hz	-91 dBm/Hz	-91 dBm/Hz	-91 dBm/Hz	-91 dBm/Hz	-90 dBm/Hz

A.5. Receiver #2 LCD DTV: -68 dBm/5.38 MHz Test



	n-10	n-8	n-5	n-3	n-2	n-1	n=0	n+1	n+2	n+3	n+4	n+6	n+8	n+9	n+10	n+15
Receiver #2	-22	-22	-24	-24	-26	-37	-78	-29	-25	-22	-22	-24	-24	-24	-24	-23
ATSC A/74	-11	-11	-12	-20	-24	-35	-83.5	-35	-24	-20	-12	-11	-11	-11	-11	-18

A.6. Receiver #2 LCD DTV: -68 dBm/5.38 MHz Test

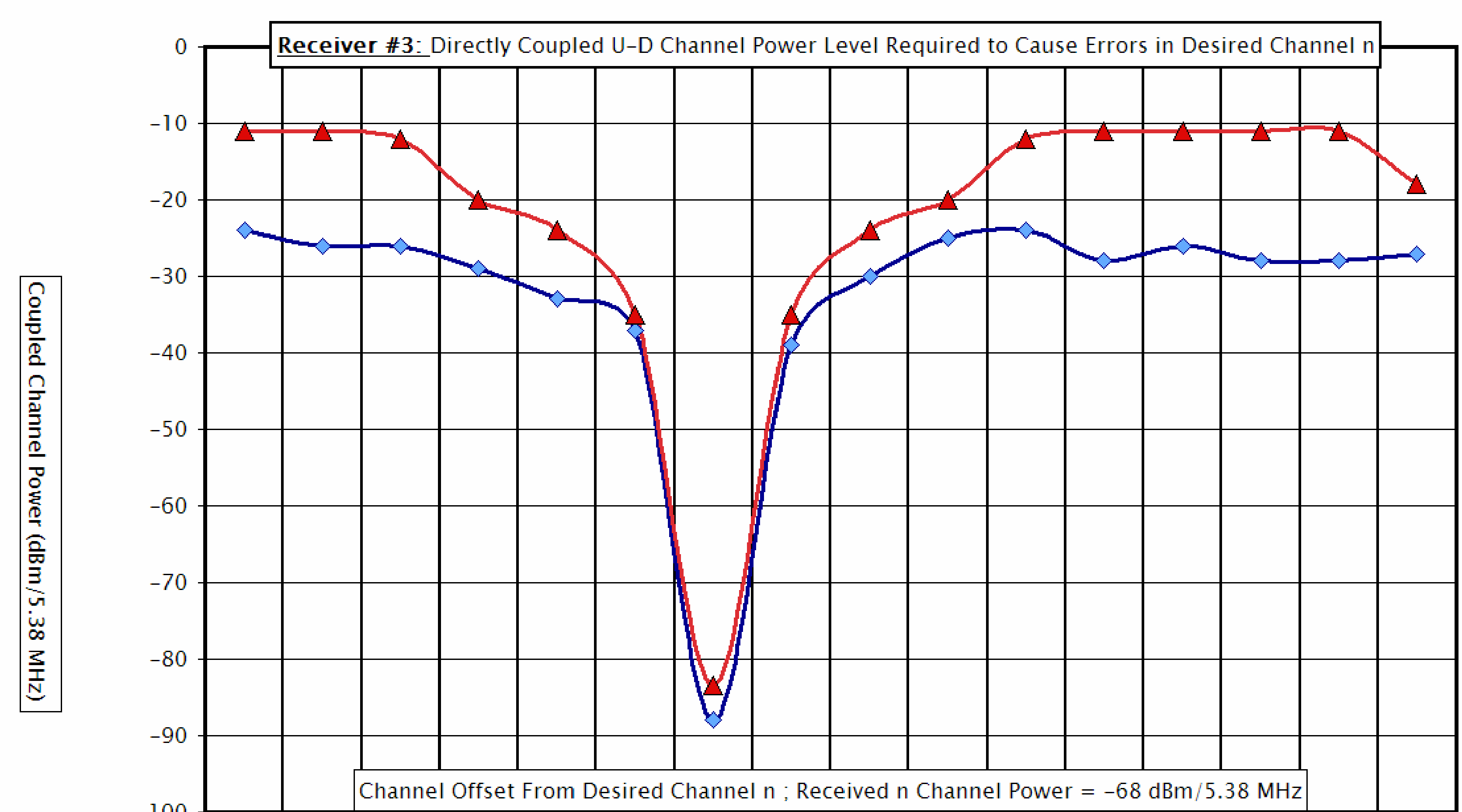


	n-10	n-8	n-5	n-3	n-2	n-1	n=0	n+1	n+2	n+3	n+4	n+6	n+8	n+9	n+10	n+15
