SATELLITE TRANSPONDER OPERATION WITH VIDEO AND MULTIPLE SUBCARRIERS

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ABSTRACT

Over the past four years, extensive operational experience has been gained with multiple subcarrier technology. Driven by marketplace demands for low cost audio and data distribution capabilities, the development of the techniques of multiple subcarrier operation has reached a refined level. To date, over 100 channels on 40 transponders on eight different satellites are utilizing technology developing by Wegener Communications.

This paper will discuss in detail the technical principles behind multiple subcarrier operations. Areas that are of primary interest are composite deviation, modulation waveforms, occupied bandwidth and video degradation. Discussion of experiences with U.S. NTSC, European PAL and Intelsat half-transponder NTSC will be presented to illustrate the major points.

Application of multiple subcarrier technology will be detailed including audio channels of various bandwidths and data channels of various data rates. A detailed and flexible baseband plan is imperative to enable maximum transponder utilization. Examples of such plans will be presented.

The overall objective of this paper is to provide a clear understanding of transponder operation with multiple subcarriers and suggest ways in which the technologies can be put to use solving today's problems.

COMMENTS ON MULTIPLE SUBCARRIER THEORY

Analysis of Frequency Modulation starts out rather simple. If one assumes a sinusoidal modulating signal with constant frequency and amplitide, then the occupied bandwidth of an FM signal closely obeys Caron's Rule. This rule states:

OCCUPIED BANDWIDTH = 2(Peak Deviation + Modulating Frequency)

As the modulating signal becomes more and more complex, the precise occupied bandwidth becomes harder to predict. As of this writing, I know of no known precise method of predicting occupied bandwidth of a video FM signal containing multiple subcarriers.

Having no know mathematical model to go by, the next best thing is to empirically determine what can be expected as multiple subcarriers are added to a video signal. Over the past five years, Wegener Communications and its customers have conducted numerous exhaustive tests to insure that multiple subcarriers can be added with insignificant impact to primary video. While much of the work done by our customers is considered proprietary to them, some common results can be shared.

As a general rule of thumb, up to eight subcarriers can be added above video with no reduction in video deviation as long as the following rules are observed:

*All subcarriers are operated at a modulation index of 0.18 maximum. Typical range is 0.14 to 0.18.

*Wegener recommended frequency plan is followed.

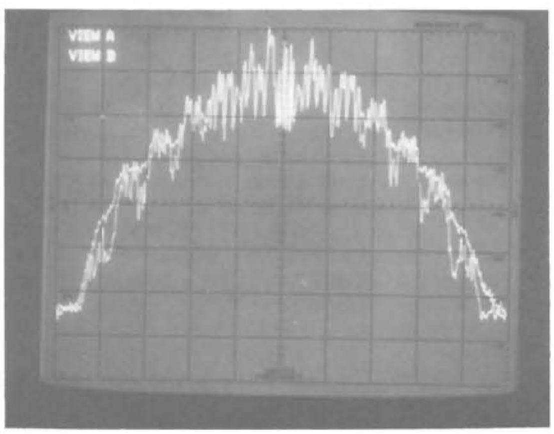
By keeping the modulation index of each subcarrier extremely low relative to the video deviation, the contribution to the occupied bandwidth of eight subcarriers is totally insignificant.

It is interesting to compare spectrum photographs of video signals with an without multiple subcarriers. Photograph #1 shows two modulation conditions superimposed as they were monitored at an uplink exciter output. Modulation source in one case was 75% color bars at 1.0V p-p and a conventional 6.8 MHz sound camera at a modulation index of 0.294. Superimposed is the same color bar signal, 6.8 MHz subcarrier and eight Wegener low level carriers each with a modulation index of 0.15. One minute peak hold was used in each case.

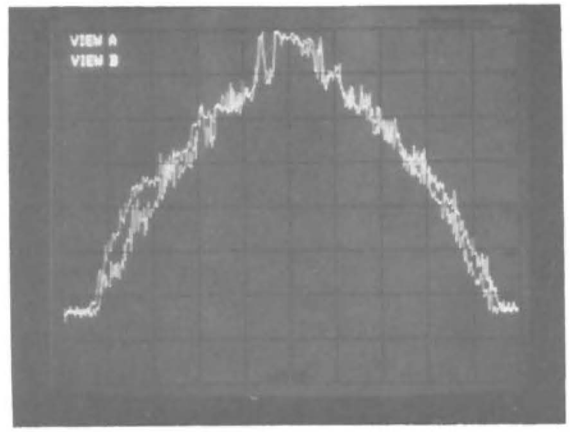
Photograph #2 is the same type of comparison using program video instead of color bars. Note that in both cases, the increased bandwidth is insignificant. In fact, the "spectrum spread" caused by the subcarriers is not really significant until you get approximately 40 dB below unmodulated carrier level.

Video Signal to Noise Ratios

Laboratory measurement of video signal to noise vs. subcarrier loading shows a very slight reduction in this parameter as the number of subcarriers is increased. The noise that was observed and measured is truly noise and not coherent beat products caused by intermodulation. Figure 1 is a plot of video signal to noise vs. subcarrier loading at four different receive carriers to noise ratios. (See Figure 1 on Page 5.)



