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Evaluation of the Performance of Prototype TV- Band White Space Devices Phase II

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Executive Summary

Introduction. The Federal Communications Commission's Laboratory Division has completed a second phase of its measurement studies of the spectrum sensing and transmitting capabilities of prototype "TV white space" devices. These devices have been developed to demonstrate capabilities that might be used in unlicensed low power radio transmitting devices that would operate on frequencies in the broadcast television bands that are unused in each local area. At this juncture, we believe that the burden of "proof of concept" has been met. We are satisfied that spectrum sensing in combination with geo-location and database access techniques can be used to authorize equipment today under appropriate technical standards and that issues regarding future development and approval of any additional devices, including devices relying on sensing alone, can be addressed.

The Commission is conducting a rulemaking proceeding to consider authorization of new, low power transmitting devices in the television broadcast spectrum at locations where channels are not being used for TV or other authorized services (ET Docket No. 04-186). This locally unused spectrum is often referred to as "TV white space." As established thus far by the Commission, white space devices (WSDs) that operate from a fixed location will be allowed into the TV spectrum simultaneous with the completion of the transition from analog to digital television broadcasting on February 17, 2009. This action will open for use a significant amount of spectrum with very desirable propagation characteristics that has heretofore lain fallow. It will also allow the development of new and innovative types of unlicensed devices that provide broadband data and other services for businesses and consumers without disrupting the incumbent television and other authorized services that operate in the TV bands. The Commission is considering whether to also allow "personal/portable" WSDs to operate in the TV spectrum.

One of the principal considerations in the white space proceeding is how to reliably determine the availability of unused frequencies in local areas. A number of parties participating in the proceeding have suggested an approach for identifying unused frequencies whereby a WSD would employ a "listen before talk" or "detect and avoid" strategy. This approach would use "spectrum sensing" techniques that listen for the signals of TV stations, wireless microphones, and other incumbent services. The Commission has requested comment on whether to require that the sensing capability of devices using this approach be able to detect signals as low as -116 dBm, or some alternative value. A second technical consideration in this matter is the potential for WSDs to interfere with TV reception and wireless microphone operations. To address these issues, the Commission announced that it would perform testing of the spectrum sensing and transmitting capabilities of the prototype WSDs.

The purpose of the testing program is to provide additional information for the record that will be considered along with other information in developing the Commission's final decision on white space devices. The tests are not intended for equipment authorization or to determine whether the devices would comply with any

possible standards that the Commission might adopt. Rather, they will provide information in support of the Commission's action in this matter. Initial tests (Phase I) under this program were completed in July of 2007.[1] This report describes the tests performed during the second (Phase II) series of tests and provides a compilation of the results of measurements of the spectrum sensing and transmitting functions of various prototype WSDs.

In October 2007, the Commission's Office of Engineering and Technology (OET) issued a Public Notice announcing that it would perform additional laboratory and field tests of white space devices and invited interested parties to submit such devices for testing at the FCC Laboratory in Columbia, Maryland.[2] Subsequently, OET issued a second Public Notice announcing that the second phase testing would begin on January 24, 2008.[3]

WSD Prototype Devices Submitted for Evaluation. Five devices were submitted for examination in the Phase II tests. These devices were provided by Adaptrum, the Institute for Infocomm Research (I2R), Microsoft Corporation, Motorola Inc., and Philips Electronics North America (Philips). These devices are not intended as actual consumer products but rather are development tools for evaluating the viability of spectrum sensing and potential interference. They do not communicate with other devices. Not all tests were performed on all devices. For example, the Microsoft device was available only for limited tests in the laboratory and the I2R device was submitted after the initial tests were completed.

Spectrum Sensing for TV Broadcast Signals. This portion of the study examined the ability of the WSDs to detect whether channels are occupied by ATSC (digital) TV signals. All of the prototype devices had capabilities for detecting TV broadcast signals on UHF channels 21-51, the operating range of the prototype devices. The tests were initially performed in the laboratory under various controlled conditions. Spectrum sensing sensitivity to clean digital TV signals in isolation and also in the presence of other TV signals on adjacent channels was measured. In addition, sensitivity tests were performed using recorded TV signals to simulate "real world" conditions. Spurious emissions generated by the prototype WSDs were also measured. The laboratory tests were followed by field tests at nine sites in Maryland and the District of Columbia to evaluate the DTV sensing performance.

Spectrum Sensing for Wireless Microphones. The wireless microphone portion of the testing looked at the ability of the WSDs to detect wireless microphones authorized

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[1] S. Jones and T. Philips , "Initial Evaluation of the Performance of Prototype TV-Band White Space Devices,", OET Report FCC/OET 07-TR-1006, July 31, 2007.

[2] FCC Public Notice DA 07-4179, "Office of Engineering and Technology Announces Additional Testing of TV White Space Devices, ET Docket No. 04-186," October 5, 2007.

[3] FCC Public Notice DA 08-118, "Office of Engineering and Technology Announces Plans for Conducting Measurements of Additional Prototype TV White Space Devices, ET Docket No. 04-186," January 17, 2008.

under Part 74 of FCC rules. Microsoft, Philips and I2R indicated that their devices were capable of sensing wireless microphones. Tests of this capability were initially performed in a controlled environment in the laboratory. Those tests were followed by field tests at two sites, one in Maryland and one in New York City, to evaluate the capability of the devices to detect wireless microphones under field conditions.

Transmitter Characterization and Interference Testing. The Adaptrum device included transmitting capability.[4] Laboratory tests were performed to characterize the transmitter's signal, which is an important element for assessing the interference potential of WSD devices. Field tests were also performed to evaluate potential interference from the Adaptrum transmitter; however, these tests were limited.

Observations:

- All of the devices were able to reliably detect the presence a clean DTV signal on a single channel at low levels in the range of -116 dBm to -126 dBm; the detection ability of each device varied little relative to the channel on which the clean signal was applied. These measurements did not take into account the antenna that would be used with personal/portable devices.

- The detection threshold sensitivity of the devices varied from -106 dBm to -128 dBm when recorded off-air DTV signals, which included multi-path fading and other "real-world" distortion, were used. The impact on detection ability varied considerably among the WSDs and with the characteristics of the different recorded signals.

- Several tests were performed with DTV signals present in adjacent channels. These tests showed that in the presence of moderate-to-strong signals in a first adjacent channel, the detection threshold sensitivity of all of the devices was severely impacted. For some of the devices, the degradation in the detection sensitivity was as much as 60-70 dB. In some cases, the degradation was such that the detection threshold could not be measured. This could impact significantly the ability of the devices to reliably detect TV signals within stations' service areas.

- The Microsoft, Philips and I2R devices were tested for their ability to sense for the presence of wireless microphones (both FM/analog and digital) operating within UHF TV channels. With no other signals present, the devices were able to detect wireless microphones at levels ranging from -103 dBm to -129 dBm depending on the type of microphone, and the device. In the presence of DTV signals in adjacent channels, the detection threshold was degraded such that it affected the ability of the devices to reliably detect the microphone signals.

[4] The Microsoft device also had a transmitting capability but that device was withdrawn from the test program before the transmitter tests were conducted.

- Scan time for the devices varied from 0.1 second per channel (Motorola) to 185 seconds per channel (Adaptrum). The Adaptrum device was modified during the tests and its scan time changed from 37 seconds per channel to 185 seconds per channel.

