5.2.5 Threshold Improvement with MAP Decoding

The performance in additive noise of the new system can be improved by using maximum-a-posteriori (MAP) decoding at the receiver, which as shown by simulations can improve the system threshold performance by approximately 0.15 dB. This decoding could not be supported by the GA hardware implementation, but can be easily implemented in a consumer receiver with a very small increase in complexity. The use of MAP decoding could reduce the noise-only threshold difference between the new system and the GA system to about 0.15 dB, based on the measured results. If the ATV transmit power were increased by 0.15 dB over that used for the GA system, it would be even less likely (see discussion of Section 5.2.2) that NTSC viewers would perceive any difference between the noise added by the two systems. Thus it can be argued even more strongly that there would be no "NTSC population lost to ATV interference" in this case. With MAP decoding, when NTSC ceases or in areas where co-channel is not a problem, the white noise performance of all receivers in the service area would be improved by about 0.45 dB for the new system as compared to the GA system.

5.3 Discussion of Other Performance Areas

5.3.1 Acquisition Time

Acquisition time at threshold can be better for the new system. At threshold a GA system compliant trellis decoder has to know if the comb is in or out to produce valid data. To determine this reliably, it would likely be necessary to average a few field syncs to determine if the comb should be in or out. For the new system, determination of the rejection filter enabled/bypassed status can be done immediately after detection of one field sync, so acquisition time is one field sync. If, for a GA compliant system, eight field syncs were averaged, then acquisition time would be improved by 24.2 x 7 = 169.4 ms for the new system.

5.3.2 Performance Under Impulse Noise

Under impulse noise, a trellis decoder will produce a burst of errors lasting over several symbol times. The GA system uses a short 1-dimensional trellis code with a 12-to-1 encoder interleave. This arrangement is fairly robust to impulse noise because the decoding bit errors are confined to a limited number of symbols (2 or 3).

In the new system the NTSC rejection filter will stretch an impulse according to the impulse response of the filter. Hence, an impulse is now spread over 52 symbols (although the filter taps are not very large, so the effective spreading is less). Additionally, the new system trellis code has a longer time span than that of the GA system, and hence an impulse, if not dispersed, would tend to produce more byte errors into the Reed-Solomon decoder.

Spreading of impulse noise due to the new system NTSC rejection filter and trellis code can be effectively countered by increasing the depth of the byte interleaver. The interleaver proposed in Section 3.4.1 (52 x 312) has 1.5 times the depth of the GA system interleaver (52 x 208). The GA system achieved threshold with 192 μs long bursts of noise. If the proposed 52 x 312 interleaver was used with the GA system, the tolerance would be increased to 271 μs which is a margin of about 79 μs. If the new system rejection filter stretches an impulse by 52 symbols, which is about

5 μs, the system has a margin of about 74 μs to deal with spreading caused by the symbol interleaver and trellis code.

5.3.3 Performance Under Co-Channel-Plus-Multipath-Plus-Noise

In the GA system two comb filter nulls are always misplaced, i.e., not located precisely at two of the NTSC (picture/sound/color) carrier frequencies [4], and therefore the equalizer has to help the comb to notch out the residual interference. This implies that the ability of the equalizer to combat multipath as well as co-channel interference is now reduced. It is difficult to quantify this effect, since multiple impairment tests involving co-channel-plus-multipath-plus-noise have not been conducted. We expect better performance with multiple impairments from the new system since the rejection filter notches are located precisely at the NTSC picture and sound carrier frequencies.

6. CONCLUSIONS

We described a new NTSC co-channel interference rejection filter with coded 6-VSB modulation which can provide better ATV service than the GA system. The new rejection filter can be switched out under broadcaster control when NTSC transmissions cease, or during the transition from NTSC to ATV broadcasting for stations for which NTSC co-channel is not a problem. With its rejection filter switched out, the new system offers better noise-threshold performance than the GA system. This gain in white noise performance is possible because the two-dimensional (2-D) trellis code of the new system is more powerful than the one-dimensional (1-D) code of the GA system. This powerful new code also helps to hold the loss in threshold performance to about 0.3 dB when the new filter is enabled, as opposed to 3 dB when the GA system comb filter is switched in.

The new system could not be fully tested. Measurements did confirm the predicted co-channel-plus-noise performance. Measurements also confirmed the approximately 0.3 dB gain (as compared to the GA system) in white noise performance when its comb filter is bypassed.

Simulation results by MSTV also showed that the new system would achieve its design goal of significantly improving ATV service area, especially in geographic areas where NTSC co-channel interference is a serious impairment to ATV reception. The new system accomplishes this by eliminating the 3 dB threshold loss associated with the GA system comb filter.

With the new rejection filter enabled, the threshold of the system as tested in hardware is slightly worse (about 0.3 dB) than the GA system (with its comb filter switched out). However this difference can be reduced to only about 0.15 dB if the ATV receiver uses MAP decoding, with a very slight increase in receiver complexity. Such a small threshold difference implies (even more strongly than for a 0.3 dB threshold difference), that the difference between the systems in "NTSC population lost to ATV interference" would effectively be zero. Thus the new system would achieve a significant improvement in ATV service without any measurable loss in NTSC service, as compared to the GA system.

The new system increases robustness to impulse noise. Multipath performance would be equivalent to the GA system, for both static and dynamic ghosts. The robustness of the new system rejec-

tion filter switching obviates concerns about the reliability of the GA system comb filter switching algorithm when subjected to impulse noise, interference, and multipath.

The co-channel rejection and trellis coding techniques described above, although tailored to an NTSC environment for the new system, can be utilized to combat interference in other mixed analog-digital transmission applications. For example, equally good results can be expected for terrestrial digital transmission using QAM, in the case of PAL or SECAM co-channel interference.