Photograph #1 - 75% Bars/6.8 vs. Bars/6.8 and Eight Low Level Subcarriers at m = 0.15



Photograph #2 - Typical Video/6.8 vs. Typical Video/6.8 and Eight Low Level Subcarriers at m = 0.15

Threshold Effects

Another interesting observation is that multiple subcarrier operation has an insignificant effect on a system operating at threshold. One common test that we have done many times it to operate a system at threshold ("Sparklies") just apparent and vary the subcarrier load. As long as the IF bandwidth is wide enough to pass the video signal (30-32 MHz typical), the threshold point does not change by adding subcarriers if Wegener practices are not violated.

Commercial Acceptance

The practice of adding multiple subcarriers has now become widespread through North America based on the acceptance of the Wegener system. To date of 150 channels on 55 different transponders on ten different satellites are in full commercial service. No generic systems problems have ever occurred that can be attributed to multiple subcarrier operation. Acceptance is rapidly becoming worldwide with systems operating in the U.S., Canada, Japan, Australia and the United Kingdom.

RECENT TESTS

While many tests have been done by our North American customers, it is interesting to look at two somewhat unique subcarrier tests -- Intelsat Half-Transponder and European PAL.

Intelsat Half-Transponder

The transmission of multiple subcarriers with video via Intelsat Half-Transponder circuits represents perhaps the most stressful situation encountered to date. Due to the narrow bandwidth (17.5 MHz) for the high peak video deviation (7.5 MHz peak) the addition of multiple subcarriers can lead to problems if not done properly. In January 1984, Wegener Communications and ATN-7 Sydney, Australia conducted extensive tests between Paumali, Hawaii and Sydney, Australia with the objective of determining how many subcarriers could be added without affecting the video. It was found that up to six subcarriers can be added at a modulation index of 0.14 each with insignificant impact to video performance. Both ATN-7 and TCN-9 Australia currently oeprated half-transponder video circuits between the U.S. and Australia with Wegener Multiple Subcarrier Systems installed. Uses include primary program audio, stereo program audio and low speed data associated with the video feeds. As a result of these tests, Wegener Subcarrier Systems were used extensively by the BBC for the 1984 Olympic Games audio feed from Los Angeles to London. Additional information on Intelsat Half-Transponder tests can be obtained from the author.

European PAL Tests

Tests were conducted in April 1984 by Wegener Communications and British Telecom International to examine multiple subcarrier behavior with PAL I video on both ECS and Intelsat V. PAL I video extends to 5.5 MHz and subcarriers between 6.30 and 7.94 MHz were used. It was determined that ten subcarriers can be accommodated with insignificant impact into the video. The following data is from these tests.

VIDEO PARAMETER	SUBCARRIERS	
	0 Subcarriers	10 Subcarriers
2T Pulse K (%)	0.5	0.1
2T Pulse/Bar K (%)	0.0	0.0
2T Bar K (%)	0.8	1.1
C-L Gain Inequality (%)	-4.0	-2.0
C-L Delay Inequality (%)	10.0	4.0
C-L Crosstalk (%)	0.4	1.1
Differential Gain (%)	1.2	1.4
Differential Phase (°)	3.3	3.4
Time Line Non-Linearity	0.5	0.8

FIGURE 2 - Video Parameter Measurements with 0 Subcarriers and 10 Subcarriers

S/N	NO SUBCARRIERS	5 SUBCARRIERS	10 SUBCARRIERS
Unweighted	48.5 dB	48.0 dB	48.0 dB
CCIR Unified Weighted	60.5 dB	60.0 dB	59.0 dB
Luminance Weighted	60.5 dB	60.0 dB	59.0 dB

FIGURE 3 - Signal To Noise Ratio Comparisons at High C/N (C/N = 24.9 dB)

S/N	NO SUBCARRIERS	5 SUBCARRIERS	10 SUBCARRIERS
Unweighted	37.5	37.5	38.0
CCIR Unified Weighted	48.0	49.0	48.0
Luminance Weighted	48.5	49.5	49.0

FIGURE 4 - Video Signal To Noise at Threshold (C/N = 12.8 dB)

Based on these tests, multiple subcarriers are now in full commercial service on ECS-1. The first use is for stereo audio associated with Thorn/EMI's "Music Box" video programming using the Wegener Panda I system. Additional details on multiple subcarriers with both PAL I and PAL B video can be obtained from the author.

SUBCARRIER PERFORMANCE

If a few parameters are known about a given TVRO downlink, the subcarrier perforamnce can easily be predicted. Assuming that one can derive the basic C/N being received at the downlink, the following analysis should prove helpful in subcarrier calculations. Note that the analysis is for a 15 kHz program audio channel and that negligable terms have been eliminated from the classical equations. Assume a subcarrier deviation of 50 kHz peak by the audio signal.

