Determination of Detection Thresholds to Allow Safe Operation of Television Band "White Space" Devices

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Abstract—The purpose of this study is to determine a range of detection thresholds at which new dynamic spectrum access (DSA) devices can safely operate in unoccupied spectrum allocated to terrestrial television (TV) broadcasting and other services (i.e., the TV "white spaces"), without causing harmful interference to other authorized operations, which include digital and analog TV stations, wireless microphones and other services. Spectrum sensing data were collected at six different locations in Northern Virginia that were strategically chosen because they were within, outside and near the edges of the predicted service contours of digital TV stations serving the Washington, D.C. and Baltimore, MD metropolitan areas.

We used a pair of DSA devices that jointly decide if a channel can be used or not. This emulates how SSC's and other DSA devices operate. The joint decision logic mitigates the propagation shadowing and hidden node problem. The separation between the DSA devices was less than approximately 10 km, which corresponds to the link range of a 10 W 802.16-based transmitter.

The DSA detectors used a high sensitivity detector that is able to detect the ATSC pilot down to a ~140 dBm level (ATSC signal power level of -128 dBm). The detector is not noise limited. "False alarms" are caused by detection of distant TV transmitters when the DSA system is located outside the Grade B contour.

Based on analysis results from data recorded from six independent locations in Northern Virginia and 13 ATSC channels, the following conclusions can be made:

1. The Listen-Before-Talk threshold-based approach is a valid dynamic spectrum access technique in the TV band when joint detection is used.
2. If the DSA system used a 10 W transmitter, then an ATSC pilot threshold of -130 dBm (-118.5 dBm ATSC power level) would provide minimal "Harm" and acceptable "False Alarm". Harm is defined is defined to be when the two DSA transceivers transmit within the ATSC service contours plus a 10 km keep out distance.
3. If the DSA system used a 100 mW transmitter, then an ATSC pilot threshold of -120 dBm (-108.5 dBm ATSC power level) would provide minimal "Harm" and acceptable "False Alarm". Harm is defined is defined to be when the two DSA transceivers transmit within the ATSC service contours plus a 10 km keep out distance.
4. The false alarm rate caused by detection of distant TV transmitters when the DSA device is located outside of the service contour is significant (20% to 40% using the above threshold values).

The proposed FCC ATSC signal power level limit is -116 dBm. The results of this study indicate that this level is to conservative for a 100 mW DSA transmit power level limit, and needs to be increased 2.5 dB for a 10 W DSA transmit power level limit.

I. Introduction

This section identifies the key technical issues under consideration by the U.S. Federal Communications Commission (FCC) with regard to the use of spectrum sensing approaches that would ensure that new radio transmitting devices sharing the television (TV) bands operate only on vacant frequencies without causing interference to broadcast television and other authorized services. We also summarize the findings of our study of the TV bands in the Washington, DC/Baltimore, MD metropolitan area.

The FCC is considering rules for permitting new radio transmitting devices to share frequency bands currently allocated to the television (TV) broadcasting service (47 CFR Part 73), auxiliary broadcasting services (47 CFR Part 74), including wireless microphones used by eligible entities, and, in some bands and cities, private and commercial land mobile radio services (47 CFR Part 90).[1] These TV "white space" devices would be authorized on frequencies that are not used by TV stations or other licensed services in each local area (i.e., in the "white spaces"). The FCC is developing technical rules to govern the safe, interference-free operation of "personal/portable" devices and "fixed/access" operations on a licensed or unlicensed basis. The FCC has also been testing white space devices and TV receivers. [2-reference FCC Lab report 1]

An important technical problem facing the FCC is how to ensure that TV white space devices operate only on vacant TV band frequencies without causing interference to broadcast television and other authorized services. One of several methods being studied is for the new dynamic spectrum access (DSA) devices to employ a "detect and avoid" or "listen before talk" strategy by which each device would utilize spectrum sensing techniques for detection of signals of TV stations, wireless microphones and other authorized transmitters. This would require each new device to have a spectrum scanning and sensing capability through which it would be able to process detected signals and determine which TV channels are occupied and which are vacant. Those channels deemed to be vacant could then be utilized by the white space device consistent with the regulatory restrictions on transmissions in such frequencies. The FCC also suggested by in its 2006 FNPRM [1] that a sensing approach could potentially be enhanced with geo-location via an embedded GPS receiver, database look-up, distributed sensing, and/or beacon identification techniques.

The FCC sought comment on whether and how to establish a detection threshold, which it defined as "the sensitivity level that would be used to determine the presence of other signals." In particular, it asked whether such sensing capability should be able to detect signals as low as -116 dBm. It noted that the presence of signals above the threshold detection level would not necessarily exclude access to the spectrum, but would be a "gating factor" that is then followed by further processing to determine whether the spectrum can or cannot be used.

The FCC's FNPRM identified certain factors and considerations that must be taken into account in establishing an appropriate detection threshold including (1) the ability to detect and protect weak signals, (2) avoiding being too sensitive to render the white spaces useless, and (3) concerns about detecting "hidden nodes." First, it is expected, that a DSA device operating in the TV band would likely be in close proximity to a TV receiver (*i.e.*, in the same or adjacent residence or business) and both would be relatively far from the TV transmitter. In this scenario, the TV receiver would be attempting to receive a relatively weak TV signal in the presence of a relatively strong signal from the DSA device. The height of the white space device's transmitting antenna also affects the potential interference distance.

Second, the FCC stated that the increased potential for "false positives" or "false alarms" must be taken into account in cases where a detection threshold that is too low results in increased false positives in response to detecting spurious radio noise or other white space devices, sharply reducing the usefulness of this spectrum for such devices.

Third, the FCC was concerned about relying solely on a detection threshold as the gating criteria for access to the white spaces spectrum and whether this approach, by itself, would be effective in preventing harmful interference to TV stations within their protected contours (and to other authorized services) due to the problem of the "hidden node" (*i.e.*, where an obstruction between the sensing receiver and the signal to be detected causes a failed detection of an occupied channel). As an alternative to decreasing the detection threshold, which would increase the possibility of false detections and result in other detrimental effects on the DSA device cost and performance, the FCC, citing Shared Spectrum Company's (SSC) reply comments, suggested the use of distributed sensing. [FNPRM at 39 and n. 52 citing SSC reply comments]. Distributed sensing or "group behavior" approaches utilize multiple antennas and sensing receivers at different locations that share channel availability information with each other. [SSC Reply Comments] As the FCC noted, "when multiple receivers that share information are used, the probability of missing a signal may be greatly reduced because only one receiver needs to detect a signal to ascertain that a particular channel is occupied, and the likelihood would seem low that every receiver in a system would be obstructed from receiving a signal." [1] Another approach suggested in the FNPRM to addressing hidden node issues would be to use sensing in combination with other information, such as geo-location, under a set of policy rules that would serve as the gating criteria for access to the spectrum.

