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White Spaces Engineering Study: CAN COGNITIVE RADIO TECHNOLOGY OPERATING IN THE TV WHITE SPACES COMPLETELY PROTECT LICENSED TV BROADCASTING?

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Policy Background

In 2004, the FCC proposed to allow unlicensed wireless devices to utilize vacant television channel frequencies in each market, a rulemaking that is currently in its final stages. The FCC discussed three methods (control signals, position determination, and cognitive radio with dynamic frequency selection) to ensure that unlicensed TV band devices operate only on vacant channels without harmful interference to broadcast TV service. Of these methods, cognitive radio has spurred the most debate. The cognitive radio method uses spectrum sensing and dynamic frequency selection (DFS) to identify and avoid occupied TV channels. This method has been approved by the Defense Department for unlicensed devices to share spectrum with military radar in the upper 5 GHz band. Potential service providers and equipment manufacturers embrace it because it does not require external infrastructure. However, TV broadcasters oppose it because they do not understand it and fear it will result in harmful interference. This report answers the following question that is central to the FCC's current rulemaking: can unlicensed TV-band devices using cognitive radio techniques completely protect licensed broadcast TV services?

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1 Introduction and Summary

This report answers the following question that is central to the FCC's current rulemaking about whether to open the unused TV-band channels in each market for wireless broadband and other innovation[1]: Can unlicensed TV-band devices using cognitive radio techniques completely protect licensed broadcast TV services? Some published reports have postulated an affirmative response to the question[2], while others have claimed the opposite[3]. This report provides the engineering support to definitively resolve this question in the affirmative; cognitive radio techniques can be used by unlicensed TV-band devices to protect licensed broadcast TV services.

Through analysis and simulation it is shown that an occupied DTV channel can be identified with practical certainty by an unlicensed device even if nearby roof mounted antennas are receiving the DTV signal at the threshold of visibility (TOV) and the unlicensed device sees the DTV signal with over 37 dB additional attenuation compared to the rooftop antennas. Once an occupied DTV channel has been identified, it can be avoided to prevent the possibility of co-channel interference (CCI). Additionally, adjacent DTV channels can also be avoided if necessary to prevent adjacent channel interference (ACI).

Cognitive radio techniques are statistical in nature. They provide virtual, not absolute certainty. However, it is shown that, even in the most adverse conditions, the probability of harmful interference can be made so small that electric power outages[4] would be a more likely cause of interruption to broadcast TV service than unlicensed TV band devices. If absolute certainty is required, it can be provided by control signal or position determination techniques.

This report does not address questions related to unlicensed TV-band device performance or design. These are issues best left to standards organizations, such as the IEEE 802 Working Groups[5] and the Wi-Fi Alliance[6]. The simple cognitive radio architecture described in this report is solely for the purpose of demonstrating that licensed TV services can be protected. No particular implementation is advocated.

When the transition from analog to digital television is complete there will be vacant channels ("white spaces") in every media market[7]. These channels are not used either because of potential interference to other broadcast channels or due to lack of commercial demand in that market. The FCC adopted a Notice of Proposed Rulemaking (NPRM) on 13 May 2004 proposing "to allow unlicensed radio transmitters to operate in the broadcast TV spectrum at locations where that spectrum is not being used"[8]. The NPRM discusses three methods (control signals, position determination, and cognitive radio) to ensure that unlicensed TV band devices operate only on vacant channels without harmful interference to the broadcast TV service.

Of these methods, cognitive radio has spurred the most debate. Potential service providers and equipment manufacturers embrace it because it does not require external infrastructure. TV broadcasters oppose it because they do not understand it and fear it will result in harmful interference. The cognitive radio method uses spectrum sensing to identify and avoid occupied TV channels. One of the issues associated with this methodology, referred

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[1] FCC, First Report & Order and FNPRM in the Matter of Unlicensed Operation in the TV Broadcast Bands, ET Docket No. 04-186, Adopted October 18, 2006.

[2] Michael J. Marcus, Paul Kolodzy and Andrew Lippman, "Why Unlicensed Use Of Vacant Tv Spectrum Will Not Interfere With Television Reception", New America Foundation, Wireless Future Program, Issue Brief #19, July 2006.

[3] "Laboratory Evaluation of Unlicensed Devices Interference to NTSC and ATSC DTV Systems in the UHF Band," Communications Research Centre Canada, November 29, 2004.

[4] Various studies have reported average power outage interruptions of 101 to 120 miniutes with average occurrences of 1.1 to 1.4 per year. See Table 3 of Kristina Hamachi LaCommare and Joseph H. Eto, "Cost of Power Interruptions to Electricity Consumers in the United States", Ernest Orlando Lawrence Berkeley National Laboratory, LBNL-58164, February 2006.

[5] http://grouper.ieee.org/groups/802/

[6] http://www.wi-fi.org

[7] "Measuring the TV 'White Space' Available for Unlicensed Wireless Broadband," Free Press and the New America Foundation, January 5, 2006

[8] FCC, NPRM in the Matter of Unlicensed Operation in the TV Broadcast Bands, ET Docket No. 04-186, FCC 04-113, Adopted 13 May 2004.

to as the “hidden node problem”, is that unlicensed devices can be shielded from TV signals. Thus the devices might incorrectly assume a channel is vacant and inadvertently make transmissions that interfere with TV signals.

The cognitive radio method takes advantage of spectral features found in TV signals to detect occupied TV channels. Detecting the presence of a signal can be done with very high probability at signal levels much lower than those required for demodulation. Detecting the presence of an analog or a digital television (DTV) signal is far easier, and can be achieved with very high probability at signal levels that are significantly lower than the levels required by a TV set.

With less than one second of observation time, an occupied DTV channel can be identified with practical certainty by an unlicensed device even if nearby roof mounted antennas are receiving the DTV signal at the threshold of visibility and the unlicensed device sees the DTV signal with over 37 dB additional attenuation compared to the rooftop antennas.

This report describes a simple detection mechanism which takes advantage of the spectral features found in both analog TV and DTV signals. Through analysis, simulation, and field measurement, it is shown that the cognitive radio approach can be used successfully to avoid harmful interference to TV signals from an unlicensed TV-band device. This mechanism is viable for both fixed and portable devices.

Section 2 of this report provides background information and brief descriptions of the three interference avoidance methods: control signals, position determination, and cognitive radio. With appropriate rules, the control signal and position determination methods can be made failsafe. They can protect licensed broadcast TV services with absolute certainty.

The application of cognitive radio methods to detecting TV signals is discussed in detail in Section 3. The analysis presented in that section demonstrates that the spectral characteristics of the DTV signal can used to detect the presence of a TV transmitter. It is shown that even with a 37 dB attenuation of the DTV signal due to the “hidden node problem”, the unlicensed device can detect the presence of a TV signal with practical certainty. This analysis takes into account the limitations imposed by transmitter and receiver frequency offsets and phase noise. It also accounts for errors in the receiver noise measurements required to compensate for temperature variations and aging. Furthermore, simulation models are used to verify the results of the analysis presented. Simulation results closely match the analytical result and confirm its conclusions.

Section 4 addresses the remaining question of how likely is it that an unlicensed device located inside a building would see a DTV signal more than 37 dB below that seen at the rooftop. Building penetration loss models based on measurement campaigns and models based on frequency selective fading are considered. In both cases, it is seen that the probability of building penetration loss exceeding 37 dB is negligible. The maximum value reported in the literature is only 30 dB.

Field measurements of DTV pilot carrier power were made inside three residences in Encino, California, a suburb of Los Angeles. They are presented in Section 5. Measurements of each of the 22 DTV transmitters covering these residences were made in each room. These measurements show that the presence of the pilot carrier, and hence the presence of the DTV signal, is readily detectable in all cases. The pilot carrier power measured in the rooms ranged from -104.7 dBm to -58 dBm. The lowest power measurement of -104.7 dBm is only 9.1 dB below the nominal pilot carrier level at threshold of visibility (TOV) of errors. Since the analysis shows that pilot carriers 37 dB below TOV can easily be detected, the weakest pilot carrier observed was easily detectable with over 27 dB of unused margin.

In conclusion, this report shows that cognitive radio techniques can be used by unlicensed TV-band devices to completely protect licensed broadcast TV services.

2 Background

Broadcast television services in the United States operate on 6 MHz channels, designated 2 through 69, in the VHF and UHF portions of the radio spectrum (see Table 1) under Part 73 of the Federal Communications Commission (FCC) rules. These rules prohibit the use of unlicensed devices in TV bands, with the exception of remote control and medical telemetry devices. The FCC is now in the process of requiring TV stations to convert from analog to digital transmissions. By February 2009, at the statutory end of the DTV transition, the spectrum presently allocated to channels 52 through 69 (698 – 806 MHz), will be reallocated to other services.

After the DTV transition there will typically be a number of TV channels in a given geographic area that are not being used by DTV stations, because such stations would not be able to operate without causing interference to co-channel or adjacent channel stations. For example, the rules for DTV allotments[9] specify minimum separations between co-channel stations ranging from 196.3 to 273.6 km, and separations between adjacent channel stations that are not co-located, or in close proximity, of 110 km. These minimum required separations between TV stations are based on the assumption that stations operate at maximum power. However, a transmitter operating on a vacant TV channel at a much lower power level would not need as great a separation from co-channel and adjacent channel TV stations to avoid causing interference. Low power unlicensed transmitters can operate on vacant channels in locations that could not be used by TV stations due to interference concerns. In addition, in some areas, not all of the channels that could be used by TV stations will be used. Those vacant channels could also be used by unlicensed devices.

The FCC adopted an NPRM on 13 May 2004 proposing "to allow unlicensed radio transmitters to operate in the broadcast TV spectrum at locations where that spectrum is not being used".[10] These "whitespaces" are frequency channels allocated for TV broadcasting that are not used in given areas. Specifically, the FCC has proposed to allow unlicensed operation in the spectrum used by TV channels 5 and 6 (76 – 88 MHz), 7 through 13 (174 – 216 MHz), 14 through 36 (470 – 608 MHz), and 38 through 51 (614 – 698) MHz[11]. This operation would be subject to protecting licensed TV services from harmful interference within their service contours. The proposed new rules would allow the operation of both fixed/access and personal/portable broadband devices on a noninterference basis.

The propagation characteristics of these bands make them ideal for providing last mile broadband solutions, and the fixed nature of TV transmitters makes it possible for unlicensed transmitters to co-exist in the same band. Whitespaces exist even in apparently congested areas.

9 47 CFR 73.623(d)

10 FCC NPRM in the Matter of Unlicensed Operation in the TV Broadcast Bands, ET Docket No. 04-186, FCC 04-113, Adopted 13 May 2004.

11 Channels 2 through 4 were excluded to eliminate the potential of interference to TV interface devices, such as VCRs and DVDs, which connect to the antenna terminals of a TV receiver. Channel 37 was excluded "due to the special interference concerns associated with the sensitive nature of radio astronomy reception and the critical safety function of medical telemetry equipment."

• Table 1 – TV Channels[12]

TV Channel Number	Frequency Band (MHz)	TV Channel Number	Frequency Band (MHz)	TV Channel Number	Frequency Band (MHz)
2	54-60	25	536-542	48	674-680
3	60-66	26	542-548	49	680-686
4	66-72	27	548-554	50	686-692
5	76-82	28	554-560	51	692-698
6	82-88	29	560-566	52	698-704
7	174-180	30	566-572	53	704-710
8	180-186	31	572-578	54	710-716
9	186-192	32	578-584	55	716-722
10	192-198	33	584-590	56	722-728
11	198-204	34	590-596	57	728-734
12	204-210	35	596-602	58	734-740
13	210-216	36	602-608	59	740-746
14	470-476	37[13]	608-614	60	746-752
15	476-482	38	614-620	61	752-758
16	482-488	39	620-626	62	758-764
17	488-494	40	626-632	63	764-770
18	494-500	41	632-638	64	770-776
19	500-506	42	638-644	65	776-782
20	506-512	43	644-650	66	782-788
21	512-518	44	650-656	67	788-794
22	518-524	45	656-662	68	794-800
23	524-530	46	662-668	69	800-806
24	530-536	47	668-674		

The NPRM discusses three methods (control signals, position determination, and cognitive radio) for ensuring that unlicensed TV band devices operate only on vacant channels. The FCC has proposed two categories of unlicensed TV band devices – fixed and portable; all three methods are viable options for both types of devices. In addition to protecting against co-channel interference (CCI), all three methods can be used to protect against adjacent channel interference (ACI) if such additional protection is required. The control signal method is discussed in Section 2.1, the position determination method in Section 2.2, and the cognitive radio method in Section 2.3.

2.1 CONTROL SIGNAL

With the control signal method, unlicensed TV band devices only transmit if they receive a control signal identifying vacant channels within their service areas. This signal can be received from a TV station, FM broadcast station, or TV band fixed unlicensed transmitter. Without reception of this "control" signal, no transmissions are permitted. This provides positive assurance that these devices will operate only on unused TV channels. Given the time and expense required to change the operating channel of an existing TV transmitter, or to construct a new transmitter, updating the control signal information on a daily basis is more than sufficient to prevent interference.

The most efficient and effective method for providing control signals to portable unlicensed devices depends on how they are networked. If they are part of a point-to-multipoint network, such as a hot spot WISP network, then having the base provide the control signals is the preferred method. Alternatively, if they are part of a peer-to-peer wireless mesh network, then it may be preferable to have an existing TV or FM broadcast station provide the control signals.

[12] 47 CFR § 73.603(a) Numerical designation of television channels
[13] Channel 37, 608-614 MHz, is reserved exclusively for the radio astronomy service

In the NPRM, the FCC did not propose specific characteristics for the control signal. This left open the issue of a control signal being received by an unlicensed device outside the valid range of its information. This issue can be addressed through proper design of the control signal to ensure that its range is comparable to, or even less than, the range over which the available channel information data is valid.

The control signal method is applicable to both fixed and mobile unlicensed TV-band devices. By requiring these devices to only transmit when they are receiving a valid control signal and limiting control signal range to their areas of validity, this method is made failsafe.

2.2 POSITION DETERMINATION

In the position determination method, an unlicensed TV-band device incorporates a GPS receiver to determine its location and accesses a database to determine the TV channels that are vacant at that location. There are two issues associated with this method: 1) the accuracy and completeness of the database and 2) the ability of the unlicensed TV-band device to determine its' location using GPS.

During the DTV transition, the FCC's databases have not been able to keep up with the changes. However, by February 2009, at the statutory end of the DTV transition, spectrum utilization will become more stable and maintaining an accurate database will become easier. Maintaining an accurate up-to-date database of vacant TV channels is not technically challenging or particularly expensive.

GPS has been shown to support the FCC's E911 requirement[14] for network based technologies of 100 meters for 67% of calls and 300 meters for 95% of calls. Even an accuracy of several kilometers would be sufficient for determining vacant channels at a given location. These accuracies are routinely achieved by GPS even deep inside buildings. Since unlicensed TV-band devices only transmit when communicating with other unlicensed TV-band devices, only one device in a network needs to be able to obtain a position fix and have access to a current database for all devices to know which channels are available.

The position determination method is applicable to both fixed and mobile unlicensed TV-band devices. By requiring that these devices only transmit when they have a current position fix and timely database information, this method is made failsafe.

2.3 COGNITIVE RADIO

In this method, the unlicensed device autonomously detects the presence of TV signals and only uses the channels that are not used by TV broadcasters (white spaces). This approach, also known as listen-before-talk (LBT), is very interesting because, unlike the approaches described earlier, it does not depend on any external database that has to be maintained by the FCC or a control signal that must be transmitted by a broadcaster.

Detection of the TV signal can be subject to the "hidden node problem." This problem can arise when there is blockage between the unlicensed device and a TV station, but no blockage between the TV station and a TV receiver antenna and no blockage between the unlicensed device and the same TV receiver antenna. In such a case, the sensing receiver may not detect the presence of the TV signal because it is blocked, and the unlicensed device could start using an occupied channel, causing harmful interference to the TV receiver.

The important fact that is ignored in this simplistic description is that the unlicensed device only needs to detect the presence of a signal and does not need to demodulate it. Detecting the presence of an analog or a DTV signal is far easier and can be achieved with very high probability at signal levels that are significantly lower than the signal levels required by a TV set.

[14] 47 CFR 20.18(h) 911 Service.

The remaining sections of this report show that the cognitive radio method can be used by unlicensed TV-band devices to protect licensed broadcast TV services with virtual certainty. The level of certainty is in fact high enough that even in the most adverse conditions, the probability of harmful interference can be made so small that electric power outages and natural disasters would be a more likely cause of interruption to broadcast TV service than unlicensed TV-band devices. The analytic results are validated by simulation studies.

It is worth noting that the cognitive radio method's spectrum sensing approach resonates with the "innovation at the edge" philosophy that has made the Internet so successful. The deployment of socially valuable unlicensed TV-band devices could be delayed if they have to depend on preconditions "in the core of the network" – control signal beacons or position determination databases.

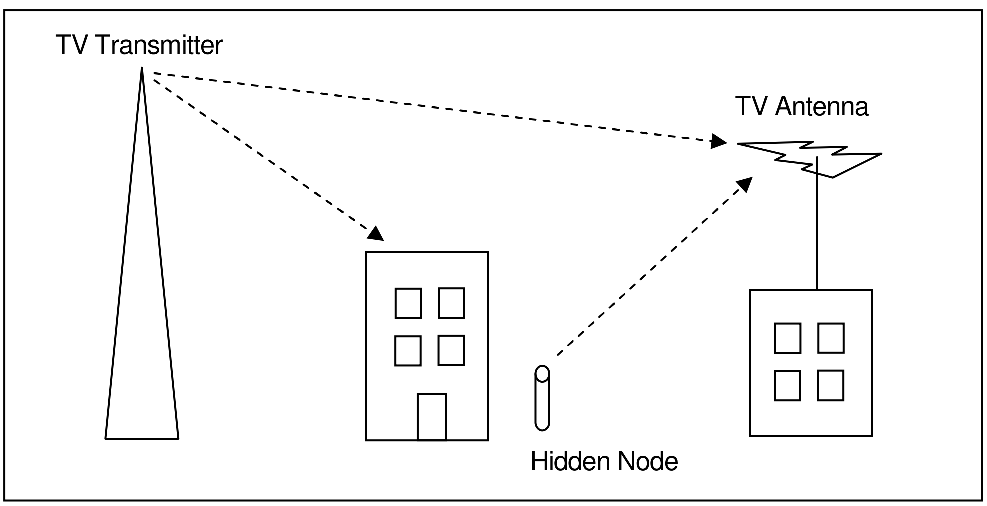
3 Detecting TV Transmissions

The cognitive radio, listen-before-talk (LBT), method ensures that unlicensed TV band devices operate only on vacant channels by incorporating sensing capabilities to detect licensed transmitters in an area. An unlicensed TV band device would incorporate processing capable of detecting signals down to a level far below that which is required by a TV receiver to determine if a particular TV channel is occupied. If no signal is detected, the channel would be considered vacant.

The Section shows that with less than a 1 second observation time, an occupied DTV channel can be identified with practical certainty by an unlicensed device even when nearby roof mounted antennas are receiving the DTV signal at threshold and the unlicensed device sees the DTV signal with over 37-dB additional attenuation compared to the rooftop antennas. The analysis and simulations used take into account the limitations imposed by transmitter and receiver frequency offsets and phase noise. They also accounts for errors in the receiver noise measurements required to compensate for temperature variations and aging.

3.1 PROBLEM STATEMENT

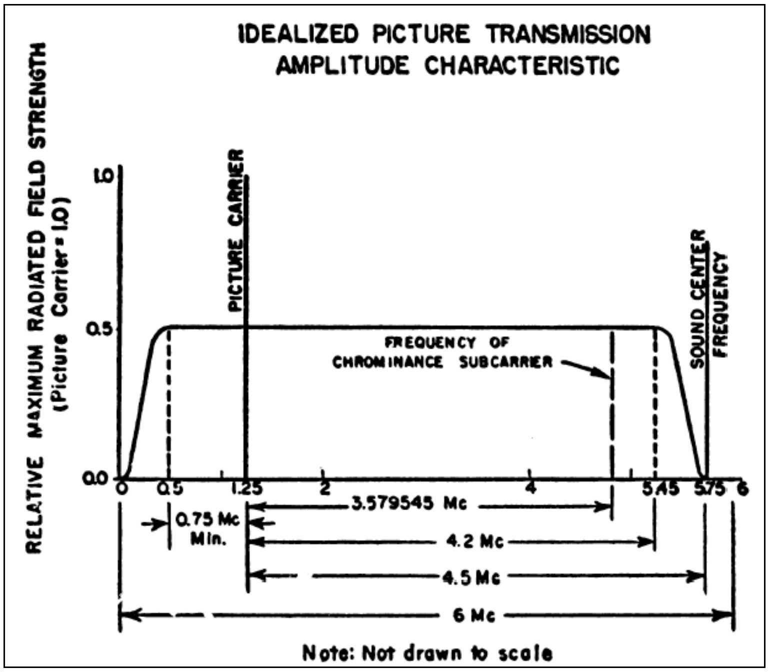
This "spectrum sensing" method is subject to the "hidden node problem" illustrated in Figure 1. This problem can arise when there is blockage between the unlicensed device and a TV station, but no blockage between the TV station and a TV receiver and no blockage between the unlicensed device and the same TV receiver. In such a case, a simple sensing receiver may not detect the presence of the TV signal because of the blockage, and the unlicensed device could start using an occupied channel, causing harmful interference to the TV receiver.



• **Figure 1 – Hidden Node Problem**

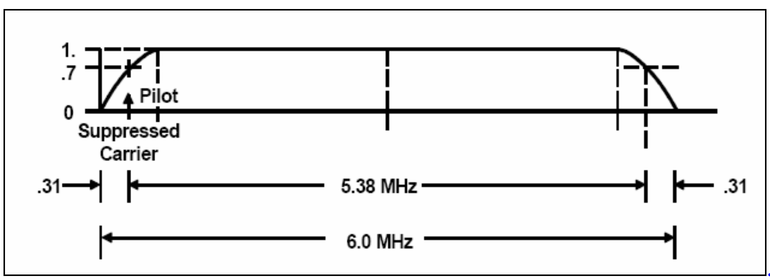
However, the hidden node problem can be solved by taking advantage of the fact that the "hidden node" must only detect the presence of a signal and, unlike a TV receiver, it does not need to demodulate it. Furthermore, the "hidden node" can take advantage of the TV signal structure and its spectral features to detect its presence.

Figure 2 shows the analog TV (NTSC) spectrum. The picture carrier, located 1.25 MHz above the lower edge of the channel, has significantly higher amplitude than any other portion of the signal. The sound carrier, located 5.75 MHz above the lower edge of the channel, is the second highest component. Either of these signals can be readily detected even when the analog TV signal is received well below the threshold level required by a TV receiver. However, with the phase out of NTSC signals by February 2009, the ability to detect these signals is moot.



• **Figure 2 – NTSC Spectrum**[15]

The DTV spectrum is shown in Figure 3. With the exception of the pilot carrier located 0.31 MHz above the lower edge of the channel, the spectrum is flat. The pilot carrier power is 11.3 dB less than the total signal power. Even though it has a small fraction of the power in the main DTV signal, its power is concentrated in a spectral line and is thus readily visible above the main DTV signal whose power is spread over 6 MHz. This is the spectral feature that is utilized in detecting the presence of a DTV signal.



• **Figure 3 – DTV Spectrum**[16]

In the sensing receiver, the pilot carrier is observed in a detection bandwidth B, centered on the pilot carrier. Thermal noise and the main part of the DTV signal are present in addition to the pilot carrier. For purposes of detecting the pilot carrier, the main signal can be modeled as additive white Gaussian noise (AWGN). The pilot carrier (PC) to main signal (S) power ratio is calculated by assuming that the main signal power is uniformly spread across the 6-MHz channel bandwidth:

$$PC/S = -11.3 \text{ dB} + 10 \times \log_{10}(6 \times 10^6 / B)$$

$$= 56.5 \text{ dB-Hz} - 10 \times \log_{10}(B).$$

[15] 47 CFR 73.699 Figure 5.

[16] Advanced Television Systems Committee (ATSC), ATSC Standard: Digital Television Standard (A/53), Revision D, Including Amendment No. 1; Doc. A/53D, 19 July 2005, Amendment No. 1, 27 July 2005, page 64.

The pilot carrier to thermal noise power ratio is calculated as a function of the main DTV signal to noise ratio (SNR):

$$PC/N = SNR - 11.3 \text{ dB} + 10 \times \log_{10}(6 \times 10^6 / B)$$

$$= SNR + 56.5 \text{ dB-Hz} - 10 \times \log_{10}(B).$$

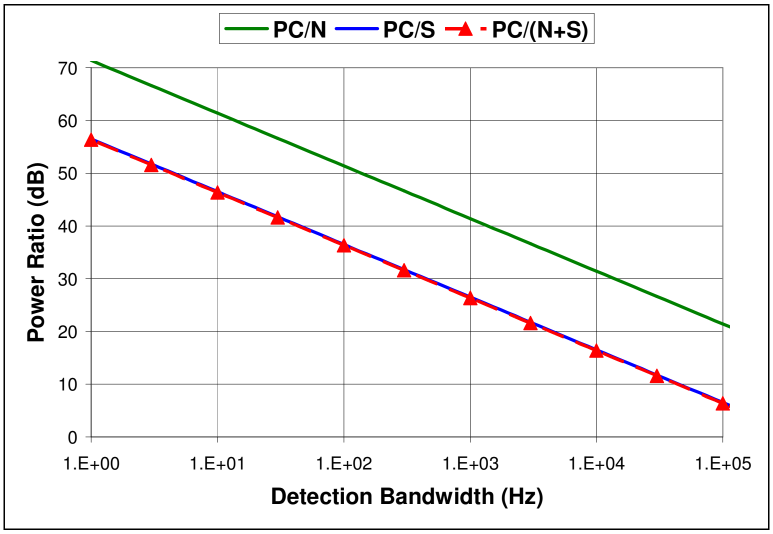
The SNR at threshold of visibility (TOV) of errors is 14.9 dB[17]. Thus, if the DTV receiver is able to recover the signal, the PC/N must be at least 71.4 dB-Hz – 10 x $\log_{10}(B)$.

The total pilot carrier to noise plus main DTV signal power ratio is given by:

$$PC/(N+S) = \frac{1}{\dfrac{1}{PC/N} + \dfrac{1}{PC/S}}$$

$$PC/(N+S) \text{ (dB)} = 56.5 - 10 \times \log_{10}(1 + 10^{-SNR/10}) - 10 \times \log_{10}(B).$$

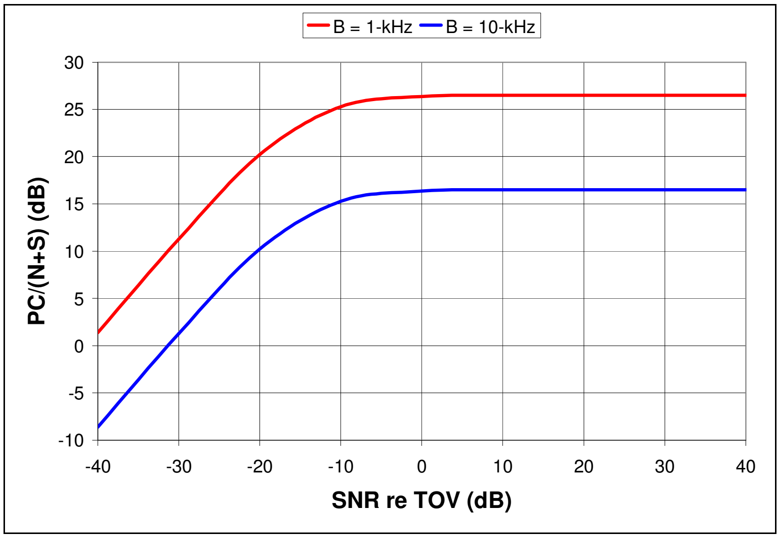
Figure 4 shows the PC/S, PC/N, and PC/(N+S) ratios at TOV as a function of detection bandwidth. So by reducing the detection bandwidth, the pilot SNR increases and, even if a hidden node situation resulted in significant blockage, it would still be possible for the sensing receiver to detect the pilot and declare the channel occupied.



