DTV REPORT
ON
COFDM AND 8-VSB PERFORMANCE

Office of Engineering and Technology
September 30, 1999

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Executive Summary

The Office of Engineering and Technology (OET) has conducted an independent assessment of Coded Orthogonal Frequency Division Multiplex (COFDM) and 8-Level Vestigial Side-band (8-VSB) systems for the provision of digital television (DTV) services in the United States. This study was initiated at the request of Commissioner Susan Ness in response to issues raised in result of indoor reception demonstrations by the Sinclair Broadcasting Group, Inc. (Sinclair). As indicated below, the OET study concludes that the ATSC 8-VSB standard should be retained.

The Sinclair demonstrations consisted of an A/B comparison of 8-VSB versus COFDM reception made at two to three locations in downtown Baltimore. Reception was attempted using a "bow-tie" type UHF antenna with two 8-VSB receivers and two COFDM receivers. The antenna was rotated 360 degrees and the range over which reception was achieved was recorded. In general, reception of COFDM was better than 8-VSB at the two sites visited. Sinclair engineers indicated that at both locations analog TV reception was either very poor or not acceptable. Independent measurements indicated that the reception difficulties at the Sinclair sites were due to the presence of strong static signal reflections, or "multipath."

A review of field tests conducted in a number of cities shows good performance for 8-VSB for outdoor reception. These studies show outdoor service availability of 80-95 percent for cities with a small to moderate percentage of obstructed sites and 63-79 percent for cities with a large percentage of obstructions. The field test data also indicate that indoor reception of DTV signals is more challenging. Indoor service availability ranged from 75-100 percent in cities with a small to moderate percentage of obstructed sites and from 31-40 percent in markets with a large percentage of obstructed sites. The above test results indicate that DTV service availability approaches that of NTSC service in most instances and with expected receiver improvements will exceed it in the near future.

OET held discussions with a number of industry representatives. Sinclair stated that its tests have raised concerns as to the ability of the 8-VSB standard to provide service using simple indoor antennas. Sinclair also indicated that it has completed additional observations in the Baltimore area, including sites located near the edge of the demonstration's predicted DTV service area. Sinclair indicated that there were no indoor sites where antenna pointing was not a significant factor in obtaining satisfactory reception of 8-VSB DTV service. It also observed that the necessity to re-orient the antenna to receive stations at different locations would be a significant impediment to DTV "channel surfing." It also stated that at their edge of service sites, there were no locations where 8-VSB was significantly easier to receive than COFDM.

In general, with the exception of Sinclair, other parties continued to support the 8-VSB system as the DTV transmission standard. They generally stated that all of the factors that have been identified regarding COFDM performance in the Sinclair demonstrations were well understood and considered at the time the DTV transmission system decision was made. They stated that the demonstration locations had very strong ghosts that were outside of the correction range of the 8-VSB receivers used by Sinclair. Most of the industry representatives stated that, in theory, 8-VSB and COFDM should be able to perform nearly the same where there is static multipath. Most also stated that COFDM can generally be expected to perform better in situations where there is dynamic multipath, *e.g.*, in mobile operations. A number of parties also stated that 8-VSB offers a number of advantages over COFDM for broadcast DTV service, including superior overall coverage, lower costs of construction and operation, and immunity to impulse noise from household appliances. Industry representatives also asserted that 8-VSB receivers that perform better than the units used in the demonstration are, in fact, available now. The consumer electronics (CE) manufacturers all viewed multipath performance as an issue that will be worked out in the normal process of improving new products.

The study finds that each system has its unique advantages and disadvantages. The 8-VSB system, in general, has better threshold or carrier-to-noise (C/N) performance, has a higher data rate capability, requires less transmitter power for equivalent coverage, and is more robust to impulse and phase noise. The COFDM system, on the other hand, has better performance in dynamic and high level static multipath situations, and offers advantages for single frequency networks and mobile reception.

The study examined and estimated the difference in service availability between COFDM and 8-VSB operation in the top-10 TV markets. In this analysis, COFDM was assumed to have an advantage in urban areas close to a station's transmitter and 8-VSB was assumed to have an advantage in fringe area coverage. These estimates appear to indicate that the relative advantages/disadvantages of either system with regard to overall coverage are generally small and vary by market. The study also investigated the impact on interference to existing NTSC stations of increasing the power of DTV stations by 4 dB in order to make up for the disadvantage of COFDM for fringe reception noted above. This analysis indicates the overall increase in interference to NTSC service from higher power COFDM operations would be generally small. OET indicated that further study is needed to examine whether COFDM could support satisfactory service on VHF and lower UHF channels due to impulse noise concerns.

The study also finds that the adaptive equalizer performance of 8-VSB receivers is very important for reception in multipath conditions. It has been suggested that a value of 22 μs seems to be a reasonable *minimum* equalizer range, but that longer ghost canceling ranges may be beneficial. While quantitative measurements on the 8-VSB DTV receivers used in the Sinclair test were not available, it has been implied that the adaptive equalizer performance for these receivers was in the range of about 10 μs or less. This appears to be a reasonable explanation for the relatively poor performance of the 8-VSB receivers in the Sinclair test, especially with regard to indoor reception.

The study finds that the Sinclair demonstration has provided useful insight into certain indoor reception conditions, particularly with regard to strong multipath conditions, and possible deficiencies of some early DTV receiver designs. However, the study concludes that the multipath reception problems identified by Sinclair are solvable with improved adaptive equalizer performance and that a well-designed 8-VSB receiver should be able to provide satisfactory reception at the Sinclair locations. It further notes that signal strength and immunity to interference from impulse noise are also important factors in successful indoor reception and that 8-VSB may have some advantage over COFDM with regard to these factors.

The study also concludes that, as with most products, performance improvements in DTV receivers will continue to be made over time. From recent announcements and claims regarding the availability of improved equalizer chips, it appears reasonable to conclude that manufacturers are working to improve 8-VSB receivers, including the receivers' indoor reception and signal acquisition capabilities. In this regard, CE manufacturers indicated that improved receivers will be available this fall and that further improvements will be introduced next year.

The study further finds that 8-VSB has about a five percent data rate advantage over COFDM. While a 5 percent data rate difference is relatively small, it could have some impact on the ability to provide certain high definition television programming.

In summary, OET concludes that both 8-VSB and COFDM have certain advantages and disadvantages, and that both systems are capable of providing viable DTV service. OET further concludes that, based on discussions with consumer equipment manufacturers and recent announcements by semiconductor manufacturers Motorola and NxtWave, reasonable solutions to the multipath issue and indoor reception problems raised by Sinclair are being developed and should be available in the near future. OET also finds that some of COFDM's benefits, *i.e.*, its advantages for single frequency network operation and mobile service, may be inconsistent with the current structure of broadcasting in the United States. Further, 8-VSB has some advantages with regard to data rate, spectrum efficiency and transmitter power requirements. Accordingly, OET concludes that the relative benefits of changing the DTV transmission to COFDM are unclear and would not outweigh the costs of making such a revision. OET therefore recommends that the ATSC 8-VSB standard be retained.

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DTV REPORT ON COFDM AND 8-VSB PERFORMANCE

Introduction

Recently, the Sinclair Broadcast Group, Inc. (Sinclair) has conducted demonstration tests comparing a Coded Orthogonal Frequency Division Multiplexing (COFDM) system with the 8-Level Vestigial Side-band (8-VSB) system developed by the Advanced Television Systems Committee (ATSC) and adopted by the Commission as the standard for digital television (DTV) transmissions. Based on these demonstrations, Sinclair has raised questions about the ability of the 8-VSB system to provide satisfactory "over-the-air" service in urban areas using simple indoor antennas.

The Office of Engineering and Technology (OET) has been asked by Commissioner Susan Ness to conduct its own independent assessment of these concerns based upon available engineering information and data and consultations with outside parties. This paper provides OET's preliminary assessment of the problems identified by Sinclair, the efforts by industry to improve 8-VSB reception, and whether there is any need for further action on this matter.