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Exhibit B

RESULTS OF LABORATORY AND FIELD TESTS OF A COFDM MODEM FOR ATV TRANSMISSION IN 6 MHZ CHANNELS

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ABSTRACT

A prototype 6 MHz COFDM transmission system (COFDM-6) for ATV terrestrial broadcasting was evaluated at the Communications Research Centre (CRC). This paper provides the laboratory and field test results of the COFDM-6 modem.

1. INTRODUCTION

In July 1995, a 6 MHz Coded Orthogonal Frequency Division Multiplexing (COFDM) transmission system prototype (COFDM-6) for Advanced TV (ATV) terrestrial broadcasting was evaluated at the Communications Research Centre (CRC) in Ottawa Canada [1]. This report outlines the results of the laboratory evaluation and the subsequent field test. The hardware was developed by HD-DIVINE and SINTEF DELAB and programmed by CRC for a 6 MHz implementation. The modem was built for the COFDM Evaluation Project LLC, a consortium of US, Canadian and Brazilian broadcasters.

2. PARAMETERS FOR THE 6 MHz COFDM MODEM

Table 2.1 lists a set of system parameters for the COFDM-6 Digital Television Terrestrial Broadcasting (DTTB) system based on preliminary studies conducted at CRC [2]. It should be pointed out that this particular optimization for a 6 MHz terrestrial broadcasting channel was constrained by the existing implementation of the prototype modem. Compromises were made on guard interval duration, data throughput, carrier spacing, robustness to dynamic multipath distortion, acquisition time, phase noise, jitters, etc.

The system was designed to operate in a local Single Frequency Network (SFN), i.e., with secondary transmitters and on-channel coverage extenders. The length of the guard interval (64 μSeconds) were chosen at the expense of an increased number of carriers, as this will enable the receiver to properly recover signals received from several synchronized transmission stations. The requirement of 6,120 carriers results in a narrow carrier spacing of 0.91 kHz. The useful

symbol duration is about 1.1 milliseconds. An 8k FFT is required (the prototype COFDM-6 hardware uses a 16k FFT instead of an 8k FFT).

TABLE 2.1: Parameters for the COFDM-6 Modem

Useful bandwidth	5.56 MHz
Carrier separation	0.9078 kHz
Useful symbol duration	1101.607 µs
Guard interval duration	64.0 µs
Total number of carriers	6120
Number of reference pilots	0
Number of data carriers	6120
FFT size required	8 k (required)
Modulation	64QAM
TCM coding rate	2/3
Reed-Solomon code	(255,239)
Number of reference symbols/frame	3
Number of symbols/frame	105
Number of data symbols/frame	102
Frame duration	122.39 ms
Total payload throughput	19.12 Mbps

3. LABORATORY SET-UP AND TEST CONDITIONS

The COFDM-6 modem was tested with and without impairment and interference. Impairment testing included random noise, and static and dynamic multipath with and without the co-existence of random noise. In the cases of interference testing, tests included adjacent and co-channel interference to and from NTSC. The Bit Error Rate (BER), and the quality degradation of the NTSC video and audio were assessed. In addition, the peak-to-average power ratio was also measured. All tests were carried out as RF back-to-back tests.

The NTSC desired signal was adjusted to three different levels: strong (-15 dBm), moderate (-35 dBm) and weak (-55 dBm). The ATV desired signal was adjusted to three different levels: strong (-28 dBm), moderate (-53 dBm) and weak (-68 dBm). When NTSC was the desired signal, the Threshold Of Visibility (TOV) and the Threshold Of Audibility (TOA) were recorded. When ATV was the desired signal, the Desired to Undesired signal ratio (D/U) was recorded for a BER = 3×10^{-6}.

When NTSC was the desired signal, the aural carrier power was adjusted to 5% of the visual carrier peak power (13 dB below). When NTSC was the undesired signal, the aural carrier power was adjusted to 20% of the visual carrier peak power (7 dB below).

The subjective evaluation was done by at least 2 expert observers. Tests were performed to determine the Threshold Of Visibility (TOV) of the ATV interference into NTSC. The video test signals were chosen to be sensitive to the ATV interference.

The objective tests included BER measurements for different types of interference and impairment conditions. The NTSC test signals were chosen to emphasize the NTSC interference effect. Appropriate measurements were also done on the NTSC signal using a waveform monitor.

4. PEAK TO AVERAGE POWER RATIO

The peak-to-average power ratio of the COFDM-6 signal was measured using a vector analyzer. The results were taken after averaging 1000 measurements, and are presented in Table 4.1.

TABLE 4.1: Peak to Average Ratio Measurements (Desired Signal Level: -10 dBm)

Peak to Average Ratio	dB
99%	6.5
99.5 %	7.0
99.9 %	8.2
99.99 %	9.5
99.999 %	10.3

5. RESULTS OF INTERFERENCE TESTS

5.1 Co-channel Interference

The purpose of this test was to determine the performance of the COFDM-6 system under co-channel NTSC and ATV interference. To compare the effect of the ATV interference into co-channel NTSC with that of white noise, the NTSC noise performances (TOV and TOA) are also presented.

By comparing Table 5.1.1 and Table 5.1.2, it can be seen that the behavior of the COFDM-6 signal is very much like that of white noise.

TABLE 5.1.1: ATV into NTSC

NTSC Signal Level	D/U @ TOV	D/U @ TOA
NTSC (strong)	53.4 dB	19.0 dB
NTSC (moderate)	53.5 dB	20.0 dB
NTSC (weak)	49.5 dB	22.0 dB

TABLE 5.1.2: Noise into NTSC

NTSC Signal Level	D/U @ TOV	D/U @ TOA
NTSC (strong)	52.0 dB	19.0 dB
NTSC (moderate)	50.5 dB	22.0 dB
NTSC (weak)	47.0 dB	20.0 dB

It is shown in Table 5.1.3 that the COFDM-6 system is very robust against co-channel NTSC interference. Table 5.1.4 presents ATV co-channel interference results.

