A Report To The Consumer Electronics Association Regarding Laboratory Testing of Recent Consumer DTV Receivers With Respect To DTV & LTE Interference

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1. EXECUTIVE SUMMARY

This CEA 2014 laboratory test was performed on 14 consumer television receivers primarily from 2012-2013, with two from 2006 for comparison. The more modern units represented an estimated 85% of DTV (tuner) shipments in the U.S. in the period 2012-2013. While general tests (signal dynamic range, added white noise threshold) were performed on all units, a subset of 6 underwent more extensive DTV-into-DTV and LTE-into-DTV interference testing.

Important guideposts for this testing were the ATSC A/74 "Recommended Practice" document[1] ("A/74") and the FCC OET test report of 2007[2] ("Martin 2007").

The CEA 2014 testing evaluated the interference rejection capability of modern DTV sets, now and in what might be expected in a post-spectrum-auction world of repacked television spectrum. Interference sources included ATSC 8-VSB DTV test transmissions and LTE (3GPP E-UTRA Rel. 10) base station test transmissions. The LTE test signals were 5 MHz and 10 MHz wide, and included a simulated "lightly loaded" 5 MHz version to probe for impact of LTE signal power variations in the absence of data traffic.

The testing was conducted in the Meintel, Sgrignoli, and Wallace (MSW) laboratory, where the test bed consisted of high-quality laboratory source and measurement test equipment, with a dynamic range beyond the expected D/U interference ratios required to be measured. Testing was performed by trained staff using industry-standard practices.

The CEA 2014 tests were designed to isolate the receiver D/U performance, and so transmitter splatter was carefully filtered out. Consequently, care must be taken in applying these results directly to any planning in the spectrum allocation process.

From the results, it can be seen that the DTV receivers performed extremely well to A/74 guidelines and in the presence of single interferers. Receiver performance was impaired in the presence of intermodulation effects from N+k/N+2k interference pairs.

Dynamic range (based on overload and sensitivity results), added white Gaussian noise, and computed noise figure all met or exceeded A/74 guidelines. Dynamic range was greater than 90 dB; sensitivity was consistently better than -84 dBm; SNR threshold better than 15.2 dB; noise figure better than 7 dB; and all receivers were able to receive signals up to +5 dBm.

With DTV co-channel interference, receivers again exceeded A/74 guidelines; with median performance of 14.4 dB D/U required (vs. 15.5 dB per A/74) in the presence of an undesired DTV signal co-channel.

With a single DTV interferer, all six receivers tested met the D/U ratio targets in A/74. Again, it is important to note that the testing was performed without the first adjacent DTV splatter; this splatter must be considered before applying these results to spectrum allocation.

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1 "A/74:2010, ATSC Recommended Practice: Receiver Performance Guidelines", ATSC, April 7, 2010.

2 Stephen R. Martin, "Interference Rejection Thresholds of Consumer Digital Television Receivers Available in 2005 and 2006", OET Report Prepared by: FCC/OET 07-TR-1003, March 30, 2007.

For cases with multiple DTV interferers, where there are no ATSC A/74 recommended targets, thresholds decreased by 5 to 20 dB as compared to single interferer scenarios. The impact of an interference pair correlates to the power in the stronger interferer, as would be expected.

When considering LTE as the interference source, the results are similar to DTV; however some additional points should be noted.

- For LTE co-channel interference, the receivers needed approximately 1 dB additional D/U ratio margin as compared to a DTV co-channel interferer
- For an LTE single channel interferer, the results are similar to those for a DTV single channel interferer.
- With a pair of sources, one LTE and one DTV for the multiple interferer pair, the results were similar to two DTV sources, including the worst case IM3 (N±k/N±2k) interference pairs.

This testing also investigated the required guard band between a DTV channel and an LTE interferer.

- DTV tuners exhibited co-channel-like behavior when the spectrum overlap between DTV and LTE was from 3 to 5 MHz (i.e., -3 to -5 MHz guard band), with some 15 dB D/U ratio required.
- Tuners transitioned to something like adjacent channel behavior when there was near or at zero guard band, but with 15 – 20 dB less robustness as compared to the true single channel interferer curves.
- There was a transition region 2 – 3 MHz wide between these two regions, and in this transition region the D/U ratios fluctuated about 1 – 2 dB. The root cause of this effect is not known, but as long as there is a guard band between LTE and DTV in the field, the effect can be avoided.

With regard to receiver-to-receiver variations, most of the modern receivers were typically clustered around similar performance points, with one receiver showing less sensitivity and linearity than the others (but still generally within the comments in this section). The two older receivers were split: one had higher noise and less apparent linearity, the other was clustered with the current (2012-2013) units.

2. BACKGROUND INFORMATION

The Consumer Electronics Association (CEA), based in Arlington, VA, contracted the firm of Meintel, Sgrignoli, and Wallace (MSW) in November 2013 to perform laboratory RF tests on a sampling of popular Advanced Television System Committee (ATSC) flat-screen consumer digital television (DTV) receivers that have been on the market during the last couple of years. The scope of work (SOW) requested by CEA was to perform laboratory RF interference tests on a calibrated test bed, followed by careful data analysis and archiving, and then conclude with a detailed written report. Specifically, the purpose of the test was to measure and compare interference performance of these modern DTV receivers to the guidelines referenced in the ATSC A/74 document[3] and similarly described in Martin 2007, a Federal Communications Commission (FCC) laboratory test document[4]. The Martin 2007 test sought to obtain DTV interference performance from:

> *"non-TV use of locally-unused spectrum within the TV broadcast spectrum, which is also often termed "white-space" use;*
>
> *"non-TV use of spectrum adjacent to or near TV broadcast spectrum (e.g., the TV channel 52 to 67 spectrum that will be auctioned for other uses); and,*
>
> *"other DTV stations."* [5]

As interference sources, the Martin 2007 testing used the 6 MHz ATSC digital television system (using 8-VSB modulation) and a 5 MHz DVB-H system (using COFDM modulation). CEA likewise desired documentation of DTV receiver interference performance as it relates to other terrestrial broadcast DTV signals (DTV-into-DTV) as well as to Long Term Evolution (LTE) signals (LTE-into-DTV) used in 4G mobile broadband systems that may share nearby spectrum after a spectrum repack following the 600 MHz Spectrum Incentive Auctions.

CEA and MSW engineers together formulated an initial detailed customized test plan to make measurements on 14 production DTV receivers in a fully-equipped and carefully-calibrated MSW laboratory by experienced test engineers following a specific written test matrix. This laboratory test utilized some of the concepts found in both the aforementioned ATSC A/74 document and Martin 2007. However, these two documents were used as general guidelines only; the CEA 2014 test plan did not call for duplicating all of these RF tests. This CEA 2014 laboratory test specifically provides information on:

(1) Co-channel and adjacent channel ("taboo") DTV set performance in the presence of other ATSC DTV signals in conditions that may be similar to that after spectrum repacking.

(2) Co-channel and adjacent channel ("taboo") DTV set performance in the presence of LTE downlink (DL) signals that may be utilizing nearby spectrum as a result of the spectrum

[3] "ATSC Recommended Practice: Receiver Performance Guidelines", Document A/74:2010, April 7, 2010.

[4] Stephen R. Martin, "Interference Rejection Thresholds of Consumer Digital Television Receivers Available in 2005 and 2006", OET Report Prepared by: FCC/OET 07-TR-1003, March 30, 2007.

[5] Ibid.

repacking, as well as a comparison of LTE-into-DTV interference and DTV-into-DTV interference.

General laboratory testing (see **Figure A-1** in **Appendix A** for photos of the laboratory) was performed on 12 recent-model and 2 older-model DTV receivers. In addition, CEA selected a subset of 6 of the recent-model receivers for detailed DTV-into-DTV interference testing, and CEA selected another single unit from the subset of 6 to test certain LTE-into-DTV interference assumptions. The RF interference testing performed with both DTV and LTE interference sources included co-channel, first adjacent channel, and “taboo” (second and beyond) adjacent channels. DTV test signals adhered to the traditional 6 MHz 8-VSB transmission signals per the ATSC A/53 standard while LTE test signals adhered to three of the pre-defined test signals for downlink performance evaluation per the 3GPP (3rd Generation Partnership Project) standard. A subset of interference tests involved DTV interference sensitivity at both weak and very weak desired signal levels with regard to a “sliding-frequency” LTE interference source, simulating one 5MHz LTE base station or two 5 MHz LTE base stations (with a single 10MHz wide signal) at various frequency offsets from the 8-VSB desired signal. This last suite of interference tests was performed on the subset of 6 recent-model DTV sets plus two older (legacy) DTV sets.

Laboratory setup, equipment procurement, and test bed documentation and calibration began in December 2013, and were subsequently completed in January 2014. The actual laboratory testing was completed on May 14, 2014. The test results provide information that relates (with certain limitations) to potential field conditions that may occur after spectrum repacking.

The specific consumer DTV receiver brands and model numbers of the units employed in these tests are not identified in this written laboratory test report. Rather, they are referenced generically by unique designations (numbers 1 through 14) and described only generally (e.g., by screen size and model year).

3. DEVICES UNDER TEST

All of the devices under test (DUT) were popular consumer flat-screen DTV receivers with internal over-the-air (OTA) tuners. In this report, these test units are referred to variously as tuners, receivers, or DTVs, depending on context (and note that at no point was an RF tuner module removed from a DTV set and tested separately; all testing was done with the receiver board in-situ). The first 12 DUTs were selected from 2012 and 2013 models, according to the following process:

1.) CEA obtained unit sales data (by year) regarding television manufacturers supplying the U.S market. CEA then contacted approximately a dozen significant manufacturers for assistance in selecting representative tuner models. During this consultation period, CEA determined that manufacturers typically design one OTA tuner for inclusion in all models of a given year, and frequently carry that tuner design over into subsequent years. As a result, CEA determined that a relatively few number of units would be representative of much of the DTV product shipping in the U.S. in the time frame of interest.

2.) Based on the unit sales data and the manufacturer input, CEA determined that 12 units carefully selected from specific manufacturers would represent approximately 85% of DTV shipments in the U.S. market in 2012 – 2013. A subset of 6 would represent approximately 75%.

3.) All 12 of the recent model DTV receivers tested were production units, with the exception of one unit which was a “pre-production” unit. Pre-production is a term of art in the industry that describes a unit with a final design and final components, built on an actual production line, but removed prior to consumer labeling and packaging. A preproduction unit is used to validate performance of the production product and provide a last check that everything is as the designers intended. CEA’s assessment, based on this information, is that this unit is representative of a production product. All 12 DTV receivers consisted of integrated flat-panel screens of various sizes (23” – 46”), and were individually shipped to the MSW laboratory. The units are described by screen size (diagonal) in **Table 1** below. However, the type of RF frontend tuner (i.e., single conversion or double conversion, can or silicon implementation) was not considered as a controlling factor in the testing.

These receivers represent DTV sets that were popular with consumers, having significant sales over the last two years, and therefore characterize well the population of DTV sets in the market at present.

As stated above, all manufacturers interviewed stated that the same tuner design was used in all models in a model year[6], regardless of flat-panel size. So, for example, the 23” model would use the same tuner design as that manufacturer’s largest model (e.g., up to the 100”+ class, if that maker has such a model). Therefore, these DTV sets used in this laboratory test are also representative of the largest models available in 2012 and 2013.

[6] An exception to this rule is when the brand uses more than one manufacturer in a given model year.

To supplement the results on current generation tuners, two receivers from 2006 (#13 and #14) were added to the test suite. The Martin 2007 report[7] provides a significant amount of data from ca. 2005. It will be some time before many LTE systems begin transmissions in the 600 MHz band, during which time many sets from earlier years will be replaced. These points were considered when selecting for 2012 – 2013 in the initial group of test receivers. However, some direct comparison to older models is appropriate, thus the selection of the two additional units.

See **Table 1** below for a list of the 14 DTVs used in the testing.

Table 1 DUT receivers and their respective performance testing.

DUT #	Test Description	Screen Size	Model Year
1	General, DTV-into-DTV, LTE-into-DTV	39”	2012 - 2013
2	General, DTV-into-DTV, LTE-into-DTV	32”	2012 - 2013
3	General, DTV-into-DTV, LTE-into-DTV	32”	2012 - 2013
4	General, DTV-into-DTV, LTE-into-DTV	46”	2012 - 2013
5	General, DTV-into-DTV, LTE-into-DTV	32”	2012 - 2013
6	General, DTV-into-DTV, LTE-into-DTV	32”	2012 - 2013
7	General	23”	2012 - 2013
8	General	32”	2012 - 2013
9	General	32”	2012 - 2013
10	General	26”	2012 - 2013
11	General	32”	2012 - 2013
12	General	32”	2012 - 2013
13	Sensitivity, AWGN, LTE-into-DTV	40”	2006
14	Sensitivity, AWGN, LTE-into-DTV	52”	2006

After unpacking the individual DTVs and applying AC power, basic operation was quickly verified to insure that no DTV set damage occurred in shipping. Immediately following this, the laboratory test bed was calibrated and documented, followed by actual device testing. The DTV sets were then scanned over the television band while exposed to three channels: CH 29, CH 30, and CH 31. This allowed not only the desired UHF test channel (CH 30) to be easily tuned, but also allowed dual channel changes for acquisition testing at the various impairment and interference thresholds (i.e., channel up/down from CH 30 to CH 31 and back to CH 30 as well as channel down/up from CH 30 to CH 29 and back to CH30).

The first group of 12 receivers was used for the general performance testing on CH 30 (sensitivity, overload, white noise threshold, DTV-into-DTV co-channel interference, and LTE-into-DTV co-channel interference) to verify that these basic performance parameters were in the expected operational range. After this general performance test confirmed that all receivers functioned properly and had good performance, CEA made their final selection of a subset of 6 receivers for further testing (this selection was again based on representing the bulk of tuner

[7] “*Interference Rejection Thresholds of Consumer Digital Television Receivers Available in 2005 and 2006*”, OET Report Prepared by: FCC/OET 07-TR-1003, March 30, 2007.

shipments). These 6 receivers, labeled #1 through #6, were selected for the specific DTV-into-DTV adjacent channel interference testing that included multi-signal overload interference, single adjacent channel interference, and IM_3-paired adjacent channel interference, such that the subset best represented the population as a whole. To keep the test matrix to a reasonable size, only one of these 6 receivers (labelled #1) was selected for all of the LTE-into-DTV interference testing.

The remaining six units, labeled #7 - #12, had no further tests performed on them beyond the general tests. Units #13 and #14 were tested for sensitivity and white noise threshold, as a baseline, and for LTE-into-DTV “sliding” interference tests, to provide comparison data to the 2012-2013 units’ performance.

The specific test matrix is described in the next section.

4. TEST PLAN

4.1. Overview

A laboratory test plan was developed jointly by CEA and MSW, and implemented in the MSW laboratory. A test matrix was created summarizing all 1045 tests that were performed, documented, analyzed, and included in this written test report.

The test plan called for MSW to perform calibrated conducted (rather than radiated) RF reception tests on consumer DTV sets with ATSC-compatible over-the-air receivers using a single desired UHF channel (CH 30). The ATSC A/74 document was used only as a guideline for testing, and was not used as a specific test plan. CEA requested general performance tests (sensitivity, overload, added white noise threshold, co-channel interference) as well as adjacent channel interference tests for both DTV-into-DTV and LTE-into-DTV to be performed. While the desired (D) signal was always a typical 6 MHz ATSC DTV signal on UHF channel 30, the undesired (U) interference signals were either one or two DTV signal (6 MHz ATSC 8-VSB signal in a 6 MHz RF channel) or one LTE signal (5 MHz or 10 MHz 3GPP OFDMA signal) or one LTE and one DTV signal. The interference performance metric for these laboratory tests was the ratio of the desired (D) average signal power level to the undesired (U) average signal power level, referred to as D/U. Each D/U measurement was taken at a threshold of video (TOV) error point; depending on the test, one of two TOV criteria was used.

All testing was performed on a 50-Ohm test bed, except at the final outputs to the consumer DTV sets which were converted to 75-Ohms to match the nominal input impedances of their RF tuners. The RF tests were all performed with an unimpaired (i.e., "clean" ATSC signal ≥ 33 dB SNR) desired DTV signal on physical CH 30 (569 MHz center frequency) at a power level of either strong (-28 dBm), moderate (-53 dBm), weak (-68 dBm), or very weak (-81 dBm). That is, the desired DTV source signal did not have any added linear distortion (e.g., non-flat amplitude or group delay response, carrier phase noise, nor any propagation-induced multipath) or non-linear distortion (e.g., AM/AM, AM/PM, or IM3). The only impairments added to the desired DTV signal during testing were white Gaussian noise (only in one of the general tests), undesired DTV interference signals, or undesired LTE interference signals.

The undesired interference signals were also considered "clean" in that they did not have the usual non-linear-induced third order intermodulation (IM3) energy that causes DTV splatter to occur in adjacent channels in practical commercial-grade transmitter equipment. Therefore, the DTV interference results obtained in this laboratory test are focused on relative DTV receiver evaluation; in the field with high-power transmitters, this level of performance may be reduced due to the presence such splatter.

With a few exceptions, interference tests were performed with a variety of interference signals on UHF CH 20 through UHF CH 45 with the desired CH 30 DTV signal at a weak level of -68 dBm. The exceptions are the single interferer tests which were performed at both weak (-68 dBm) and strong (-28 dBm) desired signal levels; and the sliding LTE tests which were performed at weak (-68 dBm) and very weak (-81 dBm) levels. All desired and undesired signal and noise power measurements were made over the entire FCC-defined television channel bandwidth of 6 MHz using integrated band power marker methods employed in a spectrum analyzer. **To be consistent, even the 5 MHz LTE interference signals were measured with 6**

MHz integrated band power markers, although only the 5 MHz LTE pass band energy contributed any meaningful power to the signal power measurement.