Receiver #2	-46	-46	-44	-44	-42	-31	10	-39	-43	-46	-46	-44	-44	-44	-44	-45
ATSC A/74	-57	-57	-56	-48	-44	-33	15.5	-33	-44	-48	-56	-57	-57	-57	-57	-50

A.7. Receiver #3 Set-top ATSC Tuner: -68 dBm/5.38 MHz Test

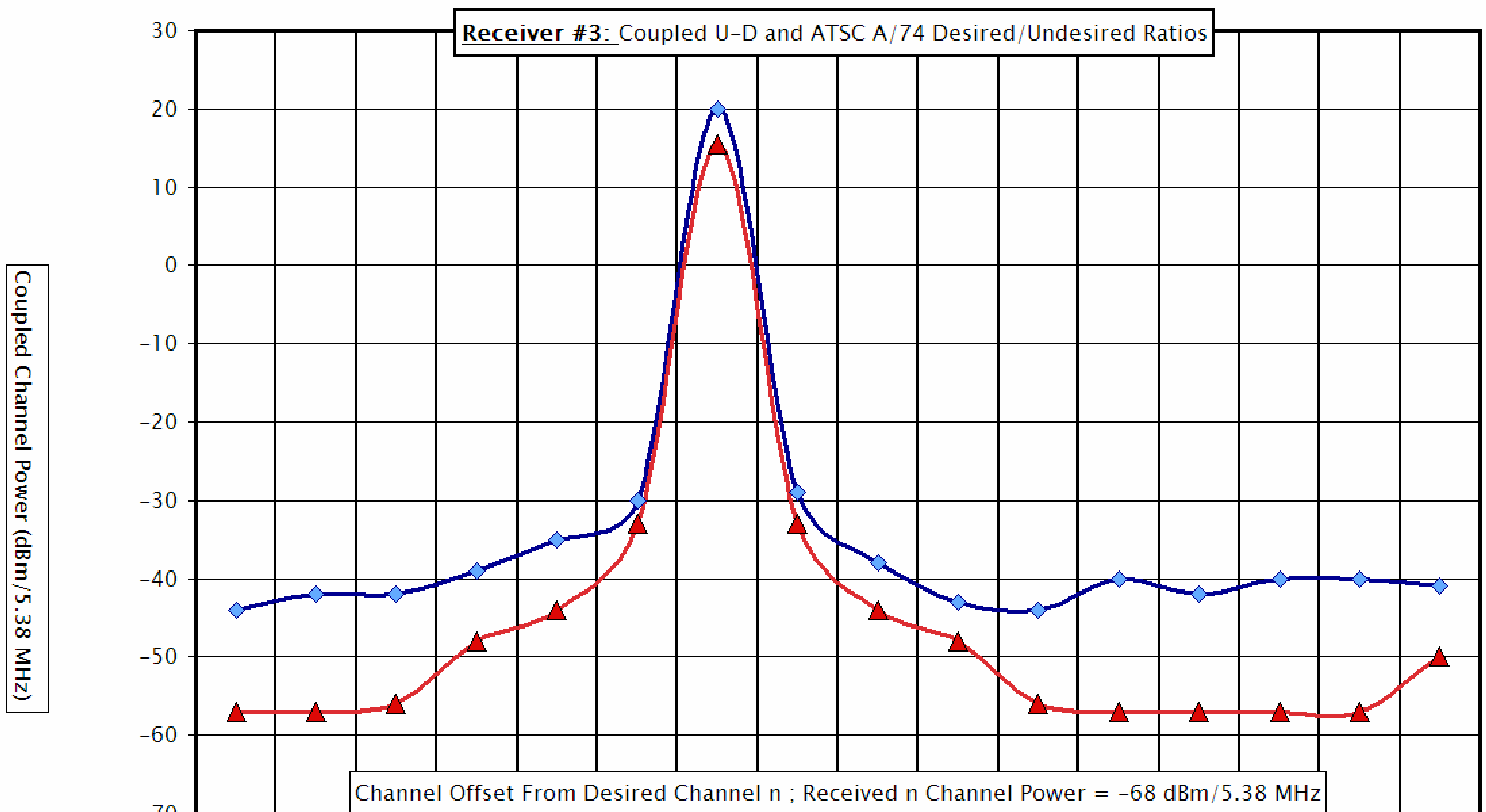
Receiver #3 Set-top ATSC Receiver				20-Nov-06				
KMCI CH 36 605 MHz								
Channel Power		-68 dBm/5.38 MHz		-130 dBm/Hz				
CH 36 Offset	-10	-8	-5	-3	-2	-1	0 (Co-channel)	+1
U-D Channel Number f0	CH 26 545 MHz	CH 28 557 MHz	CH 31 575 MHz	CH 33 587 MHz	CH 34 593 MHz	CH 35 599 MHz	CH 36 605 MHz	CH 37 611 MHz
U-D Channel Power/5.38 MHz	-24 dBm	-26 dBm	-26 dBm	-29 dBm	-33 dBm	-38 dBm	-88 dBm	-39 dBm
	-91 dBm/Hz	-93 dBm/Hz	-93 dBm/Hz	-96 dBm/Hz	-100 dBm/Hz	-105 dBm/Hz		-106 dBm/Hz
CH 36 Offset	+2	+3	+5	+6	+8	+9	+10	+15
U-D Channel Number f0	CH 38 617 MHz	CH 39 623 MHz	CH 41 635 MHz	CH 42 641 MHz	CH 44 653 MHz	CH 45 659 MHz	CH 46 665 MHz	CH 51 695 MHz
U-D Channel Power/5.38 MHz	-30 dBm	-25 dBm	-24 dBm	-28 dBm	-26 dBm	-28 dBm	-28 dBm	-27 dBm
	-97 dBm/Hz	-92 dBm/Hz	-91 dBm/Hz	-95 dBm/Hz	-93 dBm/Hz	-95 dBm/Hz	-95 dBm/Hz	-94 dBm/Hz