TABLE 5.1.3: NTSC into ATV

ATV Signal Level	D/U (dB)
ATV (strong)	-1.8
ATV (moderate)	-2.2
ATV (weak)	-2.7

TABLE 5.1.4: ATV into ATV

ATV Signal Level	D/U (dB)
ATV (strong)	14.6
ATV (moderate)	14.5
ATV (weak)	18.4

5.2 Adjacent Channel (n+1,n-1) Interference

The purpose of this test was to determine the performance of the COFDM-6 system against upper and lower adjacent channel interference. These tests were done without frequency offset. All adjacent channel interference results are presented in Tables 5.2.1 through 5.2.6.

TABLE 5.2.1: Upper Adjacent ATV Channel into NTSC

	D/U @ TOV	D/U @ TOA
NTSC (moderate)	-4.5 dB	-9.0 dB
NTSC (weak)	-4.9 dB	-9.0 dB

TABLE 5.2.2 Lower Adjacent Channel into NTSC

	D/U @ TOV	D/U @ TOA
NTSC (moderate)	+1.9 dB	N/A
NTSC (weak)	-1.1 dB	-17.0 dB

TABLE 5.2.3: Upper Adjacent NTSC channel into ATV

	D/U (dB)
ATV (moderate)	-46.8
ATV (weak)	-46.7

TABLE 5.2.4 Lower Adjacent NTSC channel into ATV

	D/U (dB)
ATV (moderate)	-50.8
ATV (weak)	-50.1

TABLE 5.2.5: Upper Adjacent ATV channel into ATV

	D/U (dB)
ATV (weak)	< -36

TABLE 5.2.6: Lower Adjacent ATV channel into ATV

	D/U (dB)
ATV (weak)	<-36

In the upper and lower adjacent channel ATV to ATV interference tests, Table 5.2.3, the D/U was limited to -36 dB, due to limited undesired signal power available from the test bed. By observing the constellation display, it was estimated that D/U of -37 dB and -42 dB could be achieved for upper and low adjacent ATV to ATV interference, respectively.

6. RESULTS OF SUSCEPTIBILITY TO NOISE

The purpose of this test was to determine the performance of the COFDM-6 modem under random noise impairment. The effects of phase noise were also measured.

6.1 Random Noise Performance

Using the ATV as the desired signal, the average power level was adjusted to -53 dBm (moderate). The BER versus carrier to noise ratio (C/N) was recorded for three runs of 20 seconds for each noise level and is shown in Table 6.1. The TOV (BER = 3×10^{-6}) was observed at 15.7 dB.

TABLE 6.1: BER vs. C/N

BER	C/N
2.0×10^{-2}	13.7 dB
1.7×10^{-3}	14.7 dB
1.0×10^{-4}	15.2 dB
1.0×10^{-5}	15.5 dB
3.0×10^{-6}	15.7 dB
3.0×10^{-7}	16.0 dB
no error	16.6 dB

TABLE 6.2: Phase Noise

	C/N	C/N without pilots
TOV @ 100 Hz	-54.17dBc/Hz	-51.0 dBc/Hz
TOV @ 1 kHz	-70.50dBc/Hz	-67.17dBc/Hz
TOV @ 5 kHz	-79.67dBc/Hz	-76.33dBc/Hz
TOV @ 10 kHz	-83.17dBc/Hz	-80.00dBc/Hz
TOV @ 20 kHz	-87.5 dBc/Hz	-83.17dBc/Hz

6.2 Phase Noise Performance

These results describe the system's behavior with respect to phase noise. Phase noise was created by injecting a FM modulated band limited (6 MHz) white noise into the local oscillator of the up converter (IF to RF). Phase noise was measured for a BER $\cong 10^{-6}$, see Table 6.2. The phase noise was then reduced and a random noise was added to the tuner input to characterize the C/N in the presence of phase noise, see Table 6.3.

TABLE 6.3: Random noise in presence of phase noise

	C/N (with pilots*)	C/N without pilots
TOV-1dB @ 20 kHz	28.0 dB	28.0 dB
TOV-2dB @ 20 kHz	22.5 dB	20.5 dB
TOV-3dB @ 20 kHz	21.0 dB	18.5 dB
TOV-4dB @ 20 kHz	20.0 dB	17.5 dB
TOV-6dB @ 20 kHz	18.0 dB	17.0 dB
TOV-9dB @ 20 kHz	17.0 dB	16.3 dB
TOV-11dB@ 20kHz	16.3 dB	16.2 dB

*The tests with pilots were done with 49 equally spaced fixed pilots. The pilots increased the robustness against phase noise by 3 to 4 dB but decreased the C/N threshold by about 0.3 dB for a Gaussian channel.

7. RESULTS OF SUSCEPTIBILITY TO MULTIPATH AND RANDOM NOISE

The purpose of the multipath test was to determine the robustness of the COFDM-6 modem in the presence of multipath distortion as well as random noise. The BER measurement was conducted with the combinations of multipath presented in Table 7.1. The BER was recorded for three runs of 20 seconds for each test. The COFDM signal was adjusted to approximately -45 dBm. In this test, the multipath generator was connected between the COFDM-6 modulator IF output and the RF up-converter.