II. Equipment Description

This section describes the equipment used in the tests.

A. RF Chain Description

Fig. 1 shows the sensor equipment used an each of the pair of collection sites. An omni-directional discone antenna was used to receive ambient signals at each sensor location. The antenna had a height of 1.5 meters indoors and 2.87 meters outdoors.

A pre-selector was used to maintain a low noise figure while rejecting strong out of band signals. The pre-selector block diagram is given in Fig. 2. The pre-selector allowed remote automated selection of antennas, filters, amplifiers and attenuators. Only the upper pre-selector portion with a single antenna was used in these measurements (30 MHz to 1 GHz).

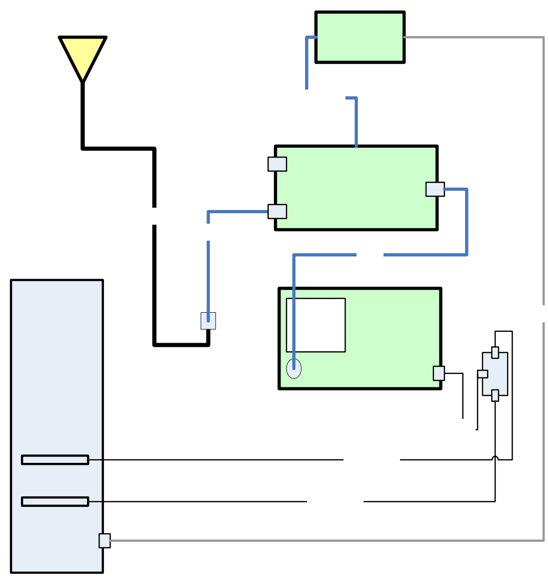

Figure 1. Signal Collection Equipment Block Diagram

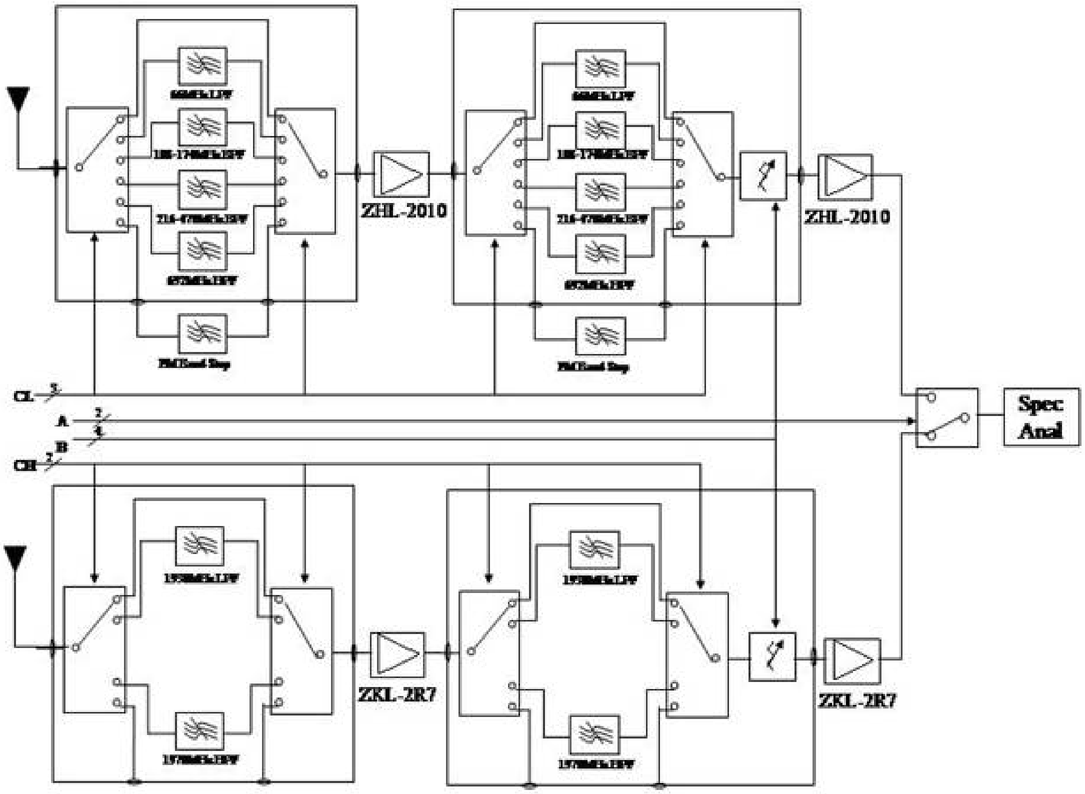

Figure 2. Pre-Selector Diagram

The signal is then fed into a Rhode & Schwarz spectrum analyzer, followed by a sampler and an embedded processor. RF from the antenna is converted to an intermediate frequency and then digitized and saved to a file. The data in the file was then analyzed and plotted. Refer to signal path in Fig. 3.

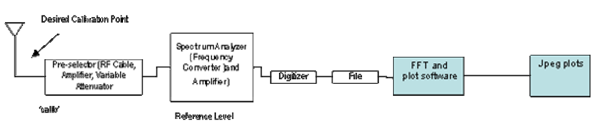

Figure 3. RF Signal Chain

B. Digital Signal Processing Description

The detector processor receives a down converted RF signal at a 20.4 MHz IF, using a spectrum analyzer. This 20.4 MHz IF is sampled at 58.5 Mega-samples/second and digitized at 14 bits of accuracy. Within a Virtex FPGA the signal is filtered and down converted to baseband. Refer to Fig. 4. The FPGA processor generates 90 thousand complex samples per second. The detector's processor performs a FFT on data sampled about 45 kHz either side of a centered TV carrier frequency for each of the 2 to 69 allocated TV channels.