A.8. *Receiver #3 Set-top ATSC Tuner: -68 dBm/5.38 MHz Test*



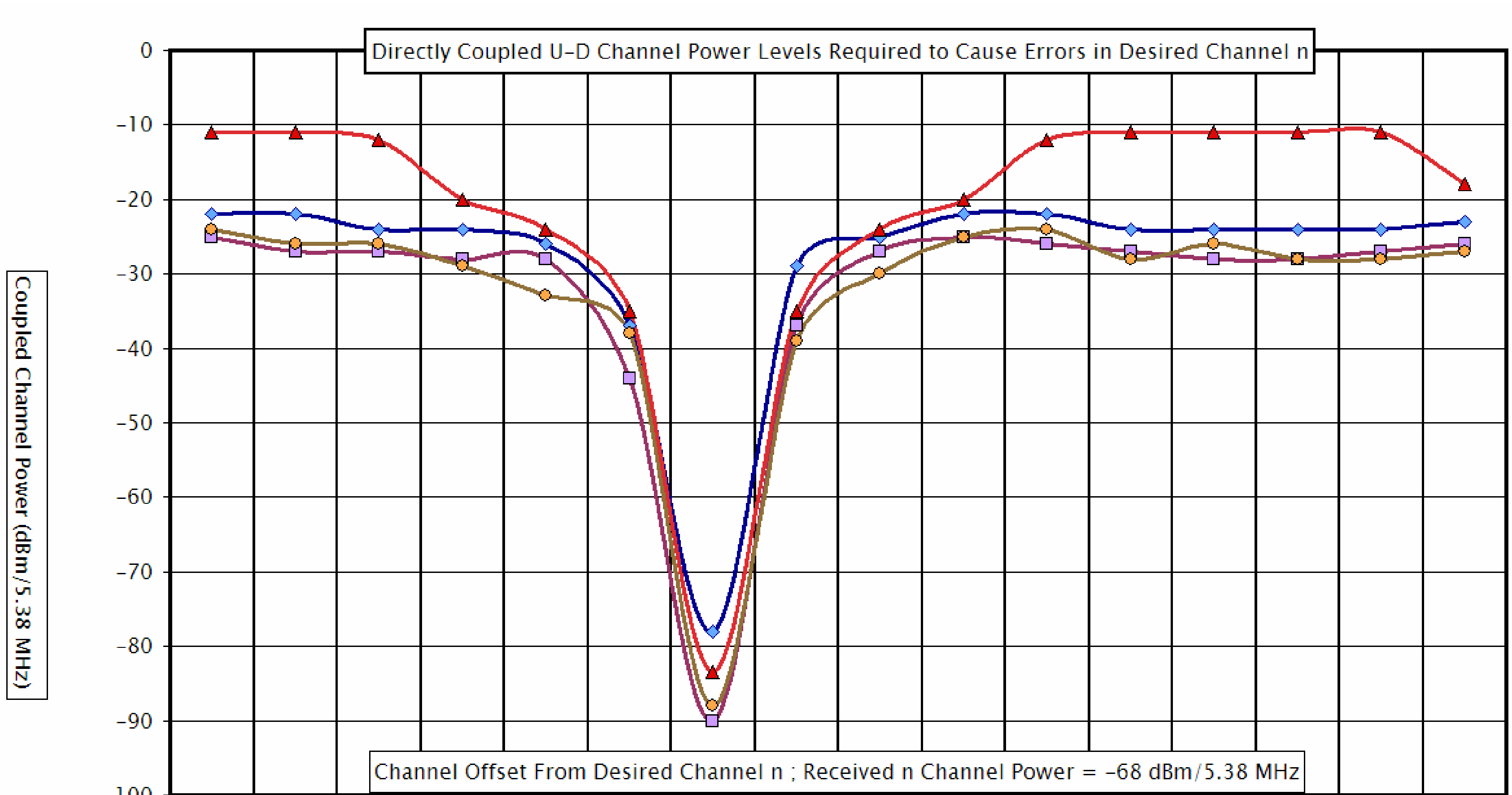
	n-10	n-8	n-5	n-3	n-2	n-1	n=0	n+1	n+2	n+3	n+4	n+6	n+8	n+9	n+10	n+15
Receiver #3	-24	-26	-26	-29	-33	-37	-88	-39	-30	-25	-24	-28	-26	-28	-28	-27
ATSC A/74	-11	-11	-12	-20	-24	-35	-83.5	-35	-24	-20	-12	-11	-11	-11	-11	-18