TABLE 7.1: Combinations of Multipath

Multipath Ensemble	Amplitude (dB)	Delay (μsecond)
A*	-20, -20, -10, -14,-18	-1.8, 0.15, 1.8, 5.7, 8.0
B*	-20, -20, -10, -14, -18	-1.75, 0.197, 1.85, 5.75, 17.95
C*	-18, -20, -20, -10,-14	-1.8, 0.15, 1.8, 5.7, 18.0
D*	-20, -20, -18, -14,-10	-1.8, 0.15, 1.8, 5.7, 18.0
E*	-20, -14, -10, -20, -18	-1.8, 0.15, 1.8, 5.7, 18.0
F*	-10, -14, -18, -20, -20	0.2, 1.9, 3.9, 8.2, 15.0
G*	-19, -22,- 17, -22, -19	-0.2, .08, 0.15, 0.3, 0.6
H**	-10, -20, -20, -10, -14	-18, -1.8, 0.15, 1.8, 5.7
SFN ***	Varied	+20

* These multipath ensembles represent those that were also used for testing the Grand Alliance 8-VSB transmission system [3].
** This multipath ensemble tests pre-echoes.
*** This multipath ensemble tests Single Frequency Network operation: One ghost at 20 μs with different amplitudes

7.1 Noise Degradation due to Multipath Distortion

Table 7.2 presents the threshold degradation due to the existence of various multipath distortions. It shows that the COFDM-6 system can withstand 0 dB echo, but it then requires a C/N headroom in comparison to a Gaussian channel case.

7.2 Static and Dynamic Multipath Susceptibility

Table 7.3 presents the test results of various multipath models with 0 dB echo, without noise injection. No transmission error was observed.

Table 7.4 shows the system's robustness under dynamic echo. Clearly the system needs improvement on the performance against dynamic ghost. In-band pilots or other fast channel estimation schemes should be implemented [4].

TABLE 7.2: Noise degradation relative to no echo

Random noise in presence of static multipath (Average BER = 3E-6 was measured over 20 sec.)	noise degradation relative to no ghost
no ghost	0.0 dB
Ensemble A	1.0 dB
Ensemble A (with 5.7μs @ 0dB)	6.0 dB
Ensemble B	1.0 dB
Ensemble C	1.5 dB
Ensemble D	1.5 dB
Ensemble E	1.5 dB
Ensemble F	1.0 dB
Ensemble SFN (-10 dB)	0.5 dB
Ensemble SFN (-5 dB)	2.0 dB
Ensemble SFN (-3 dB)	3.5 dB
Ensemble SFN (-1 dB)	8.0 dB
Ensemble SFN (0 dB)	11.5 dB
Ensemble SFN (+3 dB)	3.5 dB
Ensemble G	0.0 dB
Ensemble H	1.0 dB

TABLE 7.3: Strongest Static Echo Rejection

Static multipath	D/U	BER
30 μs in Ensemble C	0.0 dB	No errors
5.7 μs in Ensemble A	0.0 dB	No errors
Single echo @ 15 μs	0.0 dB	No errors
Single echo @ 5.7 μs	0.0 dB	No errors
Single echo @ 1.0 μs	0.0 dB	No errors

TABLE 7.4: Strongest Dynamic Echo Rejection

Dynamic multipath	D/U
1.8 μs in Ensemble A* (0 Hz)	0.0 dB
1.8 μs in Ensemble A* (0.05 Hz)	6.0 dB
1.8 μs in Ensemble A* (0.5 Hz)	16.7 dB
1.8 μs in Ensemble A*(5 Hz)	15.8 dB
1 μs @ 2Hz	17.4 dB
1 μs @ 5 Hz	16.2 dB
1 μs @ 100 Hz	16.0 dB
1 μs @ 425 Hz	15.7 dB

* This is achieved by varying the amplitude of only the +1.80 μs echo element in the multipath Ensemble A, at each of the 4 phase-rotation frequencies (0 Hz, 0.05 Hz, 0.5 Hz and 5 Hz), to determine the D/U at a BER = 3×10^{-6}.

8. TONE INTERFERENCE INTO ATV

Table 8.1 lists the tone interference results. The undesired signal was a discrete frequency carrier with its amplitude modulated (25%) by a 400 Hz sine wave. The COFDM-6 modem demonstrated very good performance in this test.

TABLE 8.1: Tone Interference

Discrete tone (MHz)	D/U	BER
201.0125	-51.2	3.0×10^{-6}
201.5125	-51.0	3.0×10^{-6}
202.0125	-50.9	2.0×10^{-6}
202.5125	-50.5	2.0×10^{-6}
203.0125	-50.3	3.0×10^{-6}
203.5125	-49.5	2.0×10^{-6}
204.0125	-44.9	3.0×10^{-6}
204.5125	-16.6	2.0×10^{-6}
205.0125	-7.5	2.0×10^{-6}
205.5125	-5.7	3.0×10^{-6}
206.0125	-6.4	2.0×10^{-6}
206.5125	-16.8	2.0×10^{-6}
207.0125	-6.3	3.0×10^{-6}
207.5125	-4.9	2.0×10^{-6}
208.0125	-6.0	3.0×10^{-6}
208.5125	-6.8	3.0×10^{-6}
209.0125	-18.1	2.0×10^{-6}
209.5125	-12.4	3.0×10^{-6}
210.0125	-10.7	2.0×10^{-6}
210.5125	-21.9	2.0×10^{-6}
211.0125	-40.6	2.0×10^{-6}
211.5125	-49.1	2.0×10^{-6}
212.0125	-50.8	2.0×10^{-6}
212.5125	-51.1	2.0×10^{-6}
213.0125	-51.2	2.0×10^{-6}

9. FIELD TRIAL RESULTS

A field trial was conducted to confirm the results obtained from the laboratory test and to verify the operation of the modem in a real life environment. These tests were done in a suburban area of relatively flat terrain with a lot of residential and commercial buildings as well as trees.

The transmitter site was located approximately 20 km from the downtown core of Ottawa (lat: E 45°20'42", long: N 75°53'06"). The encoder-modulator was installed in a three storey building at CRC. The set-up for the transmitter site is presented in Figure 9.1. The encoder was fed a pseudo-random data source. The IF output of the modulator was up-converted to the VHF broadcast channel 11 (198-204 MHz) and connected to a RF amplifier (100 Watts). To transmit, a log-periodic dipole antenna located at 23 meters above the ground was used.