- Channel Occupancy (TV sensing) field tests were performed at nine locations for the Adaptrum, I2R, Motorola, and Philips devices.
    - In most cases, the devices correctly reported channels as occupied when the device was operated within the service contour of the stations broadcasting on those channels and viewable signals were observed on the channels.
    - In some instances, the Adaptrum, I2R, and Motorola (in sensing only mode) devices incorrectly reported channels as unoccupied (available) when the WSD was operated within a station's service contour and the signal was viewable.
    - All of the devices reported some channels as occupied when the WSD was operated outside of the service contours of stations broadcasting on those channels whether the signal was viewable or not.
    - The Philips device generally reported most channels occupied, whether the WSD was operating inside or outside any service contours whether the signal was viewable or not.
    - During the field tests, the Motorola device's geolocation/database feature was used in combination with its sensing capabilities. In those tests, the Motorola device correctly reported all occupied channels used by stations within whose contours the WSD was operated.

- Wireless microphone sensing tests were performed using the I2R and Philips devices at two field locations. The tests were conducted first with microphones off, and then turned on, in pre-determined channels to determine if the devices could sense the presence of wireless microphones. At both sites and all the test locations, the Philips device reported all the channels on which the microphones were designated to transmit as occupied whether the microphone was transmitting or not. The I2R device indicated several channels as available even when the microphones were on.

- The Adaptrum device's transmitter was characterized in the laboratory and was used to investigate interference potential to DTV signal reception. Anecdotal tests demonstrated that co-channel interference would occur at line-of-sight distances of up to 360 meters at an EIRP of approximately +7 dBm when the DTV was receiving a weak signal using a receive antenna at a height of 9.3 meters. No interference was observed when the Adaptrum device transmitted on an immediate adjacent channel even with the transmitter in close proximity to the receiver with a roof-top antenna. No other configurations were tested for interference.

- Anecdotal tests were performed at two field sites to assess the interference potential from WSD transmitters to cable television reception via direct pick-up of signals by cable system components. These tests showed that under certain

circumstances, when the transmit antenna was placed in close proximity to a cable connected TV, direct pick-up interference was observed. The direct pick-up interference potential appears to be highly dependent on the interconnection among various system components (*e.g.*, cable amplifiers, splitters and set-top boxes) being used.

1 Introduction

The Federal Communications Commission's (FCC) Laboratory Division has completed the second phase of its program to measure the spectrum sensing and transmitting capabilities of devices intended to operate on frequencies in the broadcast television bands that are unused in each local area. These so-called "white space devices" (WSDs) have been developed to demonstrate features that might be used in unlicensed low power radio transmitting devices.

This measurement project was undertaken in support of the Commission's pending consideration in ET Docket No. 04-186 on whether to permit low power radio transmitting devices to operate on an unlicensed basis in the frequency bands that are currently allocated to the television broadcast and certain other licensed services.[1] Such low power operations would only be allowed on frequencies that are not used by TV stations or other licensed services in each local area. These unused, *i.e.*, vacant or "available," frequencies in local areas are often termed spectrum "white spaces." As established thus far by the Commission, fixed white space devices (WSDs) will be allowed into the TV spectrum simultaneous with the completion of the transition from analog to digital television broadcasting on February 17, 2009. This action will open for use a significant amount of spectrum with very desirable propagation characteristics that has heretofore lain fallow and will allow the development of new and innovative types of unlicensed devices that provide broadband data and other services for businesses and consumers without disrupting the incumbent television and other authorized services that operate in the TV bands. The Commission is considering whether to also allow "personal/portable" WSDs to operate in the TV spectrum.

The Commission is considering two categories of devices for unlicensed operation in the TV white spaces.[2] The first category consists of low-power "personal/portable" WSDs that will function similar to WiFi transceivers in laptop computers, and wireless in-home local area networks (LANs). The second category consists of higher-powered "fixed/access" WSDs that would typically be operated from a fixed location and might be used to provide a commercial service such as wireless broadband access. As established previously by the Commission, fixed white space devices will be allowed into the TV spectrum upon completion of the transition from analog to digital television broadcasts on February 17, 2009.[3] The Commission is now

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[1] *First Report and Order and Further Notice of Proposed Rule Making* in the Matter of Unlicensed Operation in the TV Broadcast Bands, ET Docket No. 04-186 and 02-380, October 18, 2006 (hereinafter *FNPRM*). While the focus of this proceeding is on unlicensed operation, the Commission has also requested comment on issues relevant to whether TV band low power devices should be allowed on a licensed or hybrid licensed/unlicensed basis. It also requested comment as to whether, if unused TV spectrum were made available on a licensed basis, licensed devices should be required to incorporate the same type of interference avoidance mechanisms and be subject to the same low power limits that it proposed for unlicensed devices.

[2] *Notice of Proposed Rulemaking in ET Docket Nos. 02-380 and 04-186, 19 FCC Rcd 10018 (2004).*

[3] *Id.*

considering whether to allow non-fixed "personal/portable" WSDs to also operate in the TV spectrum.

An important consideration in the proceeding is how to ensure that unlicensed devices operate only on vacant frequencies. One approach under consideration is for the WSD to employ "smart radio" features that would use a "detect and avoid" or "spectrum sensing" strategy. An alternative approach would rely on accessing a database of licensed services to identify active services near the device's location. The device location would be determined by an integral geo-location technology, such as GPS. This technique is commonly known as a "geolocation" detection approach. A second issue is the potential for signals transmitted by a WSD to cause radio frequency interference (RFI) to incumbent users of these bands (*i.e.*, TV reception and wireless microphone operations). The Commission indicated that it would test prototype devices to collect technical information regarding both of these issues.

Consistent with the Commission's plan for white space testing, the Office of Engineering and Technology (OET), through its Laboratory Division, performed initial tests of two prototype devices and issued a report on the results of those tests in July of 2007.[4] Subsequently, on October 5, 2007, OET issued a Public Notice inviting submittal of additional prototype devices for further tests (Phase II).[5] On January 17, 2008, OET issued a test plan for the Phase II tests to help ensure that the testing would be open to outside observers, and announced that the testing would commence on January 24, 2008.[6]

Five parties responded to the announcement of the Phase II testing and provided prototype WSDs to the Laboratory for testing: Adaptrum, the Institute for Infocomm Research (I2R), Microsoft Corporation (Microsoft), Motorola Inc., and Philips Electronics North America Corp (Philips).[7] The Microsoft devices malfunctioned during the test process and were not replaced. The I2R device was submitted after the initial laboratory tests were completed. As a result, not all the tests were performed on these two devices. All of these prototypes have a sensing capability, but only two (Microsoft and Adaptrum) have a transmitter. Since the Microsoft device malfunctioned before the transmitter tests were performed, its transmitter was not used in any of these tests.

This report describes the tests and measurements performed on the prototype WSDs and the results obtained, with focus on impacts to broadcast television and wireless microphone operations. In particular, this report provides the results of tests of the spectrum sensing capabilities of the prototype devices as a means for identifying TV

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[4] OET Report FCC/OET 07-TR-1006, *Initial Evaluation of the Performance of Prototype TV-Band White Space Devices*, S. Jones and T. Philips July 31, 2007 (Phase I measurement report).

[5] FCC Public Notice, DA 07-4179, "The Office of Engineering and Technology Announces Additional Testing of TV White Space Devices, DA 07-4179, October 5, 2007.

[6] FCC Public Notice DA 08-118, "Office of Engineering and Technology Announces Plans for Conducting Measurements of Additional Prototype TV White Space Devices, ET Docket No. 04-186," January 17, 2008.

[7] Microsoft submitted two units of the same device.

channels unused by TV broadcast or wireless microphone operations and, where the devices included transmission capability, their emission characteristics and potential for causing interference to those services. While other incumbent services operate in the TV bands, those services are not specifically being examined in this test program as the Commission has proposed other methods for protecting them from WSD operations.