Technical Overview of 8-VSB and COFDM

<u>8-VSB and COFDM</u>

The ATSC 8-VSB system uses a layered digital system architecture consisting of: 1) picture layer that supports a number of different video formats; 2) compression layer that transforms the raw video and audio samples into a coded bit stream; 3) transport layer that "packetizes" data; and 4) radio frequency (RF) transmission layer. The ATSC 8-VSB transmission system is a single carrier frequency technology that employs vestigial sideband (VSB) modulation similar to that used by conventional analog television. The transmission layer modulates a serial bit stream into a signal that can be transmitted over a 6 MHz television channel.

The ATSC 8-VSB system transmits data in a method that uses trellis-coding with 8 discrete levels of signal amplitude. A pilot tone is provided to facilitate rapid acquisition of the signal by receivers. Complex coding techniques and adaptive equalization are used to make reception more robust to propagation impairments such as multipath, noise and interference.[1] The 6 MHz ATSC 8-VSB system transmits data at a rate of 19.4 Mbps.

[1] The ATSC 8-VSB system provides " equalizer training sequences" every 24 milliseconds (ms) to assist the adaptive equalizer in the receiver to correct for fading and multipath. See Section 10.3, "Guide to the Use of the ATSC Television Standard," Doc. A/54, 4Oct 95.

By contrast, the OFDM system is a multicarrier technology. The principle of OFDM is to break a single data stream into many parallel, lower rate data streams. OFDM then uses many subcarriers to transmit these lower rate streams of data simultaneously. To ensure that the subcarriers do not interfere with one another, the frequency spacing between subcarriers is carefully chosen so that each subcarrier is orthogonal to one another.[2] The individual subcarriers are typically modulated using a form of either quadrature amplitude modulation (QAM) or quadrature phase shift keying (QPSK). Coding techniques (the "C" in COFDM) can be used to improve performance.

The multicarrier design of COFDM makes it resistant to transmission channel impairments, such as, multipath propagation, narrowband interference and frequency selective fading.[3] COFDM avoids interference from multipath echoes by increasing the length of the signal samples, so that it is greater than the temporal spread of the multipath, and by applying a "guard interval" between data symbols where the receiver does not look for information. Guard intervals can be designed so that most multipath echoes arrive within the guard period and therefore do not interfere with the reception of data symbols.[4] This permits COFDM to successfully operate with echoes as large as the main signal, *i.e.*, 0 dB. Further, because information is spread among many carriers, if narrowband interference or fading occurs, only a small amount of information is lost.

The Sinclair demonstrations used a COFDM system based upon the European Terrestrial Digital Video Broadcasting (DVB-T) standard using equipment that was modified to operate in the traditional 6 MHz channel used in the United States.[5] That system operated with 1705 subcarriers and 64 QAM, and provided a useable data rate of 18.66 Mbps.[6] More detailed descriptions of both COFDM and 8-VSB are provided in the attached Appendix.

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[2] Ensuring that the subcarriers are orthogonal to one another allows the signals to be separated at the receiver using correlation techniques. In general, rather than using arrays of oscillators and demodulators to create and decode the many subchannels, modern OFDM/COFDM systems employ the Discrete Fourier Transform as part of the modulation and demodulation process. Using this technique, both transmitter and receiver can be implemented using special purpose Fast Fourier Transform (FFT) hardware.

[3] "COFDM: An Overview," William Y. Zou, Public Broadcasting Service, Alexandria, VA and Yiyan Wu, Communications Research Centre, Ottawa, Canada, IEEE Transactions on Broadcasting, Vol. 41, No. 1, March 1995.

[4] Multipath echoes generally arrive within a few tens of microseconds (μs) of the main signal.

[5] The DVB Project is a consortium of public and private sector organizations. The European Telecommunications Standards Institute (ETSI) has adopted the formats developed by DVB as a European standard (ETSI EN 300 744 V1.2.1 (1999-07)).

[6] The DVB standard provides for two modes of operation, a 2K mode with 1705 subcarriers, and an 8K mode with 6817 subcarriers. The 2K mode is suitable for single transmitter operation and for small single frequency networks with limited transmitter distances. The 8K mode can be used for both single transmitter operation and for both small and large single frequency networks. ETSI EN 300 744 V1.2.1 (1999-07), p. 9.

History of COFDM

The theory of orthogonal frequency division multiplexing (OFDM) has been well known for some time. The concept of using parallel data transmission and frequency division multiplexing was first published in the mid-1960s, and a U.S. patent was filed and issued for this approach in 1970.[7] In the early 1990s, significant technical interest was shown in the use of COFDM for terrestrial digital television broadcasting. In 1992, for example, the Communications Research Centre (CRC) of Communications Canada published several papers investigating the possibility of a distributed transmission concept for digital television using a multi-carrier modulation method, such as COFDM.[8] These early studies by the CRC suggested that such systems might provide some advantages over single-carrier systems. In particular, these studies indicated that multicarrier systems would allow operation of single frequency networks and could provide improved performance under multipath distortion. In 1994, George A. Hufford of the Institute for Telecommunications Sciences of the National Telecommunications and Information Administration (NTIA) also released a report on the application of OFDM technology for high definition television.[9] In this report, Hufford indicates that "multicarrier modulation techniques such as OFDM may provide a remedy for multipath and other propagation path imperfections for over-the-air high data rate transmission systems, such as HDTV."

During this period, a number of prototype DTV systems using COFDM were also developed and demonstrated. These included the HD-DIVINE by the Nordic countries, DIAMOND by Thomson-CSF, SPECTRE by NTL of the United Kingdom, HDTVT in Germany, and others. In addition, in 1993, the Digital Video Broadcasting (DVB) project was initiated in Europe.[10]

In 1994, several U.S. and Canadian broadcast organizations solicited potential bidders to build COFDM DTV hardware for evaluation. In 1995, this group presented a proposal for a COFDM DTV system to the FCC's Advisory Committee on Advanced Television Service. The Advisory Committee, however, found that the proposed COFDM system was not ready for testing and did not demonstrate the superiority of COFDM over 8-VSB for the majority of markets.[11] In making

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[7] A U.S. patent was issued for OFDM in 1970. See, U.S. Patent 3,488,445, issued January 6, 1970.

[8] Under this concept, rather than a single high power transmitter, a number of lower power transmitters arranged in a cellular-like manner and operating on the same frequency is used to provide equivalent area coverage. See, for example, "Distributed Transmission Concept for ATV," Gerald Chouinard, Communications Research Centre, Communications Canada, Ottawa, Ontario, Canada, presented at MIT Workshop on Broadband Data Broadcasting, October 26-27, 1992; and "New Coverage Concepts for Digital Terrestrial Television Broadcasting," Gerald Chouinard, Communications Research Centre, Communications Canada, Ottawa, Ontario, Canada, presented at the 18th International Television Symposium, Montreaux, Switzerland, June 10-15, 1993.

[9] "Orthogonal Frequency Division Multiplexing: An Application to High Definition Television," George A. Hufford, NTIA Report 94-316, August, 1994.

[10] DVB is a consortium of public and private sector organizations. The European Telecommunications Standards Institute (ETSI) has adopted the formats developed by DVB as a European standard (ETSI EN 300 744 V1.2.1(1999)).

[11] "Advisory Committee Final Report and Recommendations," FCC Advisory Committee on Advance Television Service, November 28, 1995.

this decision, the Advisory Committee was, among other things, concerned about the additional transmitter power that would be required with a COFDM system.

The Sinclair Demonstration Tests

On June 24, 1999, the Sinclair Broadcast Group (Sinclair) announced that it would begin tests to determine the viability of the DTV standard using the transmission facilities of its station in Baltimore, Maryland.[12] Sinclair stated that the purpose of this testing was to compare 8-VSB and COFDM. It stated that previous tests that it had conducted raised concerns as to the ability of the 8-VSB standard to provide "over-the-air" service into homes and offices using simple indoor antennas.[13]

Sinclair invited broadcasters, equipment manufacturers, the press and others to observe its demonstration. Engineers from OET attended the demonstration on June 29, 1999.[14] The following is a report of what was observed at the demonstration by OET engineers.