• **Figure 4 – PC/S, PC/N, and PC/(N+S) Ratios at TOV as a Function of Detection Bandwidth**

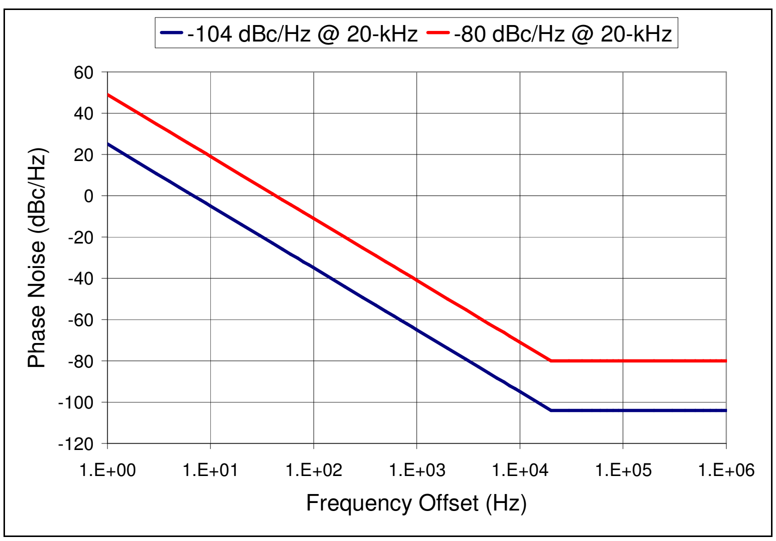
Figure 5 shows PC/(N+S) as a function of SNR relative to TOV (14.9 dB) for 1-kHz and 10-kHz detection bandwidths. Note that for SNRs below TOV the thermal noise dominates and that for SNRs above TOV the main signal noise dominates. Since the pilot carrier can easily be detected in strong signal cases, the challenge is detecting it in hidden node situations where the thermal noise is dominant.

[17] Advanced Television Systems Committee (ATSC), Recommended Practice: Guide to the Use of the ATSC Digital Television Standard, A/54A, 4 December 2003, page 74.



• **Figure 5 – PC/(N+S) As Function of SNR Relative to TOV**

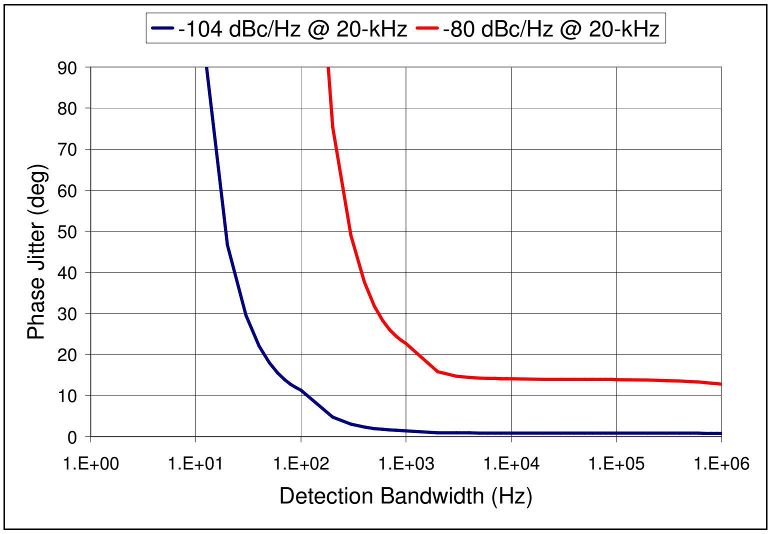
PC/(N+S) increases as the detection bandwidth is reduced. The lower limit on detection bandwidth is determined by the transmitter frequency offset and phase noise. Recommended practice for DTV transmitters is a pilot carrier frequency tolerance of ±1 kHz and maximum phase noise of -104-dBm/Hz at a 20-kHz offset from the carrier frequency[18]. Recommended practice for DTV receivers is to operate with a received signal phase noise of -80-dBc/Hz at a 20-kHz offset to accommodate repeaters with high phase noise[19]. Pessimistic phase noise curves, assuming the 20-kHz values out to the channel bandwidth and $1/f^3$ noise below 20-kHz, are shown in Figure 6. Figure 7 shows the resulting phase jitter. Even with the noisy repeater, the jitter is less than 25° in a 1-kHz bandwidth. Therefore, in determining the detection bandwidth, the dominating factor is the transmitted signal frequency tolerance.



• **Figure 6 – Pessimistic Phase Noise**

[18] Advanced Television Systems Committee (ATSC), ATSC Standard: Transmission Measurement And Compliance For Digital Television. A/64A,.30 May 2000.

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



• Figure 7 – Phase Jitter

Another consideration is receiver frequency stability. Low cost temperature compensated crystal oscillators (TCXOs) provide ±3 PPM frequency stability. This results in a ±2.1-kHz frequency offset for channel 51. Taking into account the transmitter and receiver tolerances, the minimum detection bandwidth is 6-kHz.

Receiver frequency uncertainty can also be reduced by using a DTV pilot signal to calibrate the TCXO. The pilot signals are located 310-kHz above the lower edge of the 6-MHz channel. Periodic calibration would ensure that the receiver frequency stability matches the ±1 kHz frequency stability of a DTV transmitter. This would allow the use of a 4-kHz detection bandwidth.

There are several other techniques that can be employed in order to improve the sensitivity of the unlicensed device at the expense of more complex implementation. For example, additional sensitivity can be achieved by using a bank of narrower filters covering the 6-kHz range. In that case, the limiting factor becomes the transmitter phase noise which is about 300 Hz for the noisy repeater. This technique provides 13-dB improvement in sensitivity at the expense of requiring 20 filters, which can efficiently be implemented digitally.

Another technique for improving sensitivity is to non-coherently sum power measurements made with a 6-kHz, or larger, bandwidth. This is the technique used in the following Section. It could also be combined with the filter bank technique to provide even more sensitivity by summing measurements made with a smaller bandwidth.

3.2 SIGNAL DETECTION

Signal detection is based on hypothesis testing. In this case, the decision variable is a measurement of the pilot carrier power D that is tested against a threshold T. The hypothesis test is:

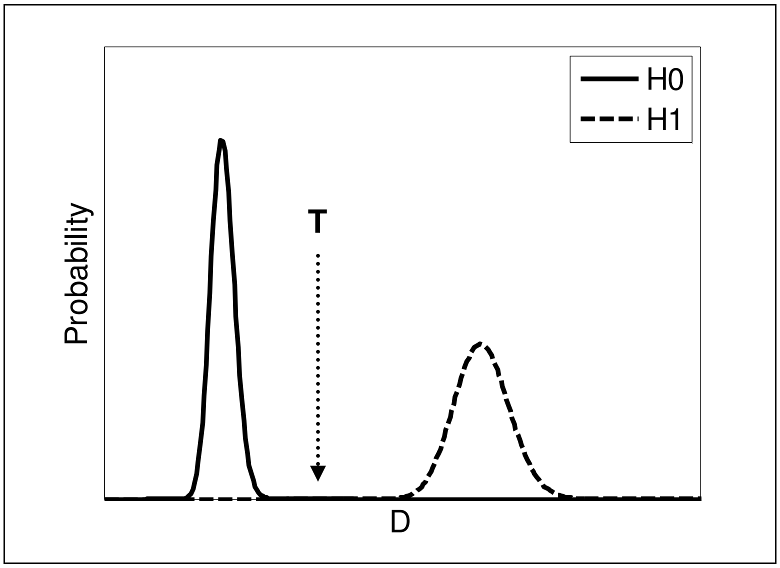
$$D \underset{H_0}{\overset{H_1}{\gtrless}} T$$

where H_0 is the null hypothesis (no signal), and H_1 is the signal present (channel used) hypothesis. Thus if D > T, a signal (occupied channel) is detected; otherwise no signal is detected (channel vacant). The performance of the test is characterized by the probabilities of false alarm (P_{FA}) and missed detection (P_{MD}):

$$P_{FA} = P[D > T \mid H_0]$$

$$P_{MD} = P[D < T \mid H_1]$$

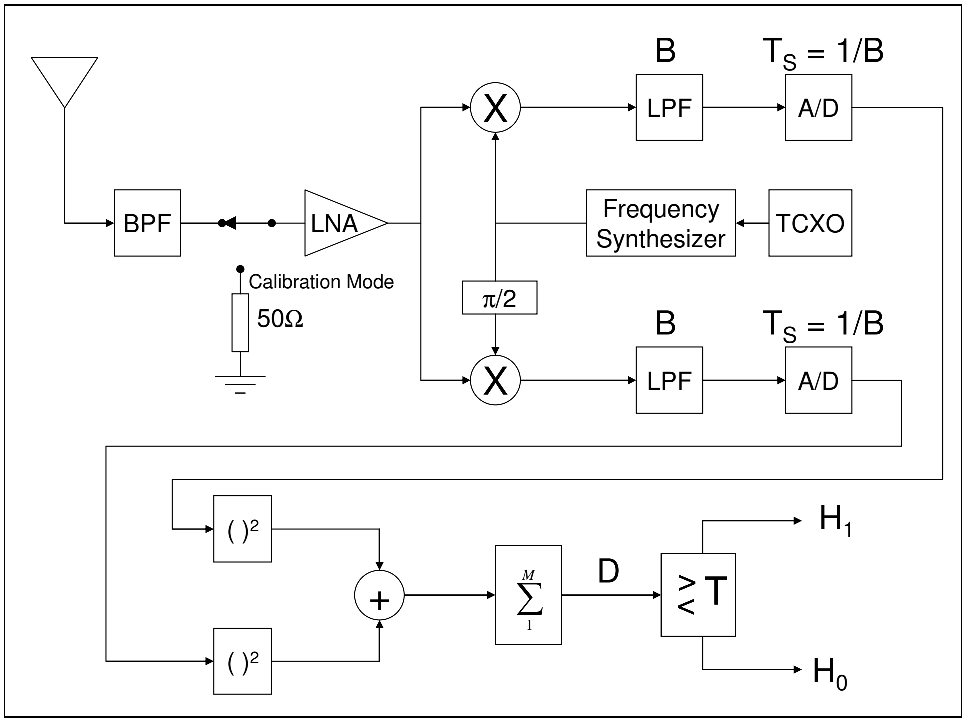
Figure 8 shows the probability density functions (pdf) for the two hypotheses. The threshold, T, is a value on the decision variable axis. The probability of false alarm is the amount of the H_0 pdf tail above the threshold and the probability of missed detection is the amount of the H_1 tail below the threshold.



• **Figure 8 – Hypotheses PDF's**

A functional block diagram of a generic detection receiver is shown in Figure 9. The antenna converts the free space propagated waveforms into RF signals. The bandpass filter (BPF) removes out-of-band energy. The low noise amplifier (LNA) sets the noise floor. The amplified signal is downconverted to baseband by mixing it with in-phase and quadrature-phase local oscillator signals generated by the frequency synthesizer. The frequency synthesizer is tuned to 310-kHz above the bottom of the 6-MHz channel, the location of the pilot carrier. The mixer outputs are lowpass filtered (LPF) with bandwidth B, the detection bandwidth. The lowpass signals are sampled at the Nyquist interval (1/B) and quantized. The digital samples are squared, added together, and summed over M sample pairs to form the decision variable, D.

The detection receiver functionality could be implemented in an unlicensed TV-band device with negligible production cost impact. Likely only the baseband ASIC would be affected. The unlicensed TV-band device already has all of the functionality through the A/D converters. Additional digital filtering might be required to achieve the desired detection bandwidth, and the squaring, summation, and comparison would be added. Compared to a typical unlicensed device baseband ASIC, the additional number of gates would be insignificant.



• Figure 9 – Detection Receiver Functional Block Diagram

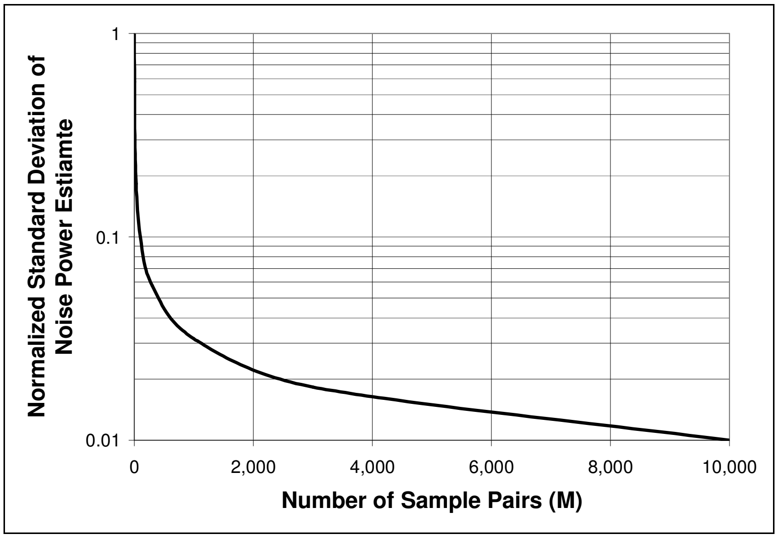
A calibration mode allows periodic measurement of the receiver noise which varies due to temperature changes and component aging. The LNA input is switched to a 50 ohm load. The decision variable divided by the noise variance (power), D / σ_N^2, is chi-square with 2M degrees of freedom. So it has mean 2M and variance 4M. In this case the noise power is estimated by:

$$\eta = D / (2 \text{ x } M)$$

and the variance of the estimate is:

$$\sigma_\eta^2 = \sigma_N^2 / M.$$

The normalized standard deviation of the noise power estimate is shown in Figure 10.



• Figure 10 – Noise Power Estimate Standard Deviation

After calibration, the distribution of the normalized decision variable, D / η, depends on which hypothesis is correct as follows:

H_0: chi-square with 2M degrees of freedom

H_1: non-central chi-square with 2M degrees of freedom and non-centrality parameter β = 2 x M x PC/N_0 / B.

Thus D / η has the mean and variance shown in Table 2.

Table 2 – Normalized Decision Variable Statistics

Hypothesis	Mean	Variance
H_0	2 x M	4 x M
H_1	2 x M x (1 + PC/N_0 / B)	4 x M x (1 + 2 x PC/N_0 / B)

The probabilities of false alarm and missed detection are given by:

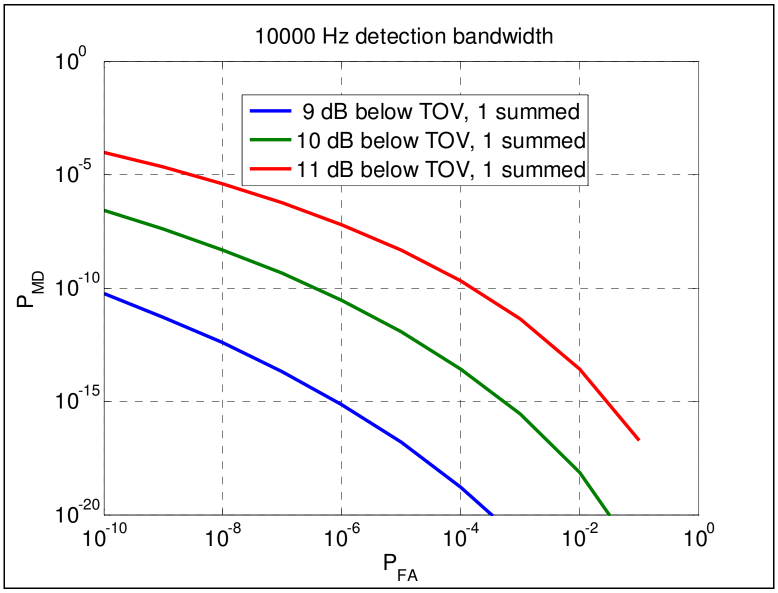
$$P_{FA}\left(T,2M\right)=\int_{T}^{\infty}\frac{t^{M-1}e^{-t/2}}{2^{M}\Gamma\left(M\right)}dt$$

and

$$P_{MD}\left(T,2M,\beta\right)=\int_{0}^{T}\frac{1}{2}\left(\frac{y}{\beta}\right)^{\frac{M-1}{2}}e^{-\frac{y-\beta}{2}}I_{M-1}\left(\sqrt{\beta y}\right)dy$$

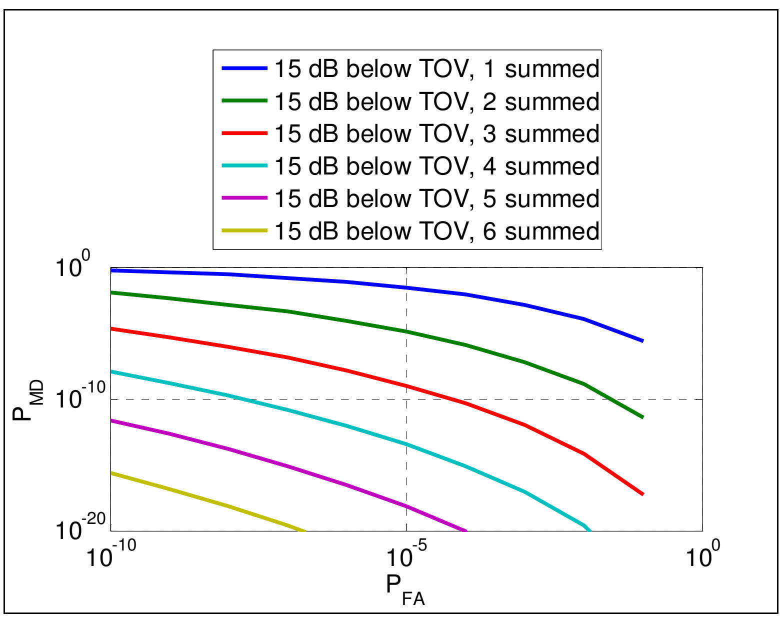
where $I_N(x)$ is the modified Bessel function of the first kind.

The detector operating characteristic (DOC) is a plot of P_{MD} versus P_{FA}. The DOC is shown in Figure 11 for a 10-kHz detection bandwidth, one sample summed, and signal levels 12, 13, and 14 dB below TOV. Note that the pilot carrier to noise density ratio, PC/N_0, and the detection bandwidth, B, only appear in the calculation of the non-centrality parameter, β. Thus any combination that results in the same value for β produces the same performance. A detector with 1-kHz detection bandwidth would be 10 dB more sensitive then a detector with 10-kHz detection bandwidth.



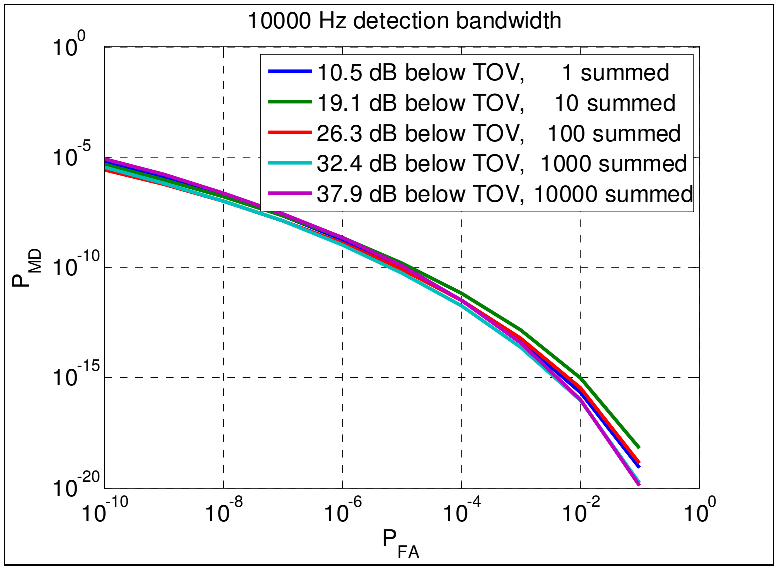
• Figure 11 – Detector Operation Characteristic (10-kHz detection bandwidth, 1 sample summed)

The DOC for a 10-kHz detection bandwidth, signal 15 dB below TOV, and various numbers of samples summed is shown in Figure 12. Increasing the number of samples summed significantly improves the detector performance.



• Figure 12 – Detector Operating Characteristic (10-kHz detection bandwidth, 15 dB below TOV)

For a constant false alarm rate (CFAR), the equation for P_{FA} can be solved for the threshold, T, and that value is used in the evaluation of the equation for P_{MD}. A value of 10^{-5} for P_{FA} means that one in every one hundred thousand times that an unlicensed device tests a channel that is vacant, it will erroneously conclude that it is occupied. This of course does not result in any interference to a TV; it only means that the unlicensed device will continue searching for a vacant channel. A value of 10^{-10} for P_{MD} means that if an unlicensed TV-band device checked for a vacant channel once a second, every second of every day, then on average, it would make a mistake and transmit on an occupied channel once every 317 years. Figure 13 shows the DOCs intersecting the (P_{FA} = 10^{-5}, P_{MD} = 10^{-10}) point.

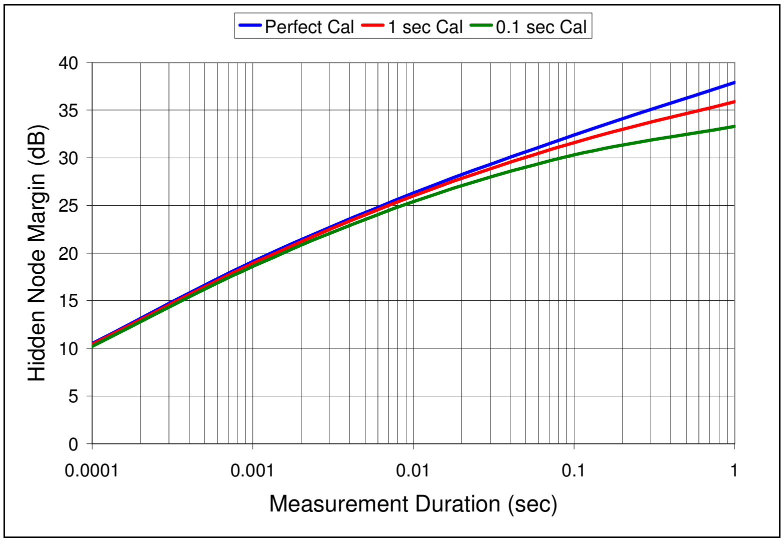


• Figure 13 – Detector Operating Characteristics Intersecting (P_{FA} = 10^{-5}, P_{MD} = 10^{-10})

Table 3 shows, for various numbers of samples summed, the threshold value T associated with 10^{-5} P_{FA}, measurement duration with a 10-kHz detection bandwidth, DTV signal strength set for reception at TOV, and P_{MD} of 10^{-10}. Three cases are provided, perfect noise scale factor, six-sigma noise scale factor with 1.0 second calibration (M_{CAL} = 10,000), and six-sigma noise scale factor with 0.1 second calibration (M_{CAL} = 1,000). The six-sigma noise scale factor ensures that the hidden node margin will be better then the value shown 99.999999% of the time. The hidden node margin versus measurement duration is plotted in Figure 14.

• Table 3 – Thresholds, Durations, and Hidden Node Margins (B = 10-kHz, P_{FA} = 10^{-5}, P_{MD} = 10^{-10})

Samples (M)	T/(2M)	Duration (sec)	Margin (dB)		
			Perfect Cal	1 sec Cal	0.1 sec Cal
1	11.5	0.0001	13.5	13.4	13.2
10	3.0	0.001	22.1	21.9	21.6
100	1.5	0.01	29.3	29.0	28.4
1000	1.2	0.1	35.4	34.6	33.3
10000	1.1	1.0	40.9	38.9	36.3

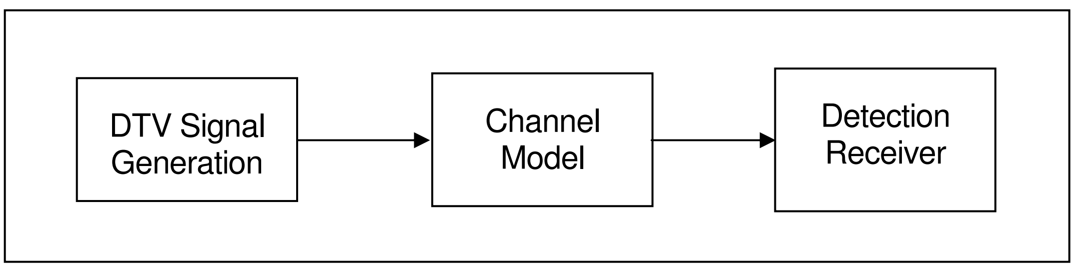


• **Figure 14 – Hidden Node Margin vs. Measurement Duration (B = 10-kHz, $P_{FA} = 10^{-5}$, $P_{MD} = 10^{-10}$)**

With one second of observation time, an occupied DTV channel can be identified with practical certainty by an unlicensed device even when nearby roof mounted antennas are only receiving the DTV signal at threshold and the unlicensed device sees the DTV signal with over 37 dB additional attenuation compared to the rooftop antennas.

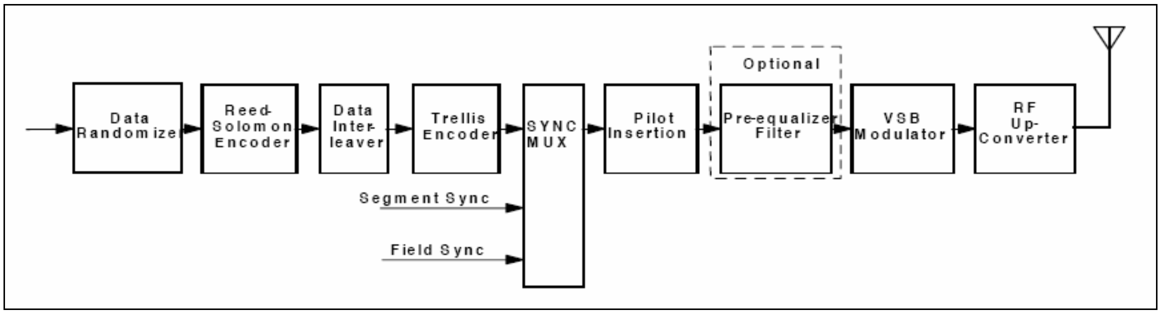
3.3 SIMULATION RESULTS

Simulation studies were conducted to validate the analytic results. A functional block diagram of the simulation is shown in Figure 15.

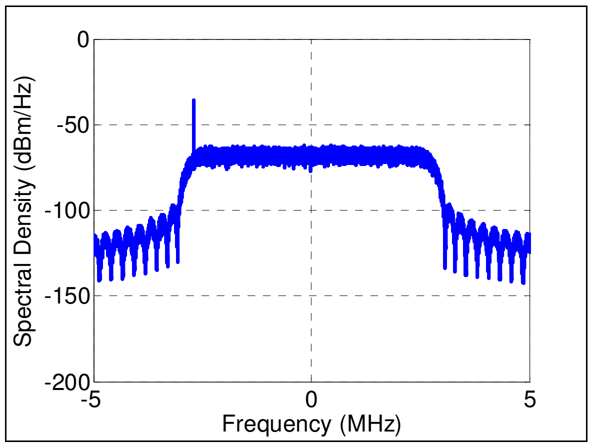


• **Figure 15 – Simulation Block Diagram**

The DTV Signal Generation block implements the DTV transmitter's 8-VSB signal generation as shown in Figure 16. Random data is generated to emulate the Data Randomizer. This data is encoded with a RS(207,187) block code followed by a convolutional byte interleaver and a rate-2/3 trellis encoder with intrasegment interleaving. The resulting symbols are multiplexed with the Segment Sync and Frame Sync symbols, and 8-VSB modulated with addition of the pilot signal. The modulated signal is then passed through a linear phase root raised cosine filter. Figure 17 shows the output signal spectrum.