1.1 Test Scope and Approach

The Phase II tests first examined the devices in the laboratory under various controlled test conditions. The WSDs' ability to sense DTV signals was evaluated in several ways: using a single DTV signal, with two DTV signals (one placed on an adjacent channel), and with recorded RF captures that exhibit various signal fading conditions. Similarly, for those devices capable of sensing wireless microphones, tests were performed with wireless microphones alone and with DTV signals present on adjacent channels. The wireless microphones were operated on various frequencies within a TV channel (both near the center of the channel and near the edges).

In preparation for the field tests, the performance of the devices in sensing off-the-air signals was recorded at various locations in the laboratory. Also, controlled tests of the Adaptrum transmitter were performed at the laboratory to estimate the distances at which it might cause interference to TV reception. Finally with input from various interested parties, nine sites were selected for field tests of the device's ability to sense TV signals, and two sites were chosen for field tests of their ability to sense wireless microphones. The field sites were selected to represent a variety of environments including urban, suburban, rural, residential and business locations. At two of the field test sites, anecdotal direct pick-up interference tests were performed to assess the impact of a WSD transmitter on cable TV reception. The following sections and the appendices provide a tabulation of the data collected during the tests.

2 White Space Prototype Devices

2.1 Adaptrum Prototype White Space Device

Adaptrum indicates that its "Cognitive Radio (CR) Platform" is an integrated hardware and software development system that has been specifically designed for TV white space operation on UHF television channels 21-51. The system is capable of various forms of TV signal sensing including waveform/signature sensing, spectral identification, signal power estimation, and network-level cooperative sensing. It detects both analog and digital TV signals, but performs those functions in two separate scans. It is not designed to detect wireless microphone signals. The system is also capable of signal transmission in the TV bands with flexible waveform, modulation, and signal bandwidth construction. It incorporates transmit power control and chain linearization to reduce adjacent channel interference. The maximum transmitter output power specification is 100 mW (+20 dBm) over the selected bandwidth. Figure 2-1 provides a photograph of the prototype device/platform.

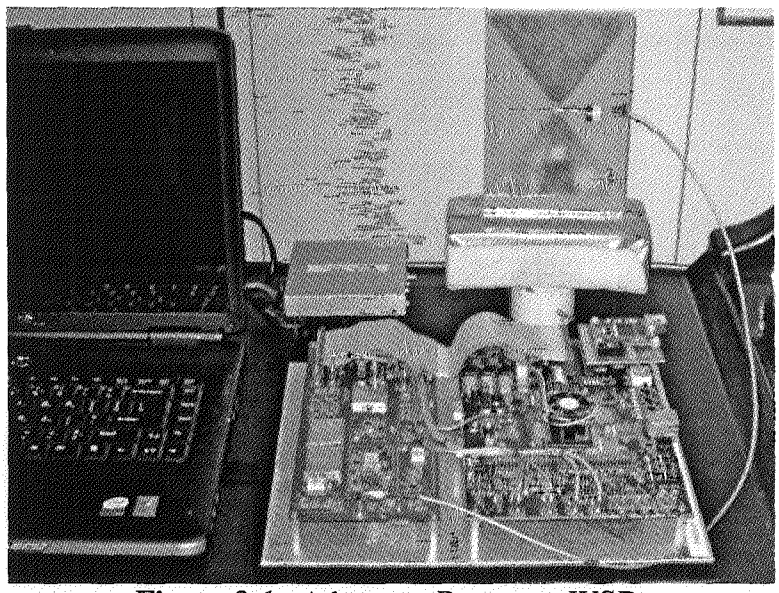

Figure 2-1. Adaptrum Prototype WSD.

The key components of the platform are: 1) a wide-band high dynamic-range radio frequency (RF) transceiver operating over the frequency range 400 MHz to 1000 MHz, 2) a field-programmable gate array (FPGA)-based hardware development board with integrated high-speed analog-to-digital converters (ADCs) and a high-density FPGA where CR baseband and protocol-layer functions are implemented, and 3) a Matlab-based integrated development environment (IDE) where the CR hardware functions are controlled using a Matlab graphical user interface (GUI) and Matlab scripts.

The scan time associated with this prototype device was initially 37 seconds per channel (sec/ch). However, a software modification installed to improve the detection sensitivity with respect to DTV signals with offset pilot carriers slowed the scan time by a factor of five to 185 sec/ch. Additional information can be obtained from the Adaptrum *ex-parte* filing in the subject rulemaking proceeding.[8]

2.2 Institute for Infocomm Research (I2R) Prototype White Space Device

The I2R prototype WSD operates on channels 21-51 and is capable of sensing analog and digital TV signals and wireless microphone signals. The device consists of: 1) a commercial TV tuner to receive television signals and translate them to their associated intermediate frequency (IF), 2) mixed-signal digital processing boards for performing ADC, downconversion and filtering, 3) a laptop computer used to configure the hardware, provide a GUI and generate reports, and 4) a fixed-length whip receive antenna.

The (I2R) device was also able to detect wireless microphones. It provided two scan modes – "DTV" and "All" and two test modes – "Lab" and "Field". In the DTV scan mode it searched only for DTV signals and in the "All" mode it searched only for microphones. The "Lab" test mode was intended only for conducted bench testing and the "Field" mode was intended only for reception of radiated signals with an antenna. Figure 2-2 presents a photograph of the I2R prototype device/platform. Additional information can be obtained from the I2R *ex-parte* filing in the subject rulemaking proceeding.[9]

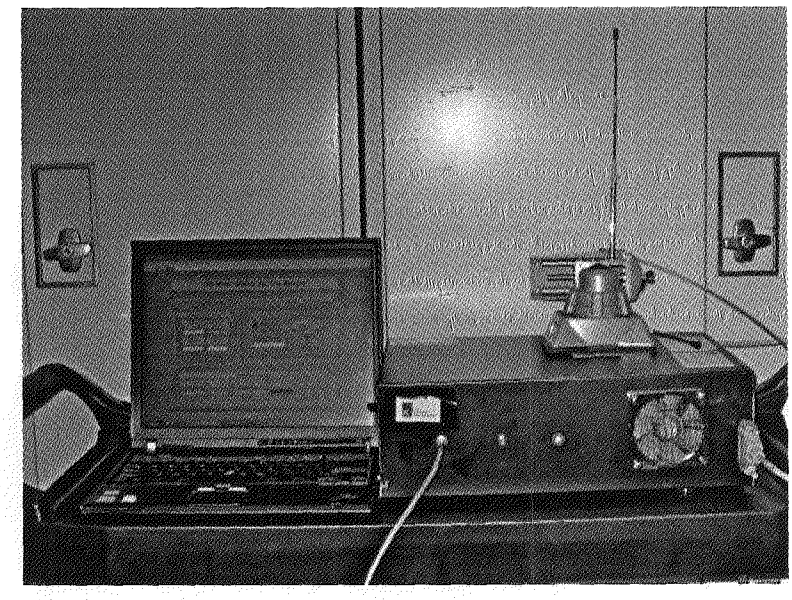

Figure 2-2. I2R Prototype WSD

[8] Adaptrum, Inc *ex-parte* filing of December 5, 2007.

[9] I2R *ex-parte* filing of June 23, 2008.

2.3 Microsoft Prototype White Space Device

The Microsoft WSD platform operates on channels 21-51 and is capable of sensing analog and digital TV signals and wireless microphone signals. The system consists of two core system subassemblies: 1) a wide-band spectrum scanner, a network processor and a tunable UHF half-duplex transceiver controlled by the network processor and 2) a Windows-based laptop computer that utilizes the Internet Explorer browser to establish a command and control user interface via an Ethernet connection. This device is also capable of transmitting on its operating channels.