The video test pattern used for the desired DTV signal in all of these laboratory tests was a moving 1920 x 1080i high definition (HD) circular zone plate (sometimes referred to as "moving HD zone plate"). This type of test signal allows easier visual determination of the error threshold in a receiver, commonly referred to as the threshold of video errors (TOV) or the threshold of audible errors (TOA). The reason for the visual sensitivity of this particular test signal to threshold identification is that the high definition moving HD zone plate video material takes up a vast majority of the available data rate allocated for video (e.g., > 18 Mbps), which minimizes the possibility of data errors occurring in data packets other than the video packets. Since the complex video pattern is moving, no video error concealment in a receiver can easily hide data errors since the entire video pattern has changed from one frame to the next (i.e., there is little correlation in the circularly-moving HD zone plate from one video frame to the next). The fact that the video signal has moving concentric circles facilitates the observation of square macro block errors within the circular video pattern that occur when the forward error correction (FEC) is overrun by the signal impairment and/or interference signal.

The video test pattern used for the undesired DTV signal in all of these laboratory tests was a high definition (1920 x 1080i) television program titled "WETA_HD". While this signal was not viewed on a DTV receiver for testing purposes, it was nonetheless used as a practical example of an interfering DTV signal. Additionally, the two types of content are easily distinguished by the test engineer, adding an element of ongoing verification of the test set-up.

The modulation used for the undesired LTE signal in all of these laboratory tests was a test signal taken from a suite of standardized E-UTRA (Evolved Universal Terrestrial Radio Access) test signals. While the transmission parameters of the ATSC DTV RF terrestrial signal (i.e., 8-VSB) are historically well defined and fixed, the primary transmission parameters of the LTE signal are flexible and selectable (i.e., OFDMA for downlink RF modulation and SC-FDMA for uplink RF modulation, up to 2048 frequency subcarriers, 1.4 – 20 MHz bandwidth, 6 – 100 resource blocks, QPSK, 16-QAM, or 64-QAM data modulation per carrier, various guard intervals, number and location of subcarrier pilots, etc.). Prior to the start of laboratory testing, CEA provided the exact LTE transmission parameters that MSW used during the laboratory tests involving 5 MHz and 10 MHz downstream link (DL) LTE interference signals. For these signal parameters, CEA selected three sets of LTE system parameters for interference signals from the 3GPP E-UTRA specification for standard base station test signals, TS 36-141. For the purposes of this testing, these signals were referred to as LTE1, LTE2, and LTE3.

LTE1: Simulates a normal, fully-loaded (heavy data traffic) base station DL signal in 5 MHz bandwidth (signal definition "E-TM 3.1" from E-UTRA TS36-141, 5 MHz option).

LTE2: Simulates a normal, lightly-loaded (minimal data traffic) base station DL signal in 5 MHz bandwidth (signal definition "E-TM 2" from E-UTRA TS36-141, 5 MHz option).

LTE3: Simulates a normal, fully-loaded (heavy data traffic) base station DL signal in 10 MHz bandwidth (signal definition "E-TM 3.1" from E-UTRA TS36-141, 10 MHz option).

The terms “fully-loaded” and “lightly-loaded” refer to the relative amount of data traffic carried by the DL at any particular time. Allocating 25 resource blocks in 5 MHz fully occupies the entire channel in the time domain. Allocating fewer resource blocks causes the RF signal to appear bursty in the time domain. Allocating one resource block maximizes the burstiness, and this worst-case burstiness behavior for LTE is what signal LTE2 was intended to test.

During this laboratory test, TOV threshold was determined using the following algorithm:

(1) Adjust the level of the interference or impairment (per the specific test procedure) in the prescribed signal level steps. For sensitivity, overload, added white noise, and co-channel interference, 0.25 dB attenuation steps were used for either the desired signal or the impairment/interference signal. For the remaining interference tests, 0.5 dB attenuation steps were used (1 dB for sliding LTE interference tests).

(2) Adjust the impairment or interference until there are observable errors in the moving HD zone plate video test pattern for three consecutive 20-second test intervals (three consecutive 60-second test intervals in the sliding LTE interference tests).

(3) Verify acquisition capability twice by performing an up/down channel change followed by a down/up channel change at TOV at the last error-free condition before recording the undesired interference signal level.

4.2. Specific Tests

The test plan called for general tests (desired signal sensitivity and overload thresholds, added white Gaussian noise (AWGN) impairment threshold, co-channel DTV-into-DTV and LTE-into-DTV interference thresholds) to be performed first on all 12 recent test receivers to verify proper operation (functionality) and performance before selecting a subset of 6 current (2012 – 2013) receivers on which to perform the remaining adjacent channel interference tests. These particular interference tests, performed with a desired DTV signal on CH 30, relate to the reception tolerance of a DTV receiver to external undesired signals, such as other DTV signals or LTE signals sharing nearby spectrum following a spectrum repack scenario (i.e., after the incentive auction). Two “legacy” receivers (from 2006) were added to the sliding LTE interference tests for comparison purposes, but verified first with sensitivity and AWGN tests.

The laboratory test plan (total of 10 different groups of tests) is summarized in the detailed test matrix contained in **Table B-1** in **Appendix B**, and was confirmed by CEA prior to the start of testing. As can be seen from the test matrix, this thorough laboratory testing consisted of 1045 individual tests.

The groups of laboratory tests are summarized below:

(1) Sensitivity
(2) Overload
(3) Added White Gaussian Noise Impairment Threshold
(4) Co-channel Interference (DTV-into-DTV and LTE-into-DTV)
(5) Multi-Signal Overload Interference: N+2/N+3 pair (DTV-into-DTV and LTE-into-DTV)
(6) Single Interferer Interference: N±10, N±8, N±7, N±6, N±5, N±4, N±3, N±2, N±1, N+13, N+14, N+15 (DTV-into-DTV and LTE-into-DTV)

(7) IM_3-Generating Interference Pairs: Equal Power: N+k = N+2k (DTV-into-DTV and LTE-into-DTV)
(8) IM_3-Generating Interference Pairs: Unequal Power: N+k > N+2k (DTV-into-DTV and LTE-into-DTV)
(9) IM_3-Generating Interference Pairs: Unequal Power: N+k < N+2k (DTV-into-DTV and LTE-into-DTV)
(10) Sliding 5 MHz and 10 MHz LTE Signal Interference

An important aspect of this laboratory test is that it is not attempting to precisely simulate actual commercial DTV and LTE high-power transmitter hardware that may exhibit somewhat degraded in-band signal quality or adjacent channel splatter characteristics. Rather, high quality instrument-grade DTV and LTE sources were used to create “clean” desired and undesired test signals, and thus measure consumer DTV receiver performance under “ideal” conditions for comparison to the A/74 guidelines and historical data. Consequently, it is important to remember that the data presented here should be used directly to understand channel allocation issues only when appropriate consideration of the out-of-band spectral energy (i.e., first adjacent channel splatter) found in all commercial transmission equipment has been made.

4.2.1. Sensitivity

This test determines the sensitivity of a receiver to an unimpaired desired DTV signal on CH 30, that is, the minimum unimpaired DTV signal level that will produce an acceptable digital picture and sound under ideal conditions (i.e., without signal impairments or interference and with perfect RF impedance matching). The minimum signal level is determined by the tuner’s internal white noise level (related to its noise figure by “kTB+NF”, where NF is primarily determined by the first RF preamplifier), ATSC white noise threshold (ideally, ≈15 dB), automatic gain control (AGC) range, and any undesired receiver-created electromagnetic interference (EMI) that is present at the tuner input. This test is a basic DTV receiver reference performance parameter that is part of the general test suite.

This minimum DTV signal level value for TOV is theoretically around -84 dBm, assuming a 7 dB tuner noise figure, and kTB tuner noise of -106.2 dBm/6 MHz (at room temperature). Since many of the interference tests in this project are performed with a “weak” desired signal (-68 dBm), the measured sensitivity threshold value should be much lower (16 dB or more) than this “weak” signal level, and therefore have minimal effect on the measured interference performance. Note that the 7 dB noise figure is only an assumption, and lower values are possible.

This general test is performed by reducing the unimpaired desired DTV signal from a matched impedance feed in 0.25 dB steps until TOV is achieved. Acquisition is verified at TOV by performing a dual channel change test (up/down and then down/up), and then TOV is documented. Sensitivity threshold was tested on all 14 receivers (6 recent-model test receivers plus the two older-model test receivers).

4.2.2. Overload

This test determines the overload capability of a receiver to an unimpaired desired DTV signal alone on CH 30, that is, the maximum unimpaired desired DTV signal that will produce an acceptable picture and sound. The maximum signal level is determined by AGC range, tuner non-linearities (e.g., mixer, RF preamplifier, IF amplifier), and white noise threshold. This test is also a basic DTV receiver reference performance parameter that is part of the general test suite.

This maximum signal level value for TOV on current DTV receivers is often much greater than -8 dBm, the industry-recommended maximum signal level expected at a DTV tuner input in the field. Since the multi-signal overload test (described later in this document) calls for two -8 dBm undesired signals (either two DTV or one LTE signal and one DTV signal) to be present concurrently as an unimpaired desired DTV signal is decreased until TOV is reached, it is very helpful to know the level beyond -8 dBm that the desired signal alone can be before TOV occurs.

This test limited the maximum signal input to a receiver at +5 dBm. This was the only time in the laboratory test plan where this large signal value was used. This +5 dBm value exceeds the A/74 guideline of -5 dBm (Section 5.1, Sensitivity), and is 13 dB higher than the largest signal level expected by the industry to occur in the field (i.e., -8 dBm)

This general test is performed by increasing the unimpaired desired DTV signal from a matched impedance feed in 0.25 dB steps until TOV is achieved (or +5 dBm is reached). Acquisition is verified at TOV by performing a dual channel change test (up/down and down/up), and then TOV is documented. Overload threshold was tested on all 12 receivers.

4.2.3. Added White Noise Threshold

This test determines the actual signal-to-noise ratio (SNR) at TOV for a moderate (-53 dBm) unimpaired desired DTV signal on CH 30 when white Gaussian noise is added (i.e., random noise with a Gaussian amplitude probability distribution and flat spectrum over the entire 6 MHz television RF channel). This is another basic DTV receiver reference performance parameter that is part of the general test suite.

Since a moderate signal level (-53 dBm) is used for the desired signal, the tuner's internal white noise is insignificant compared to the externally-added white noise, and therefore is not a factor in the TOV measurement. Likewise, any receiver-created EMI that is present at the input as well as any AGC shortcomings also become insignificant. Therefore, this test allows a fairly true measurement of the ATSC transmission system SNR at TOV; this SNR is dependent on the 8-VSB modulation and forward error correction (Reed-Solomon and trellis-coded modulation) that are part of the A/53 DTV transmission standard; and on receiver implementation.

This SNR value at the white noise TOV is typically 15 dB ± 0.2 dB, and should be very consistent when carefully measured in a stable and calibrated laboratory setting. Measured values of this parameter are typically very repeatable in the laboratory, and are often a good indicator if something in the receiver is not operating quite right.

This general test is performed by adjusting the unimpaired desired signal from a matched impedance feed to a moderate level (-53 dBm) and then adding white noise in 0.25 dB increments until TOV is achieved. Acquisition is verified at TOV by performing a dual channel change test (up/down and down/up), and then TOV is documented. Added white noise threshold was tested on all 14 receivers (12 recent-model receivers plus the two older-model test receivers).

4.2.4. Co-Channel Interference (DTV-into-DTV and LTE-into-DTV)

This general test determines the amount of undesired DTV or LTE signal interference that can simultaneously exist at the receiver input when the interfering undesired signal and desired DTV signal on CH 30 at moderate level (-53 dBm) are on the same RF channel. This co-channel test is considered a basic DTV receiver reference performance parameter that is part of the general test suite, and also provides insight into the effects of two different types of LTE signals (fully-loaded LTE1 and lightly-loaded LTE2; LTE3 was not used in this particular test suite).

Since DTV and fully-loaded LTE signals are both noise-like with a flat spectrum across most of the channel (5.381 MHz for DTV and either 4.515 MHz or 9.015 MHz for LTE), they share many characteristics with white Gaussian noise. Therefore, the expected co-channel D/U interference ratio for DTV-into-DTV and LTE-into-LTE is generally the same 15 dB SNR value as for white noise. However, it has been observed that sometimes a slightly better (i.e., lower) D/U ratio is achieved (e.g., 14.75 dB) when DTV is the interferer. This is explained by the fact that the DTV signal (i.e., with 8-VSB modulation) is only noise-like and therefore not absolutely identical to noise. The ATSC DTV signal has a peak-to-average ratio (PAPR) that is about 2 dB less than white noise (at the 99.9% statistical level). On the other hand, the LTE signal is almost identical to noise with its very sharp spectral transition regions, and has a PAPR about the same as white noise. Therefore, the LTE PAPR is about 2 dB greater (at the 99.9% statistical level) than an ATSC signal. Consequently, the interference D/U ratio when LTE is the interferer may be closer to the white noise SNR value at threshold. However, the difference between the two bandwidths (i.e., 6 MHz DTV versus 5 MHz LTE) may compensate somewhat for any difference in the PAPR in terms of interference threshold. Therefore, the interference threshold D/U values for DTV and the fully-loaded LTE1 co-channel interferer would be expected to be approximately the same value as the 15-dB white noise threshold value. An additional co-channel test was performed with the lightly-loaded LTE2 signal to evaluate its co-channel effects on DTV receivers.

This general test is performed by adjusting the unimpaired desired signal from a matched impedance feed to a moderate level (-53 dBm) and then adding an undesired DTV or LTE interference signal on the same channel in 0.25 dB steps until TOV is achieved. Acquisition is verified at TOV by performing a dual channel change test (up/down and then down/up), and then TOV is documented. Both DTV-into-DTV and LTE-into-DTV co-channel interference was tested on all 12 receivers.

4.2.5. Multi-Signal Channel Interference (DTV-into-DTV and LTE-into-DTV)

This test determines the effect on DTV receivers tuned to a desired DTV signal on CH 30 from two equal undesired interfering DTV signals or one DTV signal and one LTE signal at a maximum expected receiver input signal level transmitted on nearby channels. However, the relative channel positions selected for this undesired pair do not create the strongest IM_3 interference pairs that are possible (i.e., they are not N+k/N+2k adjacent channel IM_3 pairs) yet still close enough in frequency to the desired signal to have some influence on receivers designed with wideband RF AGC. Therefore, N+2 and N+3 interference channels were used with respect to the desired CH 30 DTV signal.

The -8 dBm undesired signal level that is used for this test is a value assumed in the broadcast industry to represent the maximum expected DTV signal power expected at the tuner input of a DTV set from either a high gain antenna used in a close-in reception environment or via a mast mounted preamplifier in a more distant reception environment. The two undesired noise-like DTV interference signals can cause either IM_3 intermodulation and/or cross modulation in the DTV tuner due to non-linearities. IM_3 pairs generate noise sideband products (i.e., an elevated noise spectrum) in certain bands, which is an important issue in DTV reception. Nevertheless, in this particular test, cross modulation is the focus while third order intermodulation is the focus in other tests in this laboratory project. It should be noted, however, that use of N+2 and N+3 undesired signals still cause tuner non-linearities to create noise-like splatter that fall into the desired channel N, just not at the strongest IM_3 levels (such as in the N+1 and N+2 IM3-paired channels).

Expected LTE base station signal levels at the input to DTV receivers in the field are not yet generally known, but large values can still exist in a similar manner as DTV signals, including indoor-antenna use that can also receive a signal from a nearby unlicensed device or an LTE cellular phone. Similar to two DTV interferers, undesired noise-like LTE and DTV interference signals can combine to cause either IM_3 intermodulation and/or cross modulation, which generates noise sideband products (i.e., elevated noise spectrum) in certain bands. The increased PAPR of LTE signals by 2 dB (compared to DTV) tends to increase interference but may possibly be offset somewhat by the fact that the undesired LTE signal, which is centered in the DTV channel for these laboratory tests, is only 5 MHz wide and thus provides a 0.5 MHz guard band around them compared to 6 MHz DTV interferers.

This interference test is performed by adjusting one specific pair (N+2 and N+3) of DTV or LTE signals to -8 dBm; that is, the two signals in this pair have equal undesired power of -8 dBm. After removing any out-of-band noise energy on CH 30 from the interference test sources with a wideband stop band filter, the unimpaired desired DTV signal from a matched impedance feed is then added to these two undesired signals. The desired signal is then reduced in signal strength in 0.5 dB steps until TOV is achieved. Acquisition is verified at TOV by performing a dual channel change test (up/down and then down/up), and then TOV is documented. DTV-into-DTV interference was tested on 6 receivers while LTE-into-DTV interference was tested on 1 receiver for comparison.

4.2.6. Single Interferer Interference (DTV-into-DTV and LTE-into-DTV)

This test determines the effect on DTV receivers from a single adjacent channel DTV or LTE interference signal. An undesired DTV interference signals is placed on one of N±1, N±2, N±3, N±4, N±5, N±6, N±7, N±8, N±10, N+13, N+14, N+15 channels with respect to the desired DTV signal on CH 30.

For determining the parameters of this test, there are recommended values of interference threshold D/U ratios found in sections 5.4.2 and 5.4.3 of the ATSC A/74 document.

One additional benefit of this test is the determination of any differences in interference thresholds between 6-MHz, lower-valued PAPR DTV interferers and 5-MHz, higher-valued PAPR LTE interferers.

These interference test channels represent a large spread of possible interfering signals that can stress the non-linearities of the tuner input (RF preamplifier, mixer, and IF amplifier). The expected type of interference is cross-modulation as well as large signal de-sensitization. Any tracking band pass filter present at the tuner input, which is necessary to reduce N+14 and N+15 image frequencies for single-conversion tuners, helps to reduce interfering signals that are farther away in frequency from the desired channel. Having symmetrical interference test channels facilitates the process of determining de-sensitization versus offset channel. Many of these interference test channels are the same used in the IM_3-paired interference tests described later in this document, which then allows comparison of interference D/U ratios with a single interferer with those of IM_3 pairs of interferers. The N+4 interference channel evaluates any ½-IF interference that might be present. The N+7 interference channel evaluates any effect on the receiver's local oscillator. The N+14 and N+15 are the image frequencies for single conversion tuners, which often exhibit worse interference performance than the other nearby offset channels due to this fact. The addition of N+13, which is not an image frequency, provides a better idea of how the effective interference performance curve looks versus offset channels.