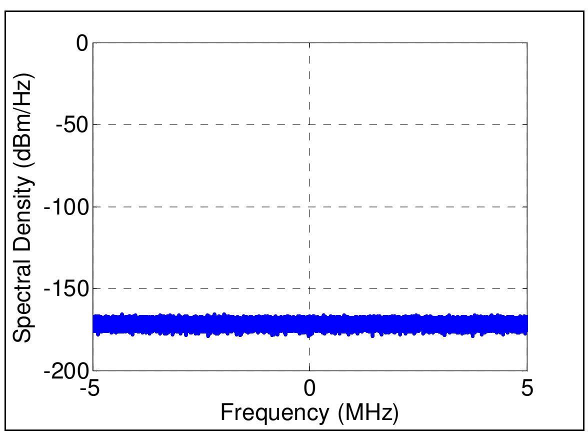


• **Figure 16 – DTV 8-VSB Signal Generation Functional Block Diagram**[20]



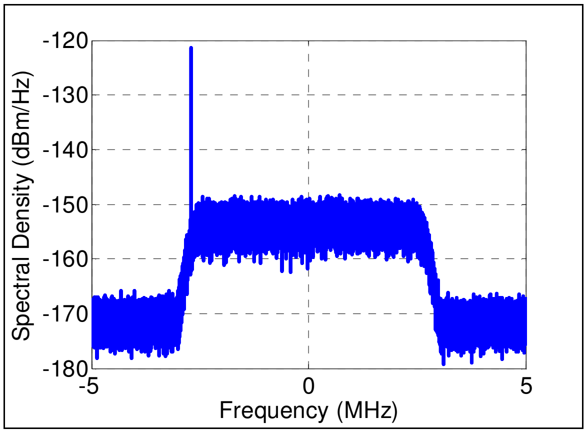
• **Figure 17 – Spectrum at DTV Signal Generation Output**

The Channel Model block scales the signal to the desired SNR and adds white Gaussian noise to model the receiver input noise. The receiver input spectrum signal is shown without a signal in Figure 18, and with a signal at TOV (14.9 dB SNR) in Figure 19. In calibration mode, the SNR is set to -100 dB which effectively removes the signal component.



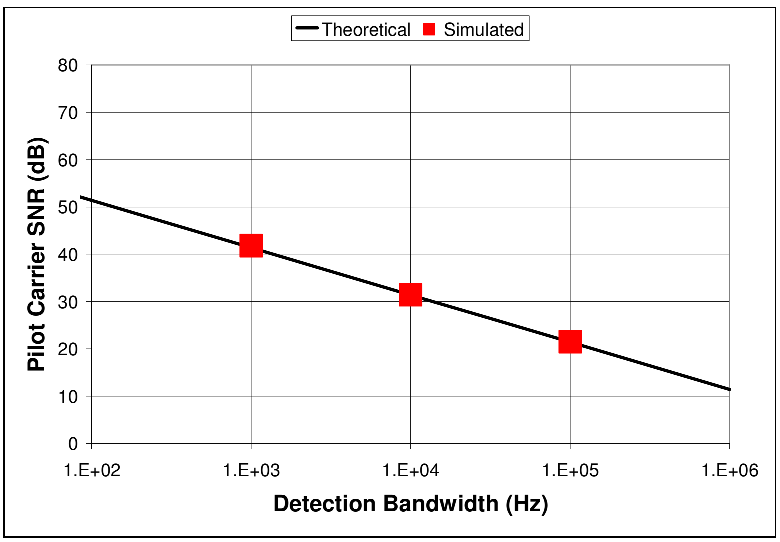
• **Figure 18 – Receiver Input Spectrum Without Signal**

[20] Advanced Television Systems Committee (ATSC), ATSC Standard: Digital Television Standard (A/53), Revision D, Including Amendment No. 1; Doc. A/53D, 19 July 2005, Amendment No. 1, 27 July 2005, page 75.



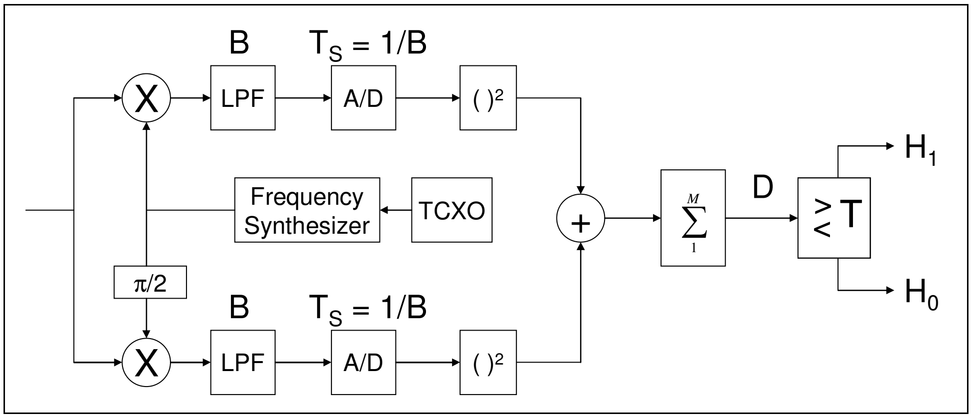
• Figure 19 – Receiver Input Spectrum With Signal at 14.9-dB SNR

The pilot carrier power to thermal noise ratio (PC/N) measured in the simulation bandwidth with the DTV signal set at TOV (14.9 dB DTV SNR) as a function of detection bandwidth is shown in Figure 20. Also shown are the theoretical values from Section. They are in excellent agreement.



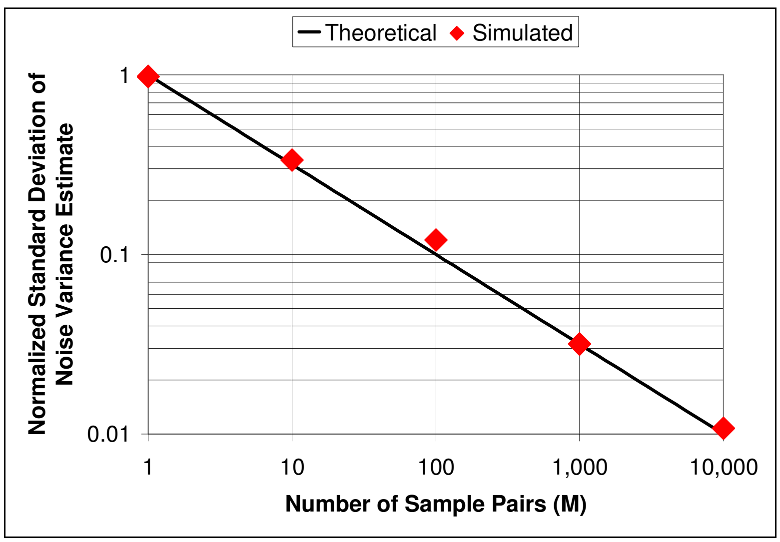
• Figure 20 – Pilot Carrier Power to Thermal Noise Ratio at TOV (Theoretical and Simulated)

The Detection Receiver block implements the functionality of the simplistic detector shown in Figure 21. The detection bandwidth is set to 10-kHz. The calibration mode is used to estimate the noise power. The detection threshold is calculated as a function of the number of samples summed, M, and the desired probability of false alarm, P_{FA}. Then the normalized decision variable is measured and compared to the threshold. If it is greater than the threshold, the channel is declared occupied; otherwise, the channel is declared vacant, a whitespace.



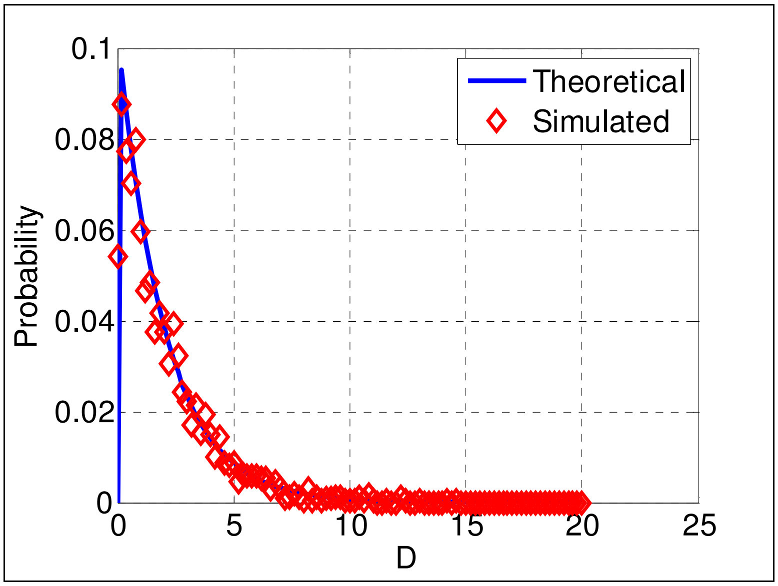
• Figure 21 – Detection Receiver Model

The normalized standard deviations of the noise power measurements generated by the simulation in calibration mode are shown in Figure 22 along with the corresponding theoretical values. They are in excellent agreement. This confirms the noise power estimation error model used in the analysis.

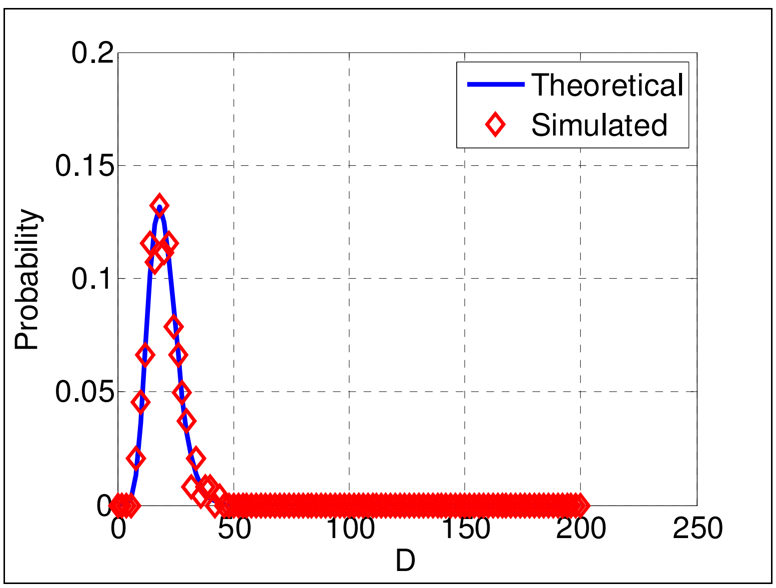


• Figure 22 – Noise Power Estimate Standard Deviation (Theoretical and Simulation Results)

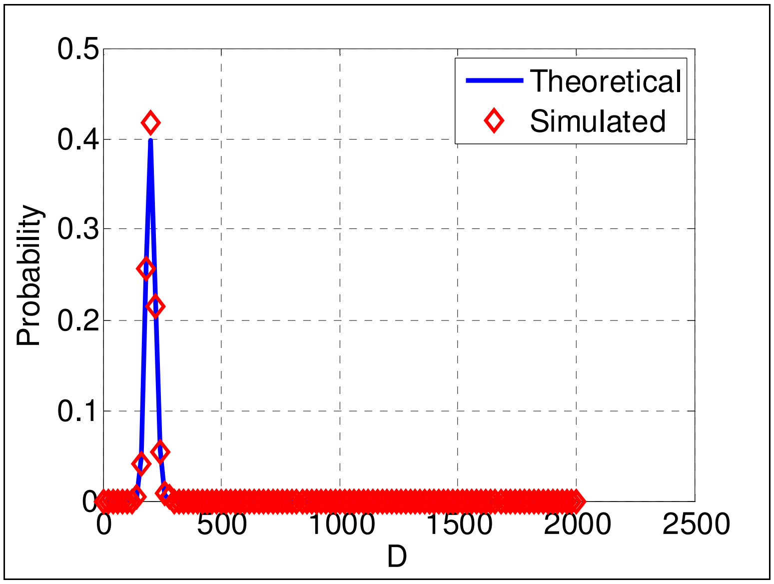
In the no signal case the distributions of the decision variables generated by the simulation are shown in Figure 23, Figure 24, and Figure 25 for 1, 10, and 100 samples summed, respectively. The theoretical distributions are also shown. Again, they are in excellent agreement. This confirms the channel vacant hypothesis, H_0, model used in the analysis.



• **Figure 23 – Decision Variable Distribution (M = 1, No Signal)**

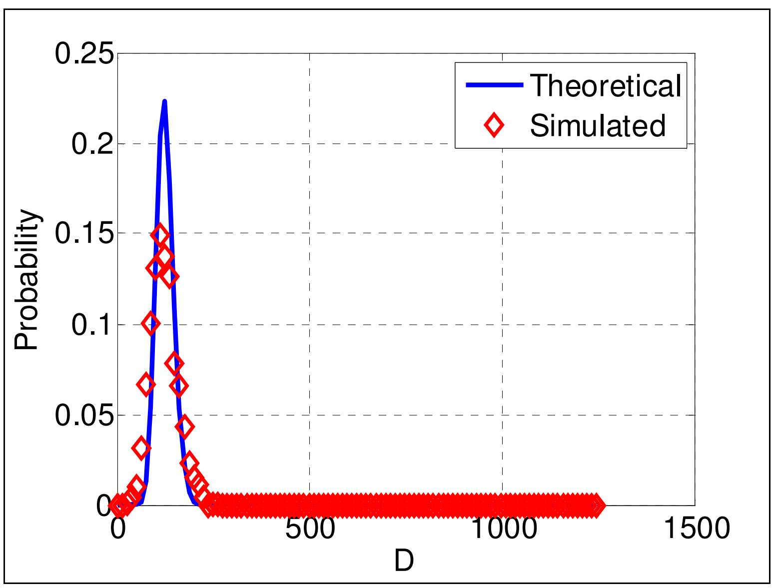


• **Figure 24 – Decision Variable Distribution (M = 10, No Signal)**

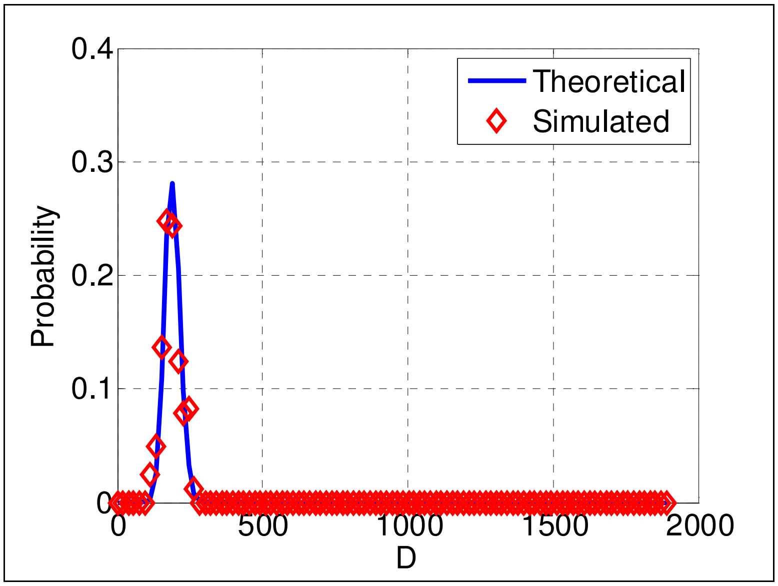


• **Figure 25 – Decision Variable Distribution (M = 100, No Signal)**

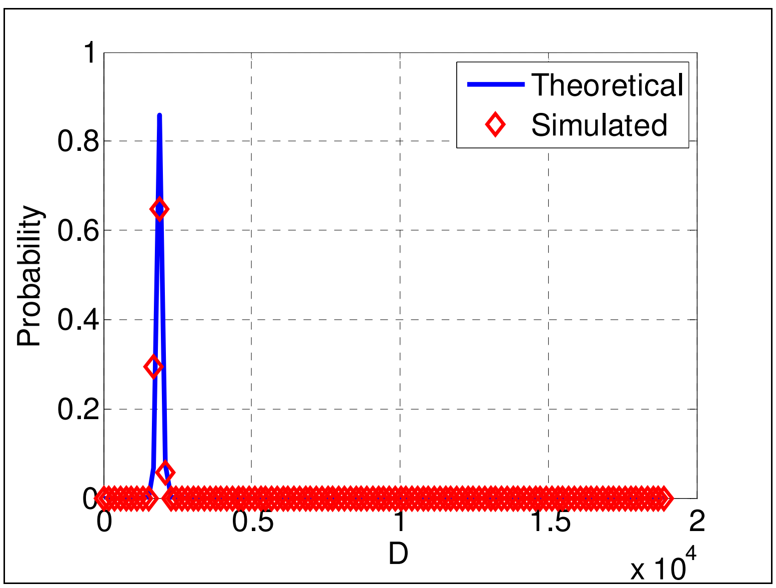
Figure 26, Figure 27 and Figure 28 are decision variable distributions generated by the simulation at the SNRs corresponding to $P_{FA} = 10^{-5}$ and $P_{MD} = 10^{-10}$ for 1, 10, and 100 samples summed, respectively. Again, the theoretical distributions are shown and they are in excellent agreement. This confirms the channel occupied hypothesis, H_1, model used in the analysis.



• **Figure 26 – Decision Variable Distribution (M = 1, SNR = -10.5 dB re TOV)**



• **Figure 27 – Decision Variable Distribution (M = 10, SNR = -19.1 dB re TOV)**



• **Figure 28 – Decision Variable Distribution (M = 100, SNR = -26.3 dB re TOV)**

Simulation results validate the conclusion reached in Section 3.2 that presence of DTV signals can detected with practical certainly by an unlicensed device even if nearby roof mounted antennas are receiving the DTV signal at the threshold of visibility (TOV) and the unlicensed device sees the DTV signal with over 37 dB additional attenuation compared to the rooftop antennas.

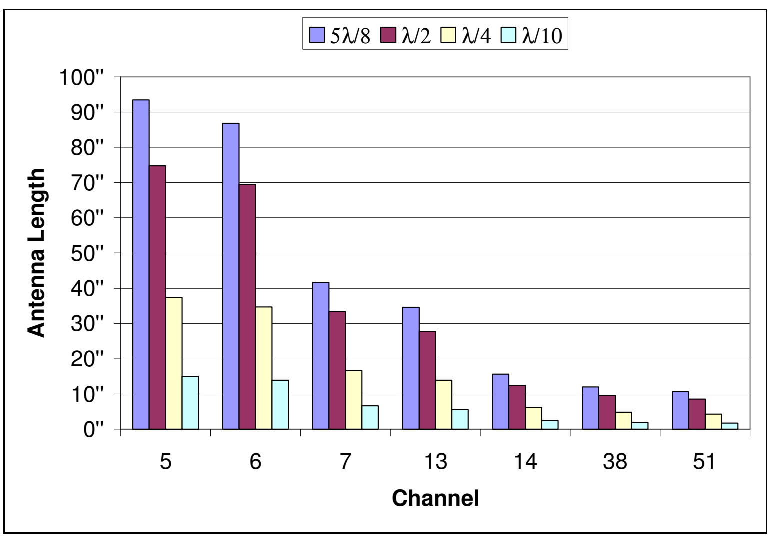
3.4 RECEIVER SENSITIVITY

Table 4 shows that DTV receivers with outdoor antennas have similar figures of merit (G/T) to those likely for indoor unlicensed devices. The DTV antennas provide significantly more gain, but they are followed by lossy downlead lines and high noise figure electronics. While typical unlicensed devices have small, low gain, antennas, they also have minimal feedloss and low noise preamps.

• Table 4 – DTV Planning Factors[21], Typical Unlicensed TV-Band Device Parameters, and Calculated G/T

	Low-VHF	High-VHF	UHF
Channels	**2 - 6**	**7 - 13**	**14 - 51**
DTV Receiver			
Antenna Gain	4 dB	6 dB	10 dB
Download Line Loss	1 dB	2 dB	4 dB
System Noise Figure	10 dB	10 dB	7 dB
G/T	-31.6 dB/K	-30.6 dB/K	-25.6 dB/K
Typical Unlicensed Device			
Antenna Gain	-3 dB	-2 dB	3 dB
Feedloss	1 dB	1 dB	1 dB
Receiver Noise Figure	3 dB	3 dB	3 dB
G/T	-31.6 dB/K	-30.6 dB/K	-25.6 dB/K

Low gain, omnidirectional in azimuth, VHF/UHF antennas suitable for unlicensed TV-band devices include vertical dipoles, vertical monopoles, and normal mode helixes. These antennas have nominal lengths ranging from λ/10 to 5λ/8 with gains of -3 dBi to +6 dBi depending on length and ground plane. They require tuning, band switching, or multi-band designs in order to cover all of the VHF and UHF TV channels. Figure 29 shows nominal antenna lengths optimized for various TV channels. Limiting operations to the UHF band (channels 14 and above) reduces the required antenna length by a factor of 6. This fact combined with the more predictable UHF propagation characteristics favors the UHF channels for use by unlicensed TV-band devices.



• Figure 29 – Nominal Antenna Lengths

Commercial preamplifiers with noise figures of 3 dB, or less, covering the VHF and UHF TV bands are available from several suppliers. The Channel Master Spartan 3 and Titan 2 series and the Winegard AP series are examples. TV receiver manufactures often do little to optimize noise figure, hence the high planning factor values. The rationale is that receivers are typically connected to cable or satellite converters which have strong output

[21] FCC OET BULLETIN No. 69, Longley-Rice Methodology for Evaluating TV Coverage and Interference, July 2, 1997.

signals. Customers without access to either cable or satellite are assumed to be in rural areas requiring antenna mounted preamps anyways.

4 Building Penetration Loss

Section 3 showed that with less than 1 second of observation time, an occupied DTV channel can be identified with practical certainty by an unlicensed device even when nearby roof mounted antennas are receiving the DTV signal at threshold and the unlicensed device sees the DTV signal with over 37-dB additional attenuation compared to the rooftop antennas. This Section addresses the remaining question of how likely is it that an unlicensed device located inside a building would see a DTV signal more than 37 dB below the rooftop level.

Section 4.1 considers building penetration loss models based on measurement campaigns. Section 4.2 models building blockage loss as frequency selective fading. In both cases, it is shown that the probability of loss exceeding 37 dB is negligible. The maximum value reported in the literature is only 30 dB.

4.1 PENETRATION LOSS

Building penetration loss is modeled as log-normal and characterized by its mean and standard deviation. Several researches have conducted measurement campaigns in the VHF and UHF bands to determine appropriate parameter values. There results are summarized below.

"Building Penetration Loss Measurements in the VHF and UHF Frequency Bands", Norddeutscher Rundfunk (NDR), Delayed Contribution to ITU-R Study Groups, Document 3J/13-E, 16 May 2001.

Ten buildings (9 residential and 1 industrial) in Munich, Germany were characterized. Measurements were made at two VHF frequencies (220 MHz and 223 MHz) and two UHF frequencies (588 MHz and 756 MHz). The measurements were made on different levels from the ground through third floors. The buildings were blocks of flats with brick walls, except for one single house and one with concrete walls. The results are summarized in Table 7.

• Table 5 – NDR Building Penetration Loss Parameters

Band	Mean	Standard Deviation	Max Loss
VHF	8.8 dB	3.5 dB	14.8 dB
UHF	7.8 dB	5.5 dB	17.8 dB

"Building Penetration Loss Measurements for DAB Signals at 211 MHz", J. A. Green, Research Department Report, BBC, BBC RD 1992/14, 1992.

Measurements where made inside each room of 23 ground floor dwelling units in brick buildings with an average of 3.2 measurements per square meter. The measurements are summarized in Table 6. Basement measurements provided a mean of 14.5 dB with a standard deviation of 3.8 dB.

• Table 6 – BBC Ground Floor VHF Building Penetration Loss Measurements

	Mean	Standard Deviation
Room With Least Loss	5.0 dB	3.2 dB
Complete Ground Floor	7.9 dB	3.0 dB
Room With Greatest Loss	10.0 dB	3.7 dB

"DIGITAL AUDIO BROADCASTING: Measuring techniques and coverage performance for a medium power VHF single frequency network", M.C.D. Maddocks, et. al., BBC Research and Development Report, BBC RD 1995/2, 1995.

Measurements were made in 13 houses and basement flats in built-up areas. The mean building penetration loss was 8.9 dB with a standard deviation of 4 dB

Finding the Right Frequency: Impact of Spectrum availability upon the Economics of Mobile Broadcasting, IET SEMINAR ON RF FOR DVB-H/DMB MOBILE BROADCAST, 30th June 2006, Savoy Place, London, Pekka Talmola, Nokia.

This presentation suggests the parameters shown in Table 7.

• Table 7 – Nokia Building Penetration Loss Parameters

Type	Band	Mean	Standard Deviation
Just Indoors	UHF	11 dB	5 dB
	VHF	11 dB	3 dB
Deep Indoors	UHF	17 dB	6 dB
	VHF	17 dB	3 dB

"DVB-T Indoor Reception, Validation of Coverage", Divitron.

Measurements were made in ten buildings at 498 MHz (TV Channel 18). The results are shown in Table 8. The mean of these measurements was 11.98 dB with a standard deviation of 4.2 dB.

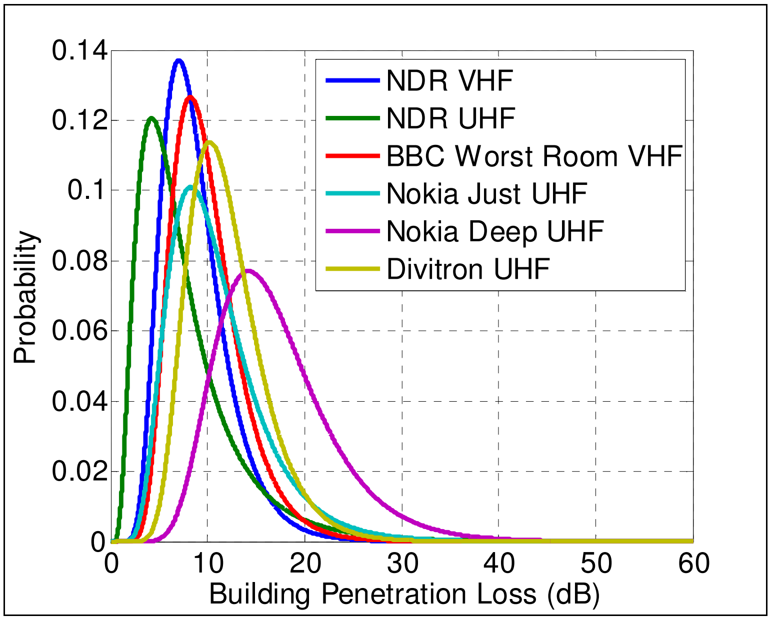
• Table 8 - Measured Building Penetration Loss (498 MHz)

Building	Penetration Loss (dB)
Mall	14.9
Mall	12.0
Mall	21.1
Flea market	14.1
Museum	12.5
City library	7.4
Shop	6.0
School	9.6
Ship terminal	12.0
Ice stadium	10.2

VALIDATE field trials of digital terrestrial television (DVB-T) , Chris Weck, Institut für Rundfunktechnik GmbH, Rundfunksystementwicklung (Broadcasting Systems Development), München, Germany, 1998.

Measurements were made in Europe as part of ACTS project VALIDATE. UHF building penetration loss measurements made at the BBC, London, UK, showed 28 to 30 dB on the ground floor and 21 to 23 dB on upper floors.

Figure 30 compares the probability distributions of the various building penetration loss models based on the researches field measurements. It can be seen that the probability of building penetration loss exceeding 37 dB is negligible. The maximum value reported by the researches was 30 dB.