A.9. Receiver #3 Set-top ATSC Tuner: -68 dBm/5.38 MHz Test



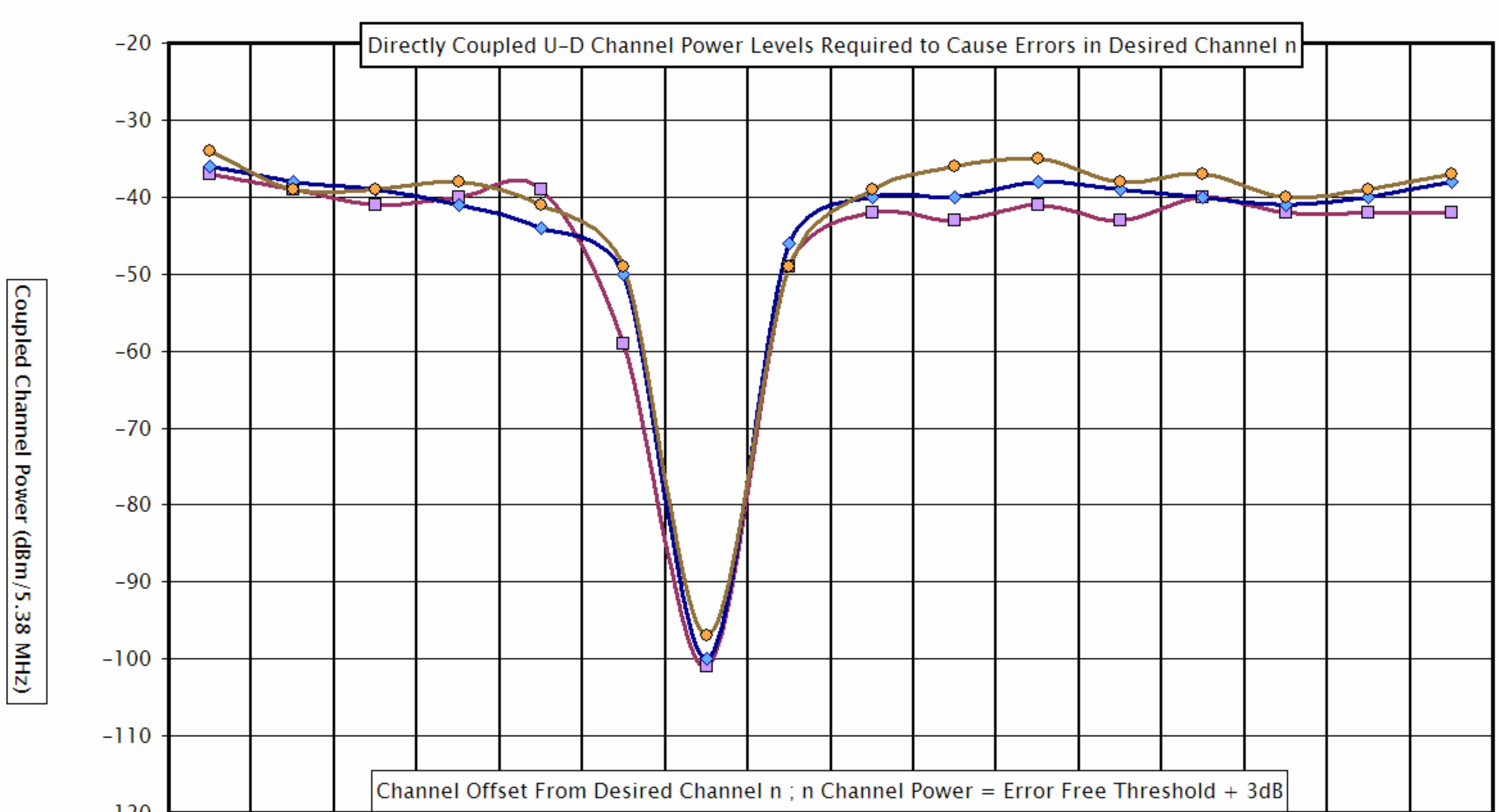
	n-10	n-8	n-5	n-3	n-2	n-1	n=0	n+1	n+2	n+3	n+4	n+6	n+8	n+9	n+10	n+15
Receiver #3	-44	-42	-42	-39	-35	-30	20	-29	-38	-43	-44	-40	-42	-40	-40	-41
ATSC A/74	-57	-57	-56	-48	-44	-33	15.5	-33	-44	-48	-56	-57	-57	-57	-57	-50

A.10. Receivers #1, #2, and #3 ATSC A/74 “Weak Desired” -68 dBm/5.38 MHz Test



	n-10	n-8	n-5	n-3	n-2	n-1	n=0	n+1	n+2	n+3	n+4	n+6	n+8	n+9	n+10	n+15
Receiver #1	-25	-27	-27	-28	-28	-44	-90	-37	-27	-25	-26	-27	-28	-28	-27	-26
Receiver #2	-22	-22	-24	-24	-26	-37	-78	-29	-25	-22	-22	-24	-24	-24	-24	-23
Receiver #3	-24	-26	-26	-29	-33	-38	-88	-39	-30	-25	-24	-28	-26	-28	-28	-27
ATSC A/74	-11	-11	-12	-20	-24	-35	-83.5	-35	-24	-20	-12	-11	-11	-11	-11	-18