The scanner/sensor function consists of a broadband (521-698 MHz) computer-controlled frequency scanner and high-speed digitizer used to incrementally scan over UHF TV channels 21-51 in 6-MHz segments. The accumulated digitized time-domain information is then passed to the network analyzer where a 2048-point Fast Fourier Transform (FFT) is performed. Signal feature templates for DTV, analog TV, and wireless microphone waveforms are sequentially compared to the resulting FFT output to determine those channels occupied by DTV or analog TV signals. Channels determined not to be occupied by DTV or analog TV signals are subsequently analyzed for potential narrowband incumbent signals such as wireless microphones. Those channels determined not to be occupied by either DTV, analog TV, or wireless microphone signals are declared to be available "white space" channels. User control and scanner results are provided via the laptop computer connection.

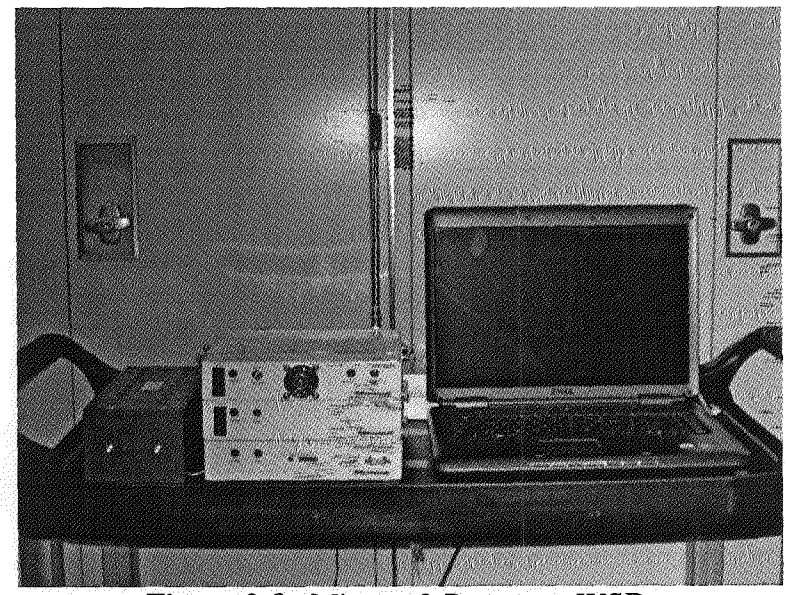

Figure 2-3. Microsoft Prototype WSD.

The UHF transmitter assembly consists of three sub-components: 1) an S-Band (2.4 GHz) 802.11g OFDM modem; 2) a Half-duplex S-Band to UHF block converter; and 3) and a network processor browser to exercise control over frequency and power. Two external fixed-frequency bandpass filters were provided for use in transmitter testing. A photograph of the Microsoft WSD platform is provided in Figure 2-3.

Additional information can be obtained from the Microsoft *ex parte* filings in the subject rulemaking proceeding.[10]

2.4 Motorola Prototype White Space Device

The Motorola WSD platform operates on channels 21-51 and includes capabilities for geo-location and sensing of digital TV signals. It does not sense analog television signals or wireless microphone signals. The system consists of a Cognitive Radio Rack and a laptop computer host connected via Ethernet. The rack consists of a UHF radio and two PRO-3500 carrier boards co-located in a compact Peripheral Component Interconnect (PCI) chassis. The cognitive engine runs on the lower board.

This WSD implements a geo-location-based approach as its primary method for the determination of occupied TV channels with a spectrum-sensing capability used to refine the results of the geo-location solution and to prioritize those channels found to be available. The geo-location capability as tested requires the user to manually input the geographic coordinates and relies on a downloaded version of the FCC's TV database for a particular geographic area.

This WSD exhibited the fastest scan execution time of 0.1 sec/ch. A photograph of the Motorola WSD is provided in Figure 2-4. More information can be obtained from Motorola *ex parte* filings in the subject rulemaking proceeding.[11]

Figure 2-4. Motorola Prototype WSD.

[10] Microsoft *ex-parte* filings of December 11, 2007 and January 15, 2008.

[11] Motorola *ex-parte* filings of November 16 and December 6, 2007.

2.5 Philips Prototype White Space Device

The Philips WSD platform operates on channels 21-51 and is capable of sensing analog and digital TV signals and wireless microphone signals consists of: 1) a commercial TV tuner for tuning to a specified television channel and translating to IF, 2) a digital signal processing board for ADC and processing and 3) a desktop computer used to configure the hardware, provide a GUI and store detection results.

Philips claims that the prototype WSD will scan UHF channels 21-51 and detect ATSC (DTV), NTSC (analog TV) or wireless microphones to a level of at least -114 dBm over a 6-MHz television channel. The channel scan time for this device varies between 8 and 50 sec/ch due to the sequential application of separate ATSC, NTSC and wireless microphone detection algorithms.

Figure 2-5 presents a photograph of the Philips WSD platform. Additional information can be obtained from Philips *ex-parte* filing in the subject rulemaking proceeding.[12]

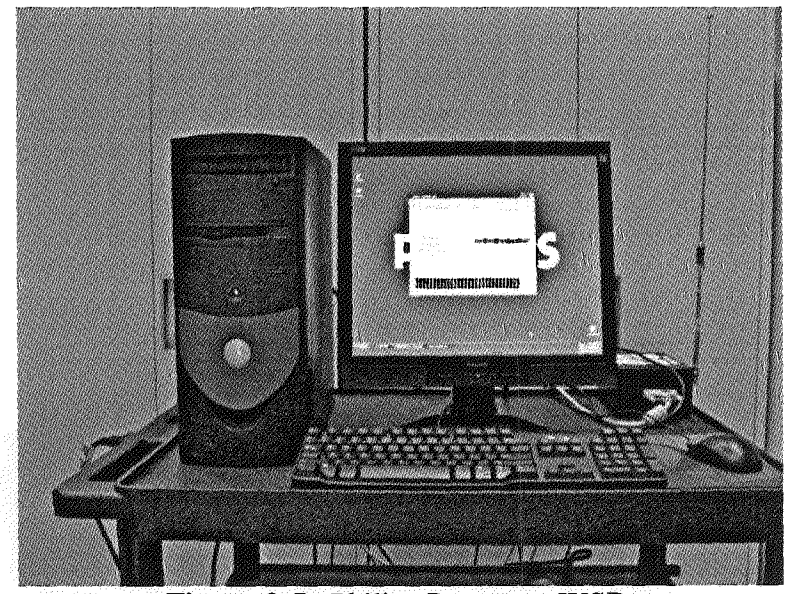

Figure 2-5. Philips Prototype WSD.

[12] Philips ex-parte filing of December 10, 2007.

3 DTV Scanning/Spectrum Sensing Capability Tests

This section describes the laboratory measurements performed on each of the prototype WSDs submitted for testing. For the sensing measurements performed in the laboratory, a simulated or recorded signal was applied to the antenna input of the WSD prototype utilizing a coaxial cable connection (*i.e.*, conducted measurements). As such, the effects of the WSD receive antenna were ignored.

Ignoring the WSD receive antenna contribution is analogous to assuming an isotropic receive antenna (*i.e.,* a theoretical antenna having uniform gain and directivity). An isotropic receive antenna for ultra-high frequency (UHF) operation represents an ideal that cannot be physically realized. Rather, the receive antenna of WSDs will likely have low and variable (or negative gain) and thus the results reported herein would have to be adjusted accordingly to describe practical devices. These measurements also make no effort to quantify other potential contributors to television signal loss such as might be experienced from shielding/absorption effects introduced by proximate human bodies.