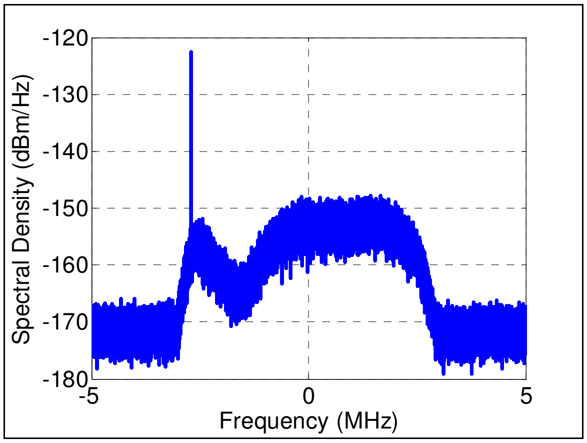
• **Figure 30 – Comparison of Building Penetration Loss Models**

4.2 BLOCKAGE LOSS

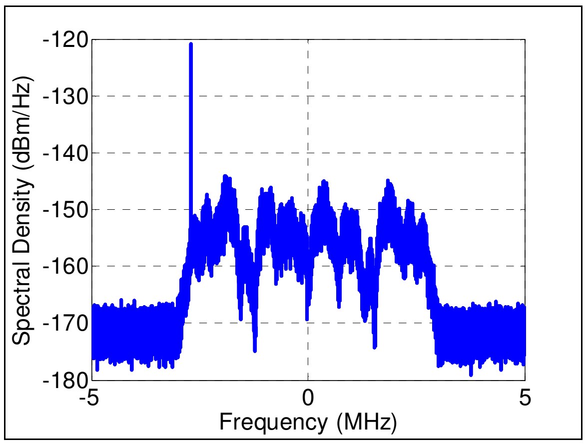
In this Section building blockage loss is modeled as a fading channel using the COST 207 wide sense stationary uncorrelated scattering (WSSUS) models with zero Doppler spread. The parameters for the 4-path rural (RA4), 6-path typical urban (TU6), 6-path bad urban (BU6), and 6-path hilly terrain (HT6) are shown in Table 9. Typical receiver input spectrums for each of these models at 14.9 dB SNR are shown in Figure 31, Figure 32, Figure 33, and Figure 34, respectively. The measured spectra presented in Section 5 show similar frequency selective fades.

• **Table 9 – COST 207 WSSUS Channel Model Parameters**

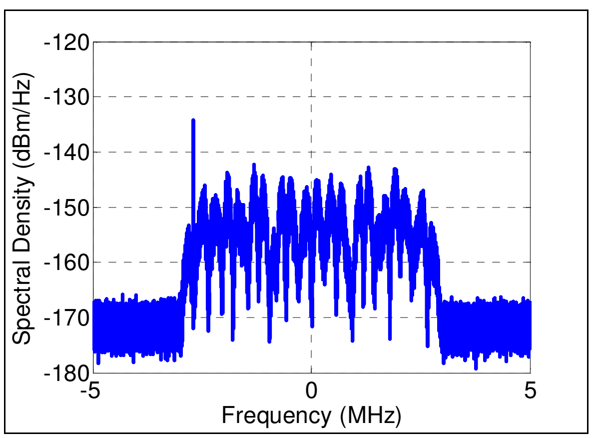
Path	RA4		TU6		BU6		HT6	
	Delay	Power	Delay	Power	Delay	Power	Delay	Power
0	0.0 µs	0 dB	0.0 µs	-3 dB	0.0 µs	-3 dB	0.0 µs	0 dB
1	0.2 µs	-2 dB	0.2 µs	0 dB	0.4 µs	0 dB	0.2 µs	-2 dB
2	0.4 µs	-10 dB	0.6 µs	-2 dB	1.0 µs	-3 dB	0.4 µs	-4 dB
3	0.6 µs	-20 dB	1.6 µs	-6 dB	1.6 µs	-5 dB	0.6 µs	-7 dB
4			2.4 µs	-8 dB	5.0 µs	-2 dB	15.0 µs	-6 dB
5			5.0 µs	-10 dB	6.6 µs	-4 dB	17.2 µs	-12 dB



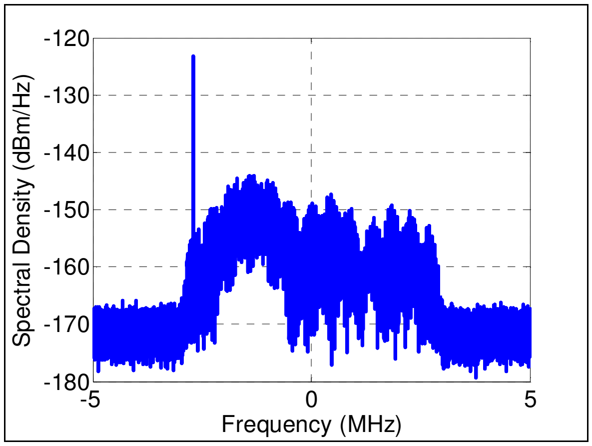
• **Figure 31 – Receiver Input Spectrum With 14.9 dB SNR & RA4 Channel**



• **Figure 32 – Receiver Input Spectrum With 14.9 dB SNR & TU6 Channel**

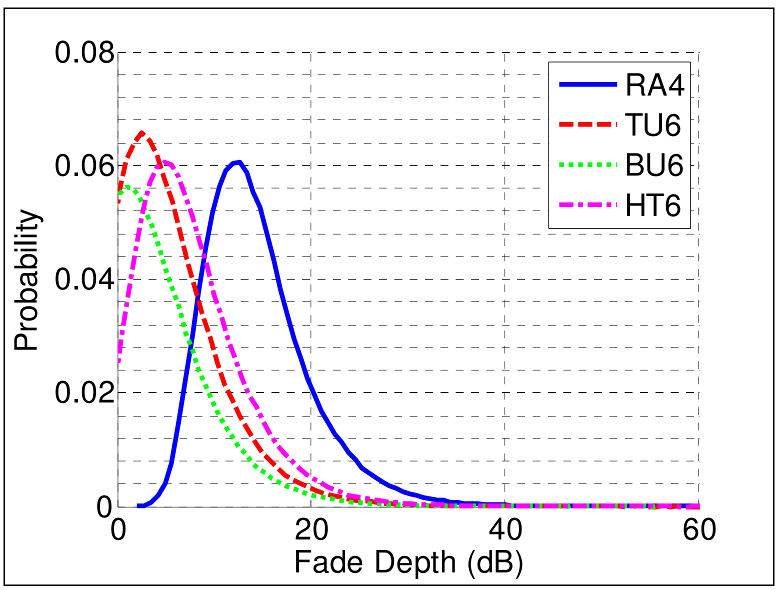


• **Figure 33 – Receiver Input Spectrum With 14.9 dB SNR & BU6 Channel**



• **Figure 34 – Receiver Input Spectrum With 14.9 dB SNR & HT6 Channel**

Figure 35 compares the probability distributions of the various building penetration loss models based on channel fading. Each curve was generated by 1 million simulation runs. It can be seen that the probability of building penetration loss exceeding 37 dB is negligible.



• **Figure 35 – Comparison of Fading Depth Models**

5 Field Measurements

To confirm the analysis and simulation results, field measurements of DTV signal pilot carrier power were made inside three residences in Encino, California, a suburb of Los Angeles. The measurements were made with an Anritsu MS2721A spectrum analyzer with an ICOM FA-1443B VHF/UHF antenna. The spectrum analyzer was configured as shown in Table 10.

• Table 10 – Spectrum Analyzer Setup

Parameter	Value
Resolution Bandwidth	10 kHz
Video Bandwidth	3 kHz
Span	6 MHz
Detection	RMS
Trace Mode	Max Hold
Preamp	On

The maximum noise figure of the MS2721A in the 10 MHz to 1 GHz band with the preamp on is 13 dB[22]. The measurement noise floor (dBm) is given by:

$$N_{FLOOR} = kT + NF + 10 \text{ x } \log_{10}(RBW)$$

where kT is Boltzman's constant times the reference temperature (-174 dBm/Hz)

NF is the noise figure (dB)

RBW is the resolution bandwidth (Hz).

So, the 10 kHz resolution bandwidth results in a -121 dBm measurement floor. This allows for the measurement of pilot carrier signals up to 25.4 dB below TOV[23]. The 3 kHz video bandwidth results in the number of samples non-coherently summed, M, approximately equal to 3. Section 3.2 shows that pilot carriers 37 dB below TOV can be detected with one second of observation time (M = 10,000). Thus, any pilot carrier that can be observed on the spectrum analyzer can easily be detected by an unlicensed TV-band device. The spectrum analyzer performs the same function as the detection receiver, only with smaller summations and hence reduced sensitivity. Also in this case the operator makes the decision visually as to whether, or not, the pilot carrier is above threshold.

The 22 DTV transmitters that provide coverage of the three residences, and the recommended roof mounted antenna types, were determined from the CEA antenna mapping program web site[24]. They are listed in Table 11. The antenna type codes are shown in Table 12.

[22] Spectrum Master MS2721A User's Guide, Anritsu, January 2006.
[23] Assuming a typical planning factor value of 7 dB for DTV receiver noise figure.
[24] http://www.checkhd.com

• Table 11 – DTV Stations With Coverage of Residences 1, 2, and 3

Antenna Type	Call Sign	Channel	Network	City	State	Frequency Assignment
SM	KTBN	23.1	TBN	SANTA ANA	CA	23
SM	KFTR	46.1	TFA	ONTARIO	CA	29
SM	KTLA	5.1	WB	LOS ANGELES	CA	31
SM	KDOC	56.1	IND	ANAHEIM	CA	32
SM	KMEX	34.1	UNI	LOS ANGELES	CA	35
SM	KNBC	4.1	NBC	LOS ANGELES	CA	36
MD	KPXN	30.1	i	SAN BERNARDINO	CA	38
MD	KVEA	39	TEL	CORONA	CA	39
MM	KLCS	58.1	PBS	LOS ANGELES	CA	41
MD	KWHY	22.1	IND	LOS ANGELES	CA	42
SM	KCAL	9.1	IND	LOS ANGELES	CA	43
SM	KAZA	54.1	AZA	AVALON	CA	47
SM	KOCE	50.1	PBS	HUNTINGTON BEACH	CA	48
SM	KJLA	57.1	IND	VENTURA	CA	49
SM	KXLA	44.1	IND	RANCHO PALOS VERDES	CA	51
SM	KABC	7.1	ABC	LOS ANGELES	CA	53
SM	KCET	28.1	PBS	LOS ANGELES	CA	59
SM	KCBS	2.1	CBS	LOS ANGELES	CA	60
LD w PA	KSCI	18.1	IND	LONG BEACH	CA	61
SM	KTTV	11.1	FOX	LOS ANGELES	CA	65
SM	KCOP	13.1	UPN	LOS ANGELES	CA	66
MD	KRCA	62.1	IND	RIVERSIDE	CA	68

• Table 12 – Antenna Types

Code	Type	Typical Gain (dB)
SM	Small, multi-directional	3 dB
MM	Medium, multi-directional	4 – 6 dB
MD	Medium, directional	7 – 8 dB
LD w PA	Large, directional with preamp	8 – 10 dB

Measurements of DTV pilot carrier power[25] were made in each room of each residence. All measurements were made during late afternoon hours. The codes used to denote the room types are shown in Table 13. The pilot carrier power measurements ranged from -104.7 dBm to -58 dBm.

Assuming a typical planning factor value of 7 dB for DTV receiver noise figure, the noise power in the 6-MHz channel bandwidth is -99.2 dBm (computed as -174 dBm/Hz + 7 dB + $10\log_{10}$[6-MHz]). At TOV, the SNR is 14.9 dB, so the signal power would be -84.3 dBm and the pilot carrier power would be -95.6 dBm (-84.3 dBm – 11.3 dB). Thus the lowest measured value was only 9.1 dB below the pilot carrier level at TOV (-95.6 dBm - -104.7 dBm). Hence the weakest pilot carrier observed was easily detectable by the detection receiver of Section 3 with over 27 dB of margin (37 dB – 9.1 dB).

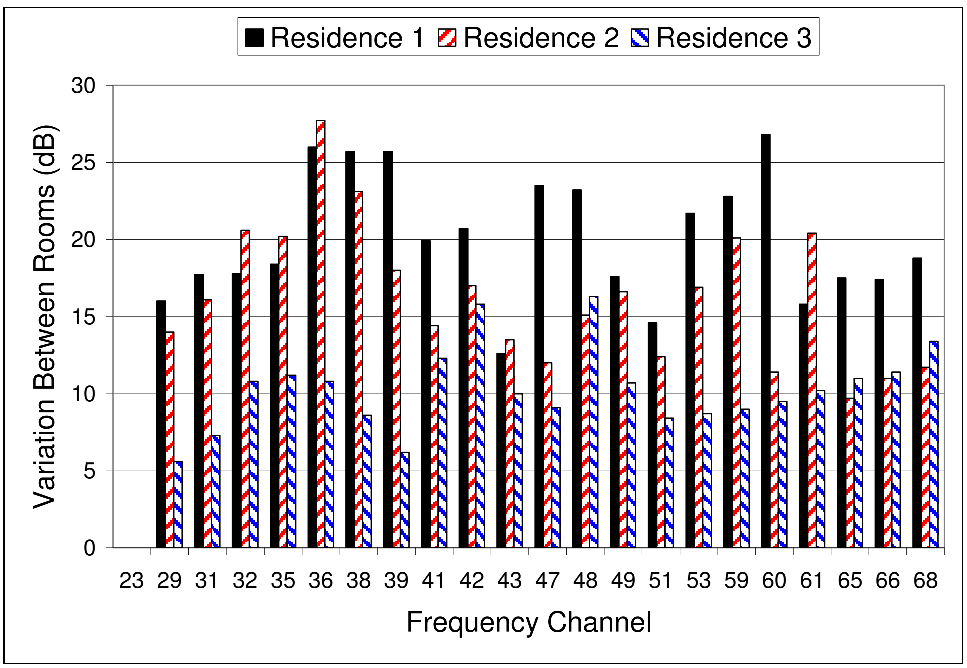
[25] Actually, the measurements are total power in the 10 kHz bandwidth around the pilot carriers. So, they include the -121 dBm spectrum analyzer noise power and the small fraction of the main DTV signal in the 10 kHz bandwidth around the pilot carrier (equal to 2.4% of the pilot carrier power). The net effect is that the actual received pilot carrier power was 0.1 to 0.2 dB lower then the raw measurements.

• **Table 13 – Room Type Codes**

BRn	bedroom
BAn	bathroom
LR	living room
FR	family room
DR	dining room
DN	den
UT	utility room
K	kitchen

In addition to the pilot carrier power measurements, the DTV signal spectrum in each of the 6 MHz channels at locations near the center of each residence were captured. For each channel, the spectrum analyzer display was allowed to stabilize for 5 to 10 seconds before the display was captured. With the exception of channel 23, the pilot carrier is readily visible in each plot. Thus each occupied channel would be correctly identified by an unlicensed TV-band device in every room of each residence. The signal observed in channel 23 does not appear to be a TV signal, but is still strong enough that it would be identified as an occupied channel.

The variation of pilot carrier power within the residences by frequency channel is shown in Figure 36.

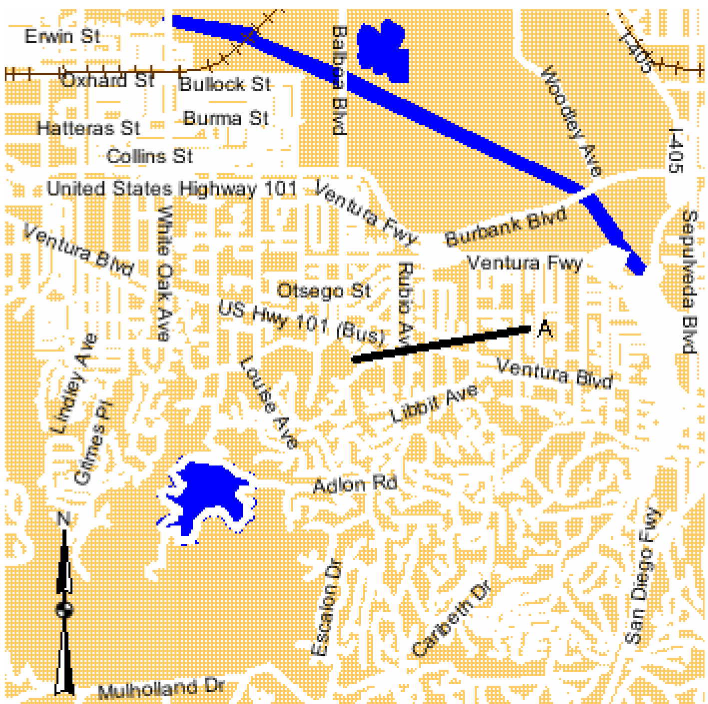


• **Figure 36 – Variation of Pilot Carrier Power Between Rooms**

5.1 RESIDENCE 1

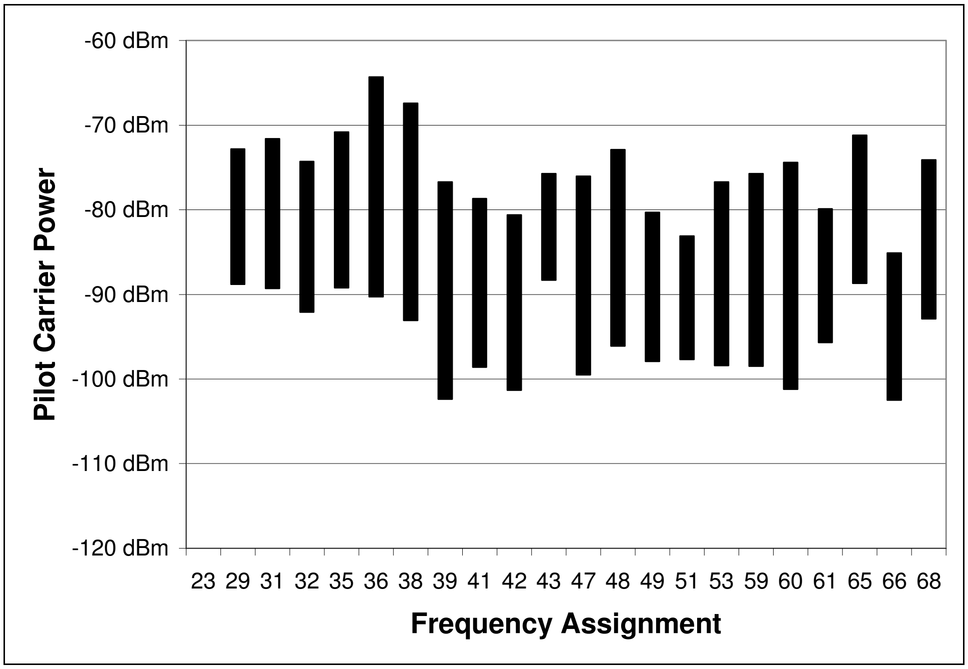
Residence 1 is a three-story 5-bedroom 5-bath 5,065 square foot house built in 1990. The house is surrounded by trees as shown in Figure 37. The DTV transmitters are located approximately 25 miles away at a compass heading of 65°. Residence 1 is at the center of Figure 38. The line “A” shows the direction of the transmitters.

• **Figure 37 – Residence 1**

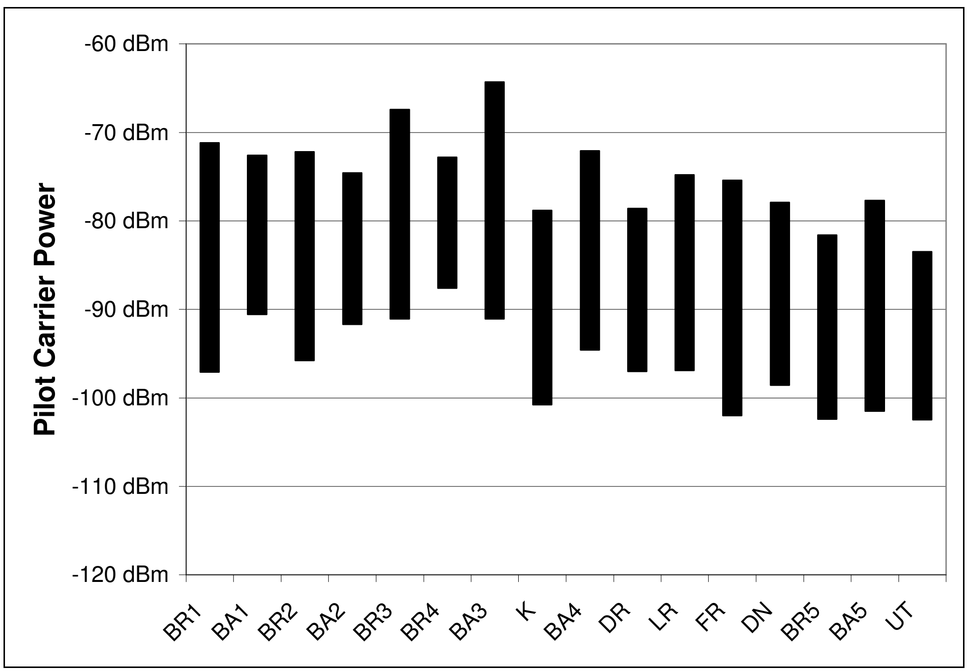


• **Figure 38 – Residence 1 Location**

The raw pilot carrier power measurements are shown in Table 14. They range from -102.5 dBm to -64.3 dBm. Figure 39 shows the variation by frequency channel and Figure 40 shows the variation by room. The average variation across rooms for a given frequency channel was 19.8 dB. The DTV signal spectrums captured in residence 1 are shown in Figure 41 through Figure 62. Many of the figures show the frequency selective fading characteristic of the WSSUS channels simulation results presented in Section 5.



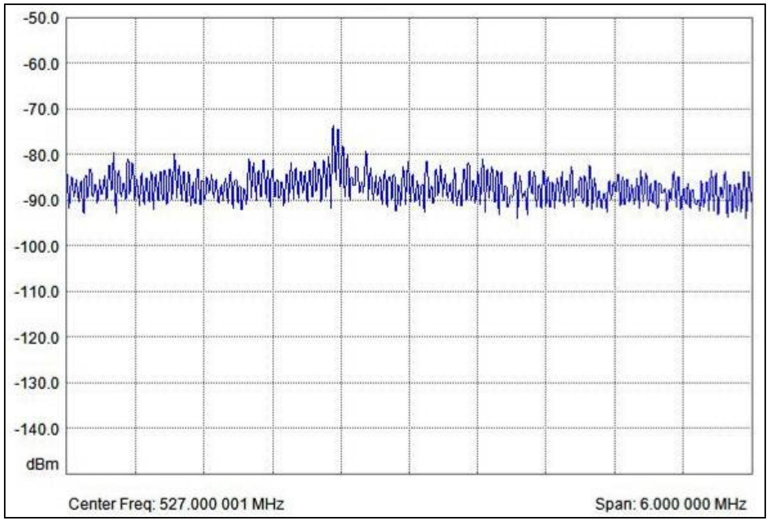
• **Figure 39 – Residence 1 Pilot Carrier Power Variance By Frequency Channel**



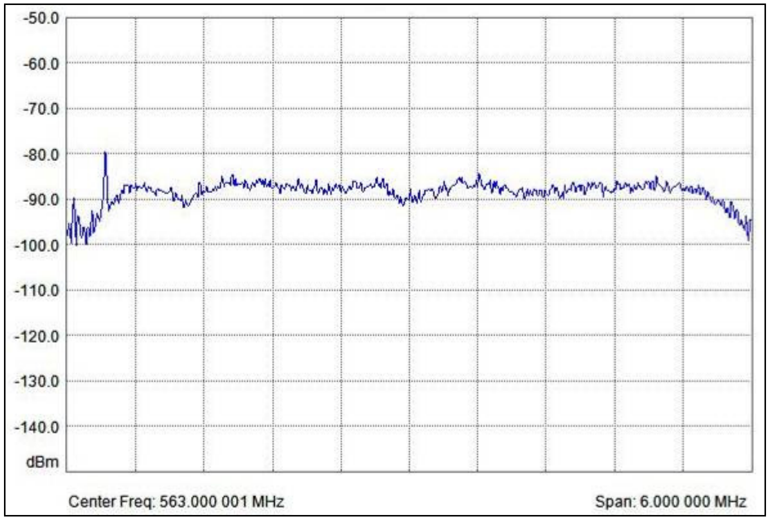
• **Figure 40 – Residence 1 Pilot Carrier Power Variance By Room**

• **Table 14 – Residence 1 Raw Pilot Carrier Measurements (dBm)**

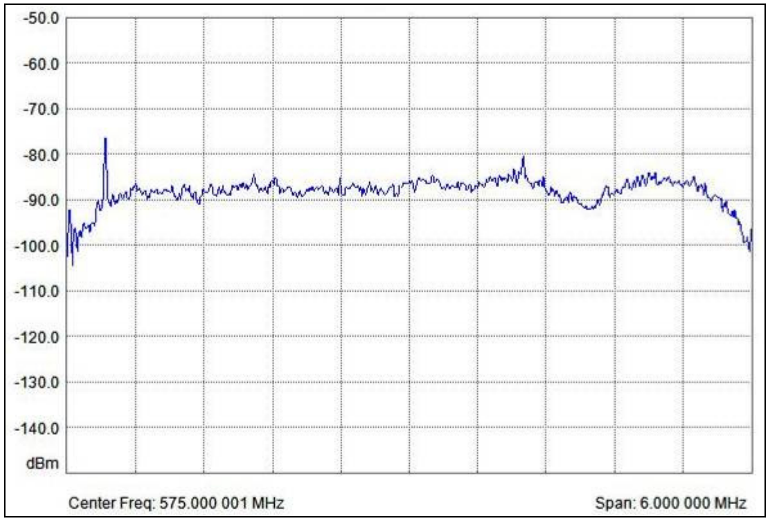
	3rd Floor							2nd Floor						1st Floor		
Frequency Assignment	**BR1**	**BA1**	**BR2**	**BA2**	**BR3**	**BR4**	**BA3**	**K**	**BA4**	**DR**	**LR**	**FR**	**DN**	**BR5**	**BA5**	**UT**
23	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
29	-78.9	-74.9	-84.4	-79.9	-78.4	-72.8	-75.9	-85.1	-76.6	-78.7	-78.2	-83.5	-86.6	-86.4	-88.8	-83.5
31	-73.0	-72.6	-75.0	-77.4	-71.6	-74.2	-74.5	-85.5	-86.8	-78.6	-82.5	-75.4	-77.9	-85.5	-77.7	-89.3
32	-74.8	-82.2	-74.3	-83.4	-80.8	-74.9	-75.6	-84.5	-81.7	-80.7	-79.6	-85.3	-79.7	-92.1	-81.9	-90.0
35	-81.3	-82.7	-73.2	-75.7	-74.9	-80.3	-70.8	-87.7	-77.5	-81.9	-89.2	-85.4	-87.4	-81.6	-86.7	-87.2
36	-75.2	-82.5	-75.0	-79.0	-79.1	-74.4	-64.3	-89.4	-74.5	-84.3	-84.1	-81.4	-84.0	-90.3	-89.6	-88.6
38	-77.5	-80.0	-72.2	-74.6	-67.4	-84.9	-69.0	-78.8	-72.1	-83.5	-77.6	-79.0	-88.9	-88.1	-81.9	-93.1
39	-81.8	-87.6	-76.7	-90.9	-77.1	-84.1	-81.1	-100.5	-84.4	-96.8	-96.9	-98.5	-94.1	-102.4	-98.5	-101.3
41	-88.2	-85.5	-80.6	-78.7	-82.3	-86.9	-86.0	-94.3	-87.8	-85.4	-88.8	-89.4	-98.6	-90.4	-90.1	-96.1
42	-97.1	-89.1	-83.2	-86.2	-80.6	-82.5	-84.7	-86.2	-88.5	-85.6	-87.6	-94.4	-90.1	-101.3	-90.9	-97.8
43	-82.2	-84.1	-75.7	-80.5	-76.4	-79.7	-83.8	-86.0	-82.0	-84.9	-86.9	-85.4	-85.6	-86.6	-88.3	-85.2
47	-81.3	-85.9	-76.0	-82.5	-81.5	-82.2	-85.6	-96.9	-85.2	-87.1	-91.1	-84.7	-92.4	-93.0	-96.3	-99.5
48	-83.8	-86.4	-76.4	-87.4	-72.9	-85.5	-80.4	-90.6	-90.1	-89.9	-88.0	-90.7	-96.1	-89.9	-89.8	-91.9
49	-89.3	-90.6	-83.1	-83.1	-80.3	-86.4	-88.0	-87.5	-83.5	-88.0	-87.7	-90.3	-97.9	-85.8	-91.3	-97.5
51	-85.0	-83.1	-85.0	-91.7	-91.1	-87.6	-91.1	-93.1	-88.6	-90.3	-85.6	-95.0	-97.7	-93.0	-89.2	-96.6
53	-83.2	-83.0	-82.5	-83.5	-76.7	-84.6	-79.8	-86.0	-93.3	-84.4	-84.2	-93.0	-98.4	-96.1	-91.2	-96.1
59	-87.7	-85.3	-78.8	-84.5	-75.7	-76.6	-83.0	-94.6	-94.6	-85.7	-87.7	-84.7	-97.5	-93.9	-91.0	-98.5
60	-77.5	-83.8	-84.6	-80.1	-86.9	-74.4	-77.4	-85.6	-93.1	-83.9	-81.6	-82.2	-83.1	-92.6	-88.8	-101.2
61	-79.9	-84.7	-81.0	-89.2	-85.2	-81.0	-83.1	-92.0	-84.5	-93.7	-85.0	-84.1	-87.5	-89.3	-88.0	-95.7
65	-71.2	-79.4	-77.1	-75.3	-76.4	-80.1	-78.1	-84.8	-79.8	-82.2	-74.8	-87.1	-88.7	-88.1	-84.0	-85.4
66	-93.3	-88.7	-95.8	-85.1	-90.3	-85.6	-87.8	-100.8	-90.8	-97.0	-91.6	-102.0	-98.2	-99.3	-101.5	-102.5
68	-80.9	-84.2	-74.1	-75.3	-79.9	-74.2	-80.3	-83.9	-88.8	-83.1	-82.3	-82.7	-92.9	-92.2	-86.4	-92.6