This interference test is performed by adjusting the unimpaired desired DTV signal level from a matched impedance feed to either a weak level (-68 dBm) or a a strong level (-28 dBm), and then raising the added interfering signal level (on one of the interference test channels) in 0.5 dB steps until TOV is achieved. Out-of-band noise energy from the interference test source is removed from CH 30 using a stop band filter before addition to the desired CH 30 DTV signal. Acquisition is verified at TOV by performing a dual channel change test (up/down and down/up), and then TOV is documented. DTV-into-DTV interference was tested on 6 receivers while LTE-into-DTV interference was tested on 1 receiver for comparison.

4.2.7. IP_3-Paired Interferer Interference: N+k=N+2k (DTV-into-DTV & LTE-into-DTV)

This test determines the effect on DTV receivers from two equal and large undesired DTV interference signals, or from two equal large undesired interference signals where one is LTE and the other is DTV, on specific pairs of channels (N+k and N+2k, where k = ±1, ±2, ±3, ±4, and ±5) whose combined energy causes maximum levels of noise-like third order intermodulation (IM_3) interference to fall within the desired channel N (i.e., CH 30).

The use of these worst case IM_3 interference signal pairs focuses on intermodulation effects in DTV receivers, and how they relate to single channel interference effects. Since the desired DTV signal and the two undesired interference signals are the only signals at the input to the receiver's tuner, the new IM_3 frequencies are created by non-linearities within the DTV set's tuner (e.g., mixer, RF preamplifier, IF amplifier, etc.).

When a single interference signal begins to experience non-linearities, IM_3 frequencies are generated according to the $2F_1$-F_2 and $2F_2$-F_1 rule. The fact that this rule stems from 3rd order intermodulation effects means that there is a quadratic F^2 and a linear F term working together to create a 3rd order effects. This means that a single noise-like flat-spectrum signal, like DTV and LTE, has non-flat noise-like IM_3 energy spread out over three channels, as shown in **Figure F-1a**. In the case of a single channel interferer, the noise-like energy spreads to the first lower adjacent and the first upper adjacent channels as well as adding to the desired signal (although hidden, lying "underneath" the desired channel's signal spectrum). Any desired DTV signal directly adjacent to a large undesired first adjacent channel interferer can be affected by this IM_3 energy if the undesired signal level is much higher than the desired signal level. This adjacent channel noise will appear as co-channel interference to the desired DTV signal. If the single undesired interference signal increases by 1 dB, then the sideband energy will increase by 3 dB (3 times the amount, in dB) according to the well-known 3rd order effect.

When a pair of undesired interference signals is placed on channels that are N+k and N+2k (where "k" is an integer) offset from the desired DTV signal on channel N, then additional spectral "noise bumps" exist, with local maximum points (worst-case interference) located on the desired channel as shown in **Figure F-1b**. Note that these discrete "noise bumps" are not necessarily flat over the entire 6 MHz DTV channel and each bump affects three 6 MHz channels, and that the first adjacent noise of the two interferer signals has increased as well. This means that any desired first adjacent channel to one of the interferer pairs will be affected by increased IM3 energy if a large additional interferer at any frequency offset is present at the receiver's tuner input.

Once again, any non-flat noise-like IM_3 energy created in a DTV receiver's tuner will raise the noise floor so that the desired DTV signal must be artificially higher than this IM3 energy by at least the usual value of 15 dB (possibly even more if the desired DTV signal has significant impairments such as multipath). Again, note that while the middle of the noise "bumps" has the worst interference, one channel on each side of these "bumps" has increased intermodulation noise floors as well. If both of the undesired interference signals are decreased by 1 dB, then the noise "bumps" decrease by 3 dB, once again according to the well-known 3rd order effect described above. **Figure F-1c** illustrates this condition with an example of both signals being reduced in power by the same amount (e.g., 5 dB), and the spectral "bumps" reducing by a 3:1 logarithmic factor (i.,e., 15 dB) due to the 3rd order intermodulation process.

The effect of these non-flat noise-like products in other bands is to effectively raise the apparent noise floor of the receiver at those frequencies. Therefore, rather than the desired DTV signal being required to be 15 dB above the tuner's internal noise floor, it must rather be 15 dB above the combined noise effects of the tuner's natural internal noise (kTB + tuner noise figure) plus the IM_3-generated noise caused by the undesired signals.

This interference test is performed by adjusting the unimpaired desired DTV signal level a matched impedance feed to a weak level (-68 dBm), and then raising the added interfering signal level (on *both* of the equal interference test channels) in 0.5 dB steps until TOV is achieved and documented. Out-of-band noise energy from the interference test sources is removed from CH 30 using a stop band filter before addition to the desired CH 30 DTV signal. DTV-into-DTV interference was tested on 6 receivers while LTE-into-DTV interference was tested on 1 receiver.

4.2.8. IP_3-Paired Interferer Interference: N+k>N+2k (DTV-into-DTV & LTE-into-DTV)

This test determines the effect on DTV receivers from two unequal large undesired DTV interference signals, or from two unequal large undesired interference signals where one is LTE and the other is DTV, on specific pairs of channels (N+k and N+2k, where k = ±1, ±2, ±3, ±4, and ±5) whose combined energy causes maximum levels of noise-like interference to fall within the desired channel N (i.e., CH 30). The closer-in interference signal (N+k) is 10 dB above the farther-out interference signal (N+2k). D/U is calculated based on the stronger of the two signals.

The use of these special IM_3 interference signal pairs focuses on 3rd order intermodulation effects in DTV receivers, and how they relate to single channel interference effects. Since the desired DTV signal and the two undesired interference signals are the only signals at the input to the receiver's tuner, the new IM_3 frequencies are created by non-linearities within the DTV set's tuner (e.g., mixer, RF preamplifier, IF amplifier, etc.).

This test includes the added parameter of the closer-in (N+k) signal of the IP_3 pair being 10 dB higher than the farther-out signal (N+2k). Compared to the noise "bumps" from the equal-power IM_3 pairs, the amount of IP_3-generated noise in the desired channel is predicted to be lower by about 10 dB (linear reduction, i.e., IM_3 components 1 dB down for every 1 dB of primary signal reduction) since it is the farther-out interference signal that has been reduced by 10 dB (rather than the closer-in signal). The interference D/U threshold from this dual unequal interferer scenario will tend to be closer to that of the single interferer case for the closer-in interference signal (since the farther-out interferer is attenuated with respect to the closer-in interferer), demonstrating the amount of any interference threshold degradation characterized in this test scenario. **Figure F-1d** illustrates this 3rd order behavior with an example of only one of the two interferers reduced in power, with the spectral "bump" closest to the reduced interference signal experiencing the larger spectral energy reduction.

This interference test is performed by adjusting the unimpaired desired DTV signal level from a matched impedance feed to a weak level (-68 dBm), and then raising the interfering signal levels (on both of the interference test channels, but maintaining the 10 dB difference in their relative levels) in 0.5 dB steps until TOV is achieved. Out-of-band noise energy from the interference test sources is removed from CH 30 using a stop band filter before addition to the desired CH 30 DTV signal. Acquisition is verified at TOV by performing a dual channel change test (up/down and down/up), and then TOV is documented. DTV-into-DTV interference was tested on 6 receivers while LTE-into-DTV interference was tested on 1 receiver.

4.2.9. IP_3-Paired Interferer Interference: N+k<N+2k (DTV-into-DTV & LTE-into-DTV)

This test determines the effect on DTV receivers from two unequal large undesired DTV interference signals, or from two unequal large undesired interference signals where one is LTE and the other is DTV, on specific pairs of channels (N+k and N+2k, where k = ±1, ±2, ±3, ±4, and ±5) whose combined energy causes maximum levels of noise-like interference to fall within the desired channel N (i.e., CH 30). The closer-in interference signal (N+k) is 10 dB below the farther-out interference signal (N+2k). D/U is calculated based on the stronger of the two signals.

The use of these special IM_3 interference signal pairs focuses on 3^{rd} order intermodulation effects in DTV receivers, and how they relate to single channel interference effects. Since the desired DTV signal and the two undesired interference signals are the only signals at the input to the receiver's tuner, the new IM_3 frequencies are created by non-linearities within the tuner (e.g., mixer, RF preamplifier, IF amplifier, etc.).

This test includes the added parameter of the closer-in (N+k) signal of the IP_3 pair being 10 dB lower than the farther-out signal (N+2k). Compared to the noise "bumps" from the equal-power IM_3 pairs, the amount of IP_3-generated noise in the desired channel is predicted to be lower by about 20 dB (quadratic reduction, i.e., IM_3 components 2 dB down for every 1 dB of primary signal reduction) since it is the closer-in interference signal that has been reduced by 10 dB (rather than the farther-out signal). The interference D/U threshold from this dual unequal interferer scenario will tend to be closer to that of the single interferer case for the farther-out interference signal (since the closer-in interferer is attenuated with respect to the farther-out interferer), demonstrating the amount of any interference threshold degradation characterized in this test scenario. **Figure F-1d** illustrates this 3^{rd} order behavior with an example of only one interferer reduced in power, with the spectral "bump" closest to the reduced interference signal experiencing larger spectral energy reduction.

This interference test is performed by adjusting the unimpaired desired DTV signal level from a matched impedance feed to a weak level (-68 dBm), and then raising the added interfering signal level (on both of the interference test channels, but maintaining the 10 dB difference in their relative levels) in 0.5 dB steps until TOV is reached. Out-of-band noise energy from the interference test sources is removed from CH 30 using a stop band filter before addition to the desired CH 30 DTV signal. Acquisition is verified at TOV by performing a dual channel change test (up/down and down/up), and then TOV is documented. DTV-into-DTV interference was tested on 6 receivers while LTE-into-DTV interference was tested on 1 receiver.

4.2.10. Sliding LTE Interference: 5 MHz and 10 MHz Signals

One final set of interference tests provided additional information on the effects of DTV reception in the presence of fully-loaded LTE interference signals that are NOT centered in a 6 MHz channel. Currently, there is much debate and investigation with regard to the specific placement of 5 MHz and 10 MHz LTE signals within the broadcast spectrum.

After the spectrum auctions (reverse and forward), a number of yet-to-be-determined broadcast channels will be turned over to the wireless communications companies, thus requiring subsequent repacking of the television broadcast spectrum. It is possible that there will be adjacent channel interference and even co-channel interference from LTE signals in adjacent markets into DTV signals, i.e., Inter-Service Interference (ISIX). This is especially true if the same amount of spectrum that is relinquished by broadcasters is not the same in every market across the country. Since interference into DTV may come from the same market or an adjacent market, impinging on the fringe area of DTV reception, this set of tests was performed at both a weak desired DTV level (-68 dBm) and a very weak desired DTV level (-81 dBm). The 5 MHz bandwidth LTE test signal was intended to simulate a single LTE channel, and the 10 MHz test signal was intended to simulate two side-by-side LTE channels.

With the desired DTV signal at very low levels, near a DTV receiver's minimum signal level threshold (i.e., TOV sensitivity), the external noise-like LTE intermodulation noise caused by IM3 non-linearities in the DTV tuner adds (in power) to the internal white Gaussian noise present at the front-end of every DTV tuner. This combination of white noise power and IM3 noise-like power limits the co-channel or adjacent channel LTE interference rejection capability of the DTV receiver, just as occurs when the interference signal is another DTV signal. The amount of interference rejection degradation can be calculated using the formula found in OET Bulletin 69[8].

This test demonstrates the effects of LTE interference on DTV receivers due to different amounts of spectrum overlap of undesired LTE and desired DTV signals. The frequency offset between the desired and undesired signals is sometimes referred to as "Off Frequency Rejection". Moving from completely co-channel to adjacent channel interference in 1 MHz steps, varying amounts of spectrum overlap will occur between the desired DTV signal and the undesired LTE signal.

Increasing spectrum overlap increases the integrated co-channel interference energy, and thus should increase susceptibility to the interfering signal. Starting with the lower band edges of the ATSC and LTE spectral signals lined up, as the LTE signal is shifted higher in frequency in 1 MHz steps, less co-channel interference and more adjacent channel interference will eventually occur. Since a DTV receiver is more sensitive to co-channel interference than adjacent channel interference, the interference D/U ratio should change from worst to best as the undesired LTE interferer signal moves out of the desired channel and increasingly into the adjacent channel. In this pair of tests, a sensitivity D/U curve can be created versus the amount of spectral overlap. Additionally, the difference in interference effects between 5 MHz and 10 MHz fully-loaded LTE signals can be evaluated as well.

However, there is an important issue to consider. As a general rule, when the partial overlap of the LTE and DTV signals is small, allowing for very low (i.e., large negative D/U values), the amount of interference energy falling into either the narrow band carrier synchronization circuitry (at the DTV signal's lower band edge) or the clock synchronization circuitry (at the DTV signal's upper band edge) can be large. Therefore, the interference threshold of data errors may be determined by either or both of two effects: excessive noise-like interference that overruns the error correction circuits or excessive stress on the synchronization circuitry due to this extreme interference noise within this circuit bandwidth.

However, since this pair of tests start with the lower band edges of the desired DTV and undesired LTE signal spectrums lined up, and this test only calls for shifting the LTE interferer higher in frequency (not lower), it is the DTV upper band edge alone that will experience a small but concentrated partial overlap in these two specific interference tests. A smaller overlap

[8] Ibid., page 21

spectrum scenario means that a larger interference signal is required to reach error threshold, but it also creates a more concentrated interference region near the upper band edge where narrow-band symbol clock recovery typically occurs. Careful testing is required in these partial overlap regions as TOV determination may be very sensitive and even time-varying (e.g., possible algorithm variations selected by smart controllers within the DTV receiver). The sharp digital "cliff effect" that is common with a broadband white noise impairment is much broader in this test scenario, making TOV determination more difficult and somewhat less accurate.

After preliminary testing revealed some testing sensitivity to TOV determination, a change in test methodology was recommended. For these sliding LTE interference tests, the TOV threshold algorithm was modified to use 1-dB interference signal steps (instead of 0.5 dB steps) and to use 3 consecutive 60-second observation intervals (instead of 20-second intervals) before the final determination of the TOV threshold point for better testing repeatability.

One factor that must be accounted for during these tests is the different total powers between the fully-loaded 5 MHz and 10 MHz LTE interference test signals. Both types of interference signals have the same power density, as they would in full-power mode in actual field applications. This means that the 10 MHz LTE interference signal will have twice the power (i.e., will be a 3 dB stronger signal). When D/U ratios are calculated, this 3-dB difference needs to be noted. It is possible to normalize any resulting D/U interference curves by accounting for this 3-dB difference, if so desired, during analysis, especially when comparing sliding interference results between the two types of LTE test signals.

This interference test is performed by adjusting the unimpaired desired DTV signal level a matched impedance feed to a weak level (-68 dBm) or a very weak signal level (-81 dBm), setting the LTE interference signal to one of the LTE center frequencies in the test matrix, and then raising the added interfering signal level in 1.0 dB steps until TOV is achieved. For the part of the test where the LTE interference signal is completely in the adjacent channel (i.e., no overlap with the desired DTV signal), out-of-band noise energy from the interference test sources is removed from CH 30 using a stop band filter before addition to the desired CH 30 DTV signal. Acquisition is verified at TOV by performing a dual channel change test (up/down and down/up), and then TOV is documented. The LTE center frequency is then adjusted to a new value, and the process repeated until all LTE frequencies have been tested. LTE-into-DTV interference was tested on 8 DTV receivers (6 recent-model test receivers plus the two older-model test receivers) for both 5 MHz and 10 MHz LTE interference signals.

5. TEST BED

MSW provided the required laboratory test equipment (signal sources and measurement) for performing the desired RF interference tests except for the rented LTE signal generator and signal synthesis software that CEA provided, and the 14 (12 recent-model plus two older-model) ATSC consumer television receivers (DTVs) that were tested.

The RF test equipment used for the CEA laboratory test included three appropriate frequency-agile ATSC DTV sources (one desired and two undesired interferers), one appropriate frequency-agile LTE undesired interferer source (with selectable 5 MHz or 10 MHz signal bandwidths, and three sets of transmission signal parameter settings selected by CEA), one broadband white Gaussian noise source, a spectrum analyzer, a power meter for calibration, one high-power RF amplifier (capable of providing +5 dBm signals at the DTV receiver input), signal combiners, signal splitters, calibrated 0.25 dB step attenuators, 50Ω-to-75Ω matching pads and transformers, and 50Ω double-shielded coaxial cables of required length with connectors of appropriate type and gender. The RF test bed was a 50-Ohm system design that utilized 50-to-75-Ohm impedance converters at the final feed point to the DTV sets.

Moderately large signals were delivered to the end of the well-shielded coaxial cables feeding the DTV receivers before being reduced by fixed attenuation pads in order to minimize any leakage into the cables, and thus provide good measurement accuracy.

One of the DTV sources was an RF capture playback unit (6 MHz RF test stream with moving HD zone plate picture and sound) that acted as the desired CH 30 DTV signal, and had a pristine output signal with an SNR ≥ 33 dB (typically 35 dB).

Various testing configurations were employed for dynamic range and desired signal overload tests, added white noise test, and the interference tests. The test block diagrams of the different configurations are illustrated in **Appendix C**. These different configurations were necessary for the various types of tests (between impairment and interference as well as between different interference scenarios).

The block diagram in **Figure C-1** describes the test setup for the general desired channel ***sensitivity*** threshold measurement test.

The block diagram in **Figure C-2** describes the test setup for the general desired channel ***overload*** threshold measurement test.

The block diagram in **Figure C-3** describes the test setup for the general desired channel ***Additive White Gaussian Noise*** (AWGN) threshold measurement test.

The block diagram in **Figure C-4** describes the test setup for the general ***DTV-into-DTV co-channel*** interference threshold measurement test.

The block diagram in **Figure C-5** describes the test setup for (1) the general ***LTE-into-DTV co-channel*** interference threshold measurement test, and (2) the ***sliding 5 MHz and 10 MHz LTE-into-DTV*** interference threshold measurement test.