The general approach to these tests was to provide a DTV input signal at progressively lower amplitude levels until the prototype could no longer detect it with complete (100%) reliability.

It is recognized that some of the WSD detection algorithms interpret detection reliability as low as 50% as indicative of an occupied channel, but the design intentions of the algorithms in other devices were not readily apparent.

3.1 Clean DTV Signal Measurements

The objective of the clean DTV signal measurements was to determine the detection sensitivity of the scanning/sensing capability of the WSD prototype devices submitted for evaluation with respect to a "clean" (undistorted) DTV signal.

For these measurements the input was a single, simulated DTV signal produced by a Rhode and Schwarz DTV Test Broadcast System (SFU). The generated DTV signal was provided to the antenna input of the WSD prototype under test via a coaxial cable. An external variable attenuator bank was used to adjust the signal power. Block diagrams showing the measurement equipment and related interconnections in addition to detailed equipment information are provided in Appendix A. The detailed procedure used to perform these measurements follows:

- The SFU was used to produce a single, clean DTV signal that was provided via coaxial cable through a variable attenuator and into the RF input of a spectrum analyzer.

- With the variable attenuator set to zero, the SFU power control was adjusted to produce an average power level of -60 dBm/6 MHz, referenced to the input connection of the spectrum analyzer. This level provides a displayed signal-to-

noise ratio (S/N) of at least 20 dB. The signal power was measured using a root-mean-square (rms) detector and averaged over 100 sweeps.

- The cable from the SFU was then removed from the analyzer input and connected to the antenna input of the WSD prototype.

- The SFU-generated DTV signal was further attenuated using the external variable attenuator bank from the -60 dBm level to a level slightly higher than the expected detection threshold (*e.g.*, the variable attenuator was typically set to provide an additional 54 dB attenuation so as to produce an initial input signal level of -114 dBm)

- Thirty (30) independent detection trials were performed with the WSD tuned to channel 21 (lowest channel in tuning range). The number of successful detections of an occupied channel was recorded.

- If the successful detection rate over the thirty trials was 100%, the input signal power was reduced by increasing the variable attenuator by 1 dB and the procedure repeated.

- If the successful detection rate over the thirty trials was less than 100%, then the input signal power was increased by decreasing the variable attenuator by 1 dB and the procedure repeated.

- This iterative process was repeated until the DTV power level was found where the WSD prototype could no longer detect the occupying signal in the channel with 100% reliability.

- Additional data points were then collected above and below this breakpoint.

- The process was repeated in its entirety on two additional test channels, 36 and 51, representing the middle and upper channels within the tuning range, respectively.[13]

The figures that follow represent the results obtained from the clean signal DTV sensing measurements for each of the WSD prototype devices. Two separate plots are provided for the I2R device, representing results obtained in the two available modes of operation ("laboratory" test mode and the "field" test mode). The field test mode utilizes separate circuitry to suppress spurious reception.

[13] The Adaptrum device was found to be particularly prone to false detections on channel 36, likely because of the presence of an OTA signal on the channel. Thus, channel 37 was used as the middle test channel for this device.

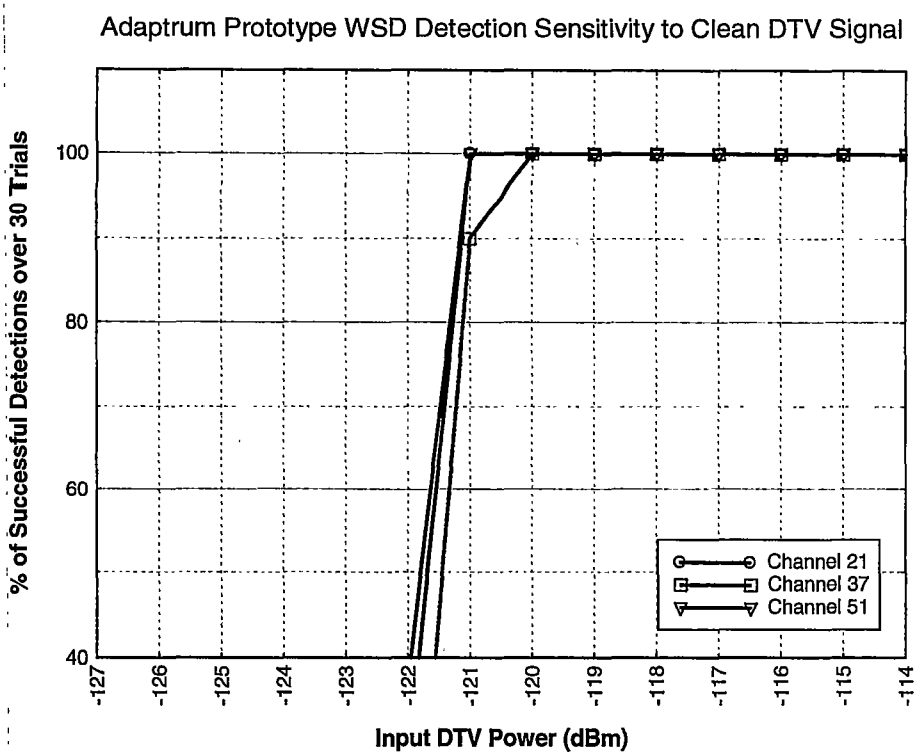

Figure 3-6. Clean Signal Sensitivity Results for Adaptrum WSD Prototype.

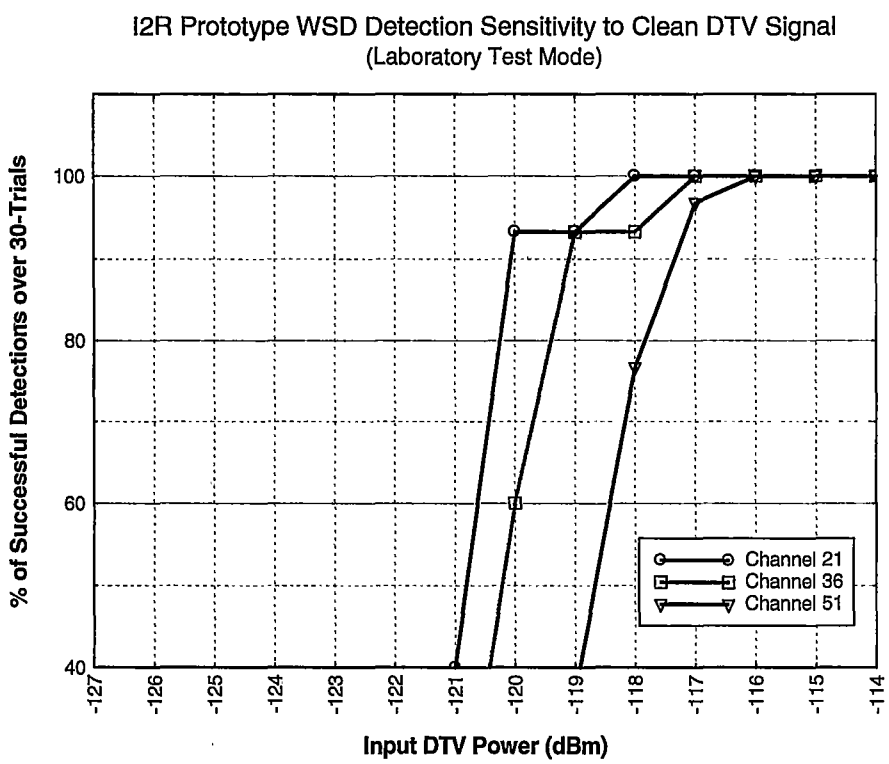

Figure 3-7. Clean Signal Sensitivity Results for I2R WSD Prototype in Laboratory Test Mode.