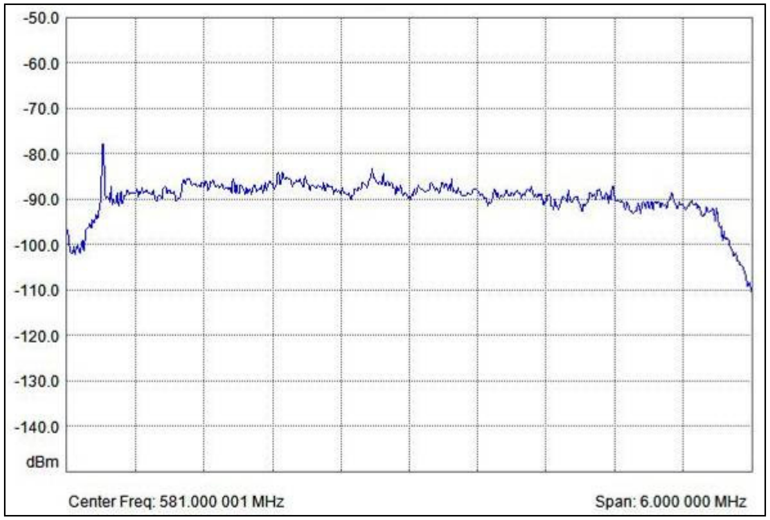
• **Figure 41 – Residence 1, Channel 23**



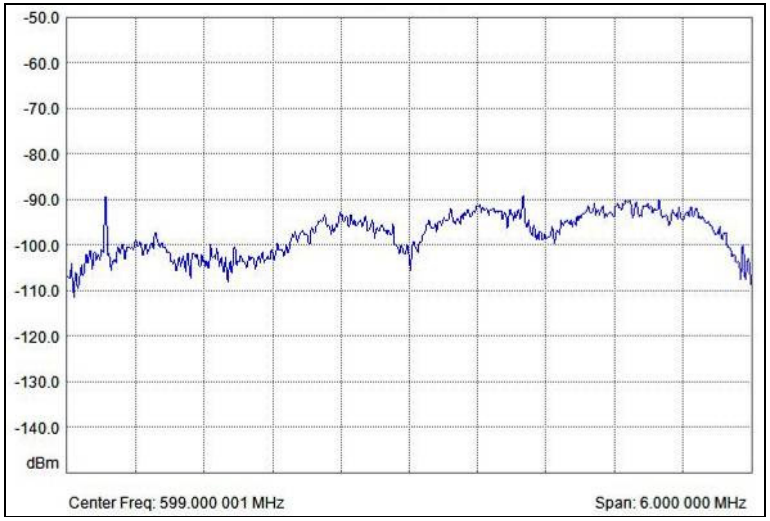
• **Figure 42 – Residence 1, Channel 29**



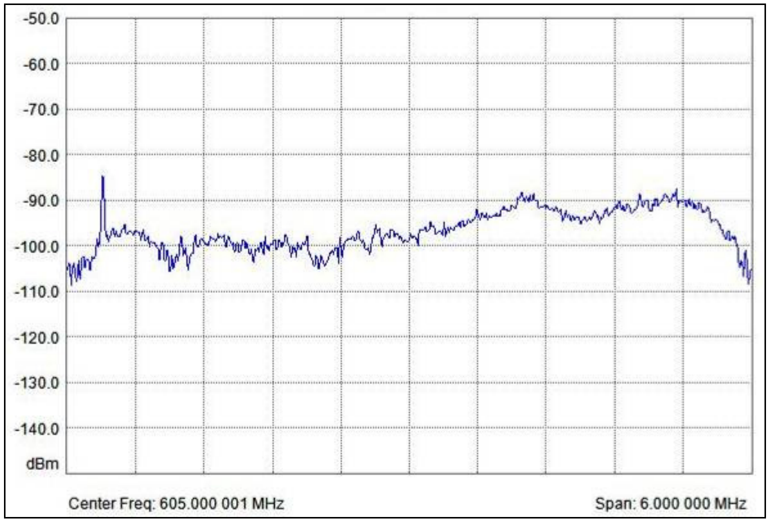
• **Figure 43 – Residence 1, Channel 31**



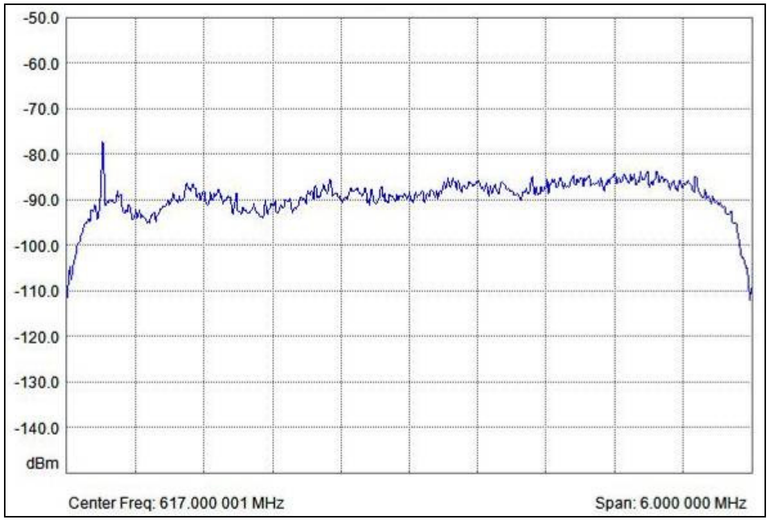
• **Figure 44 – Residence 1, Channel 32**



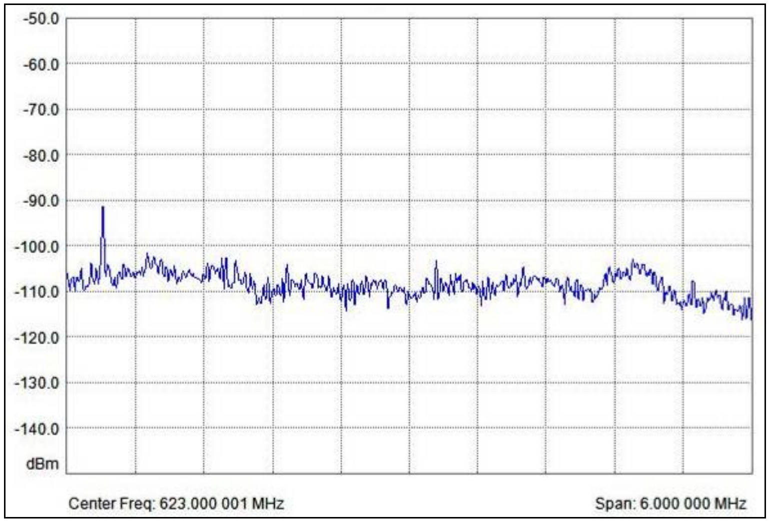
• **Figure 45 – Residence 1, Channel 35**



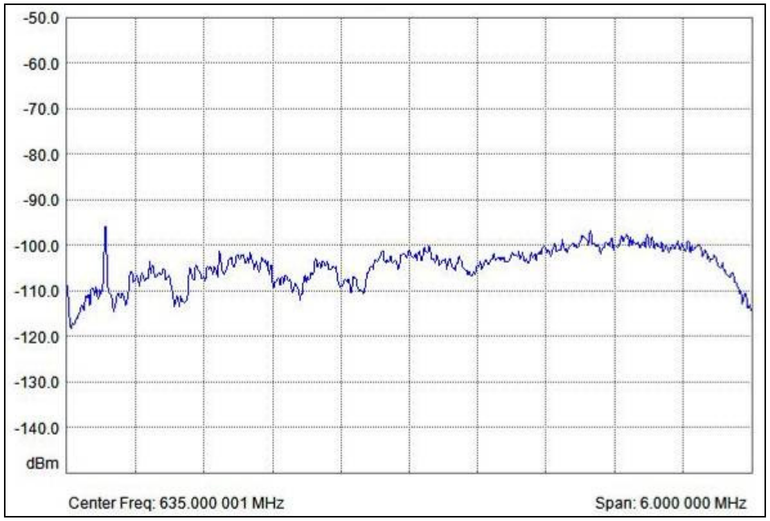
• **Figure 46 – Residence 1, Channel 36**



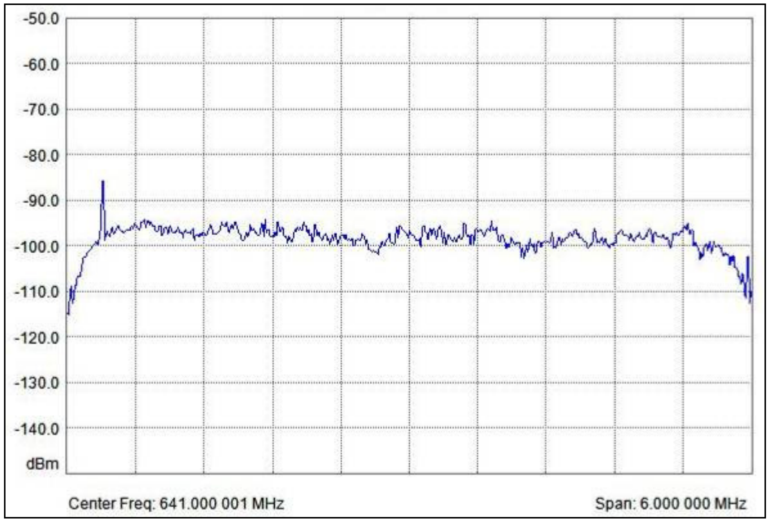
• **Figure 47 – Residence 1, Channel 38**



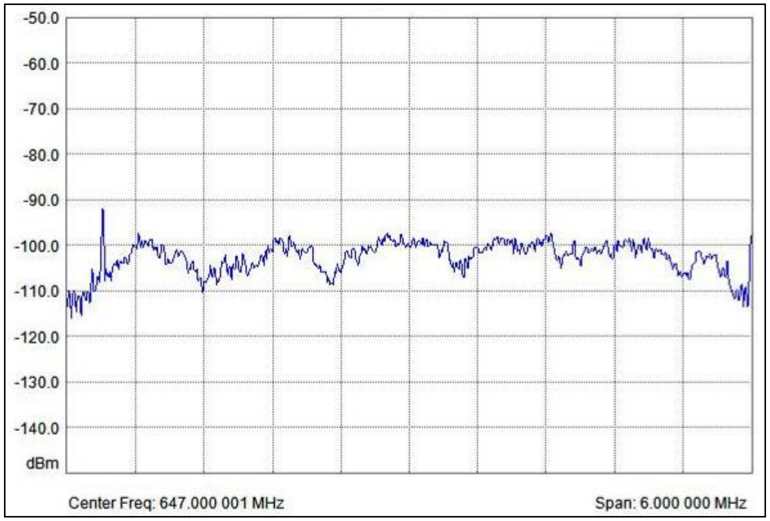
• **Figure 48 – Residence 1, Channel 39**



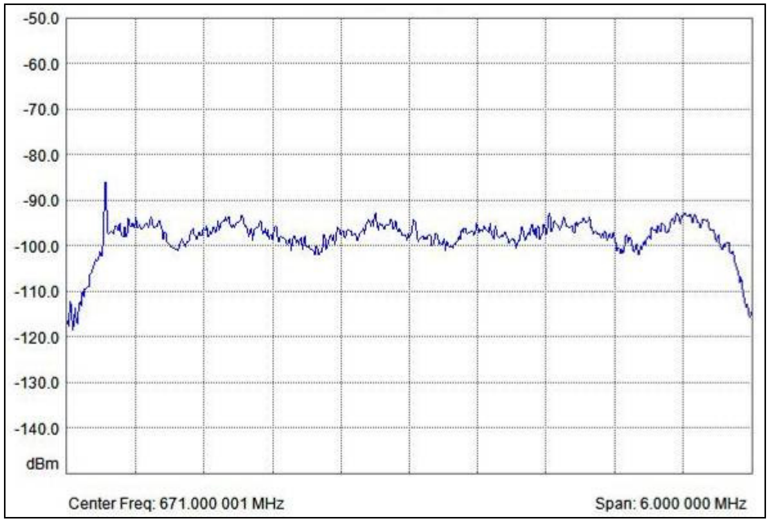
• **Figure 49 – Residence 1, Channel 41**



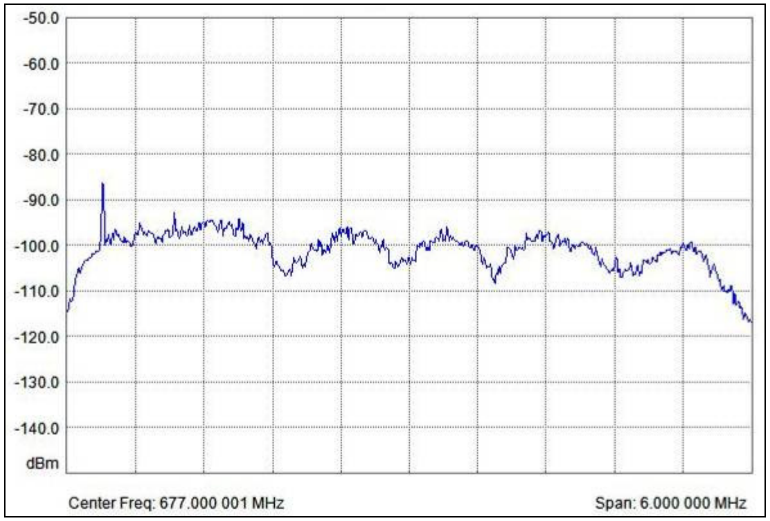
• **Figure 50 – Residence 1, Channel 42**



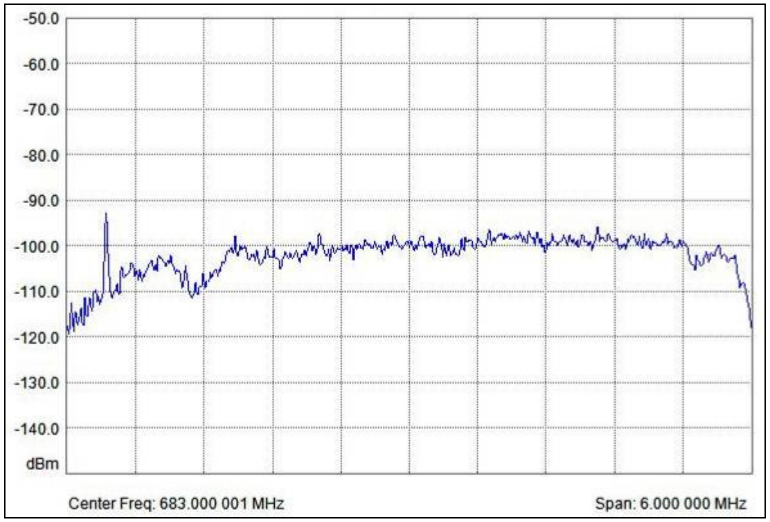
• **Figure 51 – Residence 1, Channel 43**



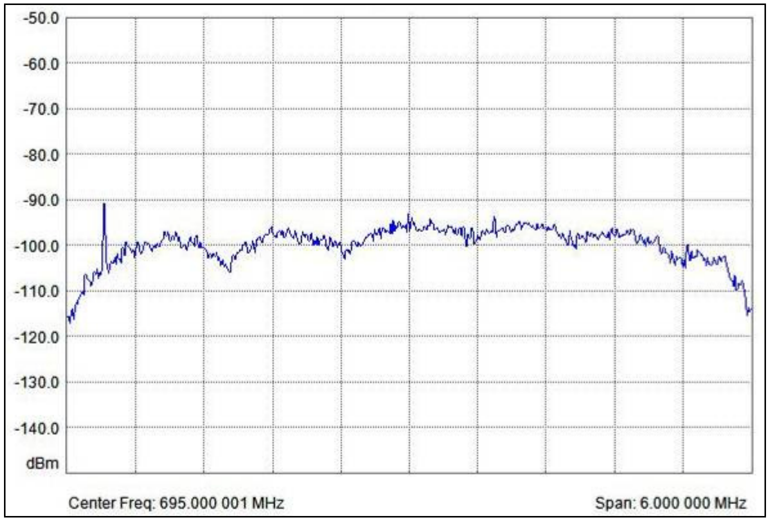
• **Figure 52 – Residence 1, Channel 47**



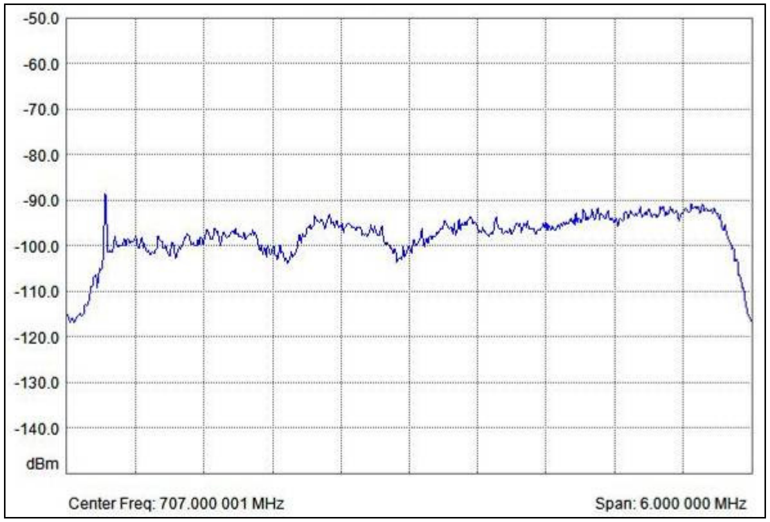
• **Figure 53 – Residence 1, Channel 48**



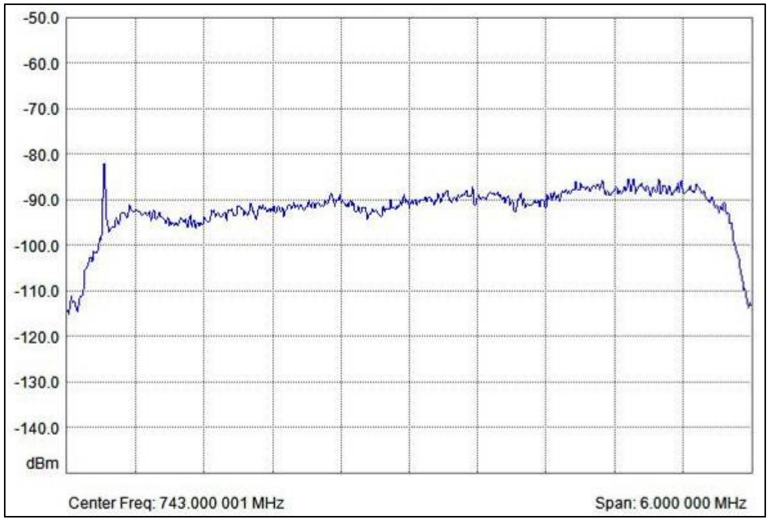
• **Figure 54 – Residence 1, Channel 49**



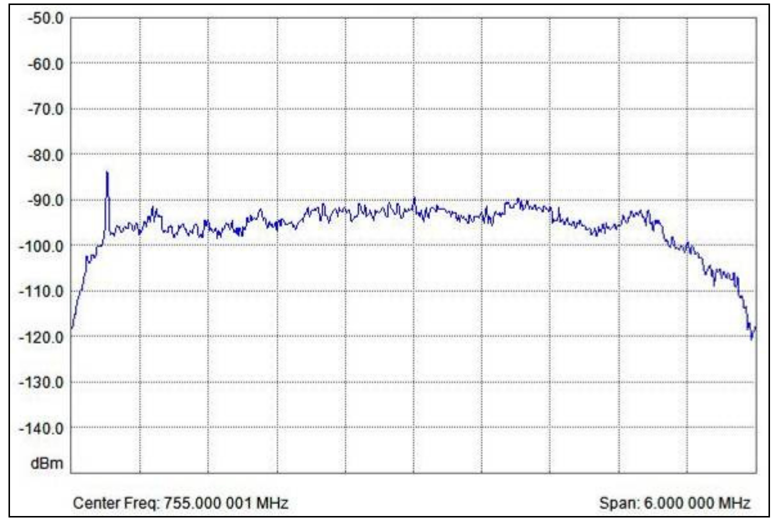
• **Figure 55 – Residence 1, Channel 51**



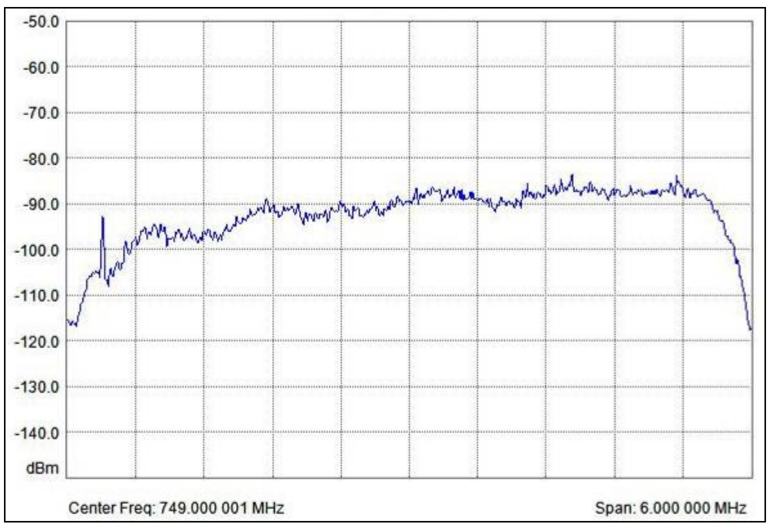
• **Figure 56 – Residence 1, Channel 53**



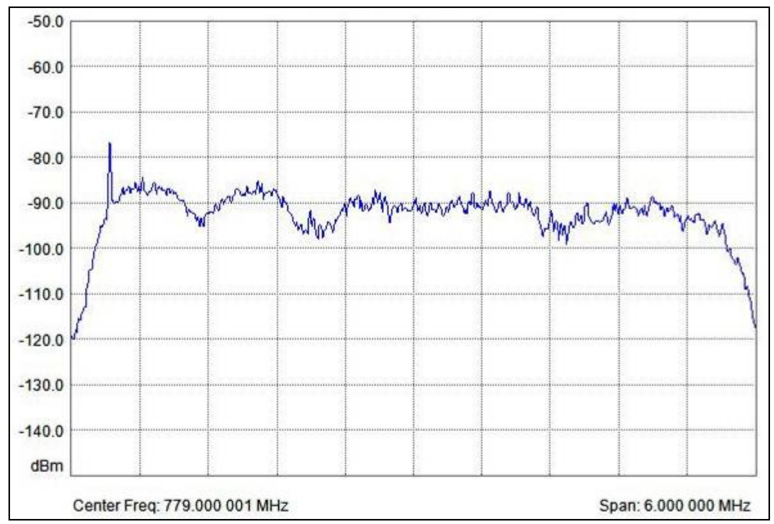
• **Figure 57 – Residence 1, Channel 59**



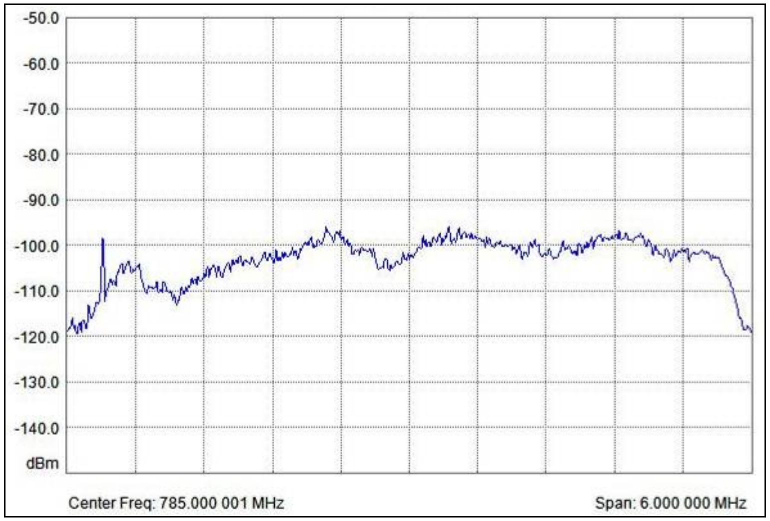
• **Figure 59 - Residence 1, Channel 61**



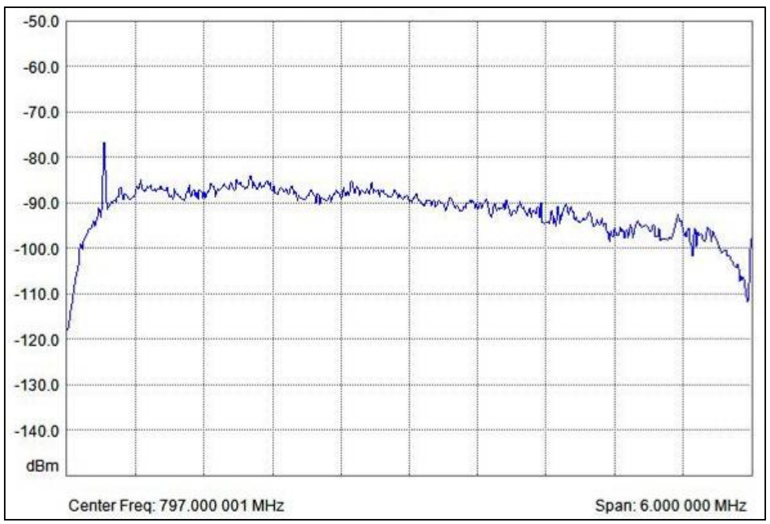
• **Figure 58 – Residence 1, Channel 60**



• **Figure 60 – Residence 1, Channel 65**



• **Figure 61 – Residence 1, Channel 66**

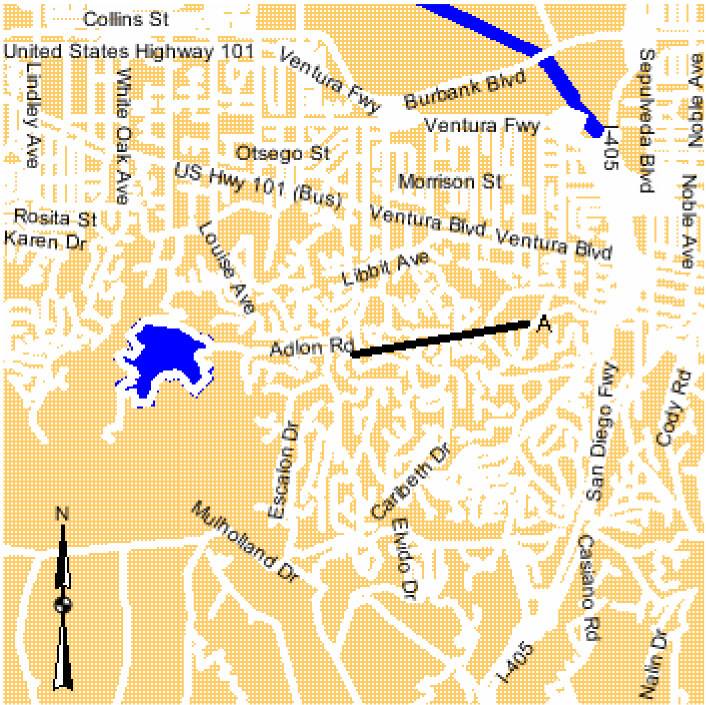


• **Figure 62 - Residence 1, Channel 68**

5.2 RESIDENCE 2

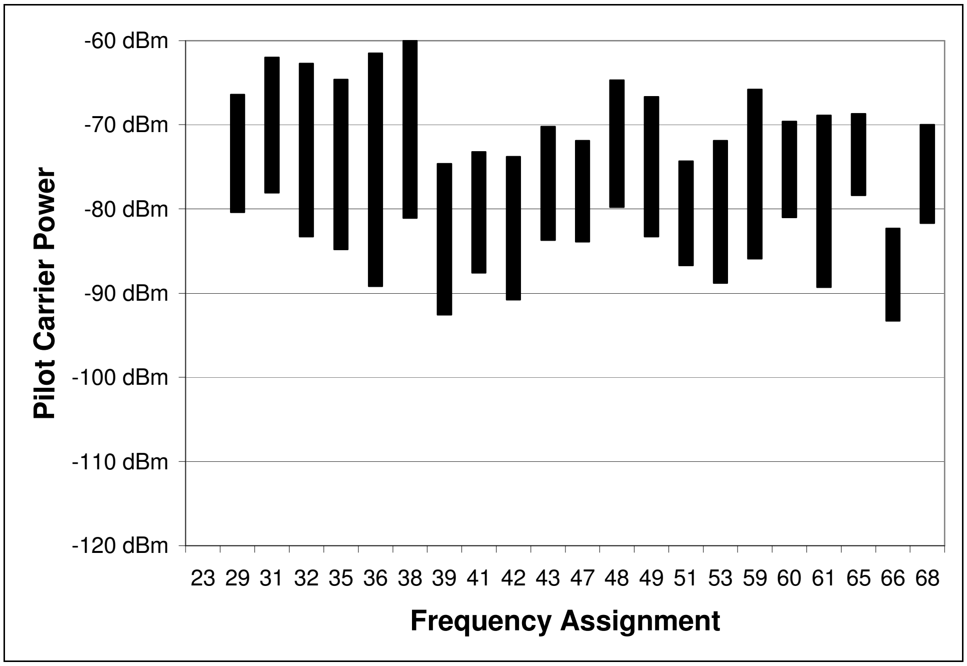
Residence 2 is an one-story, 3 bedroom, 3-bath, 2,807 square foot single family house built in 1955. The house is surrounded by trees as shown in Figure 63. The DTV transmitters are located approximately 25 miles away at a compass heading of 63°. Residence 2 is at the center of Figure 64. The line "A" shows the direction of the transmitters.