The receiver set-up is presented in Figure 9.2. The tuner and the demodulator/decoder were installed in a test van. The receiver antenna height was 11 meters high. The tests were done at 12 different sites in the Ottawa area. The measured field test results are presented in Table 9.3 as well as the predicted results using CRC-COV/PREDICT, a coverage prediction software that can take terrain and clustering into consideration. The location and time availability used in the prediction are (50,90). Table 9.2 shows that the COFDM-6 system performs appropriately and the measured C/N match closely the predicted values except when there is dynamic multipath.

FIGURE 9.1: Set-up at the Transmitter Site

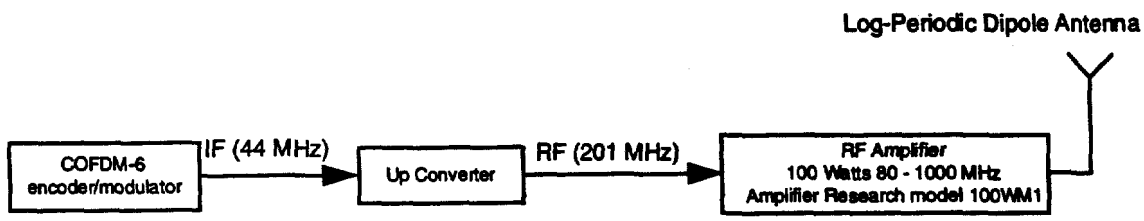

FIGURE 9.2: Receiver Set-up

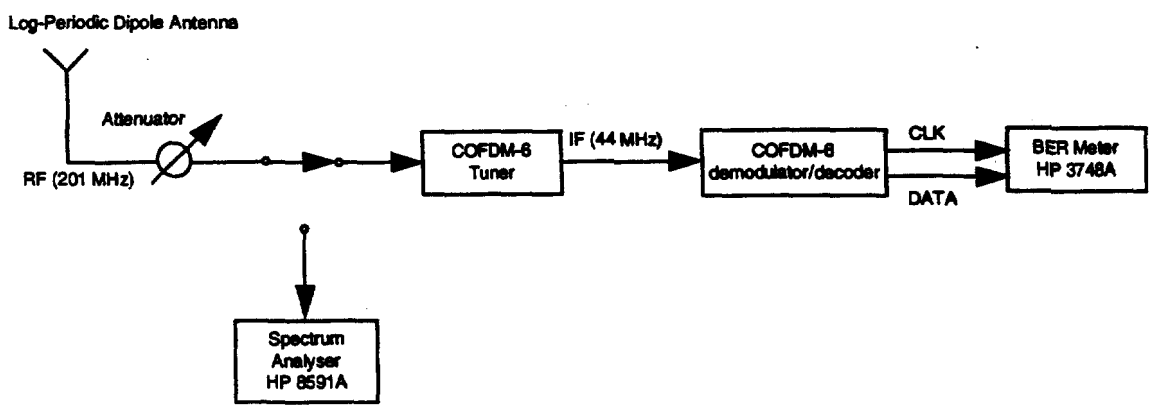

TABLE 9.3: Field Test Results

Test Site	Distance (Km)	C/N (dB)	Margin (dB)	C/N (dB) prediction	Prediction Error	Observations
1	4.75	32	15.75	31.0	-1.0	good channel
2	4.1	36	18.75	36.9	+0.9	good channel
3a	4.4	28	0	32.6	+4.6	dynamic ghost
3b	4.4	32	13.75	32.6	+0.6	multipath
4	6.5	29	10.75	29.0	0.0	multipath
5	5.9	29	9.75	27.7	-1.3	multipath
6	6.3	27	6.75	27.9	+0.9	moving ghost
7	4.3	26	4.75	24.6	-1.4	multipath
8	6.2	no signal	-	12.0	-	low signal
9	5.2	26	4.75	24.4	-1.6	multipath
10	6.5	no signal	-	8.1	-	low signal
11	6.0	32	15.75	33.1	+1.1	good channel
12	7.7	26	3.75	22.6	-3.4	dynamic ghost

10. COMPARISON OF KEY PERFORMANCES OF COFDM-6 Vs 8-VSB

Table 10.1 compares the key performance parameters of the COFDM-6 and the Grand Alliance 8-VSB modem. These tests were conducted in two separate laboratories, and direct comparisons of these measurements should be viewed with caution and cannot be considered conclusive.

The last column of Table 10.1 lists the performance difference. The values in parenthesis indicate that the 8-VSB performed better than that of the COFDM-6.

Table 10.1: Key Performance Parameters of COFDM-6 vs. 8-VSB

Test	COFDM-6	8-VSB	Difference (dB)
C/N over 6 MHz channel	15.7 dB	15.2 dB	(0.5)
Co-channel NTSC to ATV (-68 dBm)	-2.7 dB	+1.8 dB	4.5
Lower adj. NTSC to ATV (-53 dBm)	-50.8 dB	-44.5 dB	6.3
Upper adj. NTSC to ATV (-53 dBm)	-46.8 dB	-44.4 dB	2.4
Lower adj. ATV to ATV (-68 dBm)	-42.0 dB	-42.0 dB	0
Upper adj. ATV to ATV (-68 dBm)	-37.0 dB	-43.2 dB	(6.2)
Lower adj. ATV to NTSC (-55 dBm)	-1.1 dB	-5.9 dB	(4.8)
Upper adj. ATV to NTSC (-55 dBm)	-4.9 dB	-2.0 dB	2.9
In-band tone interference	<-4.9 dB	>+9.1 dB	>14.0
Single static ghost D/U (15 μs)	0 dB	5.8 dB	5.8
Ghost ensemble A D/U of 5.7 μs echo	0 dB	6.9 dB	6.9
Ghost ensembles A SNR loss	1.0 dB	3.3 dB	2.3
Ghost ensembles B SNR loss	1.0 dB	2.4 dB	1.4
Ghost ensembles C SNR loss	1.5 dB	3.2 dB	1.7
D/U of 0 Hz ghost (1.8 μs) in ensemble A	0 dB	4.2 dB	4.2
D/U of 0.05 Hz ghost (1.8 μs) in ensemble A	6 dB	7.6 dB	1.6
D/U of 0.5 Hz ghost (1.8 μs) in ensemble A	16.7 dB	9.1 dB	(7.6)
D/U of 5 Hz ghost (1.8 μs) in ensemble A	15.8 dB	12.5 dB	(3.3)
Peak-to-average power ratio 99.9 %	8.2 dB	6.2 dB	(2.0)
Peak-to-average power ratio 99.99 %	9.5 dB	6.9 dB	(2.6)