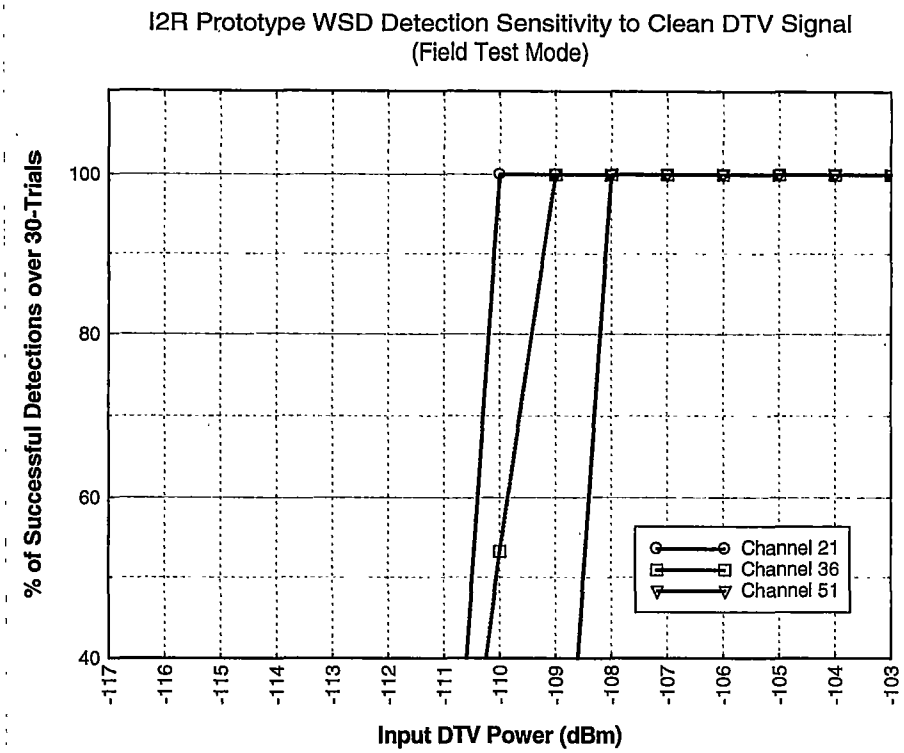

Figure 3-8. Clean Signal Sensitivity Results for I2R WSD Prototype in Field Test Mode.

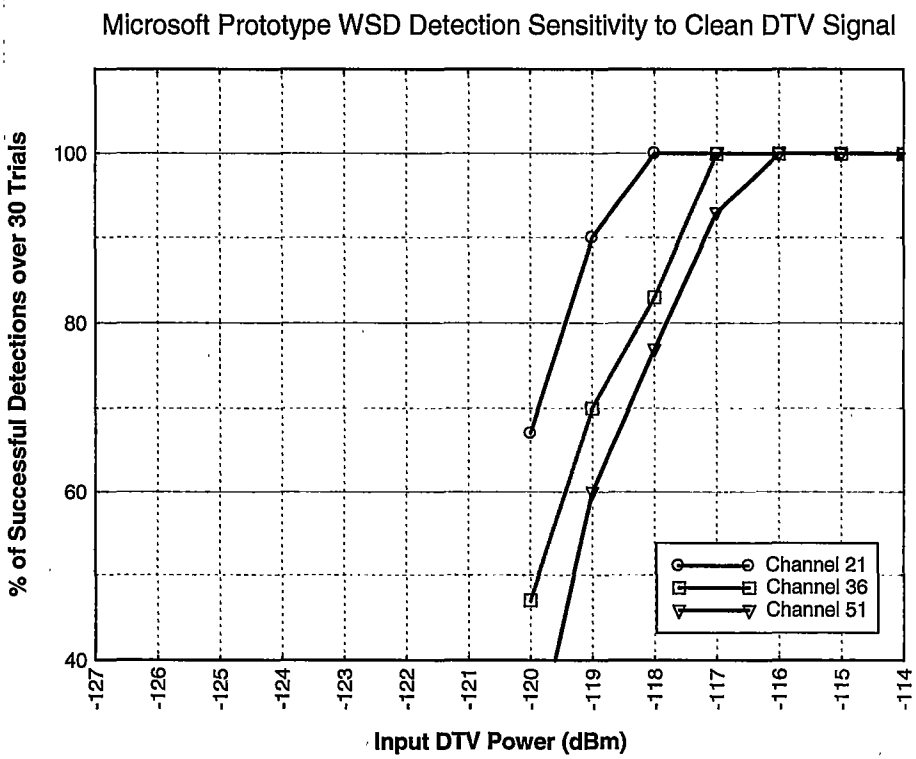

Figure 3-9. Clean Signal Sensitivity Results for Microsoft WSD Prototype.

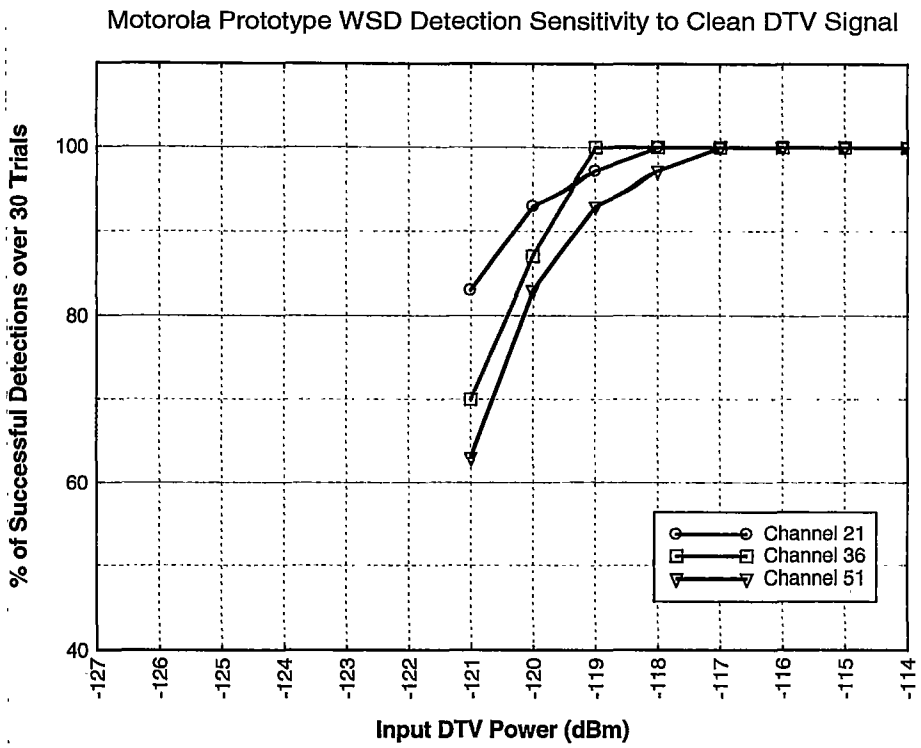

Figure 3-10. Clean Signal Sensitivity Results for Motorola WSD Prototype in Test Mode.