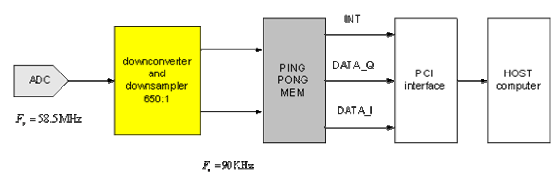

Figure 4. ATSC Detector Signal Processing

All measured powers are referenced to the antenna. Prior to calculating the received power the gain of each stage of electronics was measured across the frequency range. The RF signal path was calibrated over all frequencies and pre-selector configurations. The configuration below used a test tone at -100 dBm to calibrate the digitizer. Refer to Fig. 5.

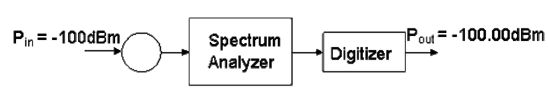

Figure 5. Calibration

Each sensor system was time synchronized to the time of a GPS receiver. In this way each sensor was receiving the same TV channel at the same time within 10 ms. A computer was used to serially step through DTV channels by controlling the center frequency of the pre-selector and spectrum analyzer. The data was collected, processed and stored to binary data files.

C. ATSC Pilot Power Detector Description

This section provides a high-level overview of the ATSC Pilot Power Detector used in the tests.

1) Detector Summary

The ATSC TV signal pilot tone distinguishes the digital TV signal and enables the TV signal to easily be detected. It is narrowband and uses the same frequency all the time. Thus, it is much easier to monitor the power received on the pilot frequency only to detect the presence or absence of the TV signal instead of detecting a 6 MHz wide signal.

2) NTSC/ATSC Signal Overlap - Offset

Nearby NTSC channels operating on same channels as the area DTV channels sometimes DTV stations use frequency offsets, if a lower adjacent channel has NTSC within 88 km if the DTV station. Area DTV channels and same channel NTSC contours are shown in Appendix A. No nearby NTSC signal exist on the DTV channels, hence, DTV pilot offsets were not necessary.

3) Pilot Signal Power Level Compared to Total Signal Power Level

The ATSC pilot contributes 0.3 dB to the total signal power. Thus, the difference between the measured carrier power level is 10*log10(1-10^0.03) = -11.45 dB. Example: Pilot measured at -100 dBm. Thus the signal power is -88.55 dBm. In general, the ATSC TV pilot tone signal power is not directly to the total TV signal power at any instant because of multi-path propagation effects. We have made extensive measurements of the NTSC carrier amplitude and the ATSC pilot tone amplitude versus time for distant TV signals. These narrow bandwidth signals are attenuated by time variable multi-path with a period of 2 to 10 minutes.

Our DSA approach is to use the maximum measured pilot tone amplitude over a 2 to 10 minute period, and then add the 11.5 dB correction factor to estimate the total received TV power value. This provides a conservative, upper limit on the total received TV power value.

D. Joint Detection Algorithm

Sensors were paired as an indoor and outdoor node and they time synchronously collected data. When the pilot power was examined, the information from the outdoor and indoor was combined to make the detection. The probability of successful detection was enhanced by considering a union of the probabilities of detection by each sensor. This ensured that if one sensor was affected by a shadowed node issue, by a building blockage or local propagation loss, the other sensor was able to compensate for the loss, by providing the accurate picture. For each time instant, the pilot power values from both sensors were compared and if one crossed the detection threshold, a detection was considered to be made.

The advantage of using both an indoor and an outdoor sensor is one of robustness. If there are situations where a multi-path null obscures the signal to one sensor, it is likely that the second sensor will pick up the signal. If any of the indoor sensors see a signal or the outdoor sensor sees the signal, the information is conveyed to all participant DSA radios, and all will then vacate to avoid causing interference.

III. Test Locations and TV Channels Used

This section describes the test locations and the TV Channels used in the tests and analysis.

A. Test Locations

The tests were designed to collect and sense the digital television signal at multiple (six) locations using a base station (outdoor antenna) and customer device (indoor antenna). The locations were chosen to cover regions inside, outside and on the boundary of DTV service contours. These tests were performed in the Northern Virginia within the DC metropolitan region.

Table 1 shows the "Indoor" node and the "Outdoor" node latitude and longitude values, and the separation between the nodes. The separations were selected to be consistent with a 10 W link distance. The actual Inside and Outside locations were also limited by the availability of overnight facility access and secure storage.

TABLE I. Test Location Coordinates and Separation Between Nodes

Location	Indoor Node Latitude (deg)	Indoor Node Longitude (deg)	Outdoor Node Latitude (deg)	Outdoor Node Longitude (deg)	Indoor-Outdoor Separation (km)
Vienna	38.9268	77.2463	38.9	77.22	3.75
Manassas	38.7882	77.448	38.7712	77.4522	1.92
Ashburn	39.02	77.43	39.05	77.48	5.46
Dale City	38.602	77.2918	38.6343	77.3512	6.29
Luray	38.68	78.42	38.7	78.44	2.82
Gainesville	38.86	77.78	38.88	77.61	14.88

Fig. 6 shows a map with the test locations.

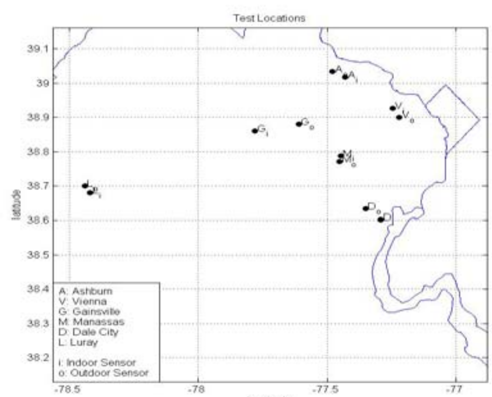

Figure 6. Measurement Locations

Fig. 7 shows the "Indoor" equipment inside a hotel room in Manassas, VA. The discone receiving antenna was mounted on a stand inside the room.

Figure 7. Measurement equipment located in the Indoor Manassas, VA location.

Fig. 8 is a photograph that shows the equipment installed in a van at the "Outdoor" Manassas, VA location. The discone receiving antenna was mounted on top of the van.

Figure 8. Measurement equipment located in van at the Outdoor Manassas, VA location.