A.11. Threshold Test: Desired Signal +3dB above "Error Free Threshold" of Receivers #1, #2, #3



	n-10	n-8	n-5	n-3	n-2	n-1	n=0	n+1	n+2	n+3	n+4	n+6	n+8	n+9	n+10	n+15
Receiver #1	-37	-39	-41	-40	-39	-59	-101	-49	-42	-43	-41	-43	-40	-42	-42	-42
Receiver #2	-36	-38	-39	-41	-44	-50	-100	-46	-40	-40	-38	-39	-40	-41	-40	-38
Receiver #3	-34	-39	-39	-38	-41	-49	-97	-49	-39	-36	-35	-38	-37	-40	-39	-37

Receiver # 1: Desired Channel Power = -80 dBm/5.38 MHz (-83 dBm/5.38 MHz EFT)
Receiver # 2: Desired Channel Power = -81 dBm/5.38 MHz (-84 dBm/5.38 MHz EFT)
Receiver # 3: Desired Channel Power = -78 dBm/5.38 MHz (-81 dBm/5.38 MHz EFT)

Appendix B – Biographical Sketches

Mr. Daniel DePardo is a Research Engineer at the Information and Telecommunication Technology Center (ITTC) of the University of Kansas, and is responsible for the radio frequency (RF) laboratory activities of the Center. Mr. DePardo has a military electronics background, and extensive test and measurement, RF hardware design, and prototype fabrication experience.

Mr. DePardo accepted a staff position with the University of Kansas Electrical Engineering and Computer Science (EECS) department in 1993, and was invited to join ITTC in 1997 because of his outstanding contributions to the research efforts of the EECS faculty.

His primary areas of research interest are transceiver and antenna design. Secondary areas of expertise include Surface Acoustic Wave device design, PCB photolithography and assembly, electronics environmental testing, and radio frequency and electromagnetic interference suppression techniques. He has designed, constructed and successfully demonstrated hardware prototypes in support of numerous defense programs and academic research projects, and holds a U.S. Patent for a novel wide-band antenna design.

Dr. Joseph B. Evans was born in New Jersey in 1961. He received the B.S.E.E. degree from Lafayette College in 1983, and the M.S.E., M.A., and Ph. D. degrees from Princeton University in 1984, 1986, and 1989, respectively.

In 1989, he joined the faculty at the University of Kansas (KU), where he is the Deane E. Ackers Distinguished Professor of Electrical Engineering & Computer Science. He is also the Director of Research Information Technology for the University of Kansas, reporting to the Vice Provost for Research. From 1997 to 2004, he served as Director of the Networking & Distributed Systems Laboratory at the Information & Telecommunication Technology Center (ITTC), the second largest research center at the University of Kansas, with approximately 150 faculty, staff, and students, and annual expenditures of approximately $7 million. He served as Acting Director of ITTC from October 1999 to August 2000.

Dr. Evans served as a Program Director in the Division of Computer and Network Systems, Directorate of Computer & Information Science & Engineering at the National Science Foundation from 2003 to 2005.

He was a co-founder and member of the Board of Directors of NetGames USA, Inc., a network gaming company acquired by Microsoft in 2000; XBox Live, Microsoft's Internet gaming service, utilizes the NetGames USA technology. Dr. Evans was also President and CEO of Ambient Computing, Inc., which developed software and hardware solutions that enable smart wireless environments.

Dr. Evans has ongoing research projects in the areas of ubiquitous computing environments, active networks, and network performance enhancement. He is currently a member of the planning group for the NSF Global Environment for Network Innovations (GENI).

He has been involved in a variety of networking projects while at KU, ranging from the MAGIC gigabit networking testbed (developing high speed SONET/ATM systems and performing protocol tuning), the ACTS ATM Internet, and the Rapidly Deployable Radio Network project (creating mobile broadband wireless systems) to a collaborative effort with the KU School of Education to deliver K-12 educational resources over the Internet during the early days of the web (students on this project were founding members of Netscape).

Dr. Evans spent the 1996-1997 academic year on sabbatical at Cambridge University and Olivetti & Oracle Research Laboratory in Cambridge, England, working in the area of mobile computing and communications systems. He participated in the Air Force Summer Research Program at Hanscom AFB in 1991.

Prior to joining the University of Kansas, he held a postdoctoral position in the Network Systems Research Department of AT&T Bell Laboratories in Holmdel, New Jersey, where he was involved in the design of a high performance integrated network. While at Princeton, he was awarded an AT&T Bell Laboratories Graduate Fellowship for 1984-1988; during this time, he was also a part time employee of Bell Labs, working in the field of speech processing algorithms for packet networks.