The demonstration was conducted using the transmitting facilities of WBFF-TV. The DTV signals were transmitted on channel 40 with an average effective radiated power (ERP) of about 50 kW, using a transmitting antenna mounted about 1000 feet above the ground. The peak-to-average power ratio was about 8.5 dB for COFDM and about 6.5 dB for 8-VSB.[15] The bandwidth occupancy was 5.7 MHz for COFDM and 5.38 MHz for 8-VSB.[16] The COFDM program material consisted of a 7-second clip of standard definition PAL material with an encoded rate of about 3.5 Mbps with extra "bit stuffing" for an effective data rate of 18.66 Mbps.[17] A server was used to provide high definition program material for the 8-VSB signal at a data rate of 19.39 Mbps.

Two 8-VSB and two COFDM receivers were used in the demonstration. The two 8-VSB receivers were commercially available consumer DTV receivers that were purchased locally by Sinclair. The COFDM receivers used were a European consumer COFDM receiver modified to operate at 6 MHz and a laboratory-type test receiver that provided data rate measurement capability. The demonstration viewed by the OET staff consisted of an A/B comparison of 8-

[12] "Sinclair Launches Tests to Determine Viability of Current Digital Television Transmission Standard," http://www.sbgi.net (August 16, 1999).

[13] Sinclair had previously conducted indoor reception tests in the Philadelphia, Pennsylvania area.

[14] Bruce Franca, Robert Bromery, and Robert Eckert of the FCC's OET attended the demonstration.

[15] *HDTV News Online*, article by Ed Williams of PBS, http://web-star.com/hdtv/edwill.html (August 16, 1999).

[16] Neither the COFDM nor the 8-VSB signals used for the demonstration complied with the out of band requirements contained in the FCC rules.

[17] Sinclair indicated that high definition program material was not available at the time for the format used by the COFDM receiver. For the purposes of the demonstration, additional random bits were transmitted to exercise the COFDM system and provide for full data payload of the system.

VSB versus COFDM reception made at two locations in downtown Baltimore.[18] Reception was attempted using a "bow-tie" type UHF antenna mounted on a tripod approximately 5-6 feet off the ground. The antenna was then rotated 360 degrees and the range over which reception was achieved was recorded. If no reception was achieved with the bow-tie antenna, a second, small UHF indoor reflector-type antenna was used. Sinclair indicated that they considered service acceptable where reception was achieved over a complete 360 degrees rotation of the antenna.

Both locations visited during the demonstration were within about eight miles of the WBFF-TV transmitter. The first location was on Lombard Street. Measurements were taken on the sidewalk at street-level. At this location, both COFDM and 8-VSB reception were achieved using the bow-tie antenna. However, reception using the COFDM system was easier to acquire and was maintained over a full 360 rotation of the antenna.[19] 8-VSB reception at this location was achieved over two arcs of about 60 degrees each, or about 120 degrees. In addition, the antenna had to be rotated more slowly and carefully for 8-VSB reception. The second location visited was an 11th floor apartment located in the Baltimore Harbor area on Lee Street. This location faced away from the transmitter site so that only reflected signals could be received. At this location, only COFDM reception was achieved with the bow-tie antenna. 8-VSB reception was only possible by placing the reflector type antenna in direct contact with the aluminum window frame. Those in attendance postulated that this effectively permitted the entire window frame and surface to become part of the receiving system. In general, reception of COFDM was better than 8-VSB at the two sites visited. Sinclair engineers indicated that at both locations analog TV reception was either very poor or not acceptable with simple indoor antennas.

As a result of these demonstrations, Sinclair argued that today, DTV does not work. They also stated that the traditional outdoor reception model used also to predict reception for DTV service is outdated. They observed that a large portion of the viewing population who rely on over-the-air broadcast service do not have outdoor antennas and instead have loop or bow-tie antennas sitting on their receivers indoors. They argued that there is a demonstrably better alternative in COFDM, and that at the least manufacturers need to improve the reception capabilities of their DTV receivers to be comparable to that available with COFDM.

Sinclair Report

On September 24, 1999, Sinclair presented a report of the results of its Baltimore reception tests to the IEEE Broadcast Symposium in Washington, D.C.[20] The report documents reception results at 40 sites in the Baltimore area.[21] Sinclair indicates that approximately three-quarters of

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[18] A third location was not visited due to time constraints.

[19] At this location, the COFDM system did appear to contain some visual impairments or artifacts to at least one of the FCC engineers although it could not be determined whether this was due to the transmission or in the program material.

[20] "Comparative Reception Testing of 8VSB and COFDM In Baltimore," Nat Ostroff and Mark Aitken, Sinclair Broadcast Group, www.sbgi.net/DTV, September 24, 1999.

[21] The Sinclair Report also notes that a number of additional sites were investigated and that while these sites were not documented the results at those sites are consistent with the 40 documented sites.

these sites were located within the "near field," *i.e.*, less than 30 miles, of the WBFF-TV transmitting antenna. It reports that 8-VSB reception was successful at 10 of 31 sites with a Panasonic receiver and at 12 sites of 31 sites with a Pioneer receiver. For COFDM, it reports successful reception at all 31 sites with a Nokia receiver and at 21 of 25 sites with an NDS receiver. Sinclair also presents "ease of reception" data showing the range in degrees of antenna orientation at which reception was achieved. The Sinclair data indicates that COFDM was less sensitive to antenna orientation than 8-VSB. Sinclair indicates that it was not possible to receive 8-VSB signals at locations with "spectrum deviations" in excess of 15 dB from a signal with "nominal reception" characteristics. It further indicates that COFDM reception was possible with spectrum deviations of up to 25 dB. Sinclair also states that 8-VSB, as compared to COFDM, was quite intolerant to dynamic multipath conditions.

Sinclair indicates that the purpose of its "far field," *i.e.*, beyond 30 miles, testing was to try to determine if a meaningful difference in performance could be observed due to the differences between 8-VAB and COFDM in threshold carrier-to-noise (C/N) ratio needed for acquisition of service. It states that while there is a 4 dB difference in the theoretical C/N performance between of the two systems in favor of 8-VSB, the average daily calibration threshold difference between the 8-VSB and COFDM receivers was 3.28 dB and that in the field this difference shrank to 2 dB. Sinclair suggests that this may be due to the effect of real world impairments that add to the theoretical "gaussian" channel values.

In its summary comments and conclusions, Sinclair states that the need for indoor reception was ignored during the design phase of 8-VSB and that portability and mobility was not given any level of priority. It argues that these factors should not be overlooked today. Further, it states that the results of the Baltimore tests demonstrate that the present generation of 8-VSB receivers being offered to the public fall far short of the performance needed to make DTV a success as an over-the-air service. Sinclair argues that the broadcast community should demand better performance from 8-VSB receivers or look elsewhere for a DTV transmission system.

<u>Oak Technology Report</u>

Oak Technology Ltd., a manufacturer of DVB-T chipsets and other semiconductors, has published a brief report with some technical information on the demonstration.[22] The Oak report contains measurement data and observations from five sites in Baltimore that were visited on June 24, 1999. These sites included Sinclair's offices and the Lombard Street and Lee Street Apartment sites visited by OET staff. In addition, the Oak report contains data from two other sites: the "Latin Fields" School parking garage and the "Panda Mall" parking garage. The Oak report is important in that it "quantified" the received signals and multipath conditions present at each of the Sinclair sites they visited. That is, at each site, samples of both the COFDM and 8-VSB signals were captured.

The "Latin Fields" site is described as a fairly open site about 4 miles from the station with no direct line of sight. The spectrum of the received signal at this location was described as "good"

[22] "Report on Data Captured from Sinclair Broadcast Transmissions in the Area of Baltimore, USA," Jonathan Parker, Mat Collins, and Doug Pulley, Oak Technology Ltd., Bristol, U.K., July, 1999.

with some ripple. The channel impulse response showed significant multipath components at –18 dB at + 1 µs and –29 dB at +1.5 µs.[23] Both COFDM and 8-VSB reception were described as good, with COFDM reception being more robust to antenna rotation.

At the "Panda Mall" site, the spectrum was described as highly shaped with a deep null indicating a strong short delay echo. The channel impulse response showed significant multipath components at –10 dB at +0.5 µs, -25 dB at +1.5 µs, and –29 dB at +2 µs. At this location, both COFDM and 8-VSB reception were described as good.