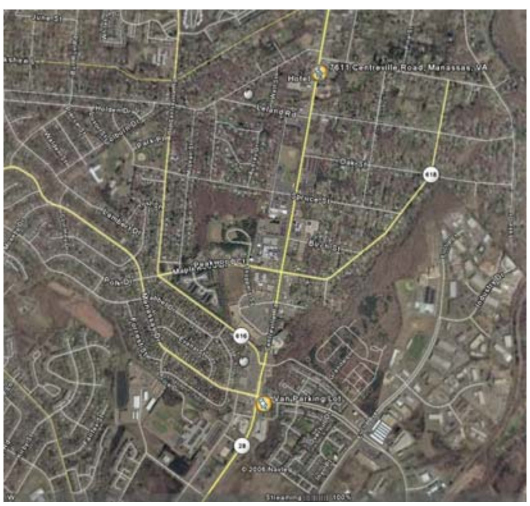

Figure 9. Map showing location of Manassas, VA Test Locations

B. TV Channels in the Test Area

TV Channels from 2 to 51 were investigated for identifying available white space. Channels 52 – 69 were excluded as those channels are slotted for reassignment to public safety device and other non television usage in the near future. Data was collected for these channels during each experiment.

Table 2 shows the list of DTV channels in this area with an ERP higher than 500 kW based on the FCC website. A 2.4º by 2 º region between lower left corner at 37.9 N, -78.7 W and upper right corner at 39.9 N, -76.3 W (approximately 36343 square kilometer area centered on the test locations) were considered as the area of influence for this analysis. Only these channels were used in the analysis described in later sections. Channel 38's licensed ERP is 1000 kW, but it transmitted at 306 kW during our tests. Channel 40's licensed ERP is 845 kW, but it transmitted at 9.2 kW during our tests.

TABLE II. AREA ATSC CHANNELS

Channel No.	Call Sign	ERP (kW)	HAAT (m)	Latitude	Longitude	City, State
21	WBOC-TV	635	279	N 38 30 17.0	W 75 38 37.0	Salisbury, MD
23	WLYH-TV	500	381	N 40 15 45.0	W 76 27 51.0	Lancaster, PA
24	WATM-TV	1000	311	N 40 34 06.0	W 78 26 38.0	Altoona, PA
30	WGCB-TV	500	174.2	N 39 54 18.0	W 76 35 00.0	Red, PA
32	WTAJ-TV	883	305.2	N 40 34 01.0	W 78 26 30.0	Altoona, PA
34	WUSA	1000	254	N 38 57 01.0	W 77 04 47.0	Washington DC
36	WTTG	1000	201	N 38 57 22.0	W 77 04 59.0	Washington DC
38	WJZ-TV	306	312	N 39 25 05.0	W 76 39 03.0	Baltimore, MD
39	WJLA-TV	646	254	N 38 57 01.0	W 77 04 47.0	Washington DC
40	WNUV	9.2	372.8	N 39 20 10.0	W 76 38 59.0	Baltimore, MD
47	WPMT	933	385	N 40 01 41.0	W 76 36 00.0	York, PA
47	WUPV	1000	249	N 37 44 31.0	W 77 15 15.0	Ashland, VA
48	WRC-TV	813	242	N 38 56 24.0	W 77 04 54.0	Washington DC

Table 3 shows the distance and bearing of the test locations to the location of the service stations of the area ATSC channels.

TABLE III. DISTANCE AND BEARING OF TEST LOCATIONS TO THE SELECTED ATSC SERVICE STATIONS

	Gainesville		***Vienna***		***Ashburn***		***Dale City***		***Manassas***	
Ch#	**Dist (km)**	**Bear.**	**Dist (km)**	**Bear.**	**Dist (km)**	**Bear.**	**Dist (km)**	**Bear.**	**Dist (km)**	**Bear.**
21	182.64	347.80	145.23	342.27	167.42	340.31	146.44	355.59	159.84	349.54
23	187.38	416.12	163.86	426.52	161.56	418.63	197.11	428.34	185.30	423.16
24	199.41	108.49	211.12	118.97	191.16	115.90	237.21	113.56	216.31	112.84
30	149.59	410.65	123.60	423.34	123.10	412.83	156.58	426.28	145.65	419.49
32	199.20	108.45	210.90	118.94	190.94	115.87	236.99	113.53	216.09	112.81
34	54.01	369.72	13.92	377.23	33.53	345.58	42.48	420.49	37.26	390.73
36	53.83	370.45	13.85	380.15	33.10	346.54	42.90	421.26	37.35	391.81
38	251.95	294.91	242.63	285.54	260.30	289.00	213.67	289.93	234.40	291.07
39	54.01	369.72	13.92	377.23	33.53	345.58	42.48	420.49	37.26	390.73
40	104.05	390.21	68.89	403.22	77.52	386.66	98.73	414.18	92.76	402.09
47	159.46	414.21	135.35	426.52	133.40	416.91	168.62	428.63	156.86	422.52
47	131.19	287.20	130.26	269.20	143.85	277.06	97.59	273.49	116.64	278.50
48	53.67	368.54	13.46	372.79	33.68	343.62	41.40	419.91	36.55	389.32

Table 4 shows the list of NTSC channels in the area.

TABLE IV. AREA NTSC CHANNELS

Channel No.	Call Sign	ERP	HAAT	Latitude	Longitude	City, State
2	WMAR-TV	100	297	N 39 20 6.0	W 76 39 3.0	Baltimore, MD
3	WHSV-TV	8.32	646	N 38 36 5.0	W 78 37 57.0	Harrisonburg, VA
4	WRC-TV	100	227	N 38 56 24.0	W 77 4 54.0	Washington DC
5	WTTG	100	235	N 38 57 22.0	W 77 4 59.0	Washington DC
6	WTVR-TV	100	256	N 37 34 0.00	W 77 28 36.0	Richmond, VA
7	WJLA-TV	316	235	N 38 57 1.0	W 77 4 47.0	Washington DC
8	WRIC-TV	269	321	N 37 30 45.0	W 77 36 5.0	Petersburg, VA
9	WUSA	316	235	N 38 57 1.0	W 77 57 1.0	Washington DC
10	WTAJ-TV	231	335	N 40 34 1.0	W 78 26 30.0	Altoona, PA
11	WBAL-TV	316	299	N 39 20 5.0	W 76 39 3.0	Baltimore, MD
12	WWBT	316	241	N 37 30 23.0	W 77 30 12.0	Richmond, VA
13	WJZ-TV	316	292	N 38 20 5.0	W 76 39 3.0	Baltimore, MD
21	WHP-TV	1200	372	N 40 20 43.0	W 76 52 9.0	Harrisburg, PA
22	WMPT	5000	273	N 39 0 36.0	W 76 36 33.0	Annapolis, MD
23	WCVE-TV	2300	346	N 37 30 45.0	W 77 36 5.0	Richmond, VA
24	WUTB	1170	326	N 39 17 15.0	W 76 45 38.0	Baltimore, MD
25	WHAG-TV	1350	375	N 39 39 35.0	W 77 57 57.0	Hagerstown, MD
26	WETA-TV	2290	235	N 38 57 50.0	W 77 6 16	Washington DC
27	WHTM-TV	2140	346	N 40 18 57.0	W 76 57 2.0	Harrisburg, PA
28	WCPB	2190	157	N 38 23 9.0	W 75 36 33.0	Salisbury, MD
29	WVIR-TV	5000	363	N 37 59 0.0	W 78 28 54.0	Charlottesville, VA
31	WWPB	4070	373	N 39 39 4.0	W 77 58 15.0	Hagerstown, MD
32	WHUT-TV	5000	213	N 38 57 49.0	W 77 6 18.0	Washington D.C.
33	WITF-TV	1100	427	N 40 20 44.0	W 76 52 7.0	Harrisonburg, PA
35	WRLH-TV	2570	384	N 37 30 22.0	W 77 42 3.0	Richmond, VA