The block diagram in **Figure C-6** describes the test setup for the ***DTV-into-DTV single interferer adjacent-channel*** interference measurement test.

The block diagram in **Figure C-7** describes the test setup for the ***LTE-into-DTV single interference adjacent-channel*** interference measurement test.

The block diagram in **Figure C-8** describes the test setup for (1) the ***DTV-into-DTV multiple signal overload*** threshold measurement test, and (2) the ***DTV-into-DTV IM3-paired adjacent channel*** interference threshold measurement test.

The block diagram in **Figure C-9** describes the test setup for (1) the ***LTE-into-DTV multiple signal overload*** threshold measurement, and (2) the ***LTE-into-DTV IM3-paired adjacent channel*** interference threshold measurement test.

The following table shows the detailed logistics of the test bed equipment utilized in this conductive laboratory RF performance test.

Table 2 Test bed equipment summary.

Manufacturer	Model #	Description
SRS	DS-345	Accurate & Stable 19.391 MHz Clock Source
Sencore/Adherent	AD953	MPEG Video/Audio ***Desired*** Source (Moving 1920x1080i HD Zone Plate)
Tektronix	Stream Station	MPEG Video/Audio ***Undesired*** Source (1920x1080i "WETA_HD" Program)
Harris	Custom	DVB-SPI to SMPTE 310M Transport Stream Adapter
Wavetech	WS2100	DTV Desired Source; RF Waveform Playback unit (with IF output capability)
Harris	CD-1	DTV Desired Source; 8-VSB ATSC IF modulator
General Instrument	C6U	Dual IF-to-RF Upconverter
Wavetech	WS2100	DTV ***Undesired*** Source; RF Playback unit (1920x1080i "WETA_HD" Program)
Agilent	N5172B EXG	LTE ***Undesired*** Source RF Vector Waveform Generator
Agilent	N7624B	LTE ***Undesired*** Source; PC Waveform Synthesis Software
NoiseCom	UFX-7110	Broadband White Gaussian Noise Generator
Weinschel	8200 series	0 – 127.75 dB GPIB 0.25-dB-stepAttenuators
Mini-Circuits	ZHL-1010	Broadband High-IP3 RF Amplifier
Mini-Circuits	ZFSC-2-4	Hybrid RF Signal Combiner
Mini-Circuits	ZFSC-2-5	Hybrid RF Signal Splitter
MFC	18854	Narrowband Notch Filter (for noise/interference removal on CH 30; N±1 testing)
MFC	16195	Wideband Notch Filter (for noise/interference removal on CH 30; ≥ N±2 testing)
Times Microwave	Ultraflex	50-Ohm, high-quality double-shielded foil & braid coaxial cable for microwave
Agilent	89441A	Vector Signal Analyzer (for signal spectrum, PAPR, SNR/MER measurements)
Hewlett Packard	E437B	RF Power Meter (for calibration purposes)
Hewlett Packard	8481D	RF Power Sensor (for calibration purposes)
-----	-----	Lab-grade 50/75Ω Min loss pads & transformer impedance converters, fixed loss pads

Note 1: Multiple units for some of the above components were utilized.

5.1. Test Bed Components

Generally, the RF test bed was carefully calibrated at each expected desired and undesired (interference) test frequency at least once every test day and before the start of each major test. This RF calibration covered all the system components such as test signal sources, amplifiers, coaxial cables, attenuators, loss pads, impedance converter pads and transformers, etc. However, D/U ratios were determined by direct measurement of RF signals at impairment and interference thresholds using analyzer bandpower markers.

The following describes the special, one-time test bed calibration for documentation purposes that was performed on individual test equipment as well as on the entire RF test bed prior to the start of laboratory testing. The dynamic range limits of the test bed were determined from these calibration measurements.

5.1.1. DTV Sources

Three DTV sources were employed in this laboratory test. One source provided the desired CH 30 DTV signal and two of them provided the various undesired DTV interferers. Two of the DTV sources were Wavetech WS2100 RF capture playback units with previously sampled and recorded DTV RF signals on their hard drives that, when played back in conjunction with a frequency-agile upconverter, provided DTV RF signals on any selected 6 MHz U.S. television channel. The third source was a Harris CD-1 exciter that, when used in conjunction with a frequency-agile upconverter, provided a modulated DTV RF output signal on any selected 6 MHz U.S. television channel. The video signal used for the desired ATSC DTV signal was a Moving HD Zone Plate while the undesired DTV interference signal was a "typical" single HD video program with motion (WETA_HD).

The ATSC RF signal spectrum was measured and recorded (**Figure D-1a**). The in-band signal spectrum was extremely flat (< 0.25 dB ripple), with the traditional root-raised-cosine transition regions (620 kHz) at each band edge and the relatively small in-phase pilot carrier at 310 kHz above the lower band edge.

Additionally, the DTV RF envelope complementary cumulative distribution function (CCDF) of the DTV source signal was measured and plotted (**Figure D-1b**), illustrating the well-known typical 6.3 dB peak-to-average power ratio at the 99.9% statistical level. The faint white line shown in the figure, for comparison, represents the CCDF of a white Gaussian noise signal, and illustrates the lower peak-to-average power ratio of the 8-VSB RF signal compared to white noise.

The DTV RF signal was also photographed in the time domain, and had the expected noise-like characteristics (**Figure D-1c**). The in-band signal quality SNR value for the desired DTV source was measured and found to be very acceptable (>33 dB, and typically 35 dB).

It should be noted that the DTV interference signals were created with a high-quality, instrument-grade test equipment, and not by commercial-grade hardware that is found in broadcast transmitter sites, thereby potentially allowing much better out-of-band energy performance than what might be found in the field. Just as discussed in the A/74 document, laboratory test signals with minimal out-of-band splatter provide good and repeatable benchmark test results in the laboratory for comparative DTV receiver performance evaluation. However, it must be recognized that these laboratory interference test results, while repeatable in the laboratory, do not accurately reflect field interference results when actual commercial hardware is used with imperfect out-of-band characteristics. In the field, interference signals will have IM3 adjacent channel splatter that act as co-channel interference to a lower or upper first adjacent desired DTV signal, and therefore degrade interference D/U ratios that were measured in the lab with essentially no splatter. Consequently, the interference data presented here would need to be adjusted to account for high-power transmitter spectral mask compliance in order to be used in allocation planning.

The 6 MHz broadband out-of-band energy emanating from the interference sources (CH 20 through CH 45) that fall within the desired CH 30, along with the 6 MHz CH 30 integrated attenuation of one of the band-stop filters (either narrowband for N±1 testing or wideband for N±2 and beyond), determine the test bed dynamic range for interference testing. More details can be found in the section titled “Test Bed Dynamic Range”.

5.1.2. LTE Source

One LTE source was employed in this laboratory test. An Agilent N5172B EXG RF vector signal generator (with arbitrary baseband generator and 60 MHz RF bandwidth) paired with the Agilent N7624B LTE Signal Studio synthesis and simulation software suite running on a personal computer (PC) created the three types of the LTE interference signals (i.e., fully-loaded “busy” 5 MHz LTE1, the lightly-loaded “idle” 5 MHz LTE2, and the fully-loaded “busy” 10 MHz LTE3). These interference test signals were loaded into the signal generator for subsequent selection and playback. Only one signal was required at a time during the laboratory testing, with the selection between the three signal modes performed with a few simple button pushes.

The Signal Studio software mathematically creates various LTE signals by using between 1 and 25 Resource Blocks (RB) carried in 301 subcarriers per symbol. These LTE signals have the desired 5 MHz channel bandwidth (301 subcarriers * 15 kHz per subcarrier = 4.515 MHz transmission bandwidth) and include the other necessary LTE transmission parameters. A 10 MHz wide LTE signal (601 subcarriers * 15 kHz per subcarrier = 9.015 MHz transmission bandwidth) was also created this way, with 50 RBs.

Three specific 5 MHz bandwidth standardized LTE base station downlink test signals compatible with the 3GPP Evolved Universal Terrestrial Radio Access (E-UTRA) air interface were selected for laboratory interference testing: 5 MHz E-TM3.1 (fully-loaded LTE1), 5 MHz E-TM2 (lightly-loaded LTE2), and 10 MHz E-TM3.1 (fully-loaded LTE3). “Fully loaded” and “lightly loaded” simulate a base station with heavy data traffic and light data traffic, respectively.

These standard test signals were subsequently loaded into the Agilent RF vector signal generator from the Signal Studio software for use as interference signals into the desired DTV signal. When all 25 (for the 5 MHz bandwidth signal) or 50 (for the 10 MHz bandwidth signal) RBs were allocated (per user selection) for simulated data use by the software, a fully-loaded LTE1 or LTE3 “busy” channel was created (E-TM3.1 occupying either 5 MHz or 10 MHz). When only one RB was allocated for simulated data use, a lightly-loaded LTE2 “idle” channel was created (E-TM2 occupying 5 MHz). No power boosting or de-boosting was applied. There was no need to utilize actual mobile data traffic as would occur in a real-world wireless installation due to the fact that these LTE signals were only used as undesired interference test signals rather than desired LTE signals to be decoded by consumer equipment for user application.

The Agilent signal generator, which can output an LTE signal on any U.S. television channel, had enough memory to hold three 10-mSec (i.e., 1 LTE Frame = 10 mSec) LTE test signals: fully-loaded LTE1, lightly-loaded LTE2, and fully-loaded LTE3. Each of these 10 mSec signals contained one LTE Frame (10 Subframes = 20 Slots = 10 mSec). When the tester selected one of these three LTE test signals on the signal generator, it was continuously played out and repeated contiguously in a 10 mSec Frame loop during the LTE interference tests. As determined by inspection on a scope, no RF "spikes" or "gaps" occurred during the repeat transition from the end of the 10-mSec test signal to the beginning of the next one.

Specifically, the ETV-3.1 downlink test signal is fully loaded (all available resource blocks used) and provides the maximum total average LTE signal power using 64-QAM payload data while the ETM-2 downlink test signal is lightly loaded (only 1 of the available resource blocks used) and provides the minimum total average LTE signal power using 64-QAM payload data. However, it should be noted that the lightly-loaded LTE2 test signal has the same average power during its one active resource block as the fully-loaded LTE1 test signal does during each of its 25 active resource blocks, which means the two test signals had the same power density during these active RBs. Therefore, when both LTE test signals are adjusted to the maximum interference level of -8 dBm, the RF levels are set as if all the resource blocks are present. These two types (fully loaded and lightly loaded) of "extreme" undesired test signals were used as LTE interference signals for the desired DTV signal.

Average power levels for 6 MHz DTV signals and 5 MHz LTE signals were measured with 6 MHz band power markers (per the ATSC method). The difference between the fully-loaded LTE1 transmission bandwidth power measurement and its channel bandwidth power method was found to be insignificant. No LTE time domain power measurements (i.e., power versus time) were made using a base station analyzer for determination of any particular Subframe, slot, or resource block power levels, but rather a vector signal analyzer (VSA) was used to measure average power of the various signals. The VSA was fed with a synchronization pulse from the Agilent LTE vector generator source that allowed average power measurements to be made during the first part of the LTE test signal where all of the LTE interference test signals (LTE1, LTE2, and LTE3) had active resource blocks. These signal power values were then compared to a fully-loaded LTE1 signal measured in the usual manner (i.e., average power over 6 MHz bandwidth using band power markers) in order to verify power measurement accuracy compliance.

The signal spectrum of the LTE test signals was measured and recorded while at the maximum signal output power level called for in the test. For comparison, LTE1 and LTE2 are shown in **Figure D-2a** and **Figure D3a**. Lightly-loaded LTE2, with only one active resource block, had a total average power that was about 6 dB lower than fully-loaded LTE1, which had all of its 25 resource blocks active. The in-band signal spectrum of the fully-loaded LTE1 signal was extremely flat (< 0.25 dB), but the lightly-loaded LTE2 signal spectrum had ripple measuring more than 20 dB peak-to-peak. Both LTE signals had extremely sharp transition regions at each end of the 5 MHz channel, with some 3^{rd} order intermodulation (IM3) splatter observed just beyond each band edge. The 10 MHz LTE3 had a similar spectrum to LTE1, except 10 MHz wide rather than 5 MHz.

Additionally, the RF envelope CCDF of the LTE source signals was measured and recorded while at the maximum test signal output level. For comparison, see LTE1 in **Figure D-2b** and LTE2 in **Figure D-3b**. The LTE1 plot illustrates the typical higher peak-to-average power ratio of 8.3 dB at 99.9% for fully-loaded LTE1, which is essentially equal to that of a white noise signal.

The lightly-loaded LTE2 signal had a much larger measured peak-to-average power ratio (about 12.5 dB). This is 4.2 dB higher than the value for LTE1. LTE2 should have an even higher PAPR than LTE1 because the peaks on LTE2's allocated RB could be just as high, but the average power in LTE2 is 6 dB lower, and the CCDF measurement automatically references the RF envelope power to the measured average power. So while there should be about 6 dB difference in PAPR, there is only 4.2 dB. This discrepancy may be due to several factors: 1) the LTE2 signal has far fewer locations (in the time domain) for random peak power combinations; 2) the signals LTE1 and LTE2 do not represent constantly changing data, but are single 10mS frames with the same pseudo-random data repeated over and over (and thus, fewer opportunities for statistically rare high peaks); and 3) other factors not considered here.

The LTE RF signals were also observed in the time domain, and had the expected noise-like characteristics (**Figure D-2c** and **Figure D-3c**). The fully-loaded LTE1 signal appears as a constant noise-like signal while the lightly-loaded LTE2 signal can be seen to be bursted, with one obviously long burst that carries the one active resource block.

It should be noted that these LTE interference signals were created with a high-quality, instrument-grade test equipment, and not by commercial-grade hardware that is found in cellular telephone sites, thereby potentially providing much better out-of-band energy performance than what might be found in the field. Just as discussed in the A/74 document, laboratory test signals with minimal out-of-band splatter provide good and repeatable benchmark test results for comparative DTV receiver performance evaluation. However, it must be recognized that these laboratory interference test results, while repeatable in the laboratory, do not accurately reflect field interference results when actual commercial hardware is used with imperfect out-of-band characteristics. Actual field results, in the presence of interference signals with adjacent channel splatter that acts as co-channel interference, will degrade the laboratory-measured interference D/U ratios obtained in the absence of splatter. Consequently, the interference data presented here would need to be adjusted to account for high-power transmitter spectral mask compliance in order to be used in allocation planning.

The following is a summary of the LTE interference test signal parameters that were selected and used in this laboratory test.

Table 3 LTE Base Station (BS) test signal parameter description for FDD systems.

LTE Test Signal (Parameters)	LTE1 (Fully Loaded)	LTE2 (Lightly Loaded)	LTE2 (Lightly Loaded)	Parameter Units
Modulation Type	**OFDMA**	**OFDMA**	**OFDMA**	-----
Duplex	**FDD**	**FDD**	**FDD**	-----
Channel Bandwidth	**5.0**	**5.0**	**10.0**	MHz
Occupied Channel Bandwidth	**4.515**	**4.515**	**9.015**	MHz
Sub-Frame Duration	**1**	**1**	**1**	mSec
Resource Block Width [1]	**200**	**200**	**200**	kHz
Allocated Resource Blocks	**25**	**1**	**50**	-----
# of Sub-carriers/Resource Block	**12**	**12**	**12**	-----
Sub-Carrier Spacing	**15**	**15**	**15**	kHz
Guard Interval [2]	**4.7/5.2**	**4.7/5.2**	**4.7/5.2**	µSec
Cyclic Prefix	**Normal**	**Normal**	**Normal**	-----
FFT Size	**512**	**512**	**512**	samples
Channel Modulation	**64-QAM**	**64-QAM**	**64-QAM**	-----
Test Data Pattern	**9-bit**	**9-bit**	**9-bit**	PBRS [3]

Note 1: 180 kHz resource block spectrum bandwidth with additional 200 kHz spacing.

Note 2: Values presented as "value for first symbol / value for the six subsequent symbols".

Note 3: Pseudo-Random Binary Stream (or Sequence), typically created with an n-bit linear shift register with feedback to create a maximal length sequence.

5.1.3. Band-Stop Filters

Adjacent channel interference testing requires handling significant differences in signal levels between the strong undesired DTV or LTE interference signals and the weak desired DTV signals. In order to perform these types of interference tests, a test bed with a very large dynamic range is required. This presents challenges given real-world parameter limitations on test sources, amplifiers, and spectrum analyzers. A test bed performance goal for measuring first adjacent channel (N±1) and second adjacent channel and beyond (> N±2) receiver interference thresholds is a D/U ratio of at least -50 dB and -60 dB, respectively, with the test bed adding only a relatively insignificant amount of noise to the testing process. To achieve these large D/U ratios, additional test filters are required.

All test signal generator outputs have some first adjacent channel splatter energy (due to non-linearities in output circuits) as well as broadband noise that extends many channels above and below the actual interference channel that they create. Real-world DTV and LTE transmitters operate on a fixed single channel (DTV) or a relatively narrow range of frequencies (LTE), thus allowing them to utilize passive high-power narrow band-pass filter devices at the final output to pass only the in-band signal and limit this additional out-of-band noise-like energy. However, use of a band-pass filter for each interference channel presents an inconvenience in laboratory testing where multiple interference channels (e.g., CH 20 – CH 45) are typically tested in conjunction with a single fixed desired channel (e.g., CH 30). Variable band pass filters do not exhibit very good (i.e., sharp) attenuation versus frequency characteristics, thus forcing laboratory test engineers to creatively solve this dynamic range limitation problem.

The solution is to employ a very sharp band-stop filter that attenuates interference source energy at the desired channel frequency, and insert it in the path of the interference signal(s) before being added to the desired signal. This removes most of the adjacent channel splatter or broadband noise from the interference source that falls into the desired channel and thus artificially limits the D/U interference threshold measurement. In other words, this filtering extends the dynamic range of the adjacent channel interference tests so that the measured interference D/U value is determined primarily by the interferer's in-band signal energy that generates IM3 products in the test receiver rather than that of the interference source's adjacent channel splatter or broadband noise present at the DUT input. The amount of required filter attenuation (i.e., attenuation of noise-like energy from the interference test source) depends on the required D/U interference measurement range.