The Oak report also provided some indication of the signal propagation at the two sites visited by OET staff. The spectrum was described as "poor" at the Lombard street site. The channel impulse response showed many significant multipath components. In particular, significant multipath components were found at –8 dB at –0.5 µs, -14 dB at +0.5 µs, -16 dB at +0.8 µs, -25 dB at +9.5 µs, with additional multipath components from –25 to –30 dB at +2 to +5 µs and at about –30 dB at +10 to +13µs. At this location, Oak reports no reception with the "bow tie" antenna for 8-VSB. (Although, as indicated above, during the OET staff visit, 8-VSB reception was achieved.) COFDM reception was achieved, but with artifacts on one receiver. At the Lee Street apartment, Oak describes the spectrum as poor with many deep nulls indicating long delay echoes. The channel impulse response indicated "lots of multipath" with the most significant paths at –12 dB at +0.3 µs, -4 dB at +3.5 µs, -7 dB at +4.4 µs, -15 dB at +9.5 µs, -22 dB at 12.7 µs and –17 dB at +17.2 us. Oak reported COFDM reception via one of the set-top boxes and no 8-VSB reception at this site.[24]

In summary, Oak notes that there was considerable variation in signal strength at the three outdoor sites and that far less variation was seen at the apartment site due to its elevated location. Oak states that "although the channel impulse responses are quite interesting, they do not appear to be particularly 'bad.' That is, we believe that at all locations both COFDM and VSB should be receivable given an appropriately designed receiver."

OET staff conversations with various manufacturers seem to confirm Oak's conclusion that 8-VSB receivers can be designed to operate in the environments found in the Sinclair demonstration. As indicated below, several manufacturers, e.g., Harris, Hitachi, Thompson and Zenith, have used this data (or similar data taken in their own tests at some of the Sinclair sites) to simulate the reception conditions of the Sinclair demonstration. These manufacturers have stated that their existing or future equipment would perform satisfactorily under these conditions. Sinclair has also stated that they may be cooperating with a chipset manufacturer in further testing of 8-VSB reception.

[23] Values are relative to 0 dB for the main path.

[24] Oak states that this is anecdotal information since the laboratory COFDM receiver was not used to verify reception of the signal.

8-VSB Field Tests

In addition to the Sinclair demonstration, field tests of the 8-VSB system have been conducted in a number of cities. These tests have been conducted by broadcasters, transmitter suppliers, receiver manufacturers and others to gain experience with the DTV system and to provide information for improving the performance of transmitter and receiver hardware. As reported in a paper by Gary Sgrignoli of Zenith, a total of 2682 outdoor sites in nine cities and 242 indoor sites in five cities have been evaluated in these tests.[25] These tests provide data on 8-VSB performance in a variety of urban, suburban and rural environments. Other tests are currently under way in additional locations.

A summary of these tests is presented in following table:

City	Chan.	Outdoor Sites			Indoor Sites		
		No. Sites	Pctg. > Threshld.	Avail. Pctg.	No. Sites	Pctg. > Threshld.	Avail. Pctg.
Charlotte (I)	53	199	95.5	91.5	32	90.6	75.0
Charlotte (II)	6	169	100	82.2			
Raleigh	32	163	93.9	89.6	36	91.7	80.6
Chicago	20	112	99.1	92.9	10	100	100
San Jose	52	80	96.3	95.0			
New York	56	158	91.1	80.4			
Washington, D.C. (I)	30	333	89.9	78.7	67	82.9	40.6
Washington, D.C. (II)	34	279	65.3	63.0	67	56.2	31.2
Seattle (I)	38	399	88.0	68.7			
Seattle (II)	48	404	88.4	67.8			

The above table shows the city in which each test was conducted, the TV channel used, and, for both indoor and outdoor measurements, the number of sites where measurements were taken, the percentage of sites with received signal-to-noise (S/N) ratio above the 15 dB 8-VSB operating threshold, and the percentage of sites at which service was actually available.[26]

The data in the table is grouped by those cities with a small-to-moderate percentage of obstructed sites (less than about 25 percent), *i.e.*, Charlotte, Raleigh, Chicago, San Jose, and New York) and those with a large percentage of obstructed sites (38-64 percent), *i.e.*, Washington, D.C. and Seattle. Stations in the first group had transmitter antenna height above average terrain (antenna HAAT) of over 1000 feet and generally smooth terrain. Those in group two had antenna HAAT less than 800 feet and generally hilly terrain.

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[25] "Preliminary DTV Field Test Results and Their Effects on VSB Receiver Design," Gary Sgrinoli, Zenith Radio Electronics Corporation (Preliminary ICCE '99 Conference Paper). DTV field tests have been performed in nine cities, including Charlotte, Washington, D.C., Raleigh, Chicago, Seattle, New York, San Jose, Cincinnati, and Dallas.

[26] For indoor tests, the test location was chosen to be at an existing NTSC set with an indoor antenna within the home. If such a site was not present, then another site within the home was selected, typically in a corner of the living or family rooms, on in a bedroom.

The field test data generally show good performance for 8-VSB for outdoor reception.[27] These studies show outdoor service availability of 80-95 percent for cities with a small to moderate percentage of obstructed sites and 63-79 percent for cities with a large percentage of obstructions.

The field test data also indicate that indoor reception of DTV signals is more challenging. Indoor service availability ranged from 75-100 percent in cities with a small to moderate percentage of obstructed sites and from 31-40 percent in markets with a large percentage of obstructed sites. Sgrignoli suggests that indoor reception problems are generally due to lower signal strength (caused by lower antenna height, building penetration losses, and lower antenna gain), more multipath (more reflecting objects and less directional antennas), and moving objects that obstruct and reflect signals (people and vehicles).

Sgrignoli concludes that the above test results indicate that 8-VSB DTV service availability will approach that of NTSC service in most instances. He also states that DTV receiver implementation will continue to improve as second and third generation models become available in the market.

Reports in the Press

Newspaper reports of the Sinclair demonstration and concerns were typified in an article in the *New York Times* (*Times* article).[28] The *Times* article highlighted the problems Sinclair says it found with indoor reception of DTV signals. It noted that the problem with the current system is multipath distortion from reflected signals. The *Times* article described how in the demonstration it was necessary to carefully aim the antenna to receive 8-VSB service, while it was very easy to receive COFDM service. The article reported that one broadcaster viewing the demonstration stated that "You have to work to find a signal" with the 8-VSB system, "and have to work to lose it" with the other. It indicated that Sinclair seeks to revise the DTV standard and that if it is successful, much of the new DTV equipment that consumers and stations have already purchased would be rendered obsolete. The article went on to state that Sinclair intends to ask other TV station group owners to sign a petition to the FCC requesting that it consider the standards issue.

The *Times* article also reported that supporters of the current system argued that the Sinclair demonstration was flawed because it stressed the advantages of the COFDM system without addressing the trade-offs and disadvantages. It further described supporters' statements that the demonstration used first-generation 8-VSB receivers and that manufacturers would improve the

[27] It can be inferred that the differences between the percentage of sites above threshold and the availability percentage generally indicate that reception was impaired by multipath, noise, and/or other propagation phenomena, since adequate signal strength was available for reception. We further note that the results in the Table reflect DTV testing that is in some instances based on transmitter powers and antenna heights that are substantially lower than would be used in providing permanent service. Accordingly, the Table results may underestimate the actual availability of DTV reception in those markets.

[28] *See* "Broadcaster Seeks Change in Digital TV Format," Joel Brinkley, *New York Times*, July 12, 1999.

performance of their receivers in subsequent generations. It also noted that the 8-VSB system had been extensively tested and found to perform "magnificently." The *Times* article indicated that Sinclair could have trouble enlisting the support of a large group of broadcasters, noting the National Association of Broadcasters had not heard from other broadcasters indicating that they wanted to revise the DTV standard.

The trade press published a number of articles on the 8-VSB/COFDM controversy. An article in *Broadcasting & Cable* (*Broadcasting* article) reported that some broadcasters, led by Sinclair, feared loss of service to viewers unwilling or unable to mount an outdoor antenna or subscribe to cable service.[29] The *Broadcasting* article stated that the first generation of DTV receivers do a far worse job of receiving pictures than a "$79 black-and-white sitting on the kitchen counter." The article further reports that Sinclair is concerned that the reception problem threatens the potentially lucrative business for broadcasters of transmitting data to computers, particularly laptops and other portable devices. It quotes David Smith, President and CEO of Sinclair, as saying of DTV "Today, it does not work." It further indicates that within the next 60 days, Sinclair intends to petition the FCC to either impose DTV receiver standards to improve reception or reconsider 8-VSB as the U.S. standard.