Channel No.	Call Sign	ERP	HAAT	Latitude	Longitude	City, State
43	WPMT	2140	415	N 40 1 41.0	W 76 36 0.0	York, PA
45	WBFF	1290	386	N 39 20 10.0	W 76 38 59.0	Baltimore, MD
47	WKBS-TV	1510	308	N 40 34 12.0	W 78 25 26.0	Altoona, PA
49	WGCB-TV	646	177	N 39 54 18.0	W 76 35 0.0	Red, PA
51	WVPT	525	680	N 38 9 54.0	W 79 18 51.0	Red, PA

Table 5 shows the distance and bearing of the test locations to the location of the service stations of the area NTSC channels. Enlarged and detailed contour plots with state boundaries and test locations in Appendix A shows the test location coordinates and their placement relative to the service contours of the area ATSC and NTSC channels.

TABLE V. DISTANCE AND BEARING OF TEST LOCATIONS TO THE SELECTED NTSC SERVICE STATIONS

	Gainesville		***Vienna***		***Ashburn***		***Dale City***		***Manassas***	
Ch#	**Dist (km)**	**Bear.**	**Dist (km)**	**Bear.**	**Dist (km)**	**Bear.**	**Dist (km)**	**Bear.**	**Dist (km)**	**Bear.**
2	103.91	390.18	68.73	403.20	77.38	386.61	98.58	414.18	92.61	402.07
3	86.60	199.87	126.17	195.52	112.39	204.47	113.91	180.52	104.51	190.56
4	53.67	368.54	13.46	372.79	33.68	343.62	41.40	419.91	36.55	389.32
5	53.83	370.45	13.85	380.15	33.10	346.54	42.90	421.26	37.35	391.81
6	146.16	277.58	151.23	261.85	162.28	269.34	117.69	263.33	134.89	269.01
7	54.01	369.72	13.92	377.23	33.53	345.58	42.48	420.49	37.26	390.73
8	151.15	273.14	159.04	258.22	168.77	265.62	125.34	258.65	141.51	264.59
9	23.80	157.87	62.14	175.98	43.60	190.98	65.83	145.67	47.28	156.18
10	199.20	108.45	210.90	118.94	190.94	115.87	236.99	113.53	216.09	112.81
11	103.89	390.16	68.71	403.18	77.37	386.59	98.55	414.17	92.59	402.06
12	152.54	276.37	158.20	261.34	169.02	268.56	124.63	262.61	141.65	268.10
13	108.53	327.08	81.85	308.37	103.85	312.51	66.35	331.86	85.31	324.81
21	178.66	426.93	162.25	439.03	155.03	431.31	195.94	438.71	181.07	434.22
22	95.22	369.76	55.04	371.46	73.12	358.87	75.56	395.45	77.16	379.66
23	151.15	273.14	159.04	258.22	168.77	265.62	125.34	258.65	141.51	264.59
24	93.09	390.21	58.28	405.71	66.58	386.11	88.85	417.08	82.08	403.69
25	90.86	104.77	104.21	126.98	83.02	121.76	128.46	115.42	107.47	114.25
26	52.17	371.74	12.50	386.80	31.10	347.28	42.81	423.98	36.27	394.51
27	172.97	428.59	157.82	441.26	149.78	433.40	191.45	440.54	176.10	436.08
28	189.03	344.11	152.75	337.93	175.29	336.62	151.23	350.70	165.89	345.27
29	120.04	234.96	150.02	223.18	146.34	232.07	123.39	214.52	126.18	224.24
31	90.04	105.19	103.72	127.49	82.44	122.37	127.79	115.78	106.78	114.67
32	52.12	371.72	12.44	386.77	31.06	347.20	42.77	424.02	36.21	394.51
33	178.71	426.92	162.29	439.02	155.07	431.30	195.98	438.70	181.11	434.21
35	151.64	269.82	161.71	255.23	170.35	262.70	128.02	254.85	143.29	261.12
43	159.46	414.21	135.35	426.52	133.40	416.91	168.62	428.63	156.86	422.52
45	104.05	390.21	68.89	403.22	77.52	386.66	98.73	414.18	92.76	402.09
47	199.04	108.01	210.45	118.54	190.58	115.42	236.69	113.17	215.81	112.40
49	149.59	410.65	123.60	423.34	123.10	412.83	156.58	426.28	145.65	419.49
51	161.17	208.59	199.17	204.04	187.77	210.07	180.80	195.56	176.07	202.26

C. Test Locations Relative to TV Transmitter Service Contours

In this study, harmful interference is measured in the following way: If the test location is inside the channel contour boundary (Grade B) and the radio turns on, then harm (interference) is assumed to have been caused, even if received signal strength in less than -84 dBm (threshold of visibility for DTV signals according to FCC guidelines). If test location is outside the contour and device turns on, interference is measured only if received signal is within the keep out zone of operation. Otherwise, a signal detection is treated as false alarm.

Fig. 10 shows the test locations and the service contours. Test locations were inside, outside and some were also situated on the border of the service contours. The contour data was downloaded from the FCC database (http://www.fcc.gov/ftp/Bureaus/MB/Databases/fm_tv_service_areas/service_contour_data/readme.html). Channels 38 and 40, however, were operating at less than full power at the time of the experiments. Therefore using the full power contour was not appropriate. We use proportionality arguments to estimate the real reduced power contour distance. Using the FCC propagation modeling tool at http://www.fcc.gov/mb/video/tvq.html we found the expected full power contour distance and with the knowledge of the reduced power value of operation, we found the model reduced power contour distance.