Dr. Evans is a Senior Member of the IEEE, is currently Chair of the IEEE Communications Society Technical Committee on High-Speed Networks, and has recently served as Associate Editor of the IEEE Communications Letters. He is also a member of the ACM.

His current research interests include high-speed networks, active networks, ubiquitous computing environments, adaptive processing systems, and system implementations.

Dr. James A. Roberts is Vice Provost for Research for the Lawrence campus of the University of Kansas, and President and Chief Operating Officer of the KU Center for Research, Inc.

He joined the faculty at KU in 1990 as Professor and Chair of the Department of Electrical and Computer Engineering. His primary teaching and research interests are in wireless telecommunications. During his tenure as Chair (1990-97), he led the successful merger of two departments to form KU's Department of Electrical Engineering and Computer Science.

Dr. Roberts was named Associate Vice Chancellor/Provost for Research at KU in 1998. He served in that capacity until 2003, when he was named Interim Vice Provost for Research. In 2004, he was named to the position on a permanent basis. "This is a great time to be at KU," he said. "We have a tremendous opportunity to build a research powerhouse that will drive economic growth for the state and the region. We can make KU a truly outstanding place for students, now and in the future."

Since 1998, research awards at KU's Lawrence and Medical Center campuses grew by 85 percent, from $118 million in 1998 to $218 million in 2006. Federal science and engineering research expenditures grew by 128 percent, from $51 million to $116 million. Total sponsored project grants and contracts expenditures grew by 91 percent, from $104 million to $200 million.

Dr. Roberts came to KU following a lengthy and successful career in industry. From 1969 to 1983, he held management positions with ESL, Inc., a Silicon Valley start-up company that became a subsidiary of TRW in 1978. He then held management positions with TRW's Systems Integration Group in Denver from 1983 to 1990.

Dr. Roberts is a 1966 graduate of KU with a B.S. degree in electrical engineering. He received an M.S. degree in electrical engineering from M.I.T. in 1968 and a Ph.D. degree in electrical engineering from Santa Clara University in 1979. During his career, he has published extensively, been active as a principal investigator on grant-funded research, and served as a consultant to universities and state/federal agencies.

Dr. Roberts is a member of U.S. Senator Pat Roberts' Advisory Committee on Science, Technology and the Future. He also serves on the Executive Committee of the Kansas Bioscience Organization, the Board of the Lawrence-Douglas County Bioscience Authority, and the Board of the Lawrence Regional Technology Center, Inc.

He is a registered professional engineer in Kansas and a Fellow of the Institute of Electrical and Electronics Engineers (IEEE). He has served his profession for many years in national leadership positions, notably as a member (since 1996) and current Chair of the Steering Committee for the annual Frontiers in Education Conference, co-sponsored by IEEE and the American Society for Engineering Education.

Mr. Victor R. Petty IV is a graduate research assistant and Masters degree candidate at the University of Kansas. His work has involved the development of frequency-agile transceivers as well as spectrum measurements and characterization. He is also interested in software defined radios as well as embedded and reconfigurable systems. He has been an IEEE Student member since 2001 and has served as the KU IEEE Chapter President. Mr. Petty is also actively involved in the KU campus radio station KJHK and participates in educational outreach programs through the KU EECS department.

Dr. Alexander M. Wyglinski was born in Montreal, Quebec, Canada. He received his Bachelor of Engineering in Electrical Engineering with distinction from McGill University in 1999, his Master of Science (Engineering) in Electrical Engineering from Queen's University at Kingston in 2000, and his Doctor of Philosophy degree in Electrical Engineering at McGill University in 2004. He is currently an Assistant Research Professor in the Information and Telecommunication Technology Center at The University of Kansas.

Throughout his graduate studies, Dr. Wyglinski was supported by a number of postgraduate scholarships and awards, including those provided by the Natural Sciences and Engineering Research Council of Canada (NSERC) and Le Fonds "Nature et Technologies" du Quebec. He has worked for the Department of National Defence in Ottawa twice as a Defence Research Assistant during the summers of 1997 and 1998, a Graduate Research Assistant at Queen's University and McGill University from 1999 to 2004, a Faculty Lecturer at McGill University in 2003, and a Research Associate for the Center for Advanced Systems and Technologies in Communications (SYTACom) and the Agile All-Photonic Networks (AAPN) Research Network.