The *Broadcasting* article next reports on the side-by-side tests in the Sinclair demonstration and the reactions of those observing the demonstration. Typical comments of those observers indicated that the COFDM system "just worked better. It was difficult or impossible to get 8-VSB in some cases, and it was not that way with COFDM." One of those observers stated that while "it's impossible to draw any conclusions from the Sinclair tests, he would like to see more research into the merits of 8-VSB and COFDM, and sooner rather than later." The article states that Sinclair points out that the COFDM system can also support mobile reception -something that 8-VSB was not designed for. In response, supporters of the 8-VSB system note that not many people watch TV while driving along.

Reporting the general reactions of broadcast engineers, the *Broadcasting* article indicates that most aren't sure if the 8-VSB standard is actually inadequate for indoor reception or whether the Sinclair demonstration simply reflects the shortcomings of the first generation DTV receivers that were rushed to market last fall. Other reactions from broadcast engineers were typified in the statements by Andy Setos of Fox that "we didn't learn much new" and "we know chips are being developed to address those matters." The article reports that receiver manufacturers view this as a receiver issue, not a system issue and indicate that their second generation 8-VSB receivers, some of which are on the market now, offer a significant improvement in their ability to handle multipath. The *Broadcasting* article also reports that most manufacturers and broadcasters pointed out that COFDM's multipath performance comes with the trade-off that its carrier-to-noise threshold is greater than that of 8-VSB (5 dB higher), and that this means COFDM does not reach out as far as 8-VSB. It reports that the engineers stated that to achieve the same reach would require more than twice the power as 8-VSB, with larger transmitters, larger electric bills, and perhaps an overhaul of the DTV Table of Allotments.

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[29] *See* "Back to the Future, " *Broadcasting &Cable*, August 2, 1999.

The *Broadcasting* article indicates that Sinclair's stance seems to appeal to some smaller station groups that aren't sure they'll get digital carriage by cable systems. In this regard, a spokesman for Pappas Telecasting is quoted: "The concept we were sold was broadcast replication, and that's based on signal strength. But it appears you don't have replication if you can't receive the signal at the same locations as you receive an NTSC signal you'd be willing to watch." The *Broadcasting* article says that with the exception of Fox, the major networks have been quiet on the DTV debate. It states that CBS and ABC are conducting indoor tests of 8-VSB reception. The *Broadcasting* article closes with a statement by Craig Tanner of the ATSC that "What Sinclair is doing fundamentally is communicating to the world that they believe in a different set of requirements for digital broadcasting. It remains to be seen whether anyone agrees with them and whether the industry as a whole can come to a consensus."

Several other articles in the trade press have reported information essentially similar to that in the *Times* and *Broadcasting* articles.[30]

Information from Industry Representatives

OET staff also had discussions on these matters with a number of industry representatives who are variously knowledgeable about the DTV standard, the 8-VSB and COFDM transmission systems, DTV receiver performance, the Sinclair demonstration, and television stations' DTV implementation plans. These parties included representatives of broadcast trade associations, television networks, television stations, television station equipment manufacturers, consumer electronics (CE) manufacturers, and others.[31]

<u>General Views on the Transmission Standard Issue</u>

With the exception of Sinclair, the industry representatives we spoke with indicated that they continue to support the 8-VSB system as the DTV transmission standard. These parties generally stated that all of the factors that have been identified regarding COFDM performance in the demonstrations conducted by Sinclair were well understood and considered at the time the DTV transmission system decision was made. For example, Ed Milbourn of Thomson stated that there were no surprises in the Sinclair demonstration. He and others stated that there were

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[30] *See* "8-VSB – Can It Be Fixed," *HDTV News Online*, July 16, 1999; "Fallout From Sinclair Gambit On U.S. DTV Standard Lands On Receiver Makers," *Digital Technology Reports*, July 26, 1999; "8-VSB vs. COFDM: Debate Refuses to Go Away (but Should)," *TV Technology*, March 24, 1999 "Sinclair Re-examines COFDM Capability," *TV Technology*, June 16, 1999; and "You Have to Receive to Believe," Bear, Stearns, & Co. Report, August 3, 1999.

[31] We wish to thank the following individuals for their assistance in providing information for this report: Bruce Allen (Harris Communications), Lynn Claudy (National Association of Broadcasters), Dave Converse (Owned TV Station Group of ABC, Inc.), Greg DePriest (Toshiba), Peter Fannon (Panasonic/Matshushita Electric), George Hanover and Ralph Justus (Consumer Electronics Manufacturers Association), John Henderson (Hitachi), Frank Kott (North American Philips Corporation), Wayne Luplow (Zenith Electronics Corporation), Ian Matthews (Sony), Andy Setos (Fox Television Stations, Inc.), Saul Shapiro (ABC, Inc.), David Smith, Nat Ostroff and Harvey Arnold (Sinclair Broadcast Group), Victor Tawil (Association for Maximum Service Television, Inc.), Michael Tsinberg (Toshiba), and Ed Milbourn (Thomson Consumer Electronics, Inc.).

trade-offs in the potential performance characteristics of the candidate transmission systems, and that these tradeoffs were balanced in making the transmission system decision. They acknowledged that the design of the COFDM approach does have some inherent advantages over the 8-VSB design in handling multipath, and in particular the dynamic multipath that is typically seen in mobile operations. However, they also stated that the performance of 8-VSB in handling static multipath can be very close to that of COFDM. Those supporting the 8-VSB system said that they believe that the dramatic performance differences between 8-VSB and COFDM observed in the Sinclair demonstrations are the result of the relatively poor multipath signal handling capabilities of the first-generation VSB receivers used in those tests, rather than a limitation of the VSB system. Lynn Claudy of the NAB, Victor Tawil of MSTV, Bruce Allen of Harris Corporation and others stated that they are comfortable that the 8-VSB system has plenty of potential to provide satisfactory service and that manufacturers simply need to improve the multipath handling capabilities of DTV receivers.

In a follow-up conversation with Sinclair, Nat Ostroff discussed additional work that Sinclair had done with its demonstration project. He indicated that Sinclair has now completed observations on a total of 40 sites in the Baltimore area, with 12 of these sites located near the edge of the demonstration's predicted DTV service area. Ostroff indicated that they found no indoor sites where antenna pointing was not a significant factor in obtaining satisfactory reception of 8-VSB DTV service. He also observed that the necessity to re-orient the antenna to receive stations at different locations would be a significant impediment to DTV "channel surfing." Ostroff stated that at their edge of service sites, there were no locations where 8-VSB was significantly easier to receive than COFDM. He therefore discounted the concern that the 8-VSB advantage in carrier-to-noise ratio would be an important factor in the range at which service could be received. Rather, he stated that other impairments in the path of far reception seemed to swamp the C/N advantage of 8-VSB.

Ostroff also indicated that Sinclair is pleased that the industry, both broadcasters and consumer electronics manufacturers are paying more attention to the improvement of DTV receiver performance. He noted that in a little more than two months, the atmosphere has gone from denial of the problem to acceptance that action is needed and to resistance to use of the outdoor reception model for DTV. He stated that the announcement of the Motorola and NxtWave DTV demodulator chips with improved multipath handling performance is very encouraging. In this regard, he stated that he has invited NxtWave to verify the performance of their new chipset at the sites used in the Sinclair tests this September. Ostroff indicated that if the new chips work, we may be beginning to see the light at the end of the tunnel on this problem.

Some broadcasters expressed the viewpoint that the important issue is that DTV receiving equipment needs to provide satisfactory service from off-the-air signals when consumers bring it home and place it in operation. These parties stated that broadcast DTV service has to work when people buy equipment or else the service will fail. One party offered the view that supporters of COFDM have made that technology work well, so why hasn't the same happened with 8-VSB? He stated that broadcasters have been making their share of investments in DTV, and that CE manufacturers need to close the gap on their side. Dave Converse of ABC's Owned TV Station Group indicated that his organization was not surprised by what they saw at the

Sinclair demonstration and they have not reached a position on whether any changes or actions are needed.