• **Figure 63 – Residence 2**

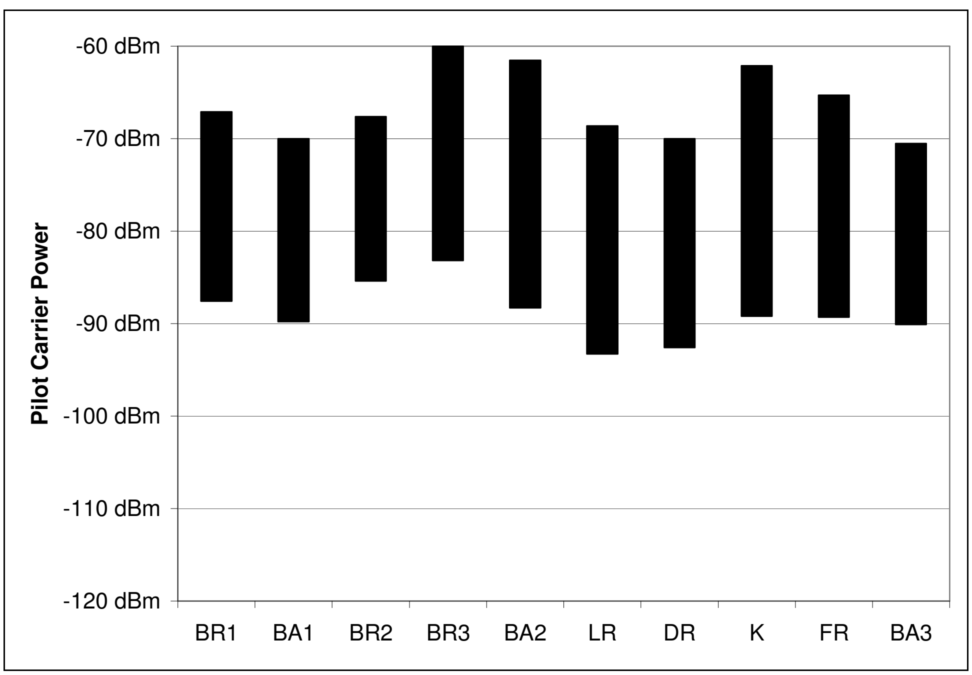


• **Figure 64 – Residence 2 Location**

The raw pilot carrier power measurements are shown in Table 15. They range from -93.3 dBm to -58.0 dBm. Figure 65 shows the variation by frequency channel and Figure 66 shows the variation by room. The average variation across rooms for a given frequency channel was 16.3 dB. The DTV signal spectrums captured in residence 2 are shown in Figure 67 through Figure 88. Many of the figures show the frequency selective fading characteristic of the WSSUS channels simulation results presented in Section 4.2.



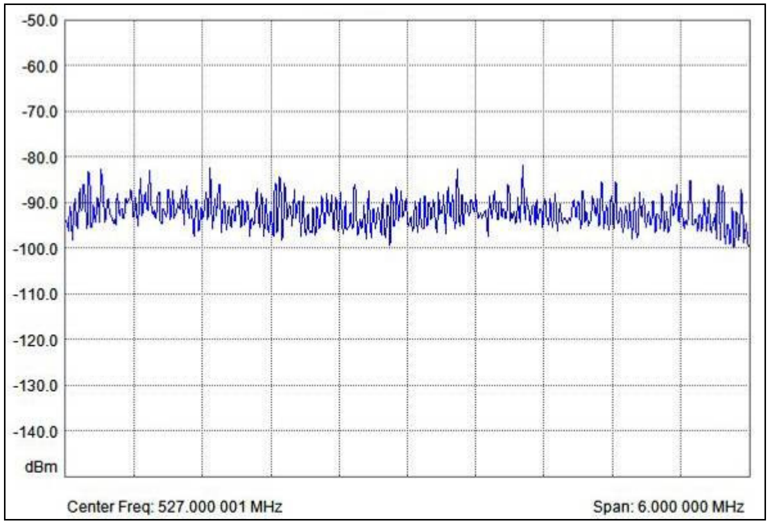
• **Figure 65 – Residence 2 Pilot Carrier Power Variation By Frequency Assignment**



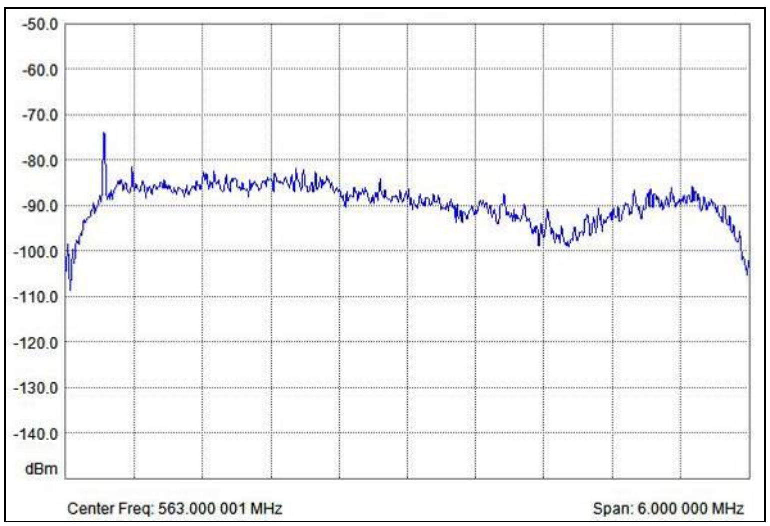
• **Figure 66 – Residence 2 Pilot Carrier Power Variation By Room**

• **Table 15 – Residence 2 Raw Pilot Carrier Power Measurements (dBm)**

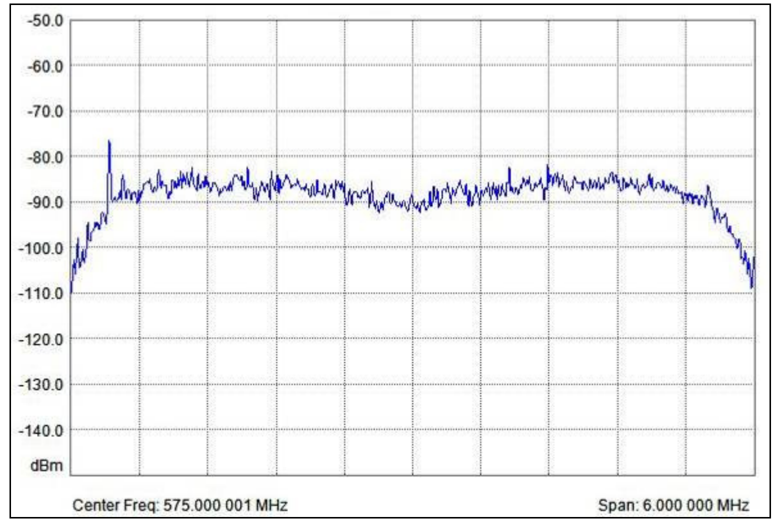
Frequency Assignment	BR1	BA1	BR2	BR3	BA2	LR	DR	K	FR	BA3
23	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
29	-77.9	-79.2	-68.1	-66.4	-67.0	-74.5	-75.9	-70.6	-75.6	-80.4
31	-68.2	-72.4	-67.6	-67.4	-62.0	-78.1	-70.0	-63.0	-71.4	-74.2
32	-67.1	-70.6	-78.2	-83.2	-62.7	-83.3	-70.5	-67.6	-75.5	-74.4
35	-68.4	-84.8	-72.7	-66.7	-64.6	-79.4	-73.7	-71.2	-70.2	-76.6
36	-67.6	-79.5	-69.4	-62.0	-61.5	-82.1	-74.9	-89.2	-76.0	-74.1
38	-68.0	-81.1	-68.1	-58.0	-69.3	-68.6	-74.4	-62.1	-65.3	-70.5
39	-84.2	-89.8	-83.1	-78.7	-88.3	-85.1	-92.6	-74.6	-86.2	-90.1
41	-79.9	-85.5	-80.5	-73.2	-76.3	-85.7	-80.5	-77.7	-87.6	-86.7
42	-78.0	-89.7	-81.0	-73.8	-76.6	-90.8	-82.1	-74.4	-79.6	-83.6
43	-78.2	-81.7	-76.3	-70.5	-70.2	-83.7	-76.5	-72.3	-78.3	-75.2
47	-78.2	-83.9	-82.1	-71.9	-78.0	-82.4	-76.2	-77.8	-81.4	-81.4
48	-74.6	-77.2	-78.7	-64.7	-73.8	-79.8	-77.9	-77.0	-78.7	-72.0
49	-79.8	-77.7	-77.8	-66.7	-83.3	-80.1	-74.2	-75.4	-78.4	-76.2
51	-82.3	-83.6	-85.4	-74.3	-80.3	-86.7	-83.0	-79.2	-85.9	-80.3
53	-87.6	-88.8	-84.8	-71.9	-77.5	-83.1	-80.9	-79.7	-84.7	-80.1
59	-81.5	-85.9	-79.9	-65.8	-76.3	-81.2	-80.9	-70.2	-75.0	-78.2
60	-79.3	-75.7	-76.0	-74.4	-79.8	-73.8	-79.1	-69.6	-81.0	-75.5
61	-80.1	-77.4	-81.9	-68.9	-73.1	-78.7	-82.8	-77.9	-89.3	-77.4
65	-73.3	-78.4	-78.0	-68.7	-76.0	-75.6	-70.0	-73.0	-70.1	-75.3
66	-84.2	-88.1	-85.4	-82.3	-83.2	-93.3	-91.6	-86.3	-87.4	-89.5
68	-77.7	-70.0	-77.1	-70.0	-78.9	-76.6	-75.5	-74.1	-72.2	-81.7



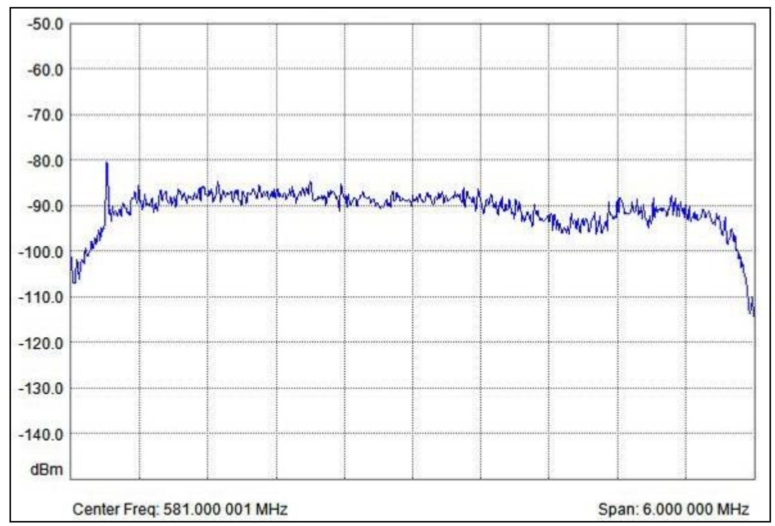
• **Figure 67 – Residence 2, Channel 23**



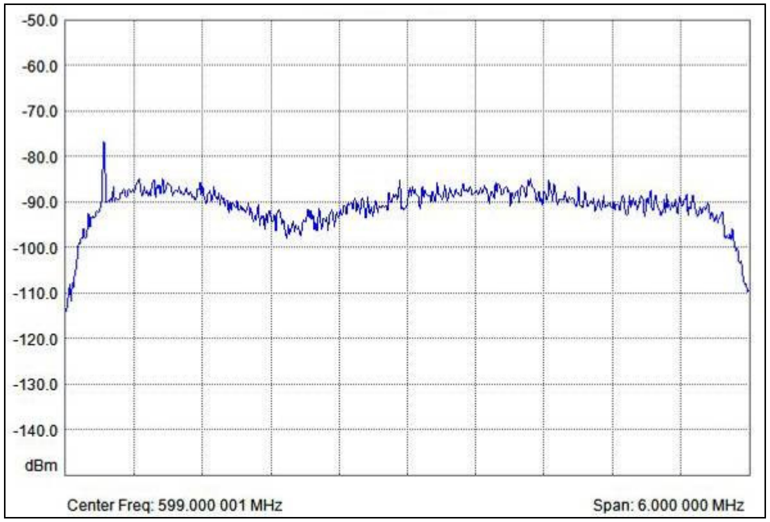
• **Figure 68 – Residence 2, Channel 29**



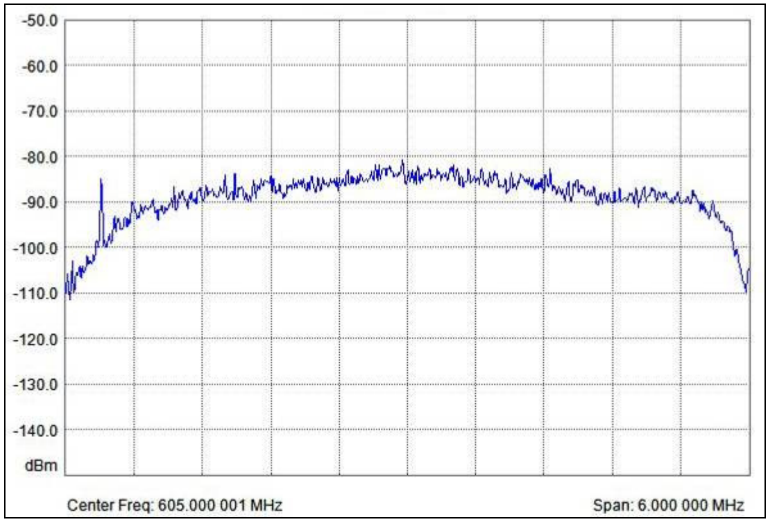
• **Figure 69 – Residence 2, Channel 31**



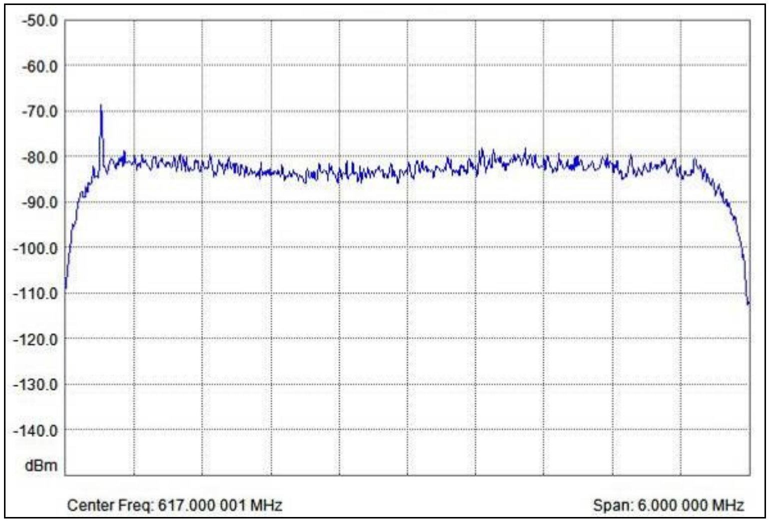
• **Figure 70 – Residence 2, Channel 32**



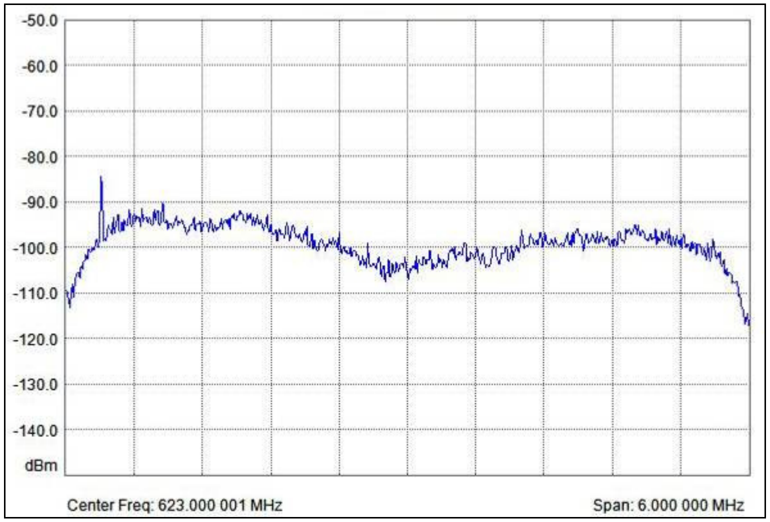
• **Figure 71 – Residence 2, Channel 35**



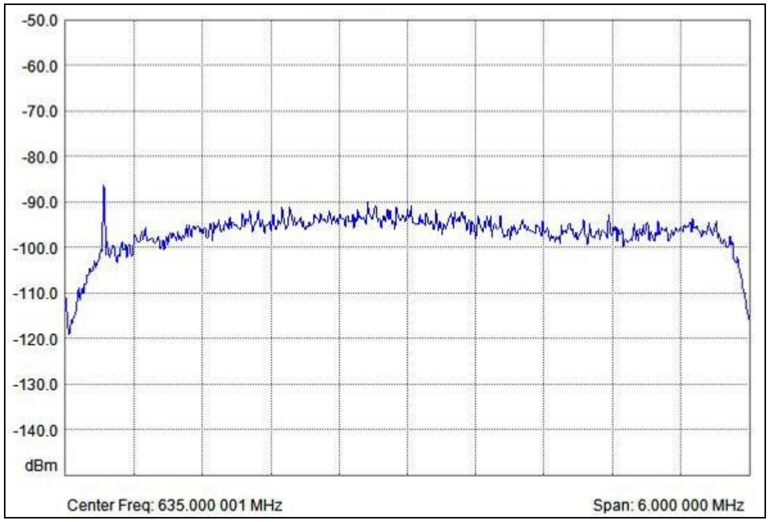
• **Figure 72 – Residence 2, Channel 36**



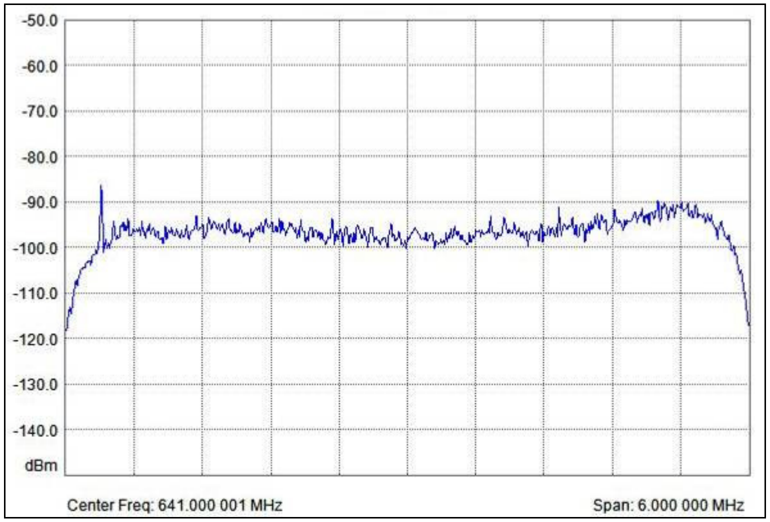
• **Figure 73 – Residence 2, Channel 38**



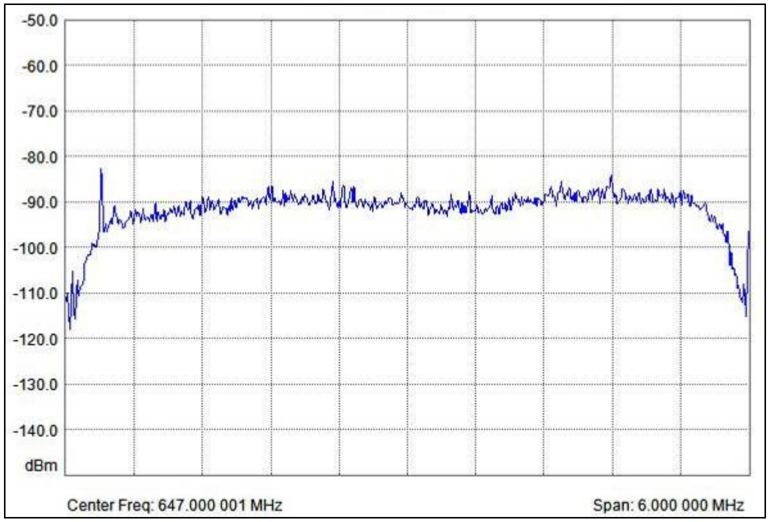
• **Figure 74 – Residence 2, Channel 39**



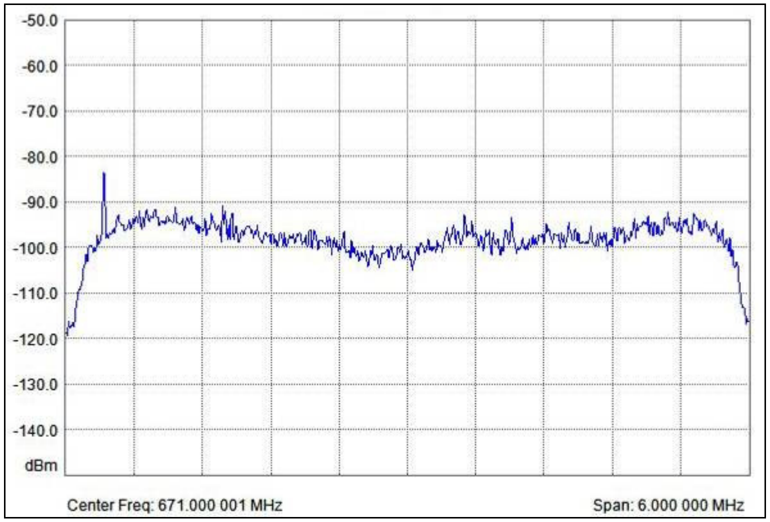
• **Figure 75 – Residence 2, Channel 41**



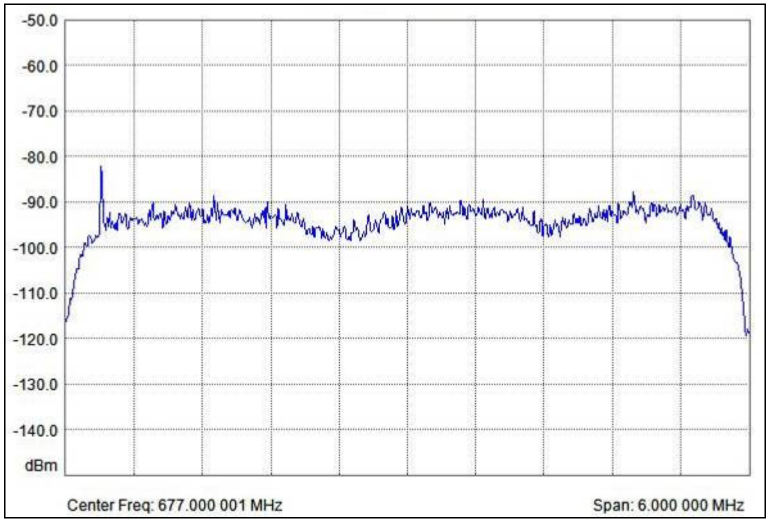
• **Figure 76 – Residence 2, Channel 42**



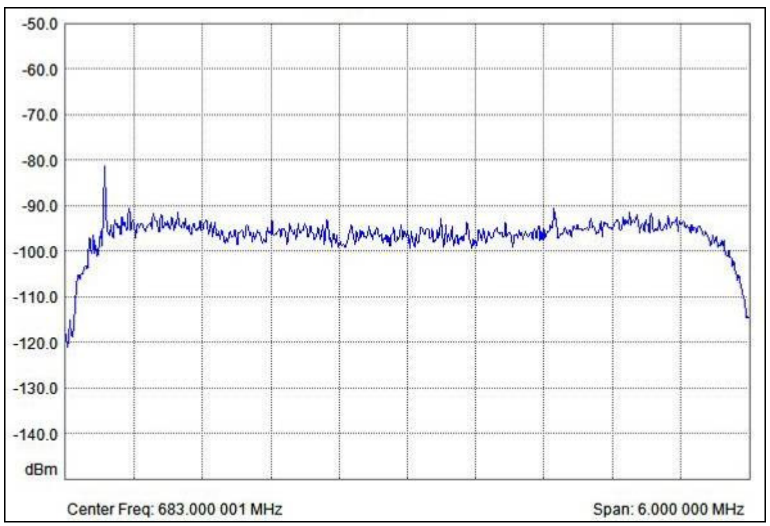
• **Figure 77 – Residence 2, Channel 43**