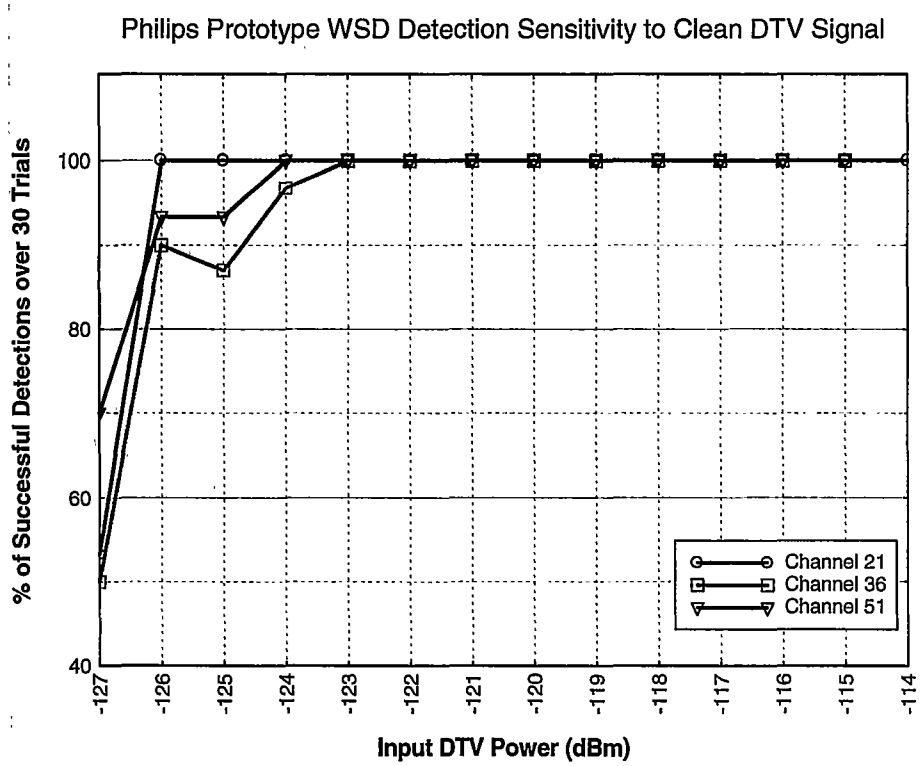

Figure 3-11. Clean Signal Sensitivity Results for Philips WSD Prototype.

3.2 Recorded (Captured) DTV Signal Measurements

The objective of the recorded DTV signal measurements was to determine the detection sensitivity of the scanning/sensing capability of the WSD prototype devices with respect to recorded over-the-air DTV signals that incorporate "real world" signal distortions resulting from reflections, multi-path fading, and other factors.

The signal input for these measurements consisted of a set of twelve recorded DTV waveforms ("captures") selected by the IEEE 802.22 subcommittee.[14] Detailed information, including frequency domain and temporal representations of each of these twelve waveforms, is provided in Appendix B of this report.

A Wavetech Services WS-2100 RF player® was used to play back the captures on the desired RF channel and to provide them to the antenna input of each of the WSD prototypes via coaxial cable. Two external variable attenuator banks were utilized to adjust the power level of the input signal. A 75-50 Ω transformer was utilized at the Wavetech player output to match system impedance.

Although different algorithms are utilized among the prototype devices to detect the presence of a DTV signal, they all appear to share a similarity in that they all sample the spectrum in proximity of an anticipated DTV pilot signal. However, the amount of time dedicated to sampling and signal processing differs significantly among the prototype devices. Since there are significant instantaneous temporal variations in many of the RF captures over their 25-second playback period (see Appendix B), the resulting detection decisions can also vary depending on when the sampling actually occurs. Efforts were made to minimize this variable (*e.g.*, the waveform playback was restarted for each independent trial); however its effect is evident in the results obtained from some of the prototype devices. Another method for reducing this variability is to increase the number of trials beyond the stated number of thirty. For some of the devices, the additional time required to execute more than thirty trials was excessive and was thus deemed impractical. However, for others (*e.g.*, the Motorola WSD), it was practical to perform additional trials. Therefore, for this device, in addition to performing the measurement over thirty independent trials, a second measurement was also performed utilizing one thousand independent trials. The results of both measurements are provided herein.

After the laboratory measurements were completed but before the field trials commenced, the prototype manufacturers were offered an opportunity to make minor adjustments to their devices based on the laboratory results. For example, one issue observed by the manufacturer of the Adaptrum prototype was difficulty in detecting a DTV signal having a frequency offset pilot tone. As a result, Adaptrum utilized this opportunity to improve this with a software modification.[15] A second set of data is presented for the Adaptrum device showing the effect of this modification.

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[14] See *ex parte* submission from Qualcomm, dated August 24, 2007.

[15] See *ex parte* filing from Adaptrum, dated June 2, 2008.

Block diagrams showing the measurement equipment and related interconnections in addition to detailed equipment information are provided in Appendix A. The measurement procedure was as follows:

- A Wavetech Services WS-2100 RF player® was used to play back each of twelve recorded DTV signals and provide the RF output via coaxial cable through an external variable attenuator bank and into the RF input of a spectrum analyzer.

- With the external variable attenuators set to zero, the average output signal power in the channel bandwidth was measured using the spectrum analyzer (over 100-sweeps utilizing an rms detector).

- The coaxial cable was then removed from the RF input of the analyzer and connected to the receive antenna input of the prototype device.

- The signal was further attenuated using the variable attenuator bank to achieve a power level near the threshold level recorded in Section 3.1.

- Thirty (30) independent trials were performed and the number of successful detections recorded.[16] Since the data from the Section 3.1 indicated relative consistency over the three channels examined, these tests were performed only on a single channel (typically channel 36, mid-channel in the WSD tuning range).[17]

- If the successful detection rate over the thirty scans was 100%, then the input signal power was reduced by increasing the attenuation by 1 dB and the procedure repeated.

- If the successful detection rate over the thirty scans was less than 100%, then the input signal power was increased by reducing the attenuation by 1 dB and the procedure repeated.

- The process was repeated until the DTV power level was found where the WSD prototype could no longer detect the signal in the channel with 100% reliability.

- Additional data points were then collected above and below this breakpoint.

The results of these measurements are provided in the figures that follow.

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[16] For some devices, an additional measurement was performed utilizing more than 30 trials (see discussion in previous text).

[17] The Adaptrum device was found to be particularly prone to false detections on channel 36, likely because of the presence of an OTA signal on the channel. Thus, channel 37 was used as the middle test channel for this device.

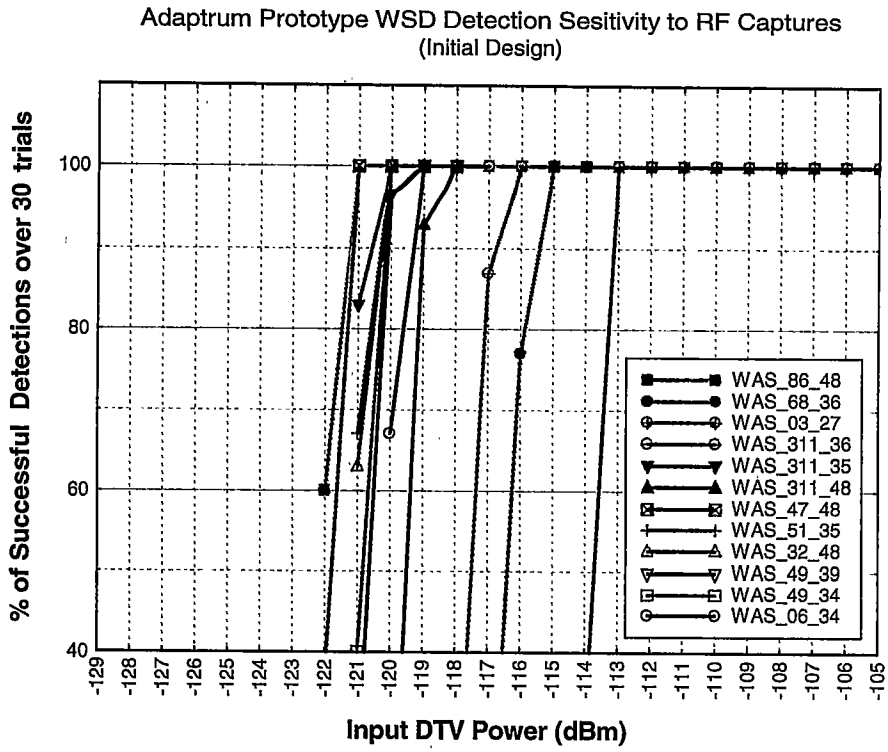

Figure 3-12. DTV Capture Results for Adaptrum WSD Prototype (initial configuration with limited freqency offset pilot capability).