11. POSSIBLE IMPROVEMENTS FOR THE COFDM-6 SYSTEM

There are possible performance improvements for the COFDM-6 system:

(1) There could be an improvement of 0.5 to 1 dB by fine tuning the hardware to reduce the implementation margin and by using a tuner that is designed for an OFDM implementation.

(2) In the COFDM-6 system, a set of off-the-shelf NTSC SAW filters were implemented. They should be replaced by custom designed SAW filters to improve the robustness against adjacent channel interference.

(3) A fast channel estimation algorithm should be implemented to improve the dynamic ghost performance.

(4) In addition to other possible improvements, all of the ATV BER performances can be improved by 0.1-0.2 dB when the R-S code block is changed from (255,239) to (204,188) to comply with the MPEG-2 transport layer interface.

12. CONCLUSIONS

The laboratory test results show that the COFDM-6 system has very strong immunity to multipath distortion and tone interference. The field test verified that the COFDM-6 system can operate in a real environment. However, improvements should be implemented to the COFDM-6 system, in particular to increase the robustness against dynamic ghosts.

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Exhibit C

A 60 Field/Sec Variation on NTSC for Simulcasting With ATV

By Charles W. Rhodes

The Grand Alliance ATV system is designed for both the NTSC field frequency 59.94 Hz and 60 fields/sec. The only reason for the NTSC field rate is to facilitate simulcasting as the new service is being introduced. This paper introduces an alternative to two field rates for ATV, a variant of NTSC for simulcasting. This variation retains the present color subcarrier frequency, but operates at 60 fields/sec with a horizontal scan rate of 15,750 lines/sec — the same rates as the 525-line monochrome system employed. Theory is explained, and experiments conducted to date are described.

Terrestrial digital television broadcasting may go through three phases in replacing NTSC. First, networks will provide dual program feeds, NTSC and ATV, to their affiliates. The ATV signal relayed to affiliates will probably be the Grand Alliance ATV digital bit stream of approximately 19.3+ Mbits/sec, which was designed for emission, not for distribution or contribution circuits. This is sometimes called "pass-through," as the affiliates would simply pass the network digital signal through their digital channel, without local program origination. In this first phase, the network (program provider) would downconvert the HDTV signal to NTSC and uplink both ATV and NTSC to the affiliates. This would entail use of additional satellite transponders. ATV may have either 59.94 Hz or 60-Hz field rate.

In the second phase, only the ATV signal would be delivered to affiliates, who would have to downconvert it from HDTV to NTSC once all affiliates are equipped to do so. Current thinking assumes that the ATV would be at 59.94 fields/sec in order to reduce the cost of the downconversion equipment at each affiliate. The cost of the downconversion equipment from HDTV to NTSC is significantly increased if field rate conversion is required. Moreover, with field rate conversion of the video, there must also be additional processing of the audio. The digital bit stream from the satellite receiver would have to be decoded, separating out the required audio bits for encoding in stereo from the video bits that will be downconverted into NTSC. If the ATV signal is at 60 fields/sec, there would be rate conversion required for the audio and frame rate conversion of the video to the NTSC field rate of 59.94 Hz. These considerations and concern over proliferation in production formats lead to asking whether it would be possible to simulcast NTSC at 60 fields/sec, so that the ATV signal need not undergo field rate conversion of video and rate conversion for the audio, which would be required.

Were it found possible to simulcast NTSC derived from ATV at 60 fields/sec, the Grand Alliance encoding system would be operated at 60 fields/sec, and therefore, no rate changing from the production field rate of 60 fields/sec would be needed. In the author's opinion, production should be at 60 fields/sec, because when programs are to be marketed overseas to 50 field/sec countries, the conversion from 59.94 to 50 fields/sec requires an unwanted intermediate step, conversion from 59.94 to 60. The operational inconveniences of operating with a noninteger number of frames per second are well known here and will not be discussed further.

In the final phase, the FCC expects to end emission of NTSC signals and ATV will become the only broadcast signal. Once NTSC is discontinued, there is no doubt that TV programming should be produced and distributed with 60 fields/sec. However, it would be desirable to produce all ATV programming in 60 fields/sec for operational reasons, outlined earlier. A mixed inventory of 59.94 and 60 field/sec tape recorded programs would be hard to deal with. Therefore, the possibility of modifying the NTSC signal to 60 fields/sec was examined by the Advanced Television Test Center (ATTC).