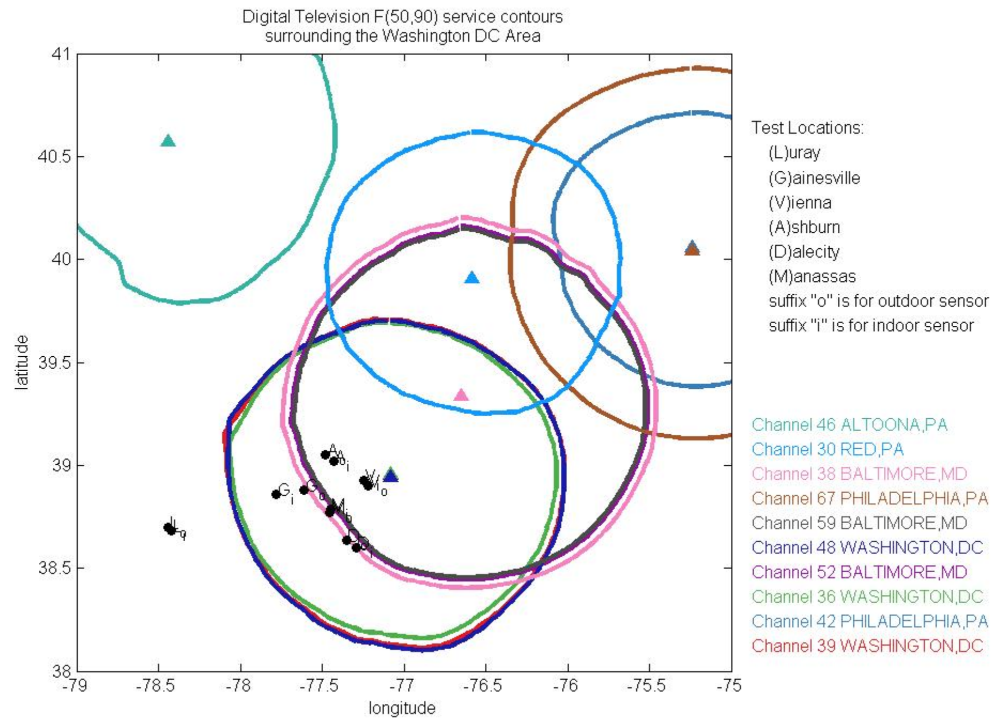

Figure 10. F(50, 90) Digital TV Service Contours

The color coded triangles in Fig. 10 indicate the broadcasting station location for the respective channels. The test locations are shown with black circles. At each location, two sets of sensors were used, one indoor (inside a building) and one outdoor and the information was integrated from the two sensors to arrive at a detection decision. The suffix "o" denotes an outdoor sensor and the suffix "i" denotes an indoor sensor.

Table VI lists the test locations and their categorization as either inside or outside of the ATSC service contours.

TABLE VI. CATEGORIZATION OF TEST LOCATIONS AS EITHER INSIDE OR OUTSIDE THE SERVICE CONTOUR OF THE ACTIVE AREA TV CHANNELS

	Area Channels												
City	**21**	**23**	**24**	**30**	**32**	**34**	**36**	**38**	**39**	**40**	**47**	**47**	**48**
Vienna	0	0	0	0	0	1	1	1	1	1	0	0	1
Manassas	0	0	0	0	0	1	1	1	1	1	0	0	1
Ashburn	0	0	0	0	0	1	1	1	1	1	0	0	1
Dale City	0	0	0	0	0	1	1	1	1	1	0	0	1
Luray	0	0	0	0	0	1	0	0	0	0	0	0	0
Gainesville	0	0	0	0	0	1	1	0	1	0	0	0	1
Channel categories 0: Outside the contour 1: Inside the contour													

D. *Measurement Duration*

The measurements at each location lasted approximately 24 hours. This enabled propagation variations such as fading, ducting and aircraft reflections to be accounted for.

IV. EXAMPLE MEASURED DATA

This section describes some example measured data.

A. *Measured Times Series*

Fig. 11 shows ATSC signal pilot power versus time for channel 39 at Dale City test location. There is significant carrier power level variation with time of the signal. For example, the peak at time about the 375^{th} minute of the experiment was missed by the indoor sensor, but owing to data from the outdoor sensor, we are able to make a successful detection. It is seen that the difference in sensor estimates in this case is negligible due to the fact that the Dale City test location is well inside the contour boundary of channel 39.

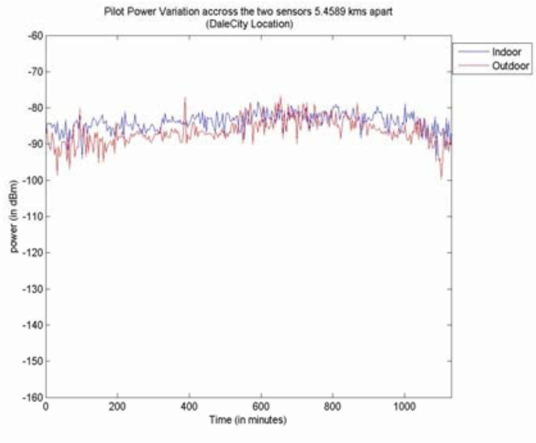

Figure 11. Pilot power Variability with Time for Channel 39 at the Dale City Test Location

In general where the outdoor locations chosen were open grounds like a camp ground, the correspondence between power levels of the indoor and outdoor pilot power was much higher than in the cases where open the outdoor locations were an area with buildings like a car dealership or a residential parking garage. This point to significant propagation losses that can be induced by building blockage of up to a 30 dB difference as shown in Fig. 12.

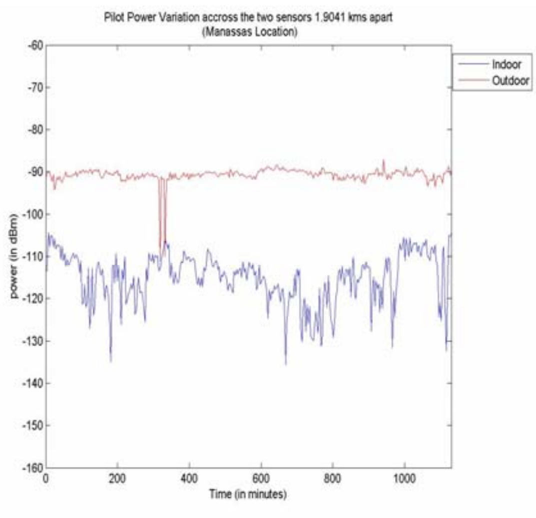

Figure 12. Pilot power Variability with Time for Channel 36 at the Manassas Test Location

V. WHITE SPACE THRESHOLD ANALYSIS

The analysis goal is to determine the upper and lower bounds on the detection threshold to be used with Digital TV pilot power measurements for safe operation of DSA devices that guarantees no harmful interference.