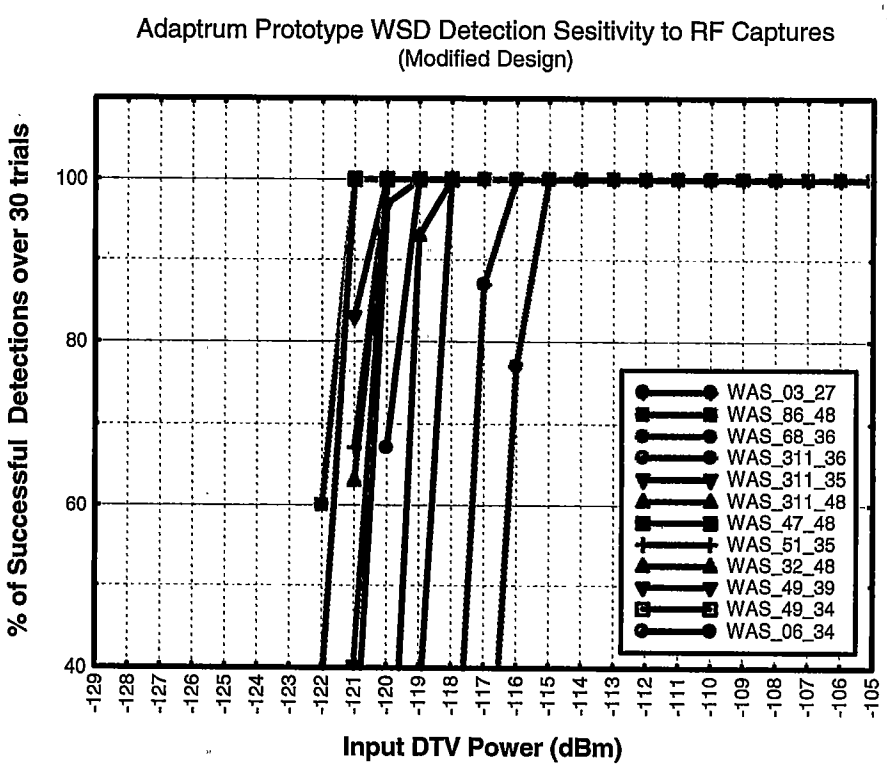

Figure 3-13. DTV Capture Results for Adaptrum WSD Prototype (modified configuration with improved frequency offset pilot capability).

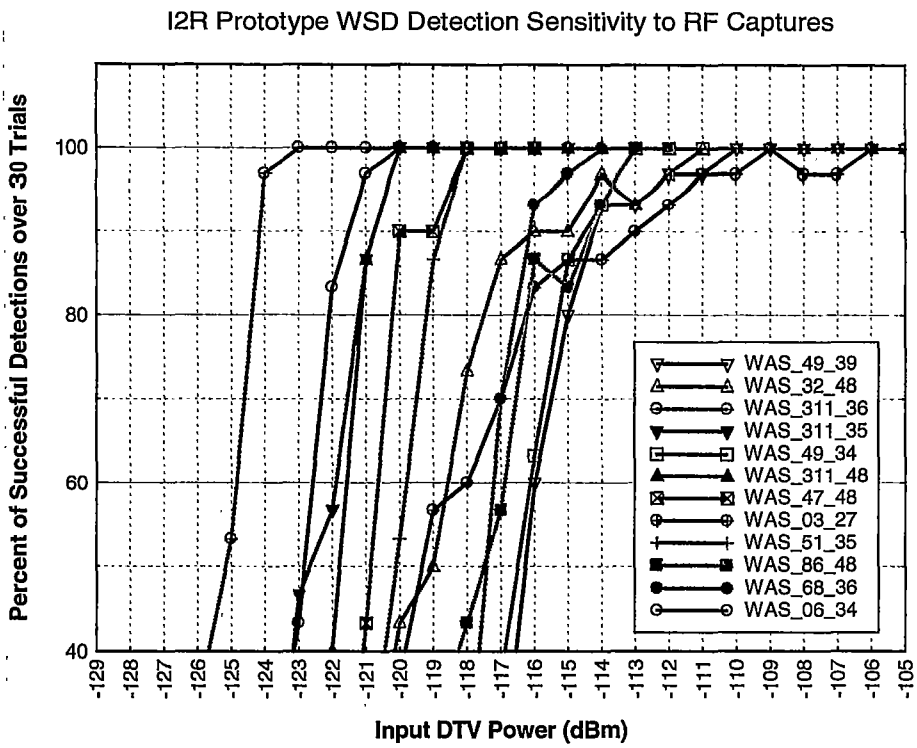

Figure 3-14. DTV Capture Results for I2R WSD Prototype (Laboratory Mode).

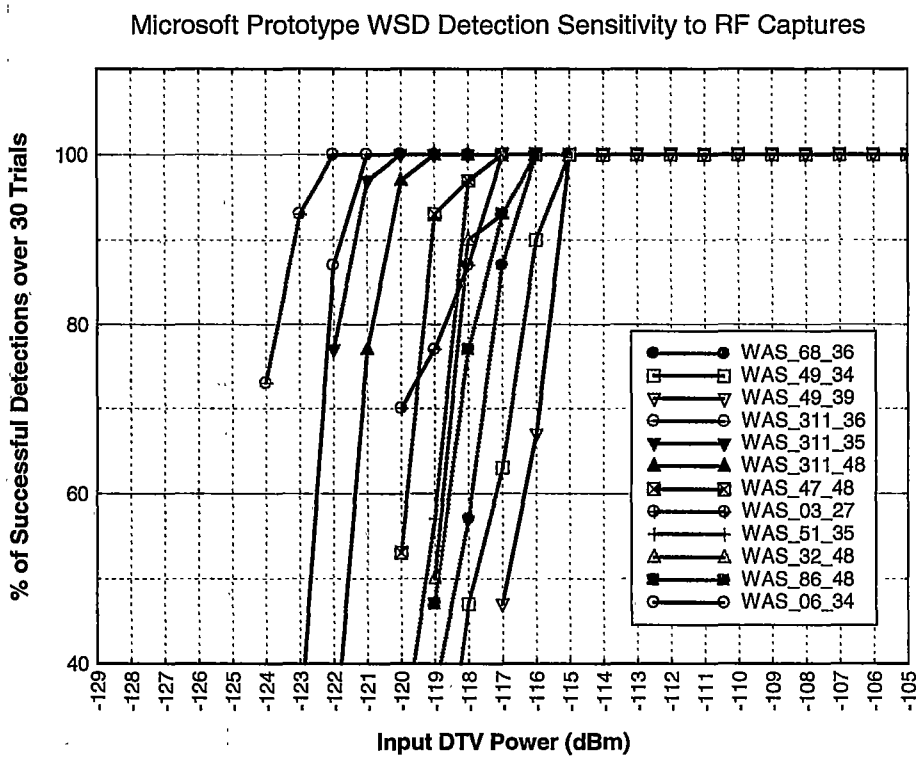

Figure 3-15. DTV Capture Results for Microsoft WSD Prototype.