Industry Views on the Sinclair Demonstration

The industry representatives who viewed the Sinclair demonstration agreed that the performance of the COFDM set-up was significantly better than that of the 8-VSB. They also agreed that the observed differences were due to the presence of multipath at the selected observation sites. However, many of these parties also offered explanations as to why such significant differences were observed. All of the industry representatives agreed that the demonstration, while not scientific, shows that the 8-VSB receivers currently available do not perform well in conditions of strong multipath signals and that the available COFDM equipment is able to work in such situations. John Henderson of Hitachi and Bruce Allen of Harris indicated that they had made their own measurements and observations at some of the locations used for the Sinclair demonstration. They indicated that at the sites selected by Sinclair, the problem affecting reception was very strong levels of multipath signals. They stated that these locations had very strong ghosts, both leading and trailing, that were outside of the correction range of the 8-VSB receivers Sinclair used. The parties also noted that NTSC service of acceptable quality was not available at the Sinclair sites. Several parties familiar with the performance of the available 8-VSB receivers stated that Sinclair used models with the poorest multipath performance.

Henderson indicated that while he didn't feel that Sinclair had picked particularly "bad" locations, he didn't see similarly strong ghosts when he used his equipment to examine the performance of the 8-VSB signals of operating DTV stations in other markets, including New York. Allen stated that Harris felt that the sites chosen for the demonstration were not typical even for an urban environment, and that in fact only a very small percentage of sites would have the strong signal and strong multipath levels exhibited in the Sinclair sites.

Both Henderson and Allen also offered a critical analysis of various elements of the Sinclair demonstration. First, they stated that the COFDM system used by Sinclair had a data transmission rate less than that of the 19.4 Mbps rate of the 8-VSB system. They indicated that this allows for longer guard intervals in the COFDM signal, which improves reception under multipath conditions. Henderson and Allen stated that a COFDM configuration with higher data rate would not have operated as well. Allen indicated that neither the 8-VSB signals nor the COFDM signals met the FCC DTV emissions mask, and that the COFDM emissions exceeded the mask by more than those of the 8-VSB signal. He indicated that the Harris tests used a DTV receiver with a better adaptive equalizer and tuner (second generation) than the units used by Sinclair, and that they were able to receive 8-VSB service at all of the Sinclair sites. However, he indicates that Harris did have to point its antenna.

COFDM vs. 8-VSB

Industry representatives stated that, in theory, the 8-VSB and COFDM systems should be able to perform nearly the same in providing service where there is static multipath but that COFDM can generally be expected to perform better in situations where there is dynamic multipath, *e.g.*, in mobile operations. These parties stated that with 8-VSB, multipath reflection, or ghosting, is processed through an adaptive equalizer and more complex equalizers are needed to handle stronger reflections and longer intervals of reflection. Wayne Luplow of Zenith stated that in practice, COFDM will always perform a little better where there is a strong main signal and a ghost that is almost as strong. Allen similarly indicated that COFDM will perform better with dynamic multipath and with static multipath where the reflection is less than 4 dB down from the main signal.

As described by Allen, Tawil and others, 8-VSB offers a number of advantages over COFDM for broadcast DTV service. First, despite Sinclair's claim that the C/N advantage of 8-VSB is mitigated by other factors, these parties maintained that 8-VSB offers superior overall coverage. Harris, for example, stated that COFDM would require substantially more power than 8-VSB (6 dB, or four times, more power than 8-VSB) to serve the same area. These parties state that broadcasters using COFDM would therefore be faced with losing substantial coverage, or incurring significantly higher costs for more powerful transmitters and additional electric power for operation. Harris stated that the additional power is needed because COFDM has a higher C/N threshold than 8-VSB and because it operates with a higher peak-to-average signal power ratio than 8-VSB.

Harris also argued that 8-VSB operation is significantly more cost effective. It indicated that COFDM station construction costs would be higher because of the need for a more powerful transmitter, heavier antenna and transmission lines, and possibly a stronger tower or tower strengthening. In addition, the cost of operating the station would increase, because more electric power would be used. Harris estimates that the cost of construction to increase from 50 kW to 200 kW operation would be $600,000, and that the annual operating costs of such a station would increase $65,000. As a second example, Harris estimates that the construction cost to increase from 250 kW to 1 MW would be $950,000, and that the annual operating costs of such a station would increase by $227,000. In this regard, Harris specifically refuted Sinclair's claim that converting to COFDM would only cost broadcasters the $50,000 price of a new COFDM exciter.

A number of parties also suggested that 8-VSB is more immune to impulse noise than COFDM. Ed Kott of Philips indicated that there have been significant problems of interference from impulse noise (RF noise from vacuum cleaners, hair dryers, light dimmers, power lines, etc.) to COFDM service in Great Britain. Allen indicated that COFDM is 8 dB more susceptible to impulse noise commonly found in consumer homes. He indicated that impulse noise occurs particularly in the VHF band and the lower portion of the UHF band, and that low band VHF channels in particular would suffer a significant loss of coverage if COFDM were used.

Harris stated that the data throughput for COFDM DTV operation in a 6 MHz channel would be less than the 19.4 Mbps provided with 8-VSB operation. They stated that this difference makes 8-VSB more efficient for data applications, including emerging broadband services, as well as more suitable for HDTV programming. Harris indicated that the higher data capacity also enables 8-VSB to provide other services, such as multichannel video and ancillary data, more efficiently. The Harris staff also suggested that in order to replicate existing NTSC service with COFDM it might be necessary to revisit the DTV Table of Allotments.

Improvements in 8-VSB Performance

Most of the parties we spoke with asserted that 8-VSB receivers that perform better than the units used in the demonstration are, in fact, available now. That is, other models are already available that can provide acceptable service at the Sinclair locations. However, those receivers would still need to have their antenna properly oriented to provide service at the Sinclair locations. The CE manufacturers we spoke with all indicated that they are working on improving their 8-VSB receivers, particularly the adaptive equalizer section of those devices that correct for multipath. They stated that these improvements are part of ongoing efforts in product development that were well underway before the current controversy arose. In this regard, they indicated that they were well aware of the less than optimal multipath performance characteristics of their current products and not surprised by the observations made in Sinclair's demonstration. The CE manufacturers all viewed multipath performance as an issue that will be worked out in the normal process of improving new products. They were all very confident that they could, and would, produce equipment that would provide satisfactory reception of 8-VSB signals in the presence of complex multipath conditions.

Peter Fannon of Panasonic, Ed Kott of Philips, Wayne Luplow of Zenith, Ian Matthews of Sony, and Ed Milbourn of Thomson indicated that their second generation receivers, many of which will be available for this Christmas sales season, will provide substantially better multipath handling capability. They further indicated that their third generation models, to be available in the future, will have further improvements. One party indicates that his firm's third generation equipment will be able to process reflections of as much as 40 μs difference from the main signal and will have faster processing capability for handling dynamic multipath. Luplow indicated that in the "concrete canyons" of central urban areas he expects there will be only a small percentage of locations where COFDM would work better than 8-VSB. He also indicated that he thinks it will always be necessary to do some antenna pointing in indoor environments. Luplow and Milbourn stated that manufacturers are already developing DTV antennas that are electronically steerable by the receiver itself, so that consumers will not have to do this manually as they do with current rabbit ear and loop antennas.

Recently, both NxtWave and Motorola announced new VSB demodulator chips that offer improved performance. The NxtWave chip claims to be able to cancel ghosts of - 4.5 to + 44.6 μs.[32] The Motorola chip is said to be able to correct ghosts of - 2.9 to + 41 μs.[33]

Evaluation and Recommendations

While the Sinclair demonstration has raised the debate between COFDM and 8-VSB, this issue is not new. In 1995, it was stated that the " … debate on COFDM versus vestigial sideband (VSB) modulation or quadrature amplitude modulation (QAM) has been engaged in the past and

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[32] "VSB/QAM Receiver Cracks the Code to Indoor and Mobile Reception," Patrick Mannion, *Electronic Design*, August 23, 1999.