NTSC-60

NTSC-60, as the scheme is called, must retain the present color subcarrier frequency because the subcarrier frequency determining element in consumer receivers is a quartz crystal. The NTSC field frequency is 60 Hz/1.001. Simply scaling the NTSC frequencies by 1.001 would increase the subcarrier frequency from 3.579545 MHz[1] to 3.583125 MHz, which is far beyond the pull-in range of these crystal oscillators. The alternative is to retain the present color subcarrier frequency and simply change the horizontal and vertical scanning rates by this factor. However, this would violate one of the most basic features of the NTSC signal: the interleaving of chrominance and luminance sidebands that results from the chroma subcarrier being an *odd harmonic of one-half the horizontal scan frequency.*

Figure 1 shows the frequency relationships of the NTSC standard. That

Aural Subcarrier = 4.500 MHz $\equiv$ **286.0 Fh**

Chroma Subcarrier $\equiv \frac{63}{88} \times 5.000\ \text{MHz} \equiv \frac{227.5\ \text{Fh}}{58.5\ \text{Fh}}$ **(~3.579545 MHz) (Beat Frequency)**

$$Fh \equiv \frac{2\,Fsc}{455} = \frac{63}{4004}\ (\text{MHz}) \qquad \frac{15{,}750}{1.001}\ \text{Hz}$$

$$Fv \equiv \frac{2\,Fh}{525} = 59.94005994\ \text{Hz} \qquad \frac{60}{1.001}\ \text{Hz}$$

Figure 1. NTSC signal component frequency relationships.

Presented at the 136th SMPTE Technical Conference and World Media Expo (paper no. 136-28) on October 14, 1994. Charles W. Rhodes is with the Advanced Television Test Center, Inc. (ATTC), Alexandria, VA 22314. Copyright © 1995 by the Society of Motion Picture and Television Engineers, Inc.

technique was essential for the compatibility between NTSC color signals and the millions of monochrome television sets then in use. It will be recalled that on monochrome receivers of the time, the chrominance signal created a visible dot pattern if the receiver's bandwidth was great enough, as was frequently the case with early monochrome TV sets.

The inventor of the PAL color TV system, Dr. Walter Bruch, noted in 1966 that NTSC could actually provide better color pictures if it employed *quarter-line offset* between its chroma subcarrier and its horizontal scanning frequency.[2] The author conducted experiments in 1967 and found that the crawling dots on vertical edges were less noticeable with quarter-line offset than with the standard half-line offset of NTSC, as suggested by Dr. Bruch. Quarter-line offset requires the subcarrier frequency of 227.25 Fh = 3.58 Hz[3] below the NTSC subcarrier. This is too great a difference to expect all NTSC receivers to be able to lock to, so quarter-line offset is deemed impractical. NTSC-60 has the standard NTSC subcarrier, which equals 227.2727627... x 15,750 Hz, the horizontal scanning frequency of NTSC-60. With this horizontal scan frequency, F_v' is precisely 60.000 Hz.

Figures 2a, 2b, and 2c show the proposed frequency relationships of NTSC-60. Given that f_{sc} = 227.5 fh for NTSC, and fh is increased by the factor 1.001, the number of cycles of subcarrier per new line period is reduced by the reciprocal of 1.001 to 227.272727...., which is a very close approximation to quarter-line offset, where f_{sc}= 227.25 fh.[4] The decimal 0.27272727... can also be expressed as 3/11. This provides a means to synthesize the basic raster clock for 60 field/sec NTSC from the *unchanged* color subcarrier frequency. The experimental setup used at the ATTC is shown in Fig. 3. The master clock required for the raster is 31,500 Hz (525 * 60 Hz). This was derived at the ATTC from 1.008000 MHz provided by a frequency synthesizer referenced to 10.000 000 MHz. 1.008 MHz 32 = 31,500 Hz. A second synthesizer, also referenced to the same 10.000 000-MHz clock, provided the standard NTSC color subcarrier. Both the raster and the color subcarrier are locked to a 10-MHz reference frequency.

The FCC defines the NTSC color subcarrier as 5.000 000 MHz * 63/88. Therefore, f_{sc} = 10.000 000 MHz * 63/176. The raster sync generator is required to produce a 31,500-Hz frequency, also locked to the reference frequency, which can readily be implemented. We would now have the raster rates exactly as they were before NTSC — fv' = 60 Hz and fh' = 15,750 Hz — while the NTSC color subcarrier would be unchanged, so f_{sc} = 227.272727... fh'.

If fv = 60 Hz, then fh = 15,750 Hz as in the monochrome 525-line standard. The raster sync generator clock for 525-line monochrome was 2 x 15,750 Hz, or 31,500 Hz. This frequency is 1.008 MHz/32. The raster sync in our experiments was derived from a 10-Hz reference frequency by a frequency synthesizer, which provided 1.008 MHz to the ÷32 counter.

Another frequency synthesizer also referenced to the same 10 MHz provided the standard NTSC color subcarrier,[5] as shown in Eq. 1.

$$10\text{ MHz} \div 2 = 5\text{ MHz}\,\frac{63}{88}\,.\,5\text{ MHz} = f_{sc}$$

$$\frac{63}{88}\,.\,\frac{10}{2}\text{ MHz} \div \frac{1.008}{32}\text{ MHz} = 227.272727... = \frac{3}{11}$$

Therefore, $f_{sc} = 227.\frac{3}{11}$ cycles/line in NTSC-60

while in standard NTSC $f_{sc} = 227\frac{1}{2}$ cycles/line. (1)

Aural Subcarrier = **4.500 MHz** **No Change**

Chroma Subcarrier = $\frac{63}{88}$ **X 5.000 MHz** **No Change**

Beat Frequency = $\frac{920.454.55\text{ Hz}}{15750.0\text{ Hz}}$ = **58.44 Fh'** **(Near minimum visibility frequency 58.50 Fh')**

2a

Fh' = **15,750 Hz** = $\frac{63\text{ MHz}}{4000}$

Fv' = $\frac{2\text{ Fh'}}{525}$ = **60.000 Hz**

$\frac{\text{Fsc}}{\text{Fh'}}$ = **227. 272727.... Cycles per line**

.272727.... = $\frac{6}{22}$

2b

NTSC - 60 : **227** $\frac{6}{22}$ **cycles per line**

Standard NTSC : **227** $\frac{11}{22}$ **cycles per line**

2c

Figure 2. Proposed NTSC-60 signal component frequency relationships: (a) basic relationships; (b) definitions of new parameter values; (c) comparison of subcarrier to line frequencies.