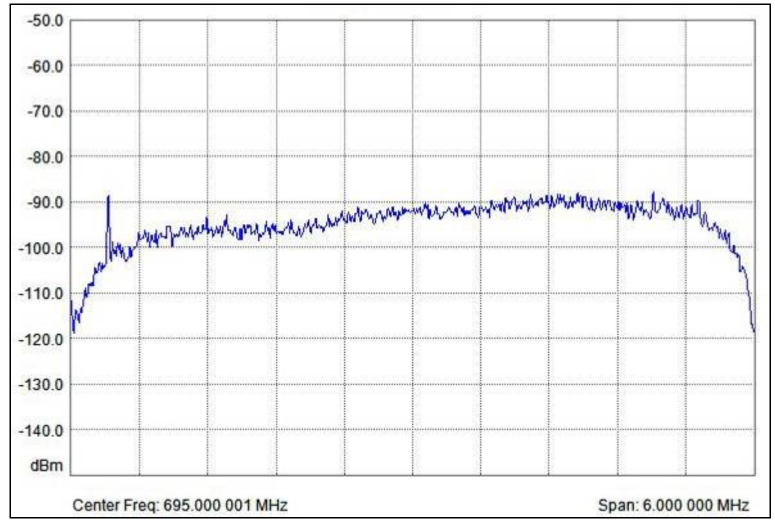
• **Figure 78 – Residence 2, Channel 47**



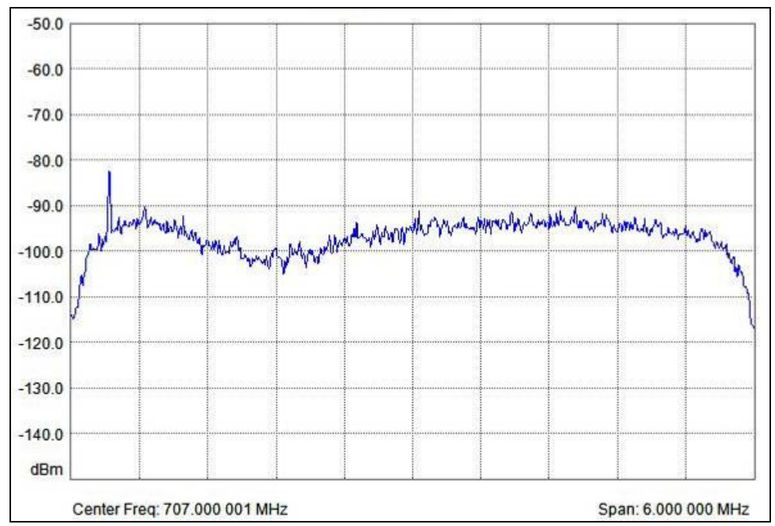
• **Figure 79 – Residence 2, Channel 48**



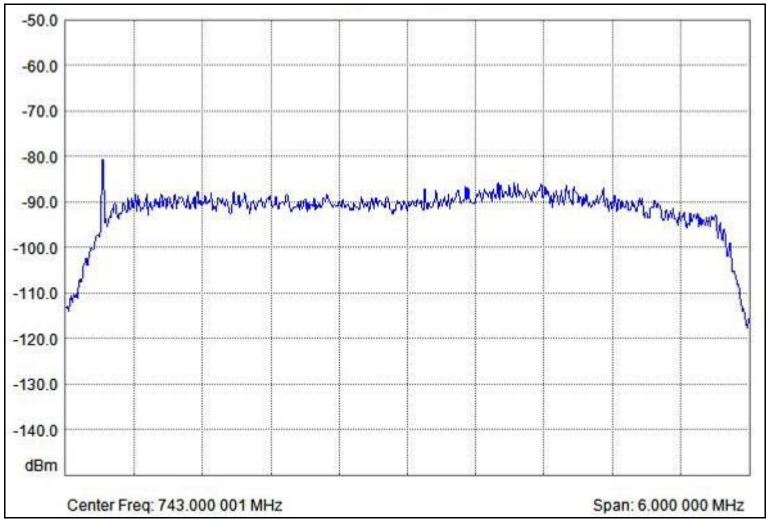
• **Figure 80 – Residence 2, Channel 49**



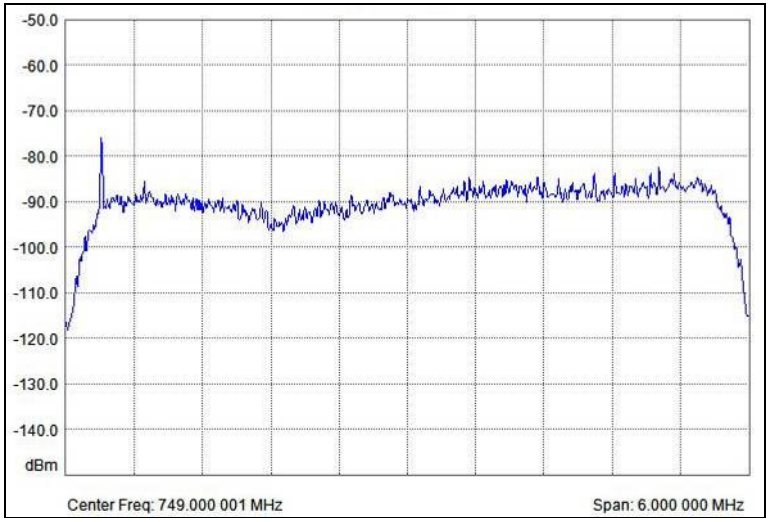
• **Figure 81 – Residence 2, Channel 51**



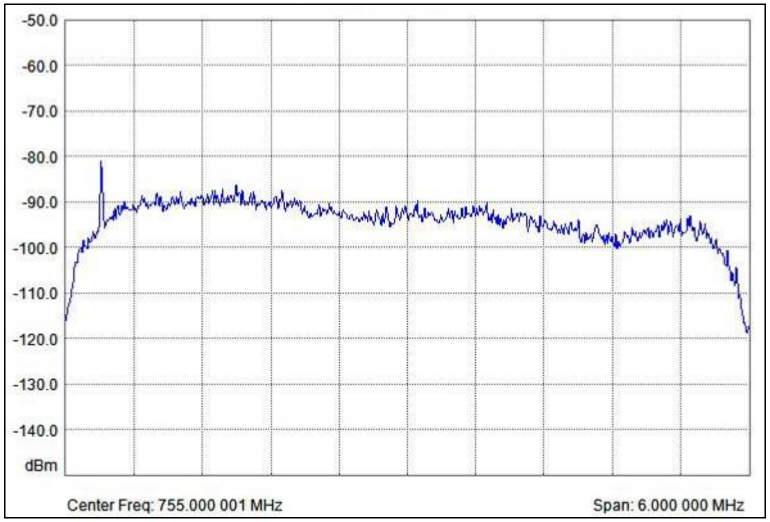
• **Figure 82 – Residence 2, Channel 53**



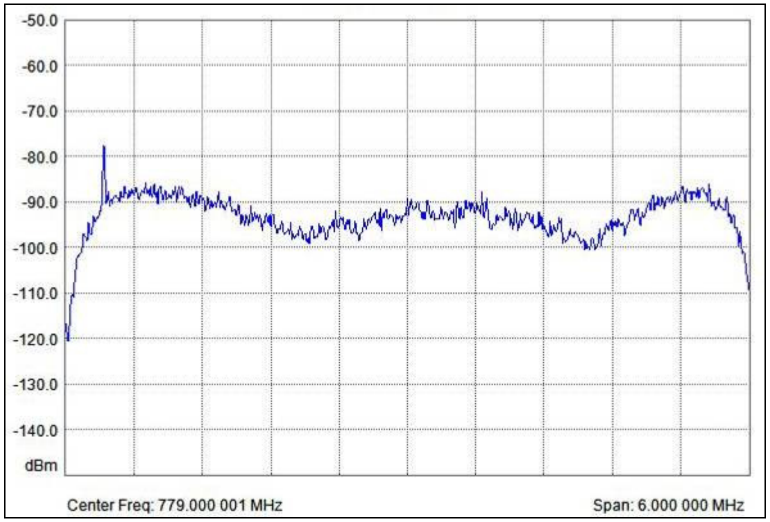
• **Figure 83 – Residence 2, Channel 59**



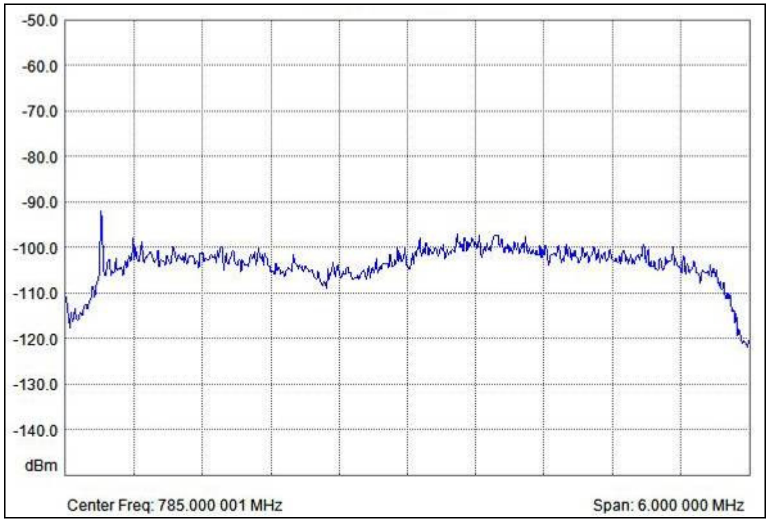
• **Figure 84 – Residence 2, Channel 60**



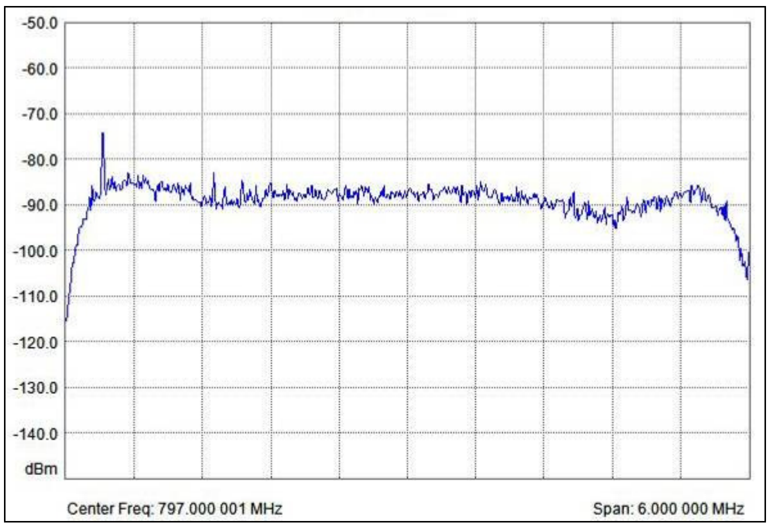
• **Figure 85 – Residence 2, Channel 61**



• **Figure 86 – Residence 2, Channel 65**



• **Figure 87 – Residence 2, Channel 66**

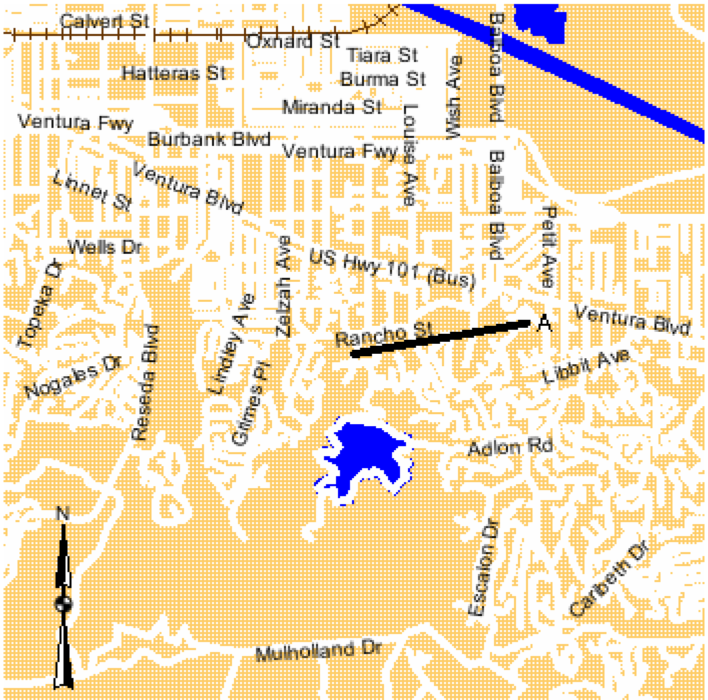


• **Figure 88 – Residence 2, Channel 68**

5.3 RESIDENCE 3

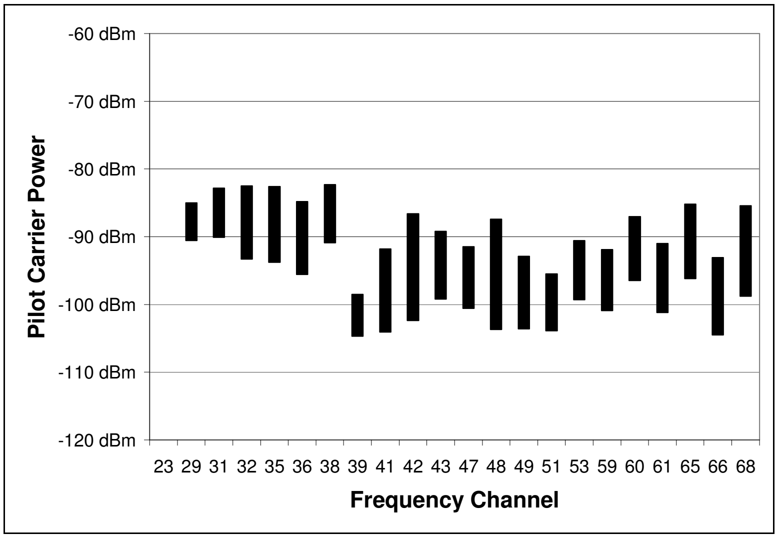
Residence 3 is an one-story, 3-bedroom, 4-bath, 3,767 square foot single family house built in 1959. The house is shown in Figure 89. The DTV transmitters are located approximately 26 miles away at a compass heading of 63°. Residence 3 is at the center of Figure 64. The line "A" shows the direction of the transmitters.

• Figure 89 – Residence 3

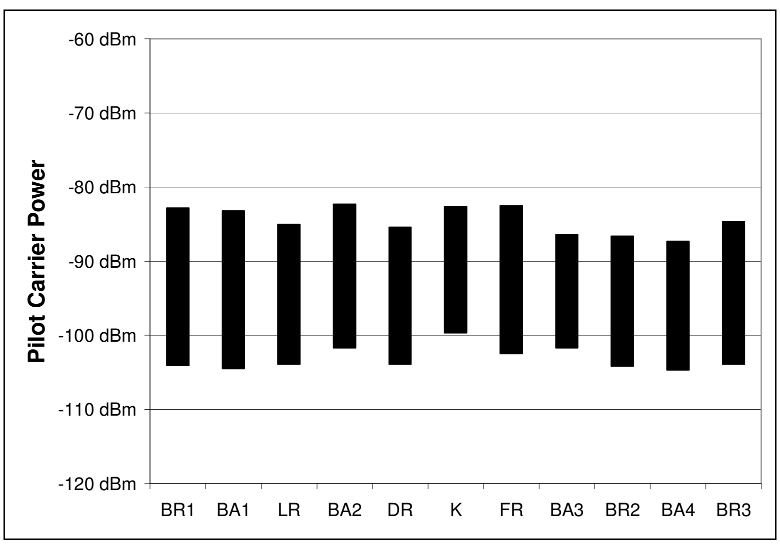


• Figure 90 – Residence 3 Location

The raw pilot carrier power measurements are shown in Table 16. They range from -104.7 dBm to -82.3 dBm. Figure 91 shows the variation by frequency channel and Figure 92 shows the variation by room. The average variation across rooms for a given frequency channel was 10.3 dB. The DTV signal spectrums captured in residence 1 are shown in Figure 93 through Figure 114. Many of the figures show the frequency selective fading characteristic of the WSSUS channels simulation results presented in Section 4.2.



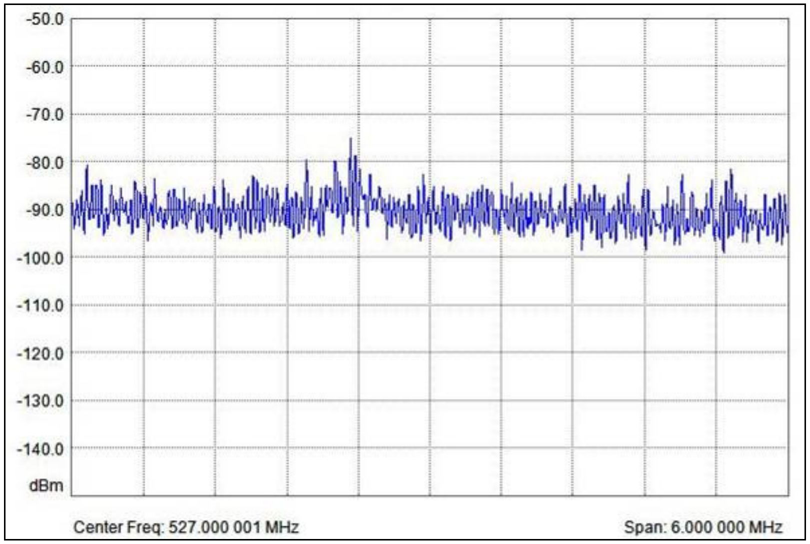
• **Figure 91 – Residence 3 Pilot Carrier Power Variation By Frequency Channel**



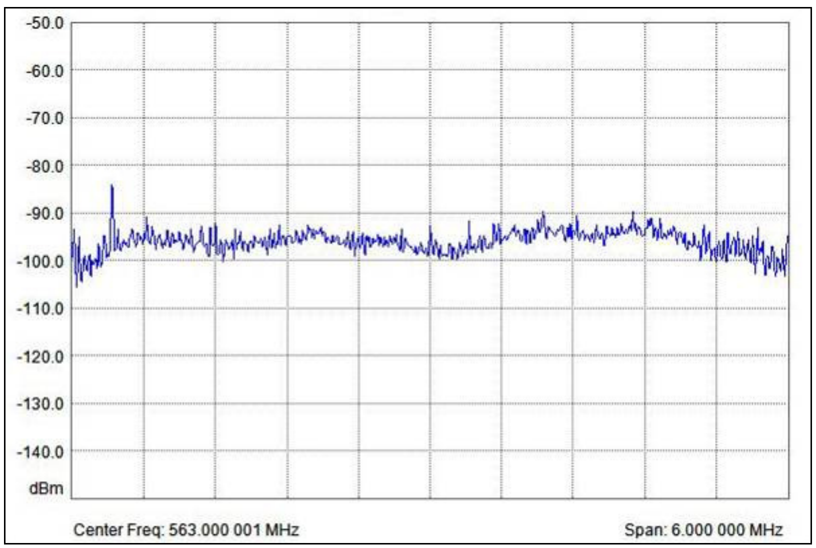
• **Figure 92 – Residence 3 Pilot Carrier Power Variation By Room**

• **Table 16 – Residence 3 Raw Pilot Carrier Power Measurements (dBm)**

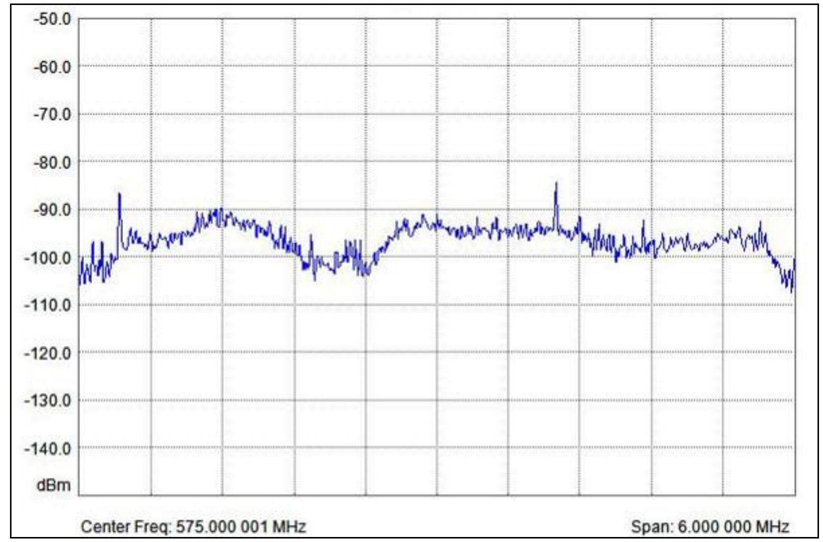
Frequency Assignment	BR1	BA1	LR	BA2	DR	K	FR	BA3	BR2	BA4	BR3
527	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
563	-86.6	-90.6	-85.0	-87.5	-85.4	-85.7	-85.5	-88.7	-86.6	-87.5	-86.0
575	-82.8	-88.5	-85.1	-85.2	-87.3	-83.2	-87.4	-88.3	-90.1	-88.0	-85.2
581	-84.4	-83.2	-86.3	-87.1	-91.3	-85.6	-82.5	-89.3	-90.6	-93.3	-84.8
599	-84.5	-93.8	-90.2	-87.3	-87.1	-82.6	-93.2	-88.7	-90.5	-91.0	-84.6
605	-86.9	-95.6	-87.4	-93.1	-90.8	-86.1	-84.8	-86.4	-89.8	-87.9	-94.0
617	-90.6	-90.0	-90.4	-82.3	-86.5	-88.3	-86.9	-90.9	-89.3	-87.3	-86.5
623	-102.1	-100.1	-102.0	-101.5	-103.0	-99.0	-102.1	-101.7	-98.5	-104.7	-101.3
635	-104.1	-96.2	-99.6	-98.7	-100.3	-99.7	-98.5	-91.8	-102.9	-100.7	-93.5
641	-98.6	-100.3	-101.4	-96.0	-101.5	-86.6	-101.8	-95.9	-99.6	-102.4	-100.2
647	-92.3	-97.1	-99.2	-90.8	-95.2	-89.2	-98.4	-93.1	-94.2	-96.0	-97.1
671	-95.8	-100.6	-95.0	-98.5	-99.6	-91.5	-97.4	-94.4	-96.9	-99.7	-95.6
677	-87.4	-103.7	-92.7	-94.6	-93.2	-98.3	-97.2	-98.1	-100.6	-95.6	-95.8
683	-99.5	-101.7	-97.3	-92.9	-95.3	-96.0	-95.6	-101.3	-95.4	-99.1	-103.6
695	-98.4	-95.5	-98.2	-96.8	-101.5	-98.4	-102.5	-99.7	-95.7	-96.8	-103.9
707	-96.9	-98.6	-98.6	-98.1	-93.9	-90.6	-96.4	-98.2	-99.3	-96.4	-92.0
743	-94.4	-100.4	-98.6	-91.9	-98.4	-92.9	-100.9	-99.7	-95.5	-99.7	-94.3
749	-93.3	-87.0	-96.5	-92.6	-93.2	-91.2	-94.9	-89.6	-96.4	-93.8	-95.5
755	-101.2	-97.4	-97.8	-97.3	-97.0	-92.4	-99.0	-91.0	-99.4	-100.3	-99.2
779	-92.2	-96.2	-91.5	-92.4	-85.8	-85.2	-90.6	-90.6	-92.1	-94.2	-92.1
785	-103.7	-104.5	-103.9	-101.7	-103.9	-93.1	-99.9	-99.1	-104.2	-102.7	-103.3
797	-94.0	-90.4	-93.0	-93.3	-93.6	-85.4	-95.8	-94.3	-93.3	-93.6	-98.8



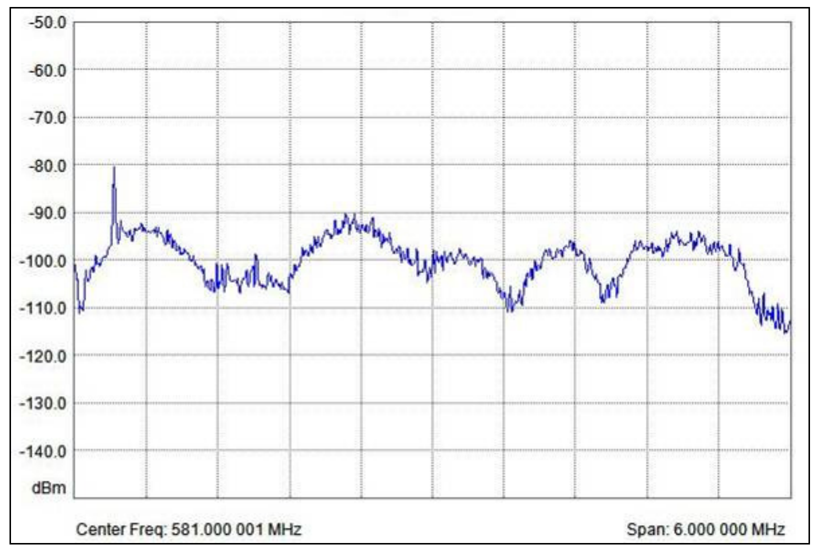
• **Figure 93 – Residence 3, Channel 23**



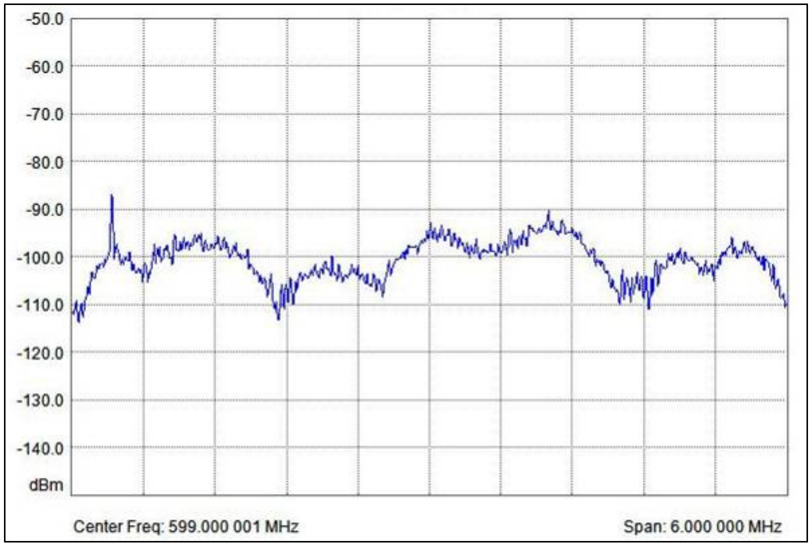
• **Figure 94 – Residence 3, Channel 29**