A. Analysis Metrics

The two metrics used to assess the performance are defined in this section:

Harm: A conservative approach is used to define the harm causing conditions. When the DSA device is inside the service contour plus the "Keep Out Distance" for a given TV channel, then the expectation is that it should always be able to detect the TV signal on that channel and stay off. Thus if the sensor does not detect the TV signal inside the contour plus the "Keep Out Distance", then, this is defined as harm condition. When the DSA device is outside the service contour for a given TV channel, but still within the keep out distance limits, we continue to flag as harm if the DSA device decides to turn on. Thus, our contour boundary is conservatively estimated at the FCC defined contour plus the keep out distance. DSA device may turn on only when it is well outside the service contour of the given TV channel. With this strategy, the DSA device may often take an overly conservative decision (so as not to harm) as the SNR of received TV signal may possibly be too low for any use (especially in the doughnut shaped region outside the FCC defined contour boundary and inside the keep out distance).

False Alarm: When a radio sensor is outside the service contour plus the "Keep Out Distance" for a given TV channel, then the expectation is there should be no TV signals there for that channel so that the radio should not be able to detect any and thus be able to turn on. If the sensor does detect a TV signal outside the contour plus the "Keep Out Distance" then, it could potentially be false alarm. However the TV signal does not arbitrary stop to exist at the contour and sometimes a good TV signal is received at locations outside of the F(50, 90) protected boundary. SNR estimates can tell us whether signal really exists or not and thus distinguish a true case of received signal outside contour limits from a false alarm. Receivers outside the contour plus the "Keep Out Distance" are not protected by FCC regulations and thus unavoidable interference may be "allowed". We flag as false alarm for the cases that, the device is outside the contour boundary and the keep out zone, and, the received signal is lower than -84 dBm (TOV), but still device has decided to remain turned off.

B. Keep Out Distance

A "keep out distance" is selected based on calculations made using FCC's TV Query model estimates. At an ERP value of 10 Watts (which is the maximum power a DSA device may be expected to use), the height of antenna being 30 meters, the field strength would go to 40 dBu at a distance of 9.406 km. 41 dBu is value used to define F(50,90) contour limits. So a 10 km keep out distance is considered beyond agreed upon contour limits in this analysis.

C. Detection Threshold Selection

If the detection threshold is continually raised, then at a point it will not be able to sense the legitimate TV signal, even a strong TV signal, and therefore with increasing detection threshold the rate of harm will go to 100%. If the detection threshold is continually lowered, then at a point it will begin to sense the noise floor and therefore with decreasing detection threshold the rate of false alarm will go to 100%. Clearly, one cannot be too conservative as a really low detection threshold will ensure "no harm", but will also raise the rate of false alarm so high that the radio is never able to turn on and be of any practical use.

Fig. 13 shows the change of the probability of harm (assuming a 10 km keep out distance corresponding to 10 W DSA transmitter) and false alarm versus the ATSC pilot power detection threshold. The ATSC signal power level is

11.45 dB above the ATSC pilot power level. This data includes the six locations and across twelve ATSC TV channels in and around the Washington D.C. area. An upright red bar indicates the harm rate and an inverted blue bar indicates the false alarm rate. These results show that a pilot threshold of -130 dBm (-118.5 dBm ATSC power level) would provide minimal “Harm” and acceptable “False Alarm”.

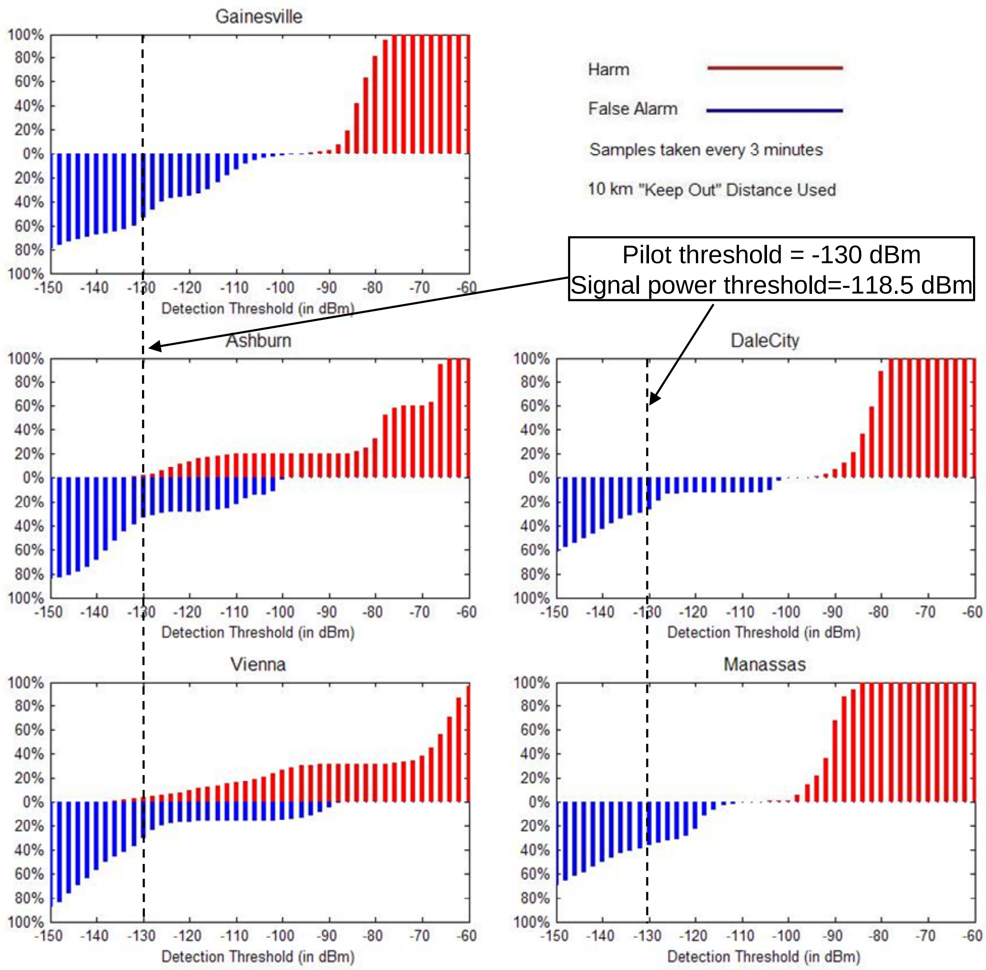

Figure 13. Probability of harm and false alarm versus detection threshold (10 km keep out zone corresponding to a 10 W DSA transmitter).