Observations

NTSC picture impairments due to NTSC artifacts have been evaluated on the 24 NTSC receivers in the viewing room of the ATTC. The impairments with NTSC-60 are no greater than with standard NTSC on these receivers. These tests were run with the NTSC video signals modulated onto the visual carrier with the aural carrier 6 dB below the visual carrier power, which is the critical case for observing any beat between f_{sc} and the aural subcarrier.

We were concerned that the beat frequency generated by intermodulation between the chroma signal and the aural subcarrier might be a problem. Standard NTSC employs a horizontal scan frequency of 15,734.26 Hz, so that any chroma sound beat is an *odd harmonic of fh/2*, i.e., of minimal visibility. This is why the vertical scan rate of NTSC was shifted from 60 Hz to 59.94 Hz to minimize the visibility of this beat. Figure 1

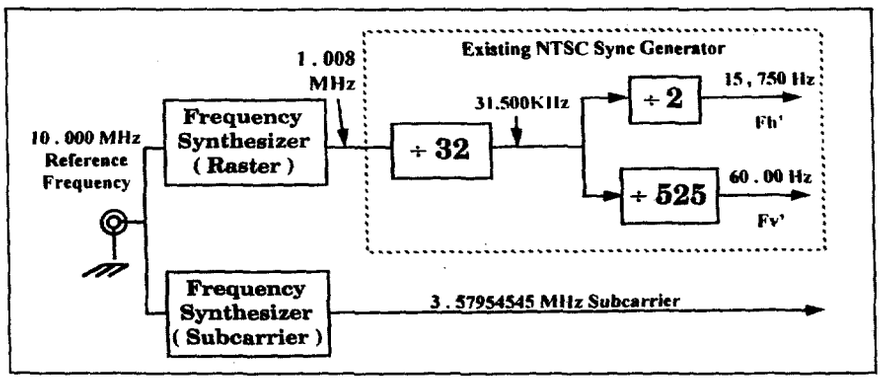

Figure 3. Sync generation for NTSC-60 at ATTC.

shows that this beat is precisely 58.5 fh for standard NTSC. Figure 2 shows the beat with the parameters of NTSC-60. Note that the beat is shifted by 0.06 fh'. The visibility of this beat would be maximized at 58.0 or 59.0 fh'.

Experiments at the ATTC indicate that modern color sets seem to have this problem under control, even when the beat is not the least visible frequency. Monochrome sets in use today have rather narrow bandwidth, so the chrominance signal is greatly attenuated and does not create a visible beat pattern.

ATTC has a 1948 RCA monochrome receiver at its facilities. The dot pattern of NTSC-60 was observed on that receiver, which still has 4-MHz video bandwidth. The rationale for half-line offset when such receivers were in use was immediately apparent.

In the early 1970s, the David Sarnoff Research Center developed the Capacitive Video Disc, in which, because the turntable motor was a synchronous motor driven by the power line, the playback NTSC signal was 60 fields/sec. The effects on picture quality were considered and deemed acceptable even on receivers employing a comb filter NTSC decoder.

When playing back a VHS recording, the relationship between the chrominance frequency and the horizontal scanning frequency is variable. Therefore, there is precedent for NTSC-60 for consumer use.

Applications

Having explained the details of NTSC-60 and summarized the limited experimental observations, the ATTC now speculates on how this technique could be exploited by ATV broadcasters. Assuming the case of a program captured at 60 fields/sec, in the 1080 *active line, interlaced* format, they will need to downconvert the demultiplexed ATV video data to Y, R-Y, and B-Y, which may remain in digital form. Then a vertical down-filter will produce an interlaced 525-line raster having 60 fields/sec. The 16:9 aspect ratio must be reduced to 4:3 by truncating each line, under control of a pan-and-scan signal if it is a component of the digital ATV data stream. The resulting components are further processed to form a digital NTSC-60 data stream which, after digital-to-analog (D/A) conversion and video reconstruction low-pass filter, is used to modulate the NTSC transmitter.

However, many broadcasters may want to record the ATV signal for delayed broadcasting. By that time, 20 Mbit/sec digital ATV recorders will probably be available. These can record the ATV signal for later conversion to NTSC, as described earlier. NTSC-60 cannot be recorded on digital studio recorders such as D-2. This is probably its biggest drawback. ATTC has recorded NTSC-60 on VHS-C cassette recorders satisfactorily, just as a viewer expects to be able to record NTSC programs at home.

Conclusion

The ATTC, in bringing this possibility to the attention of the SMPTE, hopes that it will be studied and perhaps additional tests carried out if interest warrants. Should NTSC-60 be considered useful by the Society, we may see the end of production in 59.94 fields/sec, one step further towards a single worldwide production standard.

NTSC-60 offers a way that ATV programming could be produced at 60 fields/sec so that all program inventory would have the same field rate — and the rate best suited to international program exchange.

Broadcasting of NTSC-60 would require modification of the FCC rules. This may be justified in terms of the possible acceleration of the broadcasting of ATV. It is in this spirit that the ATTC presents this report. Further testing of NTSC-60 would certainly be in order before it were adopted, and there is time to do so.

Acknowledgments

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Addendum

Since this paper was presented (October 1994), the author has learned that some NTSC transmitters that use a combined aural and visual power amplifier generate the aural carrier by phase locking the 4.5-MHz aural subcarrier to fh. This is done to reduce the visibility of the beat generated by the aural carrier and chroma in the high-power amplifier. This may pose problems in the application of NTSC-60 by stations employing such transmitters.

Several comments have been received concerning the difficulties of changing the digital audio sampling rate when video field rates are changed. These are issues which should also be considered, in favor of keeping ATV at 60 Hz throughout the production, post-production, and transmission operations.

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