Dr. Wyglinski is an active member of the research community, participating in activities that help facilitate the exchange of ideas between members within the community. Specifically, he serves the community as an editor for the IEEE Communications Surveys and Tutorials, a guest editor for the IEEE Communications Magazine Feature Topic on Cognitive Radios for Dynamic Spectrum Access, a guest editor for the ACM/Springer Mobile Networks and Applications (MONET) Special Issue on Cognitive Radio Oriented Wireless Networks and Communications, a Technical Program Committee co-chair for the 2nd International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom), and a track co-chair for the 66th and 64th IEEE Vehicular Technology Conferences. Further, he is or has been a

Technical Program Committee member for the 2006 IEEE Global Telecommunications Conference (Wireless Communications and Networking Symposium), the 2007 IEEE Consumer Communications and Networking Conference (Workshop on Cognitive Radio Networks), the 2007 IEEE Wireless Communications and Networking Conference (PHY/MAC Layer Symposium), the 2007 IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks, the 2007 IEEE International Conference on Communications (Wireless Communications Symposium, "Towards Cognition in Wireless Networks" Workshop), the 2007 IEEE Global Telecommunications Conference (Wireless Communications Symposium), and the 2008 IEEE International Conference on Communications (Communication Theory Symposium). Dr. Wyglinski is a Member of the IEEE, IEEE Communications Society, IEEE Signal Processing Society, and IEEE Vehicular Technology Society.

Dr. Wyglinski's current research interests are in the areas of wireless communications, wireless networks, cognitive radios, software-defined radios, transceiver optimization algorithms, dynamic spectrum access networks, hybrid fiber-wireless networking, signal processing techniques for digital communications, and digital communications.

Dr. Paul Kolodzy has 20 years of experience in technology development for advanced communications, networking, electronic warfare, and spectrum policy for government, commercial, and academic clients. He is currently a Communications Technology Consultant in Advanced Wireless and Networking Technology based near Washington DC.

Prior to being a consultant, Dr. Kolodzy has been: Director of the Center for Wireless Network Security (WiNSeC) at Stevens Institute of Technology; during 2002, the Senior Spectrum Policy Advisor at the Federal Communications Commission (FCC) and Director of Spectrum Policy Task Force charged with developing the next generation spectrum policy; Program Manager at the Defense Advanced Projects Agency (DARPA) in the Advanced Technology Office managing R&D for communications programs to develop generation-after-next capabilities; Director of Signal Processing and Strategic Initiatives at Sanders, A Lockheed Martin Company; and a Group Leader/Staff Member at MIT Lincoln Laboratory in the areas of Optical Systems for Laser Radars, Signal Processing, and Target Recognition for Acoustics, RF (SAR), and Optical signatures. He received his PhD and MS in Chemical Engineering from Case Western Reserve University and his BS in Chemical Engineering from Purdue University.

Michael Marcus, Sc.D. is a native of Boston and received S.B. and Sc.D. degrees in electrical engineering from MIT. Prior to joining the FCC in 1979, he worked at Bell Labs on the theory of telephone switching, served in the Air Force where he was involved in underground nuclear test detection research, and analyzed electronic warfare issues at the Institute for Defense Analyses.

At FCC his work focused on developing policies for cutting edge radio technologies such as spread spectrum/CDMA and millimeterwaves. The FCC rules that are the basis of Wi-Fi and Bluetooth are one outcome of his early leadership.

Awarded a Mike Mansfield Fellowship in 1997, he studied the Japanese language and spent a year at the FCC's Japanese counterpart.

He retired from FCC in March 2004 after serving as a senior technical advisor to the Spectrum Policy Task Force and co-directing the preparation of the FCC's cognitive radio rulemaking. He is now Director of Marcus Spectrum Solutions, an independent consulting firm in wireless technology and policy. He was recognized as a Fellow of the IEEE "for leadership in the development of spectrum management policies".