Fig. 14 shows the change of the probability of harm (assuming no keep out distance corresponding to 10 W DSA transmitter) and false alarm versus the ATSC pilot power detection threshold. The ATSC signal power level is 11.45 dB above the ATSC pilot power level. This data includes the six locations and across twelve ATSC TV channels in and around the Washington D.C. area. An upright red bar indicates the harm rate and an inverted blue bar indicates the false alarm rate. These results show that a pilot threshold of -130 dBm (-118.5 dBm ATSC power level) would provide minimal “Harm” and acceptable “False Alarm”.

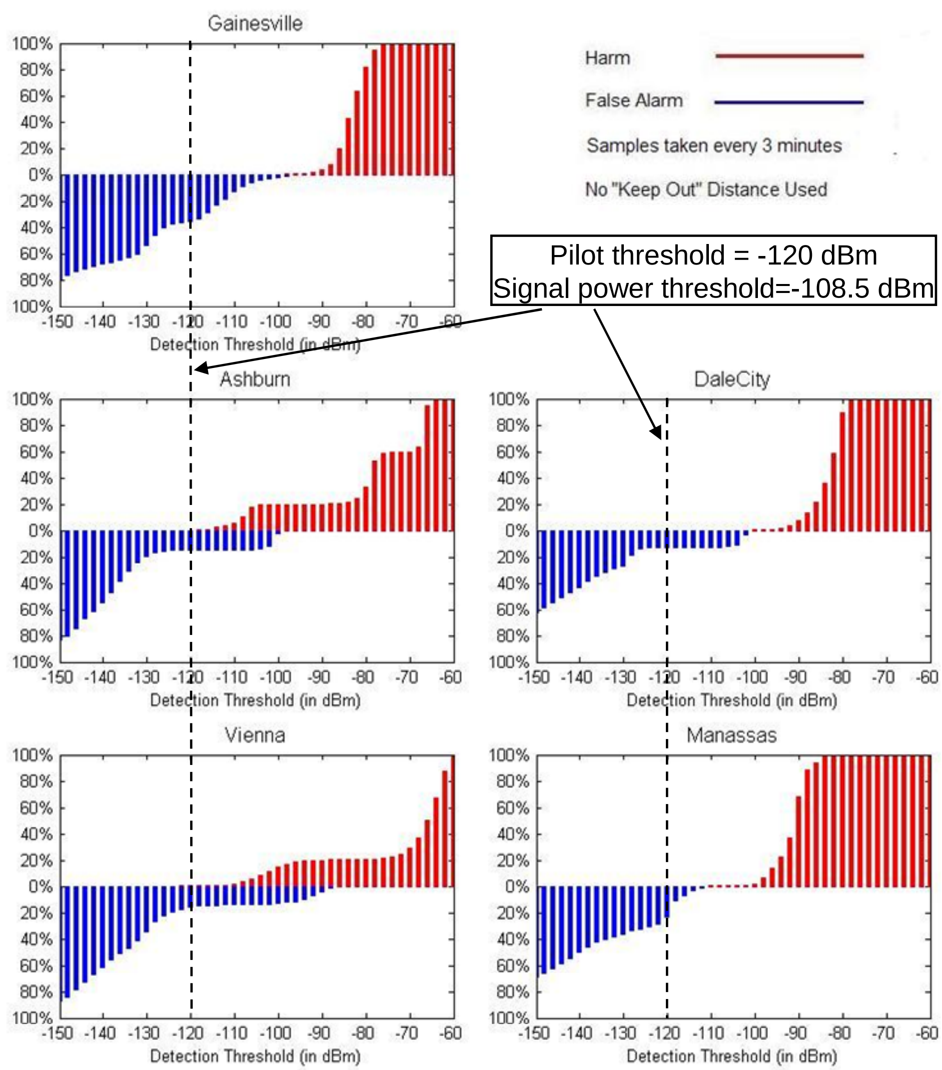

Figure 14. Probability of harm and false alarm versus detection threshold (no keep out zone corresponding to a low power, 100 mW transmitter).

VI. Conclusion

The goal of this analysis was to determine bounds on the values of detection thresholds at which dynamic spectrum access devices can safely operate in the TV bands, without causing interference to primary users.

We used a pair of DSA devices that jointly decide if a channel can be used or not. This emulates how SSC's and other DSA devices operate. The joint decision logic mitigates the propagation shadowing and hidden node problem. The separation between the DSA devices was less than approximately 10 km, which corresponds to the link range of a 10 W 802.16-based transmitter.

The DSA detectors used a high sensitivity detector that is able to detect the ATSC pilot down to a ~140 dBm level (ATSC signal power level of -128 dBm). The detector is not noise limited. "False alarms" are caused by detection of distant TV transmitters when the DSA system is located outside the Grade B contour.

Based on analysis results from data recorded from six independent locations in Northern Virginia and 13 ATSC channels, the following conclusions can be made:

1. The Listen-Before-Talk threshold-based approach is a valid dynamic spectrum access technique in the TV band when joint detection is used.
2. If the DSA system used a 10 W transmitter, then an ATSC pilot threshold of -130 dBm (-118.5 dBm ATSC power level) would provide minimal "Harm" and acceptable "False Alarm". Harm is defined is defined to be when the two DSA transceivers transmit within the ATSC service contours plus a 10 km keep out distance.
3. If the DSA system used a 100 mW transmitter, then an ATSC pilot threshold of -120 dBm (-108.5 dBm

ATSC power level) would provide minimal "Harm" and acceptable "False Alarm". Harm is defined is defined to be when the two DSA transceivers transmit within the ATSC service contours plus a 10 km keep out distance.

4. The false alarm rate caused by detection of distant TV transmitters when the DSA device is located outside of the service contour is significant (20% to 40% using the above threshold values).

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