However, there are different requirements for testing first adjacent channel interference versus 2nd adjacent channel and beyond interference. For first adjacent channel interference tests, the significant challenge is to provide acceptable stop band attenuation of unwanted interference source noise from the interference source that resides in the desired channel (e.g., CH 30) without significantly attenuating the nearby interference signal itself that resides on either adjacent channel (e.g., CH 29 or CH 31). For second adjacent channel interference (and beyond), the challenge is less because the band-stop filter can achieve much greater desired channel stop band attenuation since the required pass band specs are less restrictive due to the fact that the closest undesired interference signal is farther away from the desired signal (i.e., there is a "guard band" of at least one 6 MHz channel on each side). Fortunately, the range of D/U ratios required for first adjacent channel interference includes -50 dB while those for 2nd adjacent channel interference and beyond includes -60 dB.

It is desired that measurement of these two different D/U interference ratio limits should be performed in an environment with relatively insignificant test bed noise compared to the internally-generated IM3 interference noise in a test receiver. This means that the test bed D/U interference measurement limit (on any interference channel) should be at least 10 dB better than the D/U interference values of the test receivers.

Therefore, two separate band-stop filters were selected for laboratory interference testing that had acceptable attenuation characteristics, each providing a different tradeoff between CH 30 integrated (6 MHz) band-stop attenuation and pass-band flatness.

5.1.4. Narrowband Filter Used in First Adjacent Channel Testing

The first filter is a narrowband CH 30 band-stop filter (Microwave Filter Corporation MFC 18854) used for first adjacent channel testing. A picture of the unit can be found in **Figure D-4a** while a plot of its magnitude transfer function is shown in **Figure D-4b**. The filter is a 50-Ohm design, housed in a 2-RU metal rack-mounted chassis, with 8 cavities properly tuned to remove most of any signal energy on CH 30.

The band-stop filter attenuation, along with a DTV receiver's internal root-raised cosine (RRC) filtering that reduces any energy at each band edge, reduces any broadband noise in the interference path (prior to addition to the desired signal) that exists in the desired test channel (CH 30). This cascaded filtering effect was equivalently measured by using a 6 MHz DTV signal (8-VSB), which is already shaped with RRC transition regions in the modulator that correspond to the "matched filter" in every ATSC 8-VSB compatible receiver, to determine the total equivalent attenuation for the desired DTV channel. The net result of these two filtering processes is that an integrated attenuation of about **28 dB** is realized with the narrowband filter for first adjacent channel interference testing.

Note that there is a slightly increased band-stop filter attenuation near the band edge of each first adjacent channel interference region (amounting to perhaps 2 dB) relative to the narrowband band-stop filter's **1 dB** pass band insertion loss. For first adjacent DTV interference signals that must pass relatively unattenuated through the band-stop filter, this slight attenuation occurs at each band edge transition region of a 6 MHz DTV signal (i.e., the first 310 kHz) and therefore has minimal effect. For a 5 MHz LTE interference signal centered in the 6 MHz adjacent channel, this band-stop filter attenuation has even less effect on the interference signal due to the extra 500 kHz guard band on each side of the LTE signal. Therefore, this narrowband band-stop filter had no significant degradation effect on first adjacent channel interference test results.

As a final check, a very wideband frequency sweep of the entire UHF band was performed on the narrowband band-stop filter, and verified that there was a flat pass-band over the entire frequency range of the interfering test signals (i.e., CH 20 – CH 45), with no unexpected nulls. With regard to the undesired interference test signals on CH 20 – CH 45 (which must pass through the CH 30 band-stop filters), the average UHF pass band loss of the narrowband filter was about **1 dB**. Therefore, the response of this band-stop filter was found acceptable for first adjacent channel interference testing.

5.1.5. Wideband Filter Used in First Adjacent Channel Testing

The second band-stop filter is a wideband CH 30 band-stop filter (Microwave Filter Corporation MFC 16195) used for all other adjacent channel testing (≥ N±2). A picture of the unit can be found in **Figure D-5a** while a plot of its magnitude transfer function is shown in **Figure D-5b**. The filter is a 50-Ohm design with 6 cavities properly tuned to remove most of any signal energy on CH 30.

Just like the narrowband filter, two filtering processes (external band-stop filter and internal RRC filter) help reduce the amount of any interference source's broadband energy that exists within the desired test channel (CH 30). However, since this wideband filter is allowed to be wider in the band-stop region, the attenuation of the DTV receiver's RRC filter has much less effect on the overall net attenuation. This cascaded filtering effect was equivalently measured by using a 6 MHz DTV signal (8-VSB), which is already shaped with RRC transition regions in the modulator that correspond to the "matched filter" in every ATSC 8-VSB compatible receiver, to determine the total equivalent attenuation for the desired DTV channel. The net result of these two filtering processes is that an integrated attenuation of about **43 dB** is realized with the wideband filter for second adjacent (and beyond) channel interference testing.

Note that there is a slightly increased attenuation in the first adjacent channel interference region (couple of dB) relative to the wideband band-stop filter's **0.5 dB** pass band insertion loss, However, this is not critical since this wideband filter is not used for first adjacent channel interference testing but rather only for second adjacent channel interference and beyond. At the band edge of the second adjacent channel, the wideband band-stop filter is essential flat, and equal to its wideband insertion loss. Therefore, there was no significant degradation effect on second adjacent channel (and beyond) interference test results.

As a final check, a very wideband frequency sweep of the entire UHF band was performed on wideband band-stop filter, and verified that there was a flat pass-band over the entire frequency range of the interfering test signals (i.e., CH 20 – CH 45), with no unexpected nulls. With regard to the undesired interference test signals on CH 20 – CH 45 (which must pass through the CH 30 band-stop filters), the average UHF pass band loss of the wideband filter was **0.5 dB**. Therefore, the response of this band-stop filter was found acceptable for second adjacent channel and beyond interference testing.

5.1.6. Test Bed Dynamic Range

The dynamic range of the test bed is an important factor in evaluating receiver interference performance since large D/U threshold values are expected to be measured in these interference tests, especially two or more channels away from the desired signal. Therefore it is vital that the test bed has enough dynamic range in order to accurately determine the receiver interference capabilities. In other words, the range of error-free receiver operation should not be limited by the noise in the test bed (e.g., broadband noise from an interference source) but rather by the device under test (i.e., intermodulation noise created in the DUT's tuner).

However, any real-world interference test source will have broadband noise above and below its output signal frequency that will fall into the desired DTV test channel (i.e., CH 30). Since it is not feasible to have 21 different narrow band-pass filters, one for each interference channel to be tested, a better solution to the problem is to use a single band-stop filter (either narrowband or wideband), as described above, to remove the interference source's broadband noise from the desired channel's spectrum (i.e., CH 30) before addition of the undesired interference signal to the desired DTV signal, thus extending the measurement range of the test bed.

The limit of the test bed must be quantified for each interference channel and each interference source by determining the amount of integrated noise power that falls within the desired DTV test channel. This is accomplished by first determining the amount of broadband noise falling within the desired signal channel due to the interference source when it is tuned to the various interference test channels. Then the net attenuation must be determined for the external narrowband and wideband filters (described in the last section) in conjunction with the internal RRC filter embedded within every ATSC receiver.

Therefore, to determine the dynamic range of the test bed, two sets of parameters are required. The first requirement is to determine the amount of sideband noise from each interference source on a given interference test channel that falls within the desired 6 MHz channel (CH 30). The second requirement is to determine the net integrated attenuation that can be gained from each of the above band-stop filters (narrowband and wideband) cascaded with the DTV set's internal RRC filter.

Some basic concepts and assumptions are employed in this overall methodology:

(1) The first concept is to realize that there is no signal power measurement device (e.g., spectrum or vector analyzer) that has enough dynamic range to measure in one step the amount of sideband noise energy coming from an interference source. When the interference source is outputting an interference test signal at maximum power, a spectrum analyzer measuring its output will require the analyzer's input attenuator to be increased to avoid overload. This means that the source's broadband noise is typically below the noise floor of a

spectrum analyzer, and therefore cannot be measured. Therefore, test bed dynamic range measurement for each interference channel on each interference source requires a two-step process: 1) measure the in-band power directly at the interference source output, and then 2) measure the interference source's sideband energy with the use of a band-stop filter that removes most of the in-band signal power so that the analyzer can be adjusted to a more sensitive range without overload. While this band-stop filter that is required solely for measuring interference source sideband energy can be different from the filters described above that are used in actual interference testing, it is advantageous to use one the narrowband filter to characterize the broadband noise from an interference source, as described below.

(2) A second concept that is employed is to assume that conveniently measuring an interference test source's integrated 6 MHz sideband energy on 21 adjacent channels (e.g., ±1, ±2, ±3, ±4, ±5, ±6, ±7, ±8, ±10, +13, +14, +15) surrounding an interference test signal that is temporarily tuned to the single desired test channel (CH 30) provides essentially the same relative sideband noise energy distribution that would occur in the desired test channel (CH 30) if the interference test source were individually tuned to the actual 21 different interference test channels (e.g., ±1, ±2, ±3, ±4, ±5, ±6, ±7, ±8, ±10, +13, +14, +15). This assumes that the relative sideband noise energy surrounding any interference channel (N-10 through N+14) has the same distribution regardless of the RF channel upon which the interference test signal is ultimately placed. The advantage in using this method is that only one narrow band-stop filter (e.g., CH 30, which is already available for this test) is needed during the interference source sideband energy evaluation to overcome the aforementioned spectrum analyzer dynamic range problem instead of twenty-one different band-stop filters (i.e., one for each interference channel).

(3) A third concept is that at the interference threshold of an ATSC receiver, the total integrated white Gaussian noise power or noise-like interference power present in the desired test channel (i.e., CH 30) must be ≈15 dB below the desired signal level (i.e., $SNR_{THR} \approx 15$ dB). This is true regardless of whether the "noise" is due to the white noise Gaussian noise in the DTV tuner, intermodulation "noise" caused by non-linearities in the DTV's tuner, the interference source's adjacent channel sideband "noise, or a combination of all of them. However, the goal is to reduce the amount of test bed noise (i.e., interference source's sideband noise) to allow the DTV receiver's true interference limit to be reached or to at least verify that the receiver's D/U interference threshold is beyond an acceptably good value.

(4) A fourth concept is that in addition to the external band-stop filter (either narrowband or wideband) used in the actual interference testing that reduces broadband noise from the interference source, additional filtering takes place within every ATSC DTV receiver in the form of its RRC filter. This filter removes energy near each band edge (i.e., upper and lower). Therefore, both the external band-stop filter and the RRC filter help to reduce any interference source broadband noise that can limit the test bed's dynamic range during actual testing, and should be considered in determining the dynamic range for each interference test channel. This noise attenuation from these two filter processes can be quantified by combining their attenuation values for convenience, if desired.

The first step in determining the dynamic range is to measure the 6 MHz integrated sideband energy of an interference source for each interference test channel that will correspond to the energy falling within the desired CH 30 test channel. The integrated 6 MHz average power of the native interference signal (e.g., DTV or LTE) is measured at the direct output of the interference source (using 6 MHz band-power markers) on CH 30. Insert a narrow (i.e., one channel) CH 30 band-stop filter into the path of the interference test signal in order to remove most of the CH 30 signal energy and allow the spectrum analyzer to increase its sensitivity (i.e., lower its internal noise floor) without front-end (i.e., mixer) overload. This permits the integrated 6 MHz integrated average sideband energy in the various 21 relative 6 MHz adjacent channels to be measured more accurately. The relative integrated 6 MHz attenuation ($\mathbf{A_{Sk}}$, in dB) of sideband energy in each relative adjacent channel "k" can then be determined by calculating the difference between the original CH 30 average signal power measured before the band-stop filter and each integrated relative sideband channel energy measured after the band-stop filter, taking into account the small pass band insertion loss of this filter.

The second step in determining dynamic range is to measure the net integrated attenuation across 6 MHz (for the external band-stop filter and internal DTV RRC filter) for each of the two band-stop filters (narrowband and wideband) used in the actual interference testing. Since there is no way to measure after the RRC inside a DTV set, an equivalent method is to measure the average power in 6 MHz of a standard DTV signal (with its usual RRC spectral transition regions) before applying it to the band-stop filter under evaluation, and measuring the average power at this filter output. Since the RRC filter has essentially been applied to the DTV transmitter signal (i.e., the DTV signal looks like a flat noise-like signal that has passed through an RRC filter), the output signal of the band-stop filter has the characteristic of the cascaded band-stop and RRC filters. The difference between the average input power filter and its average output power of the band-stop, all measured in 6 MHz, is the net integrated cascaded band-stop and RRC filter attenuation ($\mathbf{A_F}$).

In a laboratory test bed, the level of the interference signal's sideband noise energy that limits a DTV receiver's interference threshold depends on two things:

(1) The sideband energy attenuation of the source itself ($\mathbf{A_{Sk}}$), which describes how far down the undesired interference source's sideband noise lies from the in-band interference signal level.

(2) The equivalent integrated attenuation from the combination of an external band-stop filter and a DTV receiver's internal RRC filter ($\mathbf{A_F}$) when tuned to the desired reference channel (e.g., CH 30).

In other words, the desired D/U interference measurement range is dependent on the sum of the test bed's interference source's sideband D/U value plus the test bed's equivalent band-stop filter's integrated attenuation (including the RRC filter attenuation). Once this test bed noise has been determined, the lowest measurable interference threshold at TOV occurs about 15 dB above this noise value.

For a desired first adjacent channel D/U dynamic range of 50 dB, the interference source sideband attenuation plus the integrated band-stop filter plus RRC attenuation must add up to at least 65 dB (i.e., 50 + 15). For a 2nd adjacent channel (or beyond) D/U measurement range of 60 dB, the total must add up to at least 75 dB (i.e., 60 + 15). It should be noted that these best-case D/U interference limits just described are defined as the case where a "perfect" DTV receiver would reach TOV due to the test bed noise limit, without any contribution from intermodulation of the DTV receiver. Therefore, the actual test bed limits should be at least 10 dB beyond (i.e., better) than these calculated values in order to accurately measure the DTV receiver's interference limit.

To calculate the dynamic range (DR) of the test bed at each interference channel, using the above assumptions and approximations, the following formula can be used, as shown in **Figure E-1**:

$$\mathbf{DR \equiv A_{Sk} + A_F - SNR_{THR} = = A_{Sk} + A_F - 15}$$

To perform the actual dynamic range evaluation of the MSW test bed, the narrowband CH 30 band-stop filter was conveniently utilized for all of these measurements. Again, in the use of the equation above, the value of the integrated band-stop filter ($\mathbf{A_F}$) attenuation conveniently includes the extra attenuation provided by the root-raised cosine filter that is included in every ATSC DTV receiver. As described above, this integrated cascaded filter attenuation value was easily measured by using a DTV signal with its inherent RRC spectral shaping to determine the band-stop filter attenuation (difference between signal level at filter input and filter output). Since the narrow band-stop filter was used in the test bed dynamic range calibration test, and its attenuation is required to be minimal at each band edge, the receiver's root-raised-cosine filter can have a significant effect on reducing any flat sideband energy at the band edge, and therefore increase the test bed's dynamic range.

The dynamic range of testing for first adjacent channel interference (N±1) using the narrowband band-stop filter was found to be approximately better than **-60 dB**, while the other adjacent channels (N±2 and beyond) using the wideband band-stop filter had better than either **-80 dB** or **-90 dB** (depending on the offset frequency from the desired CH 30). These dynamic ranges are more than sufficient to provide useful and significant interference results.

The maximum measurement dynamic range for each relative undesired test channel utilized in the test bed is recorded in **Table 4** below, and plotted in **Figure E-2**.

Table 4 Test bed dynamic range for the various interference channels utilizing any of the interference sources.

Relative Interference CH	CH #	Largest Measureable D/U Dynamic Range [2]
N-10	20	>90 dB
N-8	22	>90 dB
N-7	23	>90 dB
N-6	24	>90 dB
N-5	25	>90 dB
N-4	26	>90 dB
N-3	27	**>80 dB**
N-2	28	**>80 dB**
N-1	29	**>60 dB**
N+1	31	**>60 dB**
N+2	32	**>80 dB**
N+3	33	**>80 dB**
N+4	34	>90 dB
N+5	35	>90 dB
N+6	36	>90 dB
N+7	37	>90 dB
N+8	38	>90 dB
N+10	40	>90 dB
N+13	43	>90 dB
N+14	44	>90 dB
N+15	45	>90 dB

Note 1: N±1 interference tests require the narrow band-stop filter while all other interference tests require the wide band reject filter.

Note 2: Dynamic range denotes maximum measurable D/U value (in dB) possible using this test bed with a desired CH 30 from any of the four RF test sources, where the limiting value is determined by test bed noise floor.

6. TEST RESULTS

A summary of the raw laboratory test results are contained within tables in **Appendix G**. The data was analyzed using a desired RF CH 30 while various nearby channels were used for the interference signals.

The general tests (sensitivity, overload, AWGN threshold, co-channel interference) were performed first using the twelve 2012 – 2013 DTV receivers. These general tests were used as a pre-screen (i.e., looking for anomalous behavior) when finalizing the subset of 6 DTV receivers for the remaining interference testing, so the results were important in reducing the total population of test receivers to six. Two older model DTV receivers were added to the sensitivity and AWNG threshold tests as well as to the sliding LTE interference tests for comparative purposes. A summary of the general tests for the 6 recent-model DTV sets is contained in **Table 5** below. All tabular test results appear in **Appendix G**.

6.1. Sensitivity Threshold

The results of the sensitivity threshold test for the 12 recent-model DTV test receivers were very favorable. A summary of these results can be found in **Table G-1**.

All 12 of these receivers showed good sensitivity, better than the A/74 guideline of -83 dBm. The median signal sensitivity threshold for these 12 recent-model sets occurred at **-86.2 dBm**. The worst case AWGN threshold was **-85.1 dBm**, which is still better than the A/74 value. The sensitivity variance for all 12 receivers was only **1.3 dB**, which shows consistency amongst various consumer receivers from different manufacturers.