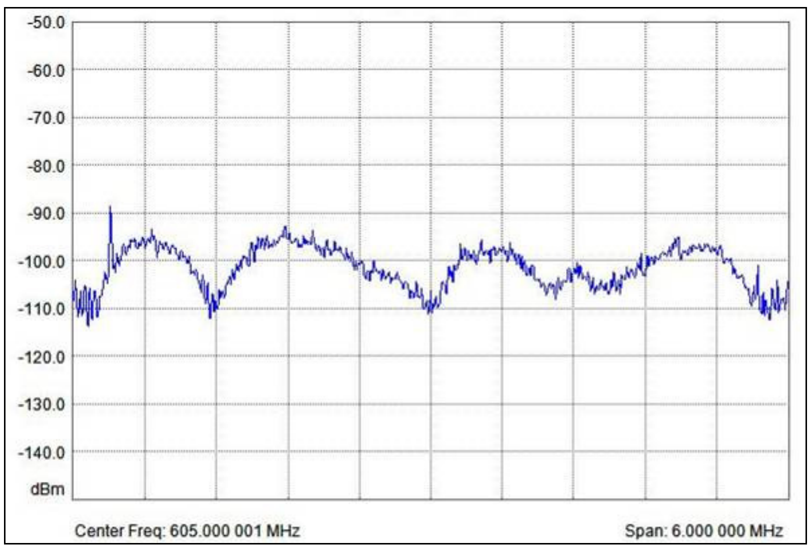
• **Figure 95 – Residence 3, Channel 31**



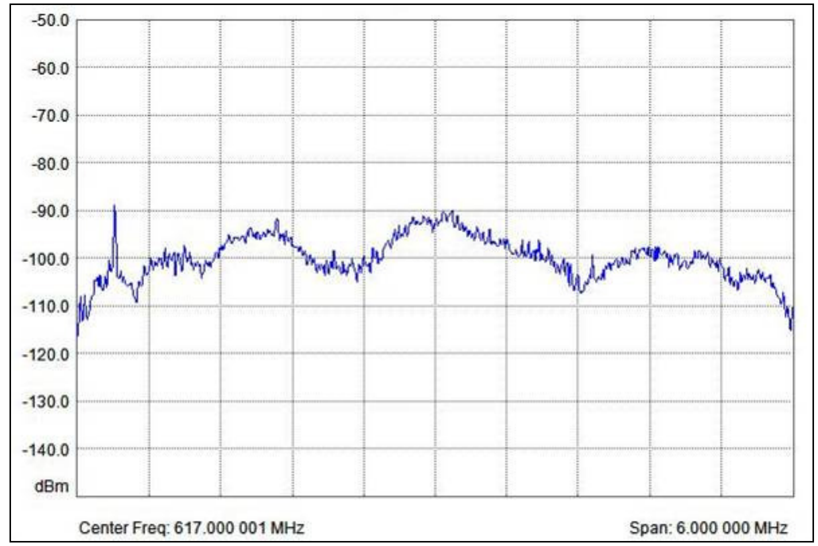
• **Figure 96 – Residence 3, Channel 32**



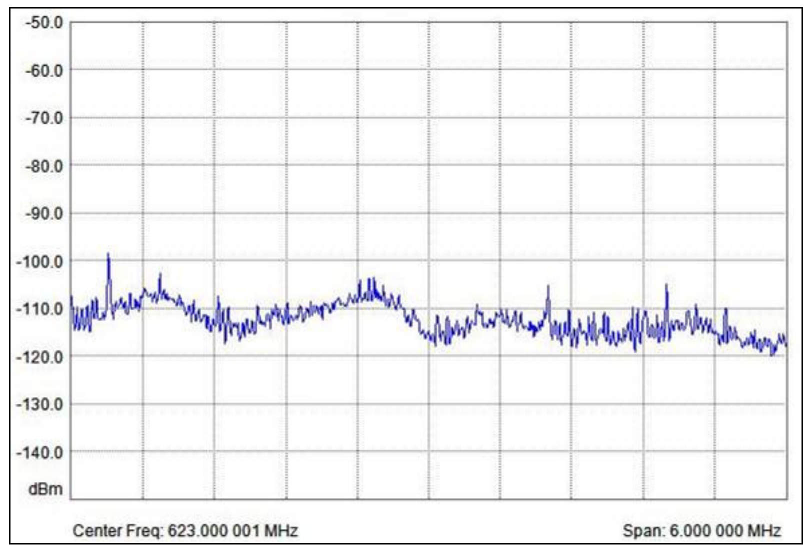
• **Figure 97 – Residence 3, Channel 35**



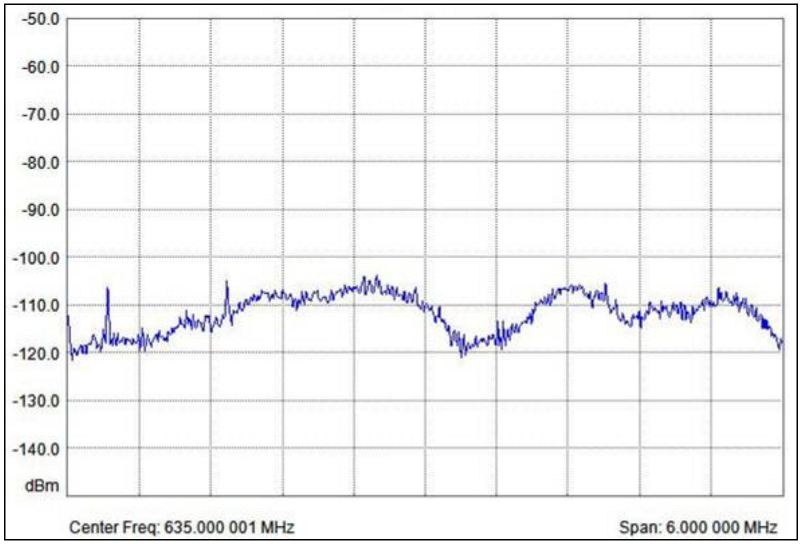
• **Figure 98 – Residence 3, Channel 36**



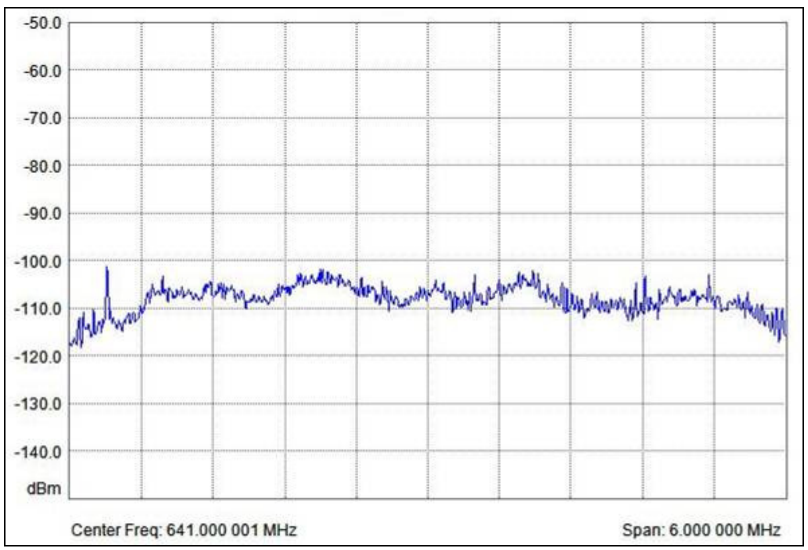
• **Figure 99 – Residence 3, Channel 38**



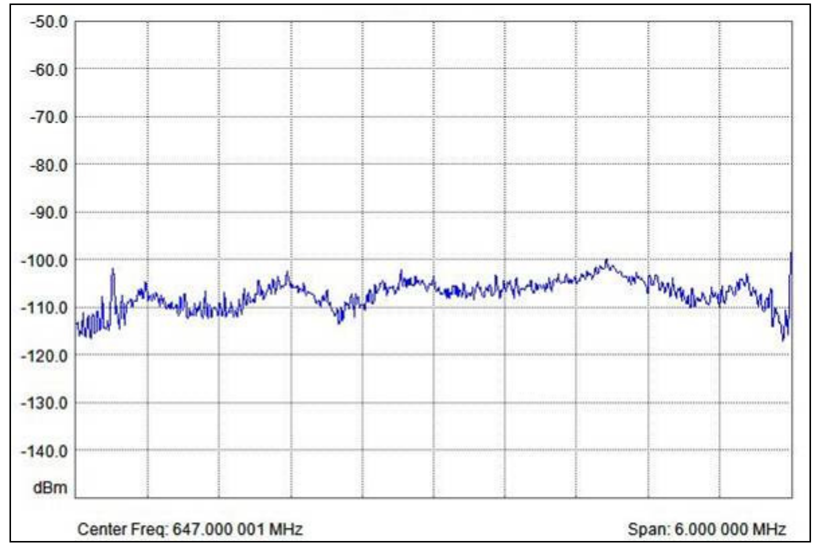
• **Figure 100 – Residence 3, Channel 39**



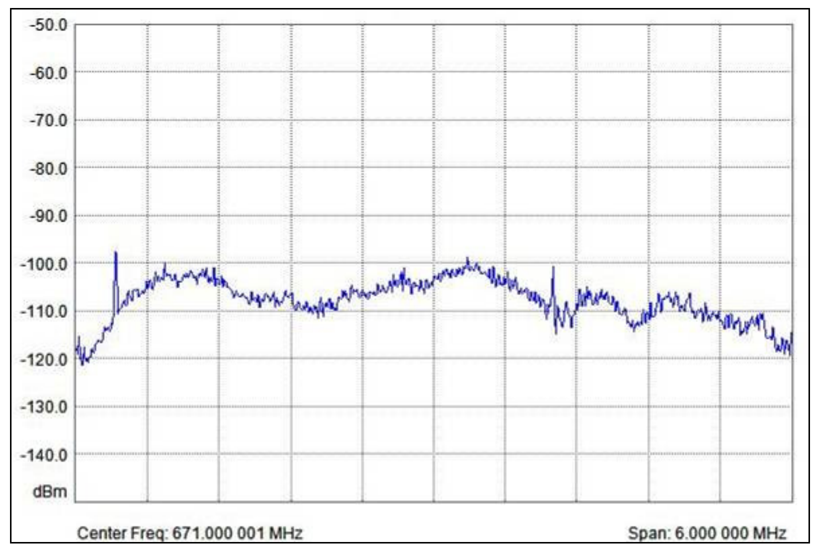
• **Figure 101 – Residence 3, Channel41**



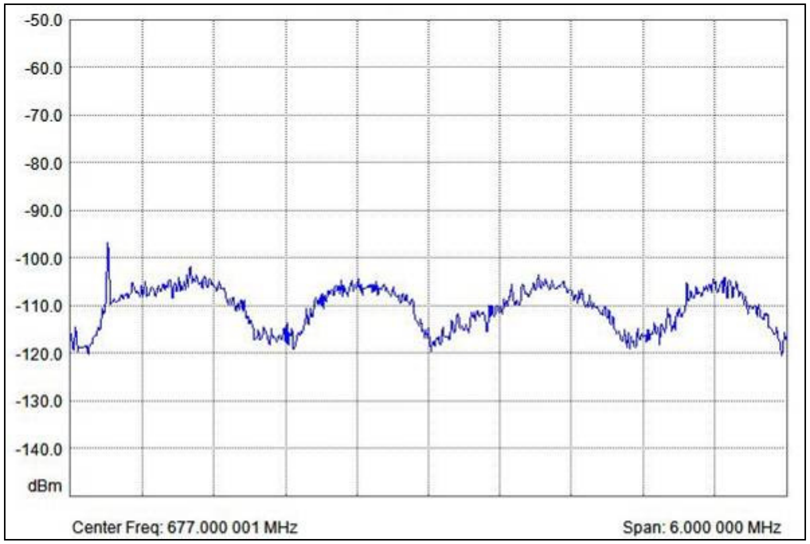
• **Figure 102 – Residence 3, Channel 42**



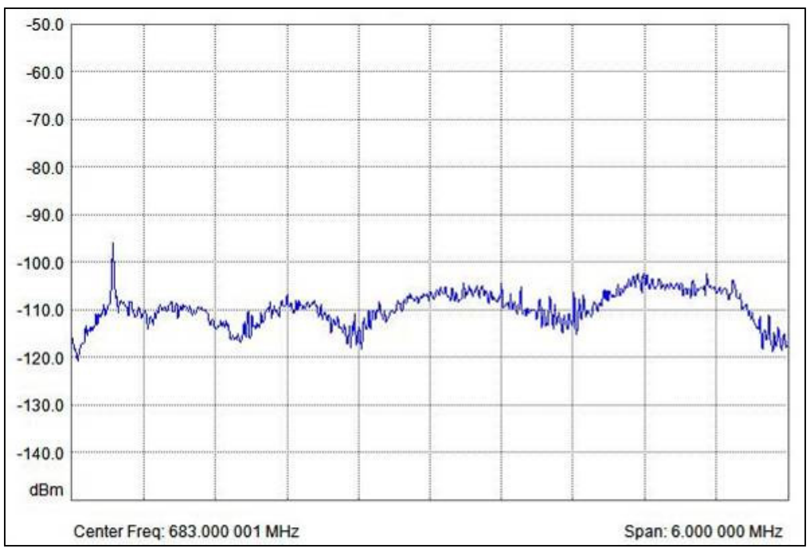
• **Figure 103 – Residence 3, Channel 43**



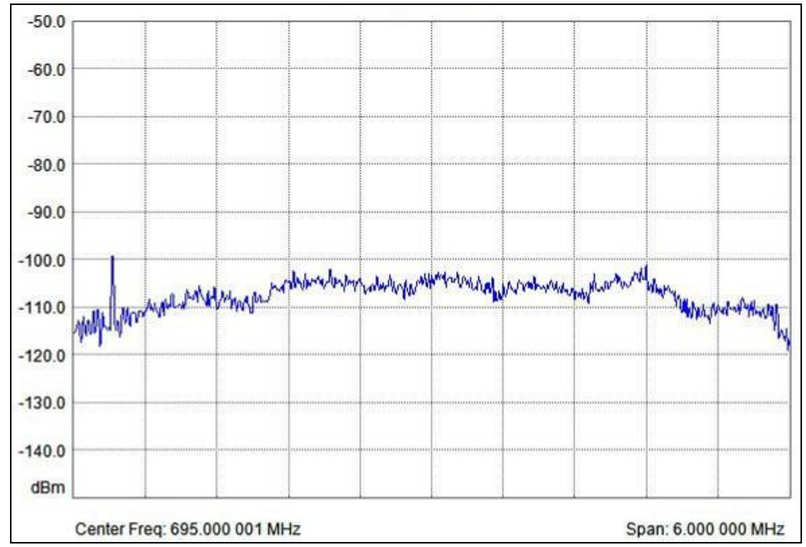
• **Figure 104 – Residence 3, Channel 47**



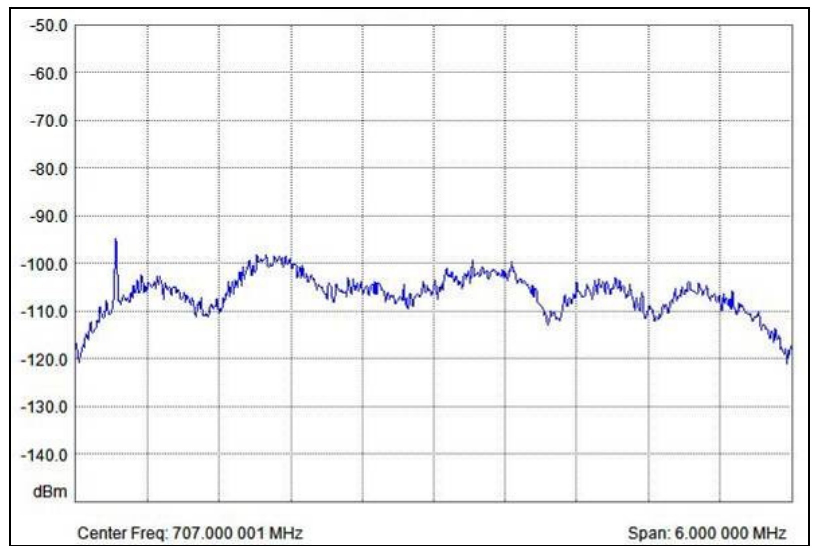
• **Figure 105 – Residence 3, Channel 48**



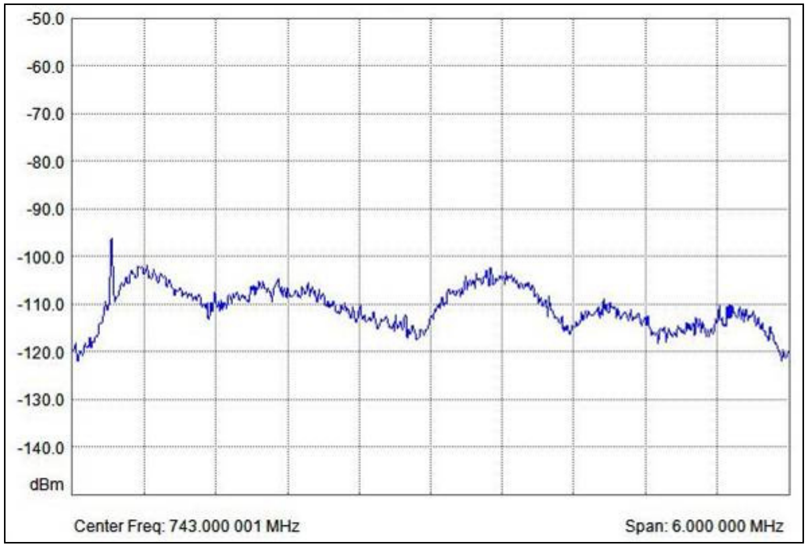
• **Figure 106 – Residence 3, Channel 49**



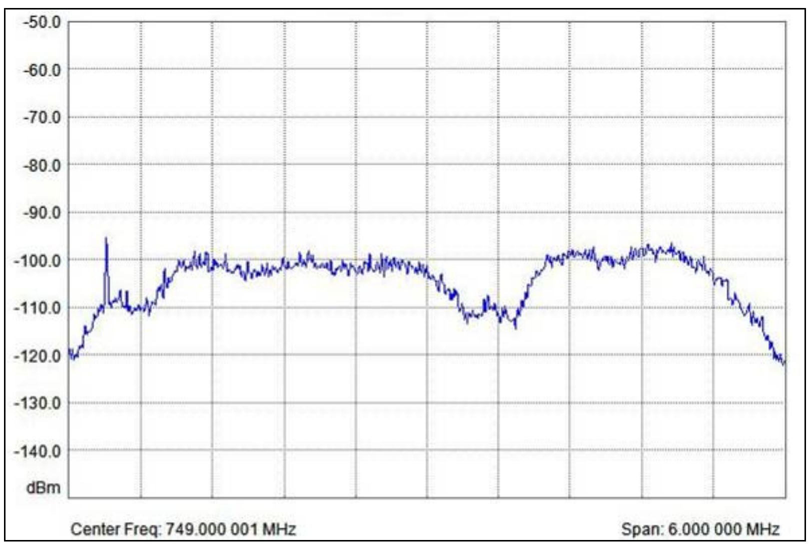
• **Figure 107 – Residence 3, Channel 51**



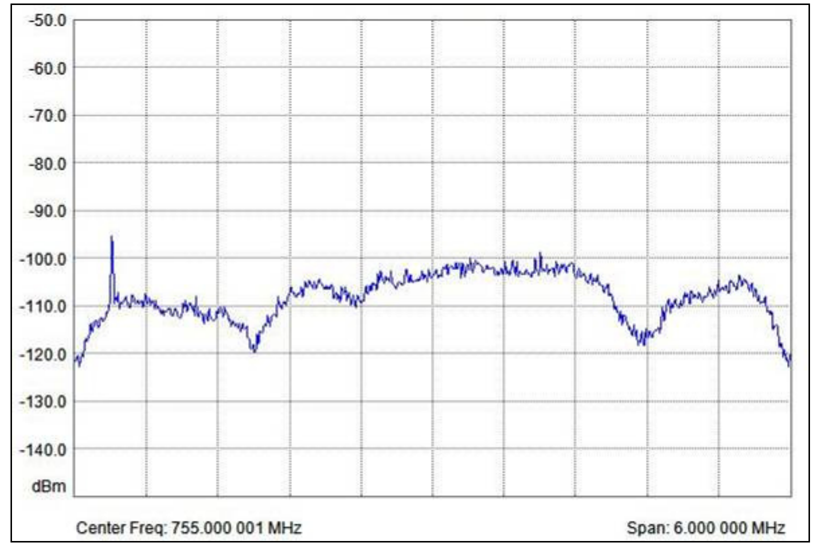
• **Figure 108 – Residence 3, Channel 53**



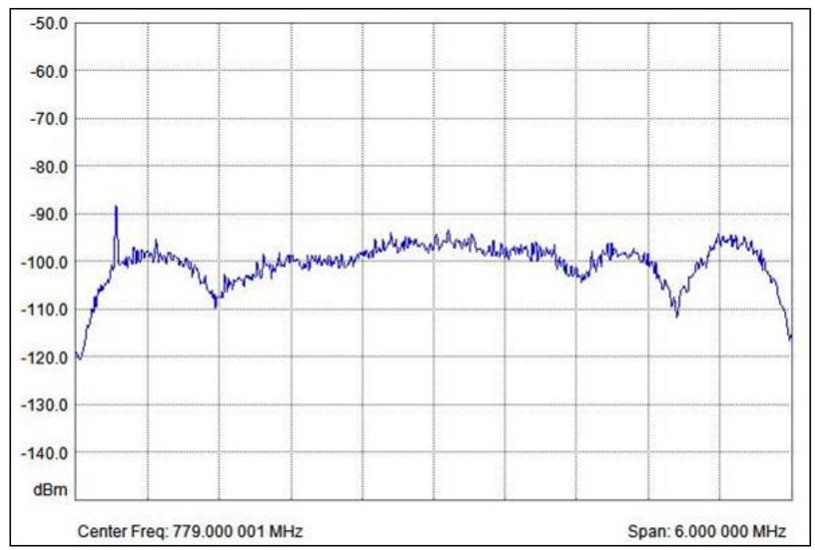
• **Figure 109 – Residence 3, Channel 59**



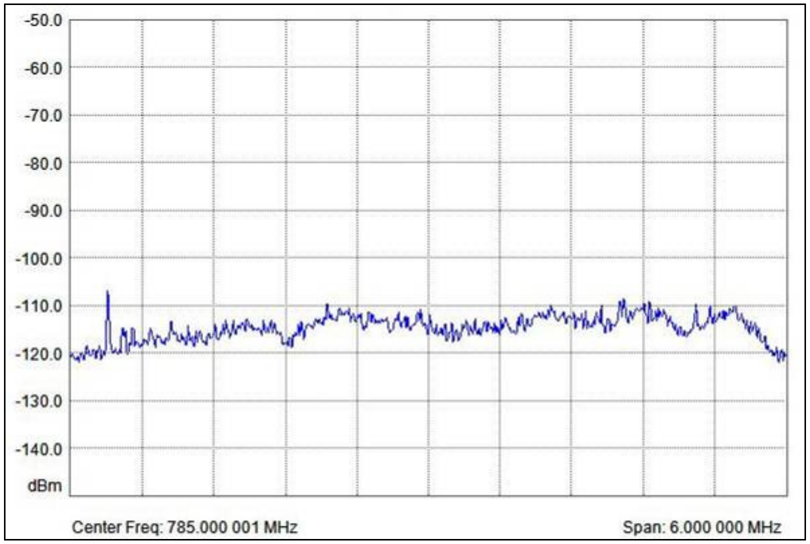
• **Figure 110 – Residence 3, Channel 60**



• **Figure 111 – Residence 3, Channel 61**

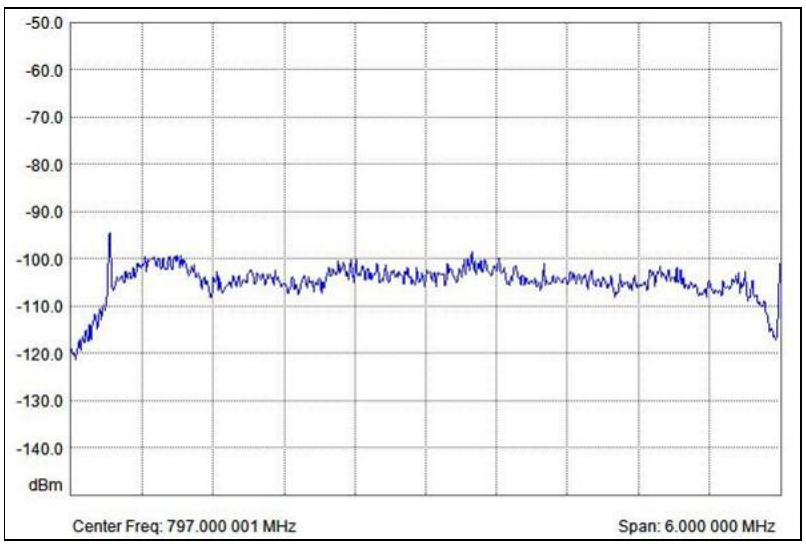


• **Figure 112 – Residence 3, Channel 63**



• **Figure 113 – Residence 3, Channel 66**

• **Figure 114 – Residence 3, Channel 68**



Engineering Credentials

This technical report has been prepared by Mark A. Sturza and Dr. Farzad Ghazvinian. Between them, they have over 60 years experience in the design, development, analysis, and regulation of communications systems.

MARK A. STURZA

Mark Sturza provides consulting expertise in the design, development, analysis, and regulation of communications systems. Areas of specialization include: satellite communication systems, microwave radio systems, radio navigation systems, spread spectrum systems, and international and domestic regulatory support.

Mark has been a member of the founding technical teams of several venture companies, including TrueSpan's digital video broadcast receiver chipsets, Menache's RF motion capture system, Teledesic's broadband LEO satellite system, PlatinumIP's communications system IP, Leo One's NVNG mobile satellite system, and Angel Technology's HALO platform. He has also been a key contributor to NAVSYS Corporation's GPS products, and SiRF Technology's GPS and wireless chipsets. For the past seventeen years, he has been President of 3C Systems Company, which he founded to provide consulting expertise in the design, development, analysis, and regulation of communications systems.

Mark's prior industry experience includes senior engineering management and technical positions at Teledyne, Magnavox, and Litton, where he worked on advanced projects for guidance systems and GPS. Mark was a member of the Board of Directors of NAVSYS Corporation, of PlatinumIP Corporation, and of Social Fabric Corporation. He holds twenty one patents in communications system design, with several additional patents pending, and has presented over 30 technical papers.

Mark has a BS in Applied Mathematics from the California Institute of Technology, a MSEE from the University of Southern California, and a MBA from Pepperdine University. He is a Senior Member of the American Institute of Aeronautics and Astronautics, a Member of the IEEE, and holds memberships in the Institute of Navigation, the Pacific Telecommunications Council, the Association for Computing Machinery, the Society of Motion Picture and Television Engineers, and the American Mathematical Society. Mark holds a General Radiotelephone Operator License.

DR. FARZAD GHAZVINIAN

Dr. Ghazvinian provides consulting services in the analysis, design, and development of communication systems as well as telecommunication regulations. Areas of interest include: wireless communication, WiMax systems, satellite communication systems, and advanced mobile technologies.

Dr. Ghazvinian has been part of several venture companies, including Teledesic broadband satellite system, Multivision Media Monitoring, and Avalist Peer-to-Peer engine. For the last four years, he has been President of TRT group, which he founded to provide consulting expertise in the design, development, analysis, and regulation of communications systems.

Dr. Ghazvinian has held many senior management and technical positions. Most recently he was Senior Vice President and CTO of Teledesic where he had overall responsibility for the technical definition, development and deployment of the Teledesic Network. As a member of the founding Teledesic team, he was involved in all aspects of the company's growth and evolution including formulation and execution of the business plan and international regulatory strategy.

Prior to Teledesic, Dr. Ghazvinian was Vice President of Communications Systems at LinCom Corporation, a provider of proprietary engineering analysis of state-of-the-art communications protocols and systems. While at

LinCom, he founded the wireless business division and provided engineering services in support of several commercial and NASA communication systems.

Dr. Ghazvinian graduated with honors in electrical engineering from the Imperial College of London, holds a master's degree in electrical engineering from the University of California at Los Angeles, and received a doctorate in electrical engineering from the University of Southern California. He is the author of numerous technical papers and holds four patents.