GIVEN: TVRO C/N = 12dB (30 MHz BW)

DETERMINE: $C/N_o = C/N + 10\log BW = 86.8\text{dB-Hz}$

$$(C/N_o)_{sc} = C/N_o + 10\log\frac{m^2}{2}$$
$$= 86.8 + 10\log\frac{.18^2}{2}$$
$$= 86.8 + (-17.9)$$
$$= 68.9\text{dB-Hz}$$

$$(S/N)_{audio} = (C/N_o)_{sc} + 10\log\frac{3(Dev)^2}{2(bn)^3} + A_c$$
$$= 68.9 + 10\log\frac{3(50\times10^3)^2}{2(5822)^3} + A_c$$
$$= 68.9 - 17.2 = 51.7\text{dB} + A_c$$

A_c Panda I ≅20dB: $(S/N)_{audio} \cong \underline{\underline{71.7\text{dB}}}$

A_c Panda II ≅40dB: $(S/N)_{audio} \cong \underline{\underline{91.7\text{dB}}}$

This shows that low level subcarriers are indeed capable of providing excellent program audio channels.

An interesting comparison is to take a conventional high level subcarrier operating with 2 MHz peak deviation. This would equate to a modulation index of 0.294 for a 6.8 MHz subcarrier. Thus:

$$(C/N_0)_{sc} = C/N_0 + 10\log \frac{m^2}{2}$$

$$= 86.8 + (-13.6) = 73.2\text{dB-Hz}$$

$$(S/N)_{audio} = 73.2 + 10\log \frac{3(237000)^2}{2(5822)^3}$$

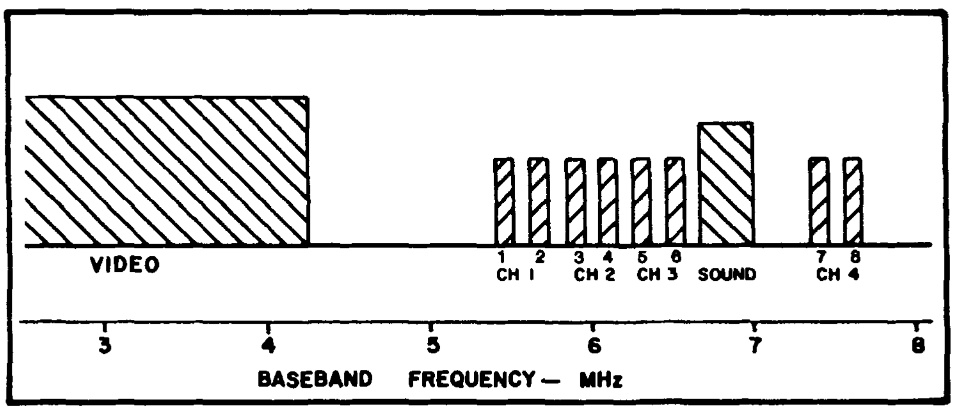
$$= 73.2 + (-3.7) = 69.5\text{dB}$$

The point of this example is to show that by utilizing clever baseband audio companding techniques, the subcarrier modulation index can be reduced to the range where impact on occupied bandwidth is insignificant while providing broadcast quality audio.

BASEBAND PLANNING

Wegener Communications has defined a standardized subcarrier baseband plan that allows for flexibility and expandability. As can be seen from Figure 5, there are eight spectral slots available for low level subcarrier energy. Each slot is spaced 180 kHz center to center. It should be noted that using 180 kHz constant spacing does not cause measurable intermodulation products to form as long as subcarrier modulation indices are kept low. Contrary to some recent writing, it is very undesirable to phase lock the subcarrier modulators. In fact, over 140 Wegener Subcarrier Channels are in operation worldwide and none of them are phase locked. Each 180 kHz slot can be used for one 15 kHz audio or further subdivided into individual 7.5 or 3.5 kHz slots. Individual carriers are used in all cases (no multiplexing due to S/N penalties) and power of individual carriers is adjusted such that they do not exceed that of a single 15 kHz audio channel per spectral slot.

Each slot can be used for data transmission as well -- and data and audio signals can be mixed adjacent to each other on the baseband. Data rates vary according to the modulation technique (AFSK, FSK, QPSK, etc.). For instance, it is possible to place a Dolby ADM digital stereo audio channel in two adjacent 180 kHz slots with a power equivalent to two low level subcarriers utilizing QPSK modulation.



CHANNEL	FREQUENCY
1	5.40 MHz
2	5.58 MHz
3	5.76 MHz
4	5.94 MHz
5	6.12 MHz
6	6.30 MHz
7	7.38 MHz
8	7.56 MHz
TV Sound	6.80 MHz

FIGURE 5 - Typical Baseband Plan - NTSC Video Plus 8 Subcarriers

An example of a very aggressive subcarrier baseband plan is shown on Figure 6. Note the mixture of 15 kHz audio, 7.5 kHz audio and various data channels. Yes -- it does work! (COURTESY UNITED VIDEO, INC.)

CONCLUSION

In spite of the complexity involved in analyzing video with multiple sub-carriers, the vast amount of data taken by Wegener Communications and our customers ove rthe past five years has given the entire satellite communications industry a very good feel for exactly what can be done. Several innovative solutions to communications problems have been developed using low level subcarrier technology. We see a steady continuation of this activity coupled with advanced system concepts in the future.

ACKNOWLEDGEMENTS

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