Although the subset of 6 recent-model receivers were not selected on the basis of performance, they had even better sensitivity statistical performance, as they varied between **-85.6 dBm** and **-89.4 dBm**, with a median value of **-87.8 dBm**. Interestingly, one of the subset of six test units had the best sensitivity value (**-89.4 dBm**) of the 12 receivers.

One of the two older-model DTV sets (Rx #14) had a good sensitivity value **(-85.8 dBm)** but the other unit (Rx #13) had a poor sensitivity value (**-81.9 dBm**) that did not meet the A/74 recommended value Since it was subsequently determined that it had a reasonable AWGN threshold, the assumption is that the poor sensitivity was the result of a poor tuner noise figure (**9.4 dB**). This poor sensitivity value indicates an increased noise floor for this unit, which has a direct effect on interference rejection performance.

The individual general receiver sensitivity values for all 14 receivers are shown in **Table G-1** in **Appendix G**.

6.2. Overload Threshold

The results of the overload threshold test for the 12 recent-model DTV test receivers were also very favorable. A summary of these results can be found in **Table G-1**.

All 12 of these receivers sustained maximum test power without reaching the threshold of errors (i.e., DTV sets always produced picture and sound), and therefore have the ability to handle more than +5 dBm DTV signals on CH 30. This **+5 dBm** maximum test value easily met the A/74 guideline of -5 dBm, and is 13 dB higher than the largest signal level expected by the industry to occur in the field (i.e., -8 dBm per ATSC A/74 “Multi-Signal Overload”). This test is the only time in the laboratory test plan where this large signal value was used. Together with the sensitivity results, all 12 recent-model receivers were observed to have better than **90 dB** dynamic range capability for a single unimpaired desired DTV signal. While signals this large are not expected in the field, this special test shows that the dynamic range of each receiver is such that its on-channel overload capability is at least 13 dB better than the maximum expected signal level in the field.

The results of this overload test using only the desired signal confirmed that the dynamic range of error-free operation is such that when the subsequent multiple signal overload test was performed with two adjacent channel signals (N+2 and N+3) each at -8 dBm, the measured limit of receiver performance will indeed be due to the effects of two interfering signals with very little contributing degradation from the receiver’s in-band dynamic range (i.e., AGC range and overload capability).

It should be noted that one (Rx #8) of the 12 receivers (not part of the subset of 6 selected for more detailed testing) exhibited some anomalous behavior above -5 dBm. This receiver appears to use some sort of algorithm to track signal strength. When the signal strength trends are unfavorable (i.e., trending towards weakness), a "signal weakening" message is displayed to the user. For very strong signals, this message also appears, claiming that signal weakening is occurring, although the opposite is happening. Perhaps this is due to a decreasing SNR caused by the noise-like IM3 components generated in the tuner. If the signal strength is slowly increased from -5 dBm to +5 dBm, the algorithm appears to adjust the tuner settings properly (i.e. with error free data recovery). However, if the signal level suddenly increases from -5 dBm to +5 dBm, the signal strength algorithm seems to become unstable, causing near continuous MPEG data errors. Similar results occur if a "re-acquisition" (e.g., channel change) is performed with the signal level already fixed at +5 dBm. Therefore, it appears that this particular receiver is unstable under these specific strong signal conditions. However, it should be noted that this anomaly for this particular receiver occurs only at very strong levels, well beyond the -8 dBm maximum signal level expected in the field.

6.3. AWGN Threshold

The AWGN threshold test, performed at a moderate desired signal level (-53 dBm) for all 12 recent model DTV test receivers, indicated very good and very consistent white noise threshold values below the expected 15 dB value assumed by industry practice for ATSC (8-VSB) receivers (and measured at the Advanced Television Test Center on the Grand Alliance reference receiver). A summary of the recent-model test results can be found in **Table G-1**.

A median value of **14.8 dB** for all 12 of these receivers was observed in this measurement, with only a **0.1 dB** standard deviation value and a mere a **0.3 dB** difference between the maximum and minimum values. Even the worst case value of **14.9 dB** (observed in only one recent-model unit) was still below the expected 15 dB value. While performance in the field can be noticeably different from this ideal impedance condition (e.g., mismatched complex impedance between antennas coupled via long cables to tuners, presence of multipath, etc.), these 12 receivers from a variety of manufacturers showed extreme consistency under well-controlled laboratory conditions.

AWGN threshold and receiver noise figure each affect the ultimate signal sensitivity threshold under these ideal impedance matching conditions (e.g., impedance mismatch loss in “real-world” applications adds to noise figure, which in turn affects sensitivity). The equivalent ideal receiver noise figure (NF) can be calculated from the sensitivity (S_{MIN}) and AWGN threshold (SNR_{THR}) measurements, as well as the amount of white Gaussian noise in a matched impedance scenario (kTB where B = 6 MHz). The following equation describes the method.

$$S_{MIN} = kTB + NF + (SNR_{THR}) \quad (1)$$

$$NF = S_{MIN} - kTB - (SNR_{THR}) \quad (2)$$

where kTB is -106.2 dBm/6 MHz at “room” temperature (i.e., 25 degrees Celsius).

For the 12 recent-model receivers, the median receiver noise figure was **5.4 dB**. The entire range of calculated noise figures was **2.0 dB** to **6.3 dB**; only one of the 12 recent-model DTV sets had a noise figure above 6 dB. The subset of 6 receivers had a superb median value of noise figure of **3.7 dB**.

The two older sets both had white noise TOV thresholds of **14.9 dB**. While this threshold value matched the worst performance of the recent-model DTV sets, it was nonetheless still less than 15 dB, and better than earlier DTV models.

6.4. Co-Channel Interference

The DTV-into-DTV co-channel interference test performed for all 12 recent-model test receivers at a moderate desired level (-53 dBm) showed that, with a couple of exceptions, the co-channel D/U threshold ratio was essentially the same or slightly better than the AWGN threshold. A summary of the results can be found in **Table G-2**.

The median value of this co-channel D/U ratio was **14.4 dB**, about **0.4 dB** below the white noise threshold. It’s possible to have a slightly better value than white noise since the ATSC (8-VSB) DTV signal has a 2-dB lower peak-to-average power ratio (PAPR) than additive white Gaussian noise (AWGN) and LTE (OFDMA) signals (at the 99.9% statistical point). The results for these12 receivers were consistent with only a **0.6 dB** standard deviation and a difference of less than **2 dB** between the absolute maximum and minimum values.

However, two of the 12 DTV receivers had higher values of DTV-into-DTV co-channel interference ratios (**15.7 dB** for receiver #10 and **16.1 dB** for receiver #5) than their white noise thresholds (**14.9 dB** and **14.8 dB**, respectively). The cause of this anomaly is not known at this time. One of the receivers (Rx #5) is part of the subset of 6 receivers.

The **LTE1-into-DTV** co-channel interference test performed for these 12 receivers showed a slightly higher (i.e., worse) D/U threshold ratio than for DTV-into-DTV co-channel interference. The median value of co-channel D/U ratio was **15.3 dB**, about **0.9 dB** greater (i.e., worse) than for its DTV equivalent, probably due in part to its higher peak-to-average power ratio. Like DTV co-channel interference, the test results for the 12 DTV sets were consistent (**0.4 dB** standard deviation).

The **LTE2-into-DTV** co-channel interference test performed for these 12 receivers showed a lower (i.e., better) D/U ratio than for DTV-into-DTV co-channel interference. However, it should be noted the lightly-loaded LTE2 signal level is defined in its cellular deployment as average power during its one active resource block (i.e., its power density) rather than the average power of the entire signal (which is about **6 dB** lower than the fully-loaded case). Therefore, the interference effects from this "bursty" LTE2 signal occurs primarily during this one active block and much less the rest of the time when the signal is at much lower levels. This is reflected by the lower (i.e., better) median D/U value of **13.7 dB** for LTE2.

Table 5 Summary of general performance test results for 12 recent-model consumer receivers.

Statistical Parameter	**Sensitivity Threshold**	**Overload Threshold**	**Dynamic Range**	**AWGN Threshold**	**Noise Figure**	**D-into-D Co-CH**	**LTE1-into-D Co-CH**	**LTE2-into-D Co-CH**
(*)	**(dBm)**	**(dBm)**	**(dB)**	**(dB)**	**(dB)**	**(dB)**	**(dB)**	**(dB)**
Mean	-86.6	> +5.0	-----	14.8	4.8	14.7	15.5	13.7
Median	-86.2	> +5.0	-----	14.8	5.4	14.4	15.3	13.7
Minimum	-89.4	> +5.0	>90.1	14.6	2.0	14.2	15.0	13.3
Maximum	-85.1	-----	-----	14.9	6.3	16.1	16.5	14.3
Std Dev	1.3	0.0	-----	0.1	1.3	0.6	0.4	0.3

6.5. Multi-Signal Overload Interference

6.5.1. DTV-into-DTV

The DTV-into-DTV multi-signal overload test performed for the subset of 6 receivers showed that while good interference results were obtained, the presence of two DTV interference signals (N+2 and N+3) is significantly worse than for a single interferer. A summary of the results can be found in **Table G-3**.

The median D/U value measured on the subset of 6 receivers for this dual (non-IM3 pair) interference scenario was **-45.5 dB**, with values ranging from **-39.8 dB** to **-46.8 dB**. Essentially, all 6 units had D/U values better than **-40 dB**, which is fairly robust. The ATSC A/74 document recommends a test methodology but does not recommend a specific performance value regarding multi-signal interferers.

6.5.2. LTE-into-DTV

The LTE-into-DTV multi-signal overload test was performed on just one DTV set (Rx #1), with LTE1 as the “closest” interference signal and DTV as the “farthest” interference signal. The interference threshold D/U was **-41 dB**, about **1.2 dB** better than the two DTV interference signals. However, it should be noted that while the LTE signal has a higher PAPR than DTV, it is also only 5 MHz wide (in reality, it is only 4.515 MHz wide in a 5 MHz transmission channel just as DTV is only 5.381 MHz wide in a transmission 6 MHz channel). Therefore, the combined IM3 splatter below these N+2 and N+3 interfering signals (approximately 9.9 MHz wide in total) will not reach as far across CH 31 and into the desired CH 30 DTV signal (compared to two 6 MHz DTV signals) to cause interference, which might explain the slightly better (**1.2 dB**) interference threshold for this particular LTE/DTV-into-DTV test.

6.6. Single Interferer Interference (DTV-into-DTV and LTE-into-DTV)

6.6.1. DTV-into-DTV

The single DTV-into-DTV interferer interference test was performed for the subset of 6 receivers at both weak (-68 dBm) and strong (-28 dBm) levels. The results showed excellent robustness, often with results that did not allow the interference error threshold to be reached for the test plan’s maximum interference level (-8 dBm) for many of the adjacent interference channels (denoted with “< -60.9 dB”). A summary of the results can be found in **Table G-4** and **Table G-5**. See **Figure H-1a** and **Figure H-1b** for summary plots.

All 6 of the test receivers met the ATSC A/74 recommended performance for all of the adjacent channel tests (even the “worst case” receiver). While both weak (-68 dBm) and strong (-28 dBm) desired signal levels were measured, it is the weak signal test that has the most interesting results since the test for the strong level resulted in error-free performance for all 6 receivers, i.e., maintaining video at or beyond the maximum signal level of -8 dBm (i.e., they did not reach TOV). Therefore the rest of this section will focus on the weak desired signal analysis.

These single interferer test results can be divided into three performance groups: 1st adjacent channel, 2nd through 4th adjacent channel, and 5th adjacent channel and beyond.

D/U thresholds had median values for first lower and upper adjacent channel interference of **-45.3 dB** and **-46.0 dB**, respectively, with values for the various receivers falling within approximately an **11 dB** range. The upper and lower adjacent channel D/U interference ratios were not identical in each unit, with differences varying between **1.0 dB** and **5.6 dB**. However, there was no consistency regarding which adjacent channel was more robust since 3 receivers had a better interference ratio for the lower adjacent channel, and 3 had a better interference ratio for the upper adjacent channel. The worst case D/U value was **-38.9 dB**, easily meeting the ATSC-recommended value -33 dB. However, this is not a valid representation of the performance in the field since this test uses interference signals with no adjacent channel splatter. Care must be taken when interpreting field performance and requirements from this laboratory data.

Second adjacent channel interference was found to have D/U values **-49.5 dB** or better, with many of them having D/U values better than **-54 dB**. Third and fourth adjacent channel D/U interference thresholds followed a similar pattern.

For adjacent interference channels N±5 and beyond, the test results exceeded A/74 single-interferer guidelines, but with less margin than closer adjacent test results. This performance demonstrates a marked improvement in consumer tuner performance over the last 7 years (e.g., see Martin 2007). Some of the receivers (Rx #1, Rx #5, and Rx #6) reached the limits of the test bed (approximately -60 dB D/U) beginning at adjacent channel N±4.

It should be noted that for special adjacent channel interference tests, no anomalies were noticed. For example, there was no interference threshold degradation on N+14 or N+15 results when interference was present on the image frequency for a single conversion tuner (i.e., threshold could not be reached due to the maximum interference test signal level of -8 dBm). The "½-IF beat" interference scenario (N+4), where the 2nd harmonic of the interference signal at the input and the 2nd harmonic of the local oscillator beat together to create a traditional 44 MHz IF frequency, was not observed either (D/U values better than **-56 dB** for all 6 receivers).

One anomaly (measurement hysteresis) that was observed during laboratory testing occurred with receiver Rx #3 on 8 different interference channels: (N-2) through (N-4) and (N+2 through (N+6). When errors were observed on their screen at the interference threshold, and the interference signal reduced by a 0.5 dB step followed by a channel change, errors did not cease. Usually a **1 dB** to **2 dB** interference signal decrease was required before error-free operation was observed. This is not a major issue, especially since only one receiver exhibited this anomaly.

6.6.2. LTE-into-DTV (Fully Loaded and Lightly Loaded LTE)

The LTE-into-DTV single interferer interference test was performed for only one of the 6 receivers at both weak (-68 dBm) and strong (-28 dBm) levels, and showed excellent robustness against LTE1 and LTE2, often with results that did not allow the interference error threshold to be reached for the test plan's maximum interference level (-8 dBm) for many of the adjacent interference channels (denoted with "< -60.9 dB"). A summary of the results can be found in **Table G-6** and **Table G-7**. See **Figure H-1c** for a summary plot.

All of the receivers did meet the ATSC A/74 recommended performance for all of the adjacent channel tests (even the "worst case" receiver). While both weak (-68 dBm) and strong (-28 dBm) desired signal levels were measured, it is the weak signal test that has the most interesting results since the test for the strong level test, just as with the DTV-into-DTV test, resulted in this receiver not being able to reach the interference threshold using the test plan's maximum signal level of -8 dBm (i.e., they did not reach TOV). Therefore the rest of this section will focus on the weak desired signal analysis.

These single interferer test results can be divided into three performance groups: 1st adjacent channel, 2nd adjacent channel, and 3rd adjacent channel and beyond.

The first adjacent channel interference D/U threshold was better for LTE1 than DTV on the upper adjacent channel (by **1.4 dB**) and slightly worse for LTE1 than DTV on the lower adjacent channel (**0.4 dB**), despite the 2 dB higher PAPR of the LTE1 signal. Part of the compensating effect for the higher PAPR might be the fact that there was a 0.5 MHz guard band between the undesired LTE signal and the desired DTV signal that exists since the 5 MHz LTE signal is centered in the 6 MHz DTV channel. The first adjacent channel interference D/U threshold was slightly better for LTE2 than DTV on both the upper adjacent channel (**0.8 dB**) and the lower adjacent channel (**0.9 dB**). The "burstiness" of the LTE2 signal, with periods of low signal level might be the compensating factor for the higher PAPR. Nevertheless, all of the LTE D/U interference ratios on this single receiver were better than -40 dB and thus easily meet the ATSC-recommended value of -33 dB (A/74 document), which was determined by taking the average of the FCC-required first adjacent D/U values and then adding 6 dB for margin[9].

Second adjacent channel interference for LTE1 was found to have D/U values better than **-50 dB** on the lower adjacent channel and better than **-57 dB** on the upper adjacent channel. For the LTE1 signal, these results were about **2 dB** to **3 dB** worse than the DTV interference for this specific receiver. On the other hand, the LTE2 signal exhibited slightly more robustness than the DTV signal on the upper 2^{nd} adjacent channel (by about **0.4 dB**) but less robustness on the lower 2^{nd} adjacent channel (by about **1 dB**). The results are such that the performance of LTE1 and LTE2 are essentially the same as DTV plus about 1 dB for these particular types of interference.

For adjacent channel interference N±3 and beyond, the test results for both DTV and LTE1 and LTE2 were all at maximum capability of the test bed, with no errors observed.

6.7. Equal-Power IM3 Paired Interference: N+k=N+2k

The equal-power **DTV-into-DTV** and **LTE1-into-DTV** IM3-paired interference test (at weak desired DTV signal level) was performed for the subset of 6 receivers. For this test, the closest (i.e., N+k) interferer and the farthest (i.e., N+2k) interferer were equal in power, with the closest interferer used as the reference interference power for D/U calculations. A summary of the results can be found in **Table G-8**, **Table G-9**, and **Table G-10**.

Good robustness was observed, but there was significant interference performance degradation (increased D/U threshold ratios) from that of the single interferer test results for both DTV-into-DTV and LTE-into-DTV. This was due to the generation of IM3 components from the specially-paired interferer channels that cause noise-like interference to fall within the desired DTV channel due to the tuner's nonlinearities.

6.7.1. DTV-into-DTV

DTV-into-DTV interference test results (**Table G-8**) for the 6 individual receivers are plotted in **Figure H-2a**. These curves show noticeable D/U variability between units (e.g. up to **15 dB** over the various paired interference channels), while clearly indicating that receivers #4 and #5 were consistently better than the other units across all 10 of the IM3-paired interferer scenarios. This figure also shows that there is not very much improvement in robustness as the interfering channels get farther from the desired channel.