[33] "New Chips Said to Fix DTV Reception Flaws," *Communications Daily*, August 23, 1999.

there is no sign that it will end soon. One reason is that neither COFDM nor VSB has a clear advantage in all of the performance aspects."[34] In our opinion, that conclusion is still valid today.

<u>Evaluation of 8-VSB and COFDM</u>

As discussed below, our analysis finds that each system has its unique advantages and disadvantages. The ATSC 8-VSB system, in general, has better threshold or carrier-to-noise (C/N) performance, has a higher data rate capability, requires less transmitter power for equivalent coverage, and is more robust to impulse and phase noise. The COFDM system has better performance in both dynamic and high level (up to 0 dB), long delay static multipath situations.[35] The COFDM system may also offer advantages for single frequency networks and mobile reception.[36]

<u>Threshold and Service Area /Interference Performance</u>. As indicated above, COFDM has an advantage close to the transmitter with regard to strong multipath signals and 8-VSB has an advantage with regard to service threshold and fringe area coverage. The following table shows estimates of the difference in service availability between COFDM and 8-VSB operation in the top 10 TV markets:

Service Availability Comparison

City (1)	VSB Total Pop. (2)	Urban Center Pop. (3)	COFDM Urban Advantage (4)	VSB Fringe Advantage (5)	Net. Advantage (6)	Percent Gain/(Loss) w/ COFDM (7)
New York	18,199,417	1,466,538	586,615	310,132	(C) 150,971	0.83
Los Angeles	14,332,652	178,304	71,232	136,273	(V) 65,041	(0.45)
Chicago	8,395,277	177,294	70,918	94,939	(V) 24,021	(0.29)
Philadelphia	8,011,757	469,872	187,949	315,846	(V) 127,897	(1.60)
Boston	6,485,082	211,469	84,588	134,438	(V) 49,850	(0.77)
San Francisco	6,207,475	145,364	58,146	125,618	(V) 67,472	(1.09)
Washington, D.C.	6,183,756	112,763	45,105	114,849	(V) 69,744	(1.13)
Detroit	5,089,907	169,784	84,892	130,002	(V) 45,110	(0.89)
Dallas/Ft. Worth	4,157,223	484,778	193,911	40,542	(C) 153,369	3.69
Atlanta	3,282,147	383,239	153,296	67,005	(C) 86,291	2.63

[34] "COFDM: An Overview," William Y. Zou, Public Broadcasting Service, Alexandria, VA and Yiyan Wu, Communications Research Centre, Ottawa, Canada, IEEE Transactions on Broadcasting, Vol. 41, No. 1, March 1995.

[35] "Performance Comparison of ATSB 8-VSB and DVB-T COFDM Transmission Systems for Digital Television Terrestrial Broadcasting", Dr. Yiyan Wu, Communications Research Centre, ICCE '99. "Guide for the Use of Digital Television Terrestrial Broadcast Systems Based on Performance Comparison of ATSC 8-VSB and DVB-T COFDM Transmission Systems, Document 11A/65-E, 11 May 1999, Special Rapporteur's Group, Study Group 11 of the Radiocommunication Study Groups of the International Telecommunications Union.

[36] Wu and others, however, suggest that mobile operation and HDTV reception cannot be achieved concurrently at this time with COFDM.

The above Table compares estimated COFDM service advantages in the downtown urban centers of the major markets and estimated 8-VSB advantages in the outer fringe service areas of those markets. Column (6) of the table shows the net advantage in population served for COFDM or 8-VSB and column (7) shows the percentage gain or loss that could be expected from COFDM operation. Column (2) shows the average population predicted to be served by DTV stations in the market with 8-VSB service. Column (3) shows the urban center population.[37] Column (4) shows the COFDM urban advantage in population served. The COFDM urban advantage is based on an assumption that 80 percent of the urban center population would have a COFDM signal above threshold and that 50 percent of these locations would be faced with a difficult multipath situation where COFDM would work and it is assumed 8-VSB would not.[38] Column (5) shows the 8-VSB fringe advantage in population served. The VSB fringe advantage is based on the assumptions that there is a 4 dB transmitter power advantage for 8-VSB that extends coverage beyond that provided by COFDM and that 50 percent of the population in this extended coverage area could receive service with 8-VSB but not with COFDM.[39]

We recognize that the service area comparison estimates provide only a rough measure of the relative performance advantages of the two systems. Nevertheless, these estimates would appear to indicate that the relative advantages/disadvantages of either system with regard to overall coverage are generally small and vary by market.

We also investigated the impact on interference to existing NTSC stations of increasing the power of DTV stations by 4 dB in order to make up for the disadvantage of COFDM for fringe reception noted above. This analysis indicates that if the 1 MW cap is retained, the overall increase in interference to NTSC service would be generally small. Most NTSC stations would

[37] The urban centers were determined from examinations of city maps. Census tract data was then aggregated for the area defined as the urban centers.

[38] The COFDM urban center service estimates were developed based on the "worst-case" indoor test data reported by Sgrignoli. This data showed signal availability of about 80 percent and reception at about 50 percent of the sites where the threshold signal level was available. The estimates also assume that all reception failures above threshold are due to multipath and can be corrected with COFDM.

[39] This analysis assumes that the same transmitters are used for both COFDM and 8-VSB. The 4 dB power advantage for 8-VSB is based on an assumption that a COFDM transmitter operates with a 2.5 dB higher peak-to-average ratio and that the COFDM receiver requires at least a 1.5 dB higher threshold signal or C/N ratio. We believe that this assumption is conservative. We note that others have suggested that the 8-VSB power advantage is 6 dB or more. For example, according to Harris and others, the ATSC 8-VSB system has at present a 6 dB performance advantage over DVB-T COFDM system from a transmitter power implementation point of view. This results from a 3.5 dB difference in C/N performance and a 2.5 dB higher peak to average power ratio for the DVB-T COFDM system. However, Wu postulates that improvements in COFDM technology may reduce this difference to 4 dB in the future. He notes that about 1.5 dB of the difference in C/N is due to the fact that the DVB-T coding was chosen to provide compatibility with the DVB-S (satellite) and DVB-C (cable) standards and can correct 8-byte transmission errors. The ATSC system uses a more powerful code that can correct up to 10-byte errors. This 1.5 dB difference is unlikely to be reduced with technical advances or system improvements, according to Wu. We also believe that the assumption that only 50 percent of households will be able to receive 8-VSB service in this "4 dB fringe area" is also conservative.

receive 1 percent or less additional interference to their predicted service area.[40] However, for a small number of NTSC stations, population service loss would be more significant. This analysis assumes that COFDM would have interference characteristics with respect to interference to NTSC similar to 8-VSB, *i.e.*, would appear like random noise. We believe that this is a reasonable assumption, but further study and testing is needed to confirm the interference characteristics of COFDM. Further study would also be needed to examine whether COFDM could support satisfactory service on VHF and lower UHF channels due to impulse noise concerns. At this time, it is unclear whether any changes in the DTV Table of Allotments would be needed to accommodate a change to COFDM.

Multipath Performance. As noted above, COFDM systems avoid multipath interference by having a sufficient guard interval between symbols and the 8-VSB system must have an adaptive equalizer of sufficient length.[41] From the Oak report, the principal propagation phenomena at the Sinclair demonstration was strong static multipath, with all of the significant multipath components between –0.5 μs and about +23 μs. The guard interval for the DVB-T COFDM system used in the Sinclair test was about 37 μs. Reflections within this interval should be able to be rejected, and the demonstration showed good performance for COFDM in this regard.

With regard to 8-VSB, Sgrignoli states that the choice of equalizer length is very important for 8-VSB receivers, and that the optimal design is still under investigation. He indicates that the initial estimate of 22 μs seems to be a reasonable *minimum* equalizer range for now, but that a longer ghost canceling range may be beneficial. While we do not have quantitative measurements on the 8-VSB DTV receivers used in the Sinclair test, it has been implied that these receivers did not meet this value and that their adaptive equalizer performance was actually in the range of about 10 μs or less. This appears to be a reasonable explanation for the relatively poor performance of the 8-VSB receivers in the Sinclair test.[42]

While the Sinclair demonstration has provided some useful insight into certain indoor reception conditions and possible deficiencies of some early DTV receiver designs, it appears that these reception problems are readily solvable. All of the CE manufacturers we talked to indicated that problems in receiving service in the presence of strong static ghosts could be solved with an improved adaptive equalizer performance. We believe that an 8-VSB receiver designed receiver to incorporate the 22 μs minimum equalizer range suggested by Sgrignoli should be able to provide satisfactory reception at the Sinclair locations. Furthermore, given the recent

[40] This estimate is based on a Longley-Rice analysis of service areas defined by the DTV Table of Allotments adopted in the *Second Memorandum Opinion and Order* in Docket No. MMB 87-268, 14 FCC Rcd 1348 (1998).