Figure H-2b shows the median results of both the single interferer and IM3-paired interferers. From this plot, the median D/U interference ratio of the 6 receivers at each IM3 pair is centered around **-40 dB** and varied only **±2 dB** around this value across 10 different interferer pairs, exhibiting a fairly flat curve. The median interference performance difference between the IM3-

[9] "ATSC Recommended Practice: Receiver Performance Guidelines", Document A/74:2010, April 7, 2010.

paired interferers and single interferers is clearly observed in this plot, especially at farther frequencies from the desired DTV channel.

Figure H-2c illustrates the calculated difference (i.e., degradation) for the 6 test receivers between each of the IM3 interference D/U ratios and its equivalent single interferer test result (**Table G-9**) using the closest (i.e., N+k) signal of the IM3-paired channels for the D/U interference calculation. In other words, this figure shows in graphical form how much the second interferer in an IM3 pair degrades the D/U performance from the single interferer case. A negative number indicates worse IM3-paired interference performance, thus illustrating the D/U degradation (and its unit-to-unit variability) from that of a single interferer. A clear degradation of this IM3-paired interferer scenario from that of the single interferer is illustrated for each IM3 pair (about **5 – 9 dB** for the first adjacent channel and **6 – 25 dB** for the taboo channels). **Figure H-2d** is a plot of the median degradation value of the 6 test receivers, where a **5 dB** degradation at N±1 and a **15 – 20 dB** degradation for the N±2 and beyond taboo channels is illustrated.

6.7.2. LTE1-into-DTV (Fully Loaded LTE)

LTE1-into-DTV interference test results are illustrated in **Figure H-5a** for one test receiver, comparing IM3-paired interference results to single interferer results. It can be seen that there is **3 – 5 dB** of degradation at the first adjacent channel and significant degradation (up to **20 dB**) occurs beyond that of a single interferer when a second IM3-paired taboo interferer is added.

A comparison between DTV and LTE interference is shown in **Table G-10**. The LTE signal for this one test receiver had slightly better interference performance over all 10 of the IM3-paired interferers (median value of **0.9 dB**) than that of the DTV signal. While the LTE signal has a higher PAPR, it is only 5 MHz wide (with a 0.5 MHz guard band) as opposed to the 6 MHz DTV signal (with no guard band), which might have a compensating effect.

6.8. Unequal-Power IM3 Paired Interference: N+k > N+2k

The unequal DTV-into-DTV and LTE1-into-DTV IM3-paired interference test (at weak desired DTV signal level) was performed for a subset of 6 receivers. For this test, the closest (i.e., N+k) interferer was 10 dB higher (i.e., N+k = N+2k+10 dB) than the farthest (i.e., N+2k) interferer, with the closest interferer again used as the reference interference power for D/U calculations. A summary of the results can be found in **Table G-11**, **Table G-12**, and **Table G-13**.

Good robustness was observed, but there was again interference performance degradation (increased D/U threshold ratios) from that of the single interferer test results for both DTV-into-DTV and LTE-into-DTV. This was again due to the generation of noise-like IM3 components from the specially-paired interferer channels that cause noise-like interference to fall within the desired DTV channel due to the tuner’s nonlinearities. However, this degradation, while noticeable, was not as significant as the equal-power case due to the fact that the farthest interferer was reduced by 10 dB from that of the closest interferer.

6.8.1. DTV-into-DTV

DTV-into-DTV interference test results (**Table G-11**) for the 6 individual receivers are plotted in **Figure H-3a**. These curves show noticeable D/U variability between units (up to **15 dB** over the various paired interference channels), similar to the equal-power IM3-paired interference test, while clearly indicating that receivers #4 and #5 were consistently better than the other units across all 10 of the IM3-paired interferer scenarios. There is some but not very much improvement in robustness as the interfering channels get farther from the desired channel.

Figure H-3b shows the median results of both the single interferer and IM3-paired interferers. From this plot, the median D/U interference ratio of the 6 receivers at each IM3 pair is centered around **-45 dB** and varied only **±2 dB** around this value across 10 different interferer pairs, once again exhibiting a fairly flat curve. The median D/U interference degradation between these unequal IM3 paired interferers and the corresponding single interferers for the 6 receivers is about **5 dB** less (**-40 dB** versus **-45 dB**) than the equal power interferers due to the farthest interferer (N+2k) signal power being 10 dB lower. The interference performance difference between IM3-paired interferers and single interferers is clearly observed in these two plots, especially at farther frequencies from the desired DTV channel.

Figure H-3c illustrates the calculated difference for the 6 test receivers between each of the IM3 interference D/U ratios and its equivalent single interferer test result (**Table G-12**) using the closest (i.e., N+k) signal of the IM3-paired channels for the D/U interference calculation. As before, a negative number indicates worse IM3-paired interference performance, thus illustrating the D/U degradation (and its unit-to-unit variability) from that of a single interferer. A clear degradation of this IM3-paired interferer scenario from that of the single interferer is illustrated for each IM3 pair (about **1 – 2 dB** for the first adjacent channel and **3 – 20 dB** for the taboo channels). **Figure H-3d** is a plot of the median value of the 6 test receivers, where a **2 dB** degradation at N±1 and a **10 – 14 dB** degradation for the N±2 and beyond taboo channels is illustrated (i.e., **5 dB** better than the equal-power scenario).

6.8.2. LTE1-into-DTV (Fully Loaded LTE)

LTE1-into-DTV interference test results are illustrated in **Figure H-5b** for one test receiver, comparing IM3-paired interference results to single interferer results. It can be seen that there is only about **1 dB** of degradation at the first adjacent channel and still significant degradation (up to **12 dB**) occurs beyond that of a single interferer when a second IM3-paired taboo interferer is added.

A comparison between DTV and LTE interference is shown in **Table G-13**. The LTE signal for this one test receiver had slightly better interference performance over all 10 of the IM3-paired interferers (median value of **2.6 dB**) than that of the DTV signal. Again, the tradeoff between higher PAPR and bandwidth (with guard band) might have a compensating effect on performance.

6.9. Unequal-Power IM3 Paired Interference: N+k < N+2k

The unequal DTV-into-DTV and LTE-into-DTV IM3-paired interference test (at weak desired DTV signal level) was performed for a subset of 6 receivers. For this test, the closest (i.e., N+k) interferer was 10 dB lower (i.e., N+k = N+2k–10 dB) than the farthest (i.e., N+2k) interferer, with the closest interferer again used as the reference interference power for D/U calculations. A summary of the results can be found in **Table G-14**, **Table G-15**, and **Table G-16**.

Good robustness was observed, but there was again an interference performance degradation (increased D/U threshold ratios) from that of the single DTV interferer test results for both DTV-into-DTV and LTE-into-DTV. This was once again due to the generation of noise-like IM3 components from the specially-paired interferer channels that fall within the desired channel due to the tuner's nonlinearities. However, this degradation was greater than that experienced in the equal-power IM3-paired interferer test due to the fact that the farthest interferer was increased by 10 dB from that of the closest interferer as well as the fact that the reference interference power was taken to be that of the closest (and lower) interferer. Since the farthest interferer is a known level (i.e., 10 dB) above the closest interferer, the IM3-paired D/U curves in the associated plots can be shifted down (i.e., improved) by 10 dB, if it is desired to use the farthest interferer as the reference point (described later).

6.9.1. DTV-into-DTV

DTV-into-DTV interference test results (**Table G-14**) for the 6 individual receivers are plotted in **Figure H-4a**. These curves exhibited noticeable D/U variability between units (up to **13 dB**) similar to the previous IM3-paired tests. Receivers #4 and #5 were consistently better than the other units across all 10 of the IM3-paired interferer scenarios. Following a similar pattern previously observed there is some but not very much improvement in robustness as the interfering channels get farther from the desired channel.

Figure H-4b shows the median results of both the single interferer and IM3-paired interferers. From this plot, the median D/U ratios of the 6 receivers for each IM3 pair is centered about **-39 dB** and varied only **±3 dB** around this value across 10 different interferer pairs, which once again exhibits a fairly flat curve. When using the closest interferer as the reference comparison, the median D/U interference degradation between these unequal IM3 paired interferers and the corresponding single interferers (**Table G-15**) for the 6 receivers is only about **1 dB** worse **(-40 dB** versus **-39 dB**) than the equal power interferers due to the fact that the 10 dB larger interferer (N+2k) is farther away and has slightly less effect than the closer interferer. The interference performance difference between IM3-paired interferers and single interferers is clearly observed in these two plots, especially at farther frequencies from the desired DTV channel.

Figure H-4c illustrates the calculated difference for the 6 test receivers between each of the IM3 interference D/U ratios and its equivalent single interferer test result (**Table G-15**) using the closest (i.e., N+k) signal of the IM3 paired channels as the D/U calculation reference point. As before, a negative number indicates worse interference performance, thus illustrating the D/U degradation (and its unit-to-unit variability) from that of a single interferer. A clear degradation of the IM3-paired interferer scenario from that of the single interferer is observed for each IM3 pair tested (about **6 – 12 dB** for the first adjacent channel and **5 – 25 dB** for the taboo channels). **Figure H-4d** is a plot of the median value of the 6 test receivers, where an **8 dB** degradation at N±1 and a **17 – 20 dB** degradation for the N±2 and beyond taboo channels is illustrated.

It should be noted that for the above analysis, the closest interferer (i.e., N+k) was used as the reference signal level for calculating D/U ratios in order to obtain a consistent comparison with the previous two IM3-paired interference test scenarios. Use of the closest interferer is quite understandable in the first two interference IM3-paired scenarios: equal power (N+k=N+2k) where both interferers are at the same level and unequal power (N+k=N+2k+10 dB) where the closest interferer is the stronger of the two interferers. For completeness, the **third scenario was also analyzed using the closest interferer as a reference** in order to determine the various effects on DTV reception when a 2nd IM3-paired interferer was added (1) at the same power level as the original single interferer, (2) below the original interferer, or (3) above the original interferer. The comparison to the single interferer scenario was then straightforward: the closest interferer was always used as the reference for D/U value calculations and the D/U interference threshold for the single interferer on this same (i.e., closest) channel was used for the comparison.

However, another possible analysis methodology is to always use the largest interference signal as the reference. This means only one change to the previous analysis, and that would be for the scenario where the farthest interferer is the larger signal. Since the power difference is exactly 10 dB, the analysis would be straightforward in that the previous calculations for the IM3-paired D/U ratio values (observed in both the tables and plots) would just be decreased (i.e., improved) by 10 dB for this one scenario. The primary difference, though, comes in the plots (6 individual receivers or the median value of all 6 of them) that compare the IM3-paired results with those of the single interferer. Instead of comparing the IM3 –paired interferer results with the closest (i.e., N+k) lower and upper adjacent channels single interferers, the farthest (i.e., N+2k) channels would be used for comparison. **Figure H-4e** illustrates this comparison for the 6 individual DTV receivers while **Figure H-4f** shows a similar comparison between the median values of the single interferer and IM3-paired interferers. Note that the results still show significant degradation with the presence of IM3-pairs compared to the single interferer scenario.

6.9.2. LTE-into-DTV (Fully Loaded LTE)

LTE1-into-DTV interference test results are illustrated in **Figure H-5c** for one test receiver, comparing IM3-paired performance results to single interferer results. It can be seen that there is only about **7 - 10 dB** of degradation at the first adjacent channel and still significant degradation (up to **20 dB**) occurs beyond that of a single interferer when a second IM3-paired taboo interferer is added.

A comparison between DTV and LTE interference is shown in **Table G-16**. The LTE signal for this one test receiver had slightly better interference performance over all 10 of the IM3-paired interferers (median value of **0.4 dB**) than that of the DTV signal. Again, the tradeoff between higher PAPR and bandwidth (with guard band) might have a compensating effect on performance. Since a direct comparison between two signals with IM3-paired interference is being made, the reference to either the closest or farthest interferer is not relevant.

6.10. Sliding LTE Interference (Weak Desired Signal)

The two separate "sliding" LTE interference test results (5 MHz LTE1 signal and the 10 MHz LTE3 signal) are included in **Table G-17** and **Table G-18**, where the D/U interference ratios vary as the undesired LTE interference signal is shifted in frequency in 1 MHz steps, providing varying amounts of overlap with the weak (-68 dBm) desired DTV signal. Units tested were the 6 recent-model DTV sets used in all of the previous adjacent channel interference tests, plus two older sets from 2006 for comparison with the recent DTV models.

In this test, certain signal spectral alignments caused TOV results to vary somewhat, in some units by as much as **3 – 5 dB**. The variation occurred when determining TOV as described for the other tests in this report. The variation was enough that getting consistently repeatable results was uncertain. An underlying goal of this effort is that the test results should be reasonably repeatable by independent tests after this report is published, and the amount of variation made this less likely. Therefore, the method of determining TOV for these tests was altered to account for those test scenarios where the interference threshold was not stable, and thus made determining TOV difficult.

The hypothesis made from the test results is that as the LTE interference signal starts off overlapping most (5 MHz signal) or all (10 MHz signal) of the desired DTV signal (i.e., with both lower band edges of the desired DTV and undesired LTE signals lined up), the D/U interference ratio (determined by the total integrated noise power of the interferer that falls within the desired channel) must be around 15 dB (same as white noise threshold). With the LTE signal this far below the desired DTV signal during this initial testing and spread out across most or all the entire desired channel, all of the DTV receiver synchronization loops in the receiver should still be working reasonably well, just as they do when the receiver is near the flat spectrum white noise threshold.

However, as the LTE interference signal is shifted in frequency (in 1 MHz steps), there is less overlap with the desired DTV signal so the undesired LTE signal strength can increase to reach about the same integrated in-band noise level at TOV. Therefore, the D/U interference ratio drops since some of the undesired LTE interference power is outside of the desired DTV channel (i.e., partially in the adjacent channel). Since the LTE signal was shifted higher in frequency, there is still overlap with the desired DTV signal at its upper band edge frequency. The symbol clock synchronization circuits in most DTV sets use the energy in this area to create a local symbol clock with which to decode the incoming symbols.

With the interfering signal shifted to this particular alignment, while the overall integrated LTE interference noise over the 6 MHz desired channel still reaches about 15 dB at TOV, the interference is not spread out evenly over the entire 6 MHz desired channel. Since it is concentrated at the upper band edge, the SNR ratio that occurs within the DTV receiver's symbol clock recovery bandwidth is now much lower due to the partial spectrum overlap. This additional interference energy in this specific region can possibly affect the DTV receiver's performance, and therefore make the normally steep digital cliff effect less well defined and more difficult to determine. When a weak desired signal level (-68 dBm) was employed that was well above the receiver's internal broadband noise floor, this particular sliding LTE interference test exhibited this adverse TOV effect when there was 4 MHz or less of partial LTE interference overlap (at the upper band edge). When a very weak signal level (-81 dBm) was used, the receiver's internal broadband noise added to the LTE noise-like interference to determine TOV, thus reducing the allowed amount of LTE interference level. Therefore, this adverse TOV effect was less significant under this condition.

During the partial spectral overlap testing when TOV was first reached (i.e., errors just became visible in the video), the video errors would come and go over a long period of time (e.g., 1 minute), thus making TOV determination long and tedious in the partial overlap region. In the 5 MHz testing, the adverse measurement effect occurred for four different center frequencies (570.5 MHz through 573.5 MHz, inclusive) and five different center frequencies in the 10 MHz testing (572.0 MHz through 576.0 MHz, inclusive). While all of the DTV sets under test exhibited this type of "variable" threshold effect, some sets were worse than others.

To alleviate this problem as much as possible and improve testing repeatability, the new TOV methodology (for this sliding LTE interference test only) called for stepping the interference signal level in 1 dB increments (instead of 0.5 dB), and waiting for three consecutive one-minute observation intervals (instead of three 20-second intervals) to get visible errors. At the first sign of visible errors in all three one-minute test intervals, the LTE interference level was recorded and the D/U interference value calculated. This methodology, while not perfect, did provide a better chance of having repeatable test results than the normal methodology used during the rest of the laboratory testing, although some measurements may still be difficult to repeat.

6.10.1. 5 MHz LTE Interference

The 5 MHz sliding LTE interference test data for 8 receivers at weak level (-68 dBm) is contained in **Table G-17**. A plot of this data is shown in **Figure H-6a**.The x-axis location of 574.5 MHz is the point at which the lower band edge of the interfering LTE signal is coincident with the upper band edge of the desired DTV signal; this is the point of zero guard band. To the left of 574.5 MHz is the overlap region; to the right is the region of increasing (nonzero) guard band.

This plot indicates that with full 5 MHz LTE interference overlap (from 568.5 MHz to 569.5 MHz) the D/U ratio is about **15 dB**, which is the typical D/U ratio for co-channel interference from a broadband, noise-like signal.

As the LTE interferer is shifted higher in frequency (in 1 MHz steps), it can be seen that the D/U ratio varies up and down by a small amount, but ultimately decreases (i.e., robustness increases) since more and more of the interference energy is out of band and therefore not causing in-band interference to the desired DTV signal. These TOV threshold variations are present to some degree in most of the receivers under test.

As the lower band edge of the LTE interferer just reaches the upper band edge of the DTV signal (i.e., at the no overlap condition at 574.5 MHz for the 5 MHz test), the LTE signal is considered to be completely a first adjacent channel interferer (with no guard band), thus exhibiting very large D/U ratios. Further increases in the frequency shift provides more guard band between the desired DTV signal and the undesired LTE interference signal, which allows for increased robustness (i.e., lower D/U ratios).

Considering this "zero guard band" point of 574.5 MHz, and referring now to the median D/U interference ratio curve (for the 6 recent receivers) in **Figure H-6b**, there is about a **2 dB** D/U improvement for each 1 MHz guard band increase. When the 5 MHz wide LTE signal is at a center frequency of 574.5 MHz, it is approximately zero MHz of guard band away from the 6 MHz wide ATSC signal at 569 MHz ("approximately" because this is only considering the allocated bandwidths of 5 MHz and 6 MHz, not the slightly smaller occupied bandwidths). At this 574.5 MHz zero guard band point, the median D/U ratio value of the 6 recent receivers reaches **-45 dB** at 574.5 MHz and decreases (improves) from there with increasingly positive guard band.

The TOV uncertainty exhibited during partial overlap of the upper band edge region is insignificant once the signal is completely in the adjacent channel. For instance, in this test with no transmitter splatter present, a 3 MHz guard band would provide an improvement in D/U interference ratio of about **5 dB**. However, for situations in the field, LTE interferer transmitter splatter will have a definite effect on first adjacent channel interference and should therefore be taken into account.

Finally, note that the performance of the older receivers (Rx #13 and Rx #14) is fairly consistent with that of the newer receivers (Rx #1 through Rx #6). With the desired DTV signal at weak level, the tuner's internal white noise is relatively small compared to the amount needed to cause TOV. Therefore, TOV is dependent on the AWGN threshold of each receiver (along with linearity characteristics), which for both of these older units was identical (**14.9 dB**). In the overlap and partial overlap regions, both older receivers replicated the performance of the better-performing recent receivers (i.e., no rise in the D/U interference ratio in the partial overlap region). However, in the far non-overlap region (with 3 MHz or more guard band), these units were slightly worse than all of the recent receivers.

6.10.2. 10 MHz LTE Interference

The 10 MHz sliding LTE interference test data for 8 receivers at weak level (-68 dBm) is contained in **Table G-18**. A plot of this data is shown in **Figure H-6c**. The x-axis location of 577 MHz is the point at which the lower band edge of the interfering LTE signal is coincident with the upper band edge of the desired DTV signal; this is the point of zero guard band. To the left of 577 MHz is the overlap region; to the right is the region of increasing (nonzero) guard band.

This plot indicates similar results as those obtained for the 5 MHz LTE sliding interference test. Note that 10 MHz interference test curve, while very similar to the 5 MHz curve, is shifted lower by about 3 dB in the overlap region. This is due to the fact that the undesired 10 MHz LTE signal power (which has the same power density as the 5 MHz signal) was measured in a 10 MHz bandwidth before being used in the D/U calculation, and therefore exhibits a 3 dB total power increase over the 5 MHz LTE signal and a 3 dB D/U interference threshold decrease.

There is an exception with regard to this 3 dB shift for the first point (shifted by only **2 dB**) since the 5 MHz LTE signal does not overlap the entire 6 MHz desired channel while the 10 MHz LTE interferer does. Note that both sets of curves are essentially the same when the LTE signal's lower band edge is shifted by 1 MHz since at this point both signals overlap the desired DTV channel by 5 MHz. Further frequency shifts of the LTE signal cause identical amounts of overlap for the 5 MHz and 10 MHz interferers. Likewise, when both types of LTE signals are completely in the adjacent channel, and only the interferer's tuner-generated IM3 splatter is present in the desired DTV channel acting as a co-channel signal to the desired DTV signal, the two signals behave similarly (with the exception of the 3 dB power reference difference); the only difference being the 10 MHz may have more splatter energy fall within the desired DTV channel because of its increased bandwidth.

As the lower band edge of the LTE interferer just reaches the upper band edge of the DTV signal (i.e., no overlap condition at 577.0 MHz for the 10 MHz test), the LTE signal is considered to be completely a first adjacent channel interferer (with no guard band), thus exhibiting very large D/U ratios. Under these conditions, only the interferer's IM3 splatter caused by non-linearities in the tuner is present in the desired DTV channel, and act as a co-channel signal to the desired DTV signal. Further increases in the LTE frequency shift add more guard band between the desired DTV signal and the undesired LTE interference signal, which allows for slightly increased robustness (i.e., lower D/U ratios).

As with the 5 MHz test in the preceding section, the performance of the older receivers (Rx #13 and Rx #14) is consistent with that of the newer receivers (Rx #1 trough Rx #6) due to their similar AWGN thresholds and tuner linearity. Again, their performance in the overlap and partial overlap regions is very good, while their performance in the non-overlap region is comparable with the moderately-performing recent receivers.

Using the median D/U interference ratio curve (for the 6 recent receivers) in **Figure H-6d**, there is about a **1 dB** D/U improvement for each 1 MHz guard band increase. The median D/U ratio value starts at **-46 dB (-43 dB** when the 3 dB power correction factor is applied) and decreases (improves) from there with increasing guard band. The TOV uncertainty exhibited during partial overlap of the upper band edge region is again insignificant once the signal is completely in the adjacent channel. For instance, in this test with no transmitter splatter present, a 3 MHz guard band would provide an improvement in D/U interference ratio of about **2 dB**. However, for situations in the field, LTE interferer transmitter splatter will have a definite effect on first adjacent channel interference and should therefore be taken into account.

A comparison of the two median curves for the 6 receivers for the 5 MHz and 10 MHz sliding LTE interference at weak desired signal level is shown in **Figure H-6e**. The 10 MHz D/U data in this plot has been shifted 3 dB down. This normalizes the 10 MHz test to the 5 MHz test in terms of power density. This curve is relevant because it represents the D/U interference performance for the 5 MHz case compared to the performance when a second, equal-strength 5 MHz LTE transmitter is added immediately adjacent to it (which, of course, is simulated here by a 10 MHz wide signal). When viewed on this basis of power density rather than total power, the two curves look quite similar in the overlap region, and the 10 MHz curve is somewhat less robust in the positive guard band region due to the additional interference energy.

6.11. Sliding LTE Interference (*Very* Weak Desired Signal)

Two additional separate "sliding" LTE interference test results (5 MHz LTE1 signal and the 10 MHz LTE3 signal) are included in **Table G-19** and **Table G-20**, where the D/U interference ratios vary as the undesired LTE interference signal is shifted in frequency in 1 MHz steps, providing varying amounts of overlap with the very weak (-81 dBm) desired DTV signal. The same 8 DTV receivers were tested again (6 recent sets plus 2 older sets).

In this test, the same variations and instability in TOV threshold determination occurred, and therefore required the use of a modified methodology identical to the one used in the weak signal condition (i.e., 1-dB steps and three 60-second observation windows).

Since the desired DTV signal is at a very weak signal level, reasonably near the DTV receiver's sensitivity threshold, less adjacent channel interference can be tolerated. The noise-like IM3 interference signal will add to the DTV set's internal tuner white Gaussian noise, with both contributing a fair amount to the limiting the interference D/U threshold. Therefore, the robustness of the DTV set at the very weak desired DTV signal condition can be degraded from that of the weak desired DTV signal condition due to this multiple impairment scenario. The amount of degradation, if any, depends on the sensitivity level (and thus the tuner's internal noise floor) for each DTV receiver.

6.11.1. 5 MHz LTE Interference

The 5 MHz sliding LTE interference test data for 8 receivers at very weak level (-81 dBm) is contained in **Table G-19**. A plot of this data is shown in **Figure H-6f**. The x-axis location of 574.5 MHz is the point at which the lower band edge of the interfering LTE signal is coincident with the upper band edge of the desired DTV signal; this is the point of zero guard band. To the left of 574.5 MHz is the overlap region; to the right is the region of increasing (nonzero) guard band.

This plot indicates that with full 5 MHz LTE interference overlap the D/U ratio is about **16 dB**, which is about **1 dB** worse than the typical D/U ratio for co-channel interference from a broadband, noise-like signal. The slight degradation is due to the fact that the desired DTV signal is near its sensitivity threshold and therefore each DTV receiver's own internal tuner noise is combining with the IM3 noise caused by the external LTE interferer signal within the tuner. During this very weak signal test, all 6 recent DTV sets behaved very consistently in the overlap region, even more so than under the weak desired signal condition, perhaps due to the presence of the fixed wideband white noise from the tuner's front end.

In the non-overlap region, the units experienced more variation than the overlap region among the 8 different DTV receivers, by as much as **10 dB**. However, more robustness was observed for all of the receivers as the guard band increased.

For the two older receivers, one unit performed consistently with the recent models. However, Rx #13 was about 6 dB worse in performance in the overlap region and somewhat less in the positive guard band region, reflecting the rather poor sensitivity performance of this unit as noted earlier. This same older receiver also was the second poorest performing receiver of the 8 test units, most likely due to a combination of its non-linearity and sensitivity performance.

Using the median D/U interference ratio curve (for the 6 recent receivers) in **Figure H-6g**, there is on the average about a **1 dB** D/U improvement for each 1 MHz guard band increase. The median D/U ratio value starts at **-46 dB** and decreases (improves) from there with increasing guard band. This increase in robustness is not as great for the very weak signal condition as it is for the weak signal condition, but there is some improvement.

6.11.2. 10 MHz LTE Interference

The 10 MHz sliding LTE interference test data for 8 receivers at very weak level (-81 dBm) is contained in **Table G-20**. A plot of this data is shown in **Figure H-6h**. The x-axis location of 577MHz is the point at which the lower band edge of the interfering LTE signal is coincident with the upper band edge of the desired DTV signal; this is the point of zero guard band. To the left of 577 MHz is the overlap region; to the right is the region of increasing (nonzero) guard band.

This plot indicates similar results as those obtained for the 5 MHz LTE sliding interference test (except for the 3 dB difference due to the 10 MHz power measurement). Performance consistency was very good among all of the recent model receivers.

In the overlap region, increased performance variation was observed among the 8 different DTV receivers, by as much as **13 dB**. However, all the units showed improved robustness with increased guard band.

For the two older receivers, as in the 5 MHz case, one unit performed consistently with the recent models but Rx #13 was perhaps **5 dB – 6 dB** worse in performance in the overlap region. This unit fared better in the positive guard band region, however, performing comparably to the less performing recent receivers.
Using the median D/U interference ratio curve (for the 6 recent receivers) in **Figure H-6i**, there is about a **1 dB** D/U improvement for each 1 MHz guard band increase. The median D/U ratio value starts at **-48 dB** (**-45 dB** when the 3 dB power correction factor is applied) and decreases (improves) from there with increasing guard band. Again, the 10 MHz D/U curve in this plot has been normalized; please see the discussion of this normalization in the preceding section (Section LTE Interference (Weak Desired Signal)).

7. SUMMARY

The Consumer Electronics Association (CEA), based in Arlington, VA, contracted the firm of Meintel, Sgrignoli, and Wallace (MSW) to perform laboratory RF tests on a sampling of recently popular Advanced Television System Committee (ATSC) compatible flat-screen consumer digital television (DTV) receivers that have been on the market in the period 2012 - 2013. Specifically, the scope of work (SOW) of the 2014 CEA testing ("CEA2014") was primarily to perform laboratory RF interference tests on a calibrated test bed, followed by careful data analysis, and then to conclude with a detailed written report of the test results.

The main goal of the tests was to evaluate overall receiver performance in the presence of simple impairments (signal dynamic range, added white noise threshold); and with various configurations of co-channel and adjacent channel DTV and LTE interference. Important guideposts for this testing were the ATSC A/74 "Recommended Practice" document[10] ("A/74") and the FCC OET test report of 2007[11] ("Martin 2007").

The A/74 guidelines provided a baseline expectation for many of the test configurations of interest, including sensitivity; multi-signal overload; co-, adjacent-, and taboo-channel rejection; two or more undesired signals; and burst noise. Martin 2007 provided historical data from receivers in the period 2005-2006 for comparison.

Martin 2007 tested with 5 MHz DVB-H using COFDM modulation as interference because of the growing prevalence of OFDM-based digital wireless systems. CEA2014 testing included a simulated LTE 4G downlink interferer, to evaluate DTV receiver performance in the presence of LTE signals (LTE-into-DTV) used in 4G cellular communication systems that may share nearby spectrum after a spectrum repack following the 600 MHz Spectrum Incentive Auctions[12].

CEA and MSW jointly created a detailed test plan that described the types of tests to be performed as well as the exact testing methodology, utilizing some of the concepts found in both the aforementioned ATSC A/74 document and Martin 2007 test document as guidelines only. MSW then generated a detailed test matrix (see **Table B-1**), which contained 10 different test groups comprising a total of 1045 individual tests.

CEA provided twelve recent-model (2012 and 2013) and two older-model (2006) DTV receivers of various screen sizes. These receivers were all production units (or pre-production in one case), from the top ten brands as ranked by U.S. market share (in unit volume). General laboratory testing was performed on these fourteen units. Based on market data and manufacturer interviews, CEA estimates that the twelve recent-model receivers represent about 85% of DTV shipments in the U.S. market during 2012 and 2013.

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10 "A/74:2010, ATSC Recommended Practice: Receiver Performance Guidelines", ATSC, April 7, 2010.

11 Stephen R. Martin, "Interference Rejection Thresholds of Consumer Digital Television Receivers Available in 2005 and 2006", OET Report Prepared by: FCC/OET 07-TR-1003, March 30, 2007.

12 FCC, "Broadcast Television Spectrum Incentive Auction NPRM, Docket 12-268, September 28, 2012.

A subset of six of these receivers was selected by CEA for detailed DTV-into-DTV adjacent channel interference testing, and another single unit was selected from the subset of 6 for LTE-into-DTV interference testing. Again based on market data and manufacturer interviews, CEA estimates that the six recent-model receivers represent about 75% of DTV shipments in the U.S. market during 2012 and 2013. Additionally, the two older-model DTV sets were included in the sliding LTE interference tests to provide some performance information on older DTV sets; both older units were earlier models from brands represented in the subset of six.

The DTV signals employed were 6 MHz ATSC A/53 signals (with 8-VSB modulation) representing traditional UHF terrestrial broadcast.

The LTE signals were traditional 5 MHz and 10MHz LTE (with OFDMA modulation) representing both fully-loaded and lightly-loaded (in terms of data traffic) LTE (3GPP E-UTRA) Release 10 base station signals utilizing nearby spectrum expected to be purchased by wireless companies in the upcoming forward auction.

However, it is imperative to note that these tests used *ideal* desired and undesired test signals under *ideal* test conditions, thus *not* simulating typical conditions found in the field, such as adjacent channel transmitter splatter. Desired DTV signals were high quality and had no impairments while DTV and LTE interferer signals were also high quality, with no non-linearity-induced adjacent channel splatter. Therefore, care must be taken in applying these laboratory test results directly to any planning in the spectrum allocation process.

The test bed consisted of high-quality laboratory test equipment (both for source generation and signal measurement). This equipment was employed in carefully assembled and calibrated system configurations, with testing performed precisely by well-trained staff using industry-standard practices. Two variations of precision commercial band stop filters (narrowband and wideband) were employed to significantly extend the dynamic range of the test bed beyond the expected D/U interference ratios.

Test results are summarized as follows (*median* test results are shown in **Figure 1** and **Figure 2)**.

(1) **DYNAMIC RANGE**: The dynamic range (difference between overload and sensitivity thresholds) of all 12 of the DTV sets was measured greater than 90 dB. The sensitivity threshold of the recent DTV receivers is noticeably improved over that observed in the early days of the DTV transition (late 1990s), with all 12 test receivers consistently having sensitivity levels better than the ATSC recommended value of -83 dBm. Likewise, all 12 receivers could handle at least +5 dBm signals as well.

(2) **IMPAIRMENT THRESHOLDS**: The additive white Gaussian (AWGN) noise threshold for all 12 receivers was better than the ATSC guideline, another improvement over early 8-VSB tuners. The resulting median SNR threshold measurement of 14.8 dB helps to lower the effects of the white noise-like intermodulation in DTV tuners that occurs from noise-like DTV or LTE interference. From the combination of sensitivity level thresholds and the AWGN thresholds, the calculated ideal noise figure for all of the units was better than 7 dB.

(3) **CO-CHANNEL INTERFERENCE THRESHOLDS**: Co-channel DTV and fully-loaded LTE interference exhibited similar performance around 14.4 dB and 15.4 dB, respectively, and therefore both types of interference met the ATSC recommended value (15.5 dB). Therefore, these two types of interference can be treated similarly in the field, assuming an additional margin of 1 dB for LTE interferers to account for the slightly worse LTE-into-DTV results.

(4) **SINGLE INTERFERER INTERFERENCE**: A significant improvement in commercial RF tuner performance since the early days of the DTV transition was observed. All 6 of the subset receivers met the recommended ATSC A/74 single interferer interference D/U ratios for both DTV-into-DTV and LTE-into-DTV for both first adjacent (-33 dB) and the taboo channels (see plots in **Appendix H**).

(5) **MULTIPLE INTERFERER INTERFERENCE**: These laboratory tests focused not only on the traditional single interferer case, but also on multiple interferers and the relative effect on DTV receiver interference thresholds. The results were clear that multiple DTV or LTE interferers, for which no A/74 recommended D/U interference values are specified, caused significantly worse thresholds (5 – 20 dB) than the equivalent single interferer scenarios. The N+2/N+3 dual interferer tests had 10-15 dB of threshold degradation from its equivalent single interferer test. Equal-power IM3 pairs that had their intermodulation components fall directly within the desired channel caused 15 – 20 dB degradation in interference thresholds compared with their single interferer counterparts. Even when one of the IM3 pairs was reduced by 10 dB, while the threshold degradation was less than the equal-power case, it still had a degrading effect (5 – 15 dB).

(6) **SLIDING LTE INTERFER INTERFERENCE**: The sliding LTE interference results were varied. The resulting shape of the interference threshold curve was predictable and verified expectations, with the most sensitive (least robust) situations occurring with the most overlap between the undesired LTE interferer and the desired DTV signal. As more undesired interference energy fell outside the desired DTV channel, the interference D/U ratio got better, achieving maximum interference rejection when all of the undesired LTE interference energy was outside the DTV channel. It was found that as the guard band increased, the interference rejection improved (2 dB/MHz for the 5 MHz LTE interferer and 1 dB/MHz for the 10 MHz LTE interferer). For very weak (-81 dBm) desired DTV signals, the LTE signal interference (co-channel or adjacent channel) was found to act like DTV interferers in that it added to the DTV receiver's internal white noise to produce a predictable D/U interference degradation in most cases. However, for some of the 6 subset receivers, the TOV thresholds that were measured with partial overlapping of the two signals near the upper DTV band edge were found to be sensitive to time-varying threshold effects. The specific cause of this anomaly are not known (although presumed to be caused by clock recovery circuitry), and are beyond the scope of this laboratory test.