[41] The ATSC 8-VSB system employs a training sequence to help determine what multipath echoes are present. This training sequence is a burst of pseudo-random data of approximately 48 μs that occurs every 24.2 ms. In theory, echoes of up to about 48 μs can be corrected by using this training sequence. Other methods may also be applied to cancel echoes.

[42] While these receivers exhibited poor indoor reception performance using a simple bow-tie antenna, we do not intend to imply that these receivers are inadequate for DTV service. Many engineering and design choices go into making acceptable consumer products. Since these receivers are intended to be used with large screen television displays, reception with simple indoor antennas may not have been a design consideration taken into account. According to Sinclair, these receivers did provide satisfactory reception with an appropriate outdoor antenna.

announcements regarding the availability of improved chips that exceed this specification, we believe it is reasonable to conclude that manufacturers are addressing and will solve this problem in the near future. We expect that, as with most products, performance improvements in DTV receivers will continue to be made over time.

Indoor Reception. To date, there has been only limited testing using indoor antennas. In this regard, there appears to be a general consensus that indoor DTV reception needs further investigation. The Sinclair demonstration has highlighted the effects of multipath. However, signal strength and immunity to interference from impulse noise are also important factors in successful indoor reception.

We note that, in general, there will always be a portion of indoor locations where a threshold signal will not be available. This is also the case with NTSC analog TV service. In the limited indoor testing reported by Sgrignoli, the percentage of sites where the field strength was below the minimum threshold level needed for service varied across markets from 8 to 44 percent.[43] Given the current 3.5 dB higher threshold signal required for successful COFDM operation, we would expect that the overall number of locations where service was not available due to insufficient signal strength would be higher with COFDM. And, in effect, the overall number of locations that would need to use outdoor antennas would increase.

Impulse noise interference occurs predominantly in VHF and low UHF bands and is caused by industrial equipment, home appliances such as vacuum cleaners, light dimmers, microwave ovens, etc., and high voltage power lines.[44] The DVB-T system is more susceptible to impulse interference than 8-VSB and there is some anecdotal information from the United Kingdom that DVB-T has experienced some difficulties in this regard. In view of these considerations and the projected improvements in 8-VSB adaptive equalizers, we believe that, while multipath may be the most significant factor affecting indoor reception of DTV service, further study would be needed before it could be concluded that COFDM has a significant overall advantage over 8-VSB for indoor reception.

In its demonstration, Sinclair also contends that service is acceptable where reception is achieved over a complete 360 degrees rotation of a simple bow-tie antenna, *i.e.*, no antenna pointing is necessary. We disagree with this position. While it is certainly desirable to avoid the need for manual antenna orientation, it is also reasonable to expect viewers to perform some antenna orientation, similar to what is done today for existing NTSC analog television. Based on our discussions with CE manufacturers, we believe that reasonable solutions to the indoor reception problems are being developed. These products will include not only receivers with improved

[43] The availability of a threshold signal is affected by transmitter power, antenna height, building height, the materials of which the building is constructed, window size, the location of the antenna and receiver within the building.

[44] "Performance Comparison of ATSB 8-VSB and DVB-T COFDM Transmission Systems for Digital Television Terrestrial Broadcasting", Dr. Yiyan Wu, Communications Research Centre, ICCE '99.

adaptive equalizers but also new electronically pointable, or “steerable,” indoor antennas that are controlled automatically by the receiver.[45]

Mobile and Single Frequency Network Operation. COFDM has an advantage in its ability to support large single frequency network operation and mobile operation over large geographic areas. For example, this would allow use of a single channel to provide the same programming concurrently over a very wide area, perhaps an entire country, and in this way could better support mobile service. In this regard, such an approach would avoid the problem of leaving the service area of an individual station during a program while travelling. This is the approach that some European countries are pursuing. However, to implement this approach in the United States would necessitate a substantial change to structure of the broadcast industry and the way it is regulated.[46]

COFDM may also offer an advantage with regard to mobile data operation within the service area of a TV station. This could be used to provide data and other communications to palm-top computers and other hand-held devices. However, trade-offs would have to be made between the rate of data transmission and the range of service. In general, a station’s mobile service range would be less than its current projected DTV service area, and at higher data rates, *i.e.*, above 18 Mbps, it would be substantially less.[47]

Data Rate. In COFDM, the spectrum of the transmitted signal is sharply confined in frequency because it is the sum of equally spaced subchannel signals, each of which is sharply confined.[48] Therefore, a COFDM system can have a higher occupied bandwidth than 8-VSB, which is limited to an occupied bandwidth of 5.38 MHz due to the Nyquist roll-off criteria needed to fit into the 6 MHz channels available.

The 6 MHz DVB-T COFDM system used in the Sinclair demonstration had an occupied bandwidth of 5.7 MHz. This provided an effective data rate for the system of 18.66 Mbps or 4 percent less than the 19.39 Mbps for 8-VSB. While COFDM systems can have higher occupied bandwidths than the 5.38 MHz of 8-VSB, we believe that the 5.7 MHz occupied bandwidth of the equipment used by Sinclair may be overly ambitious. Previous studies have suggested that to provide the same adjacent channel interference performance as 8-VSB, a COFDM system would

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[45] Electronically steerable antennas work by electronically changing the orientation of the receiving elements. Unlike the traditional “UHF loop” or “rabbit ears” antennas, the receiving elements of such antennas will remain in a fixed position at all times. Thus, the antenna pointing will be transparent to the user.

[46] For example, all stations associated with a particular television network would have to be assigned the same channel or frequency. This means that any change in affiliation by a station would require a change in the station’s channel assignment.

[47] For example, DTV service area is defined using an outdoor antenna with a gain of about 10 dB mounted at 30 feet above the ground. Mobile operation would use receivers with much less gain and at lower heights and therefore the service area would be considerably less at the same data rate.

[48] COFDM generally does not require channel-limiting filters at the transmitter. Rather, to meet an emission mask requirement, a COFDM system may simply not use carriers near the band edges.

have to limit its occupied bandwidth to 5.625 MHz or less.[49] This would result in a slight reduction in the 18.66 Mbps data rate available and would suggest that ATSC 8-VSB would have about a 5 percent data rate advantage over the DVB-T 6 MHz COFDM system used by Sinclair.

While a 5 percent data rate difference is relatively small, it could have some impact on the ability to provide certain high definition television programming. The DVB-T COFDM system is very flexible and the data rate can be increased by increasing the coding rate and/or by shortening the guard interval. These changes, however, would affect system performance. Specifically, increasing the coding rate would have a C/N penalty and decreasing the guard interval would have a penalty in multipath performance.

Summary/Recommendation

Both 8-VSB and COFDM have certain advantages and disadvantages. Both systems are capable of providing viable DTV service. We do not find that at this time the performance potential of either system is clearly superior in all respects. Based on our discussions with CE manufacturers and recent announcements by semiconductor manufacturers, we believe that reasonable solutions to the multipath issue and indoor reception problems raised by Sinclair are being developed and should be available in the near future. We also believe that COFDM's benefits for large single frequency network operation and mobile service may not be important or meaningful given the current structure of broadcasting in the United States. Further, we believe that 8-VSB has some advantages with regard to data rate, spectrum efficiency and transmitter power requirements. Accordingly, at this time, we find that the relative benefits of changing the DTV transmission to COFDM are unclear and would not outweigh the costs of making such a revision. We therefore recommend that the ATSC 8-VSB standard be retained.

[49] See, for example, Conclusions of W.F. Schrieber, Report on OFDM Meeting at MIT, 26-27 October 1992. http://wb-star.com/hdtv/cofdmschr.html (August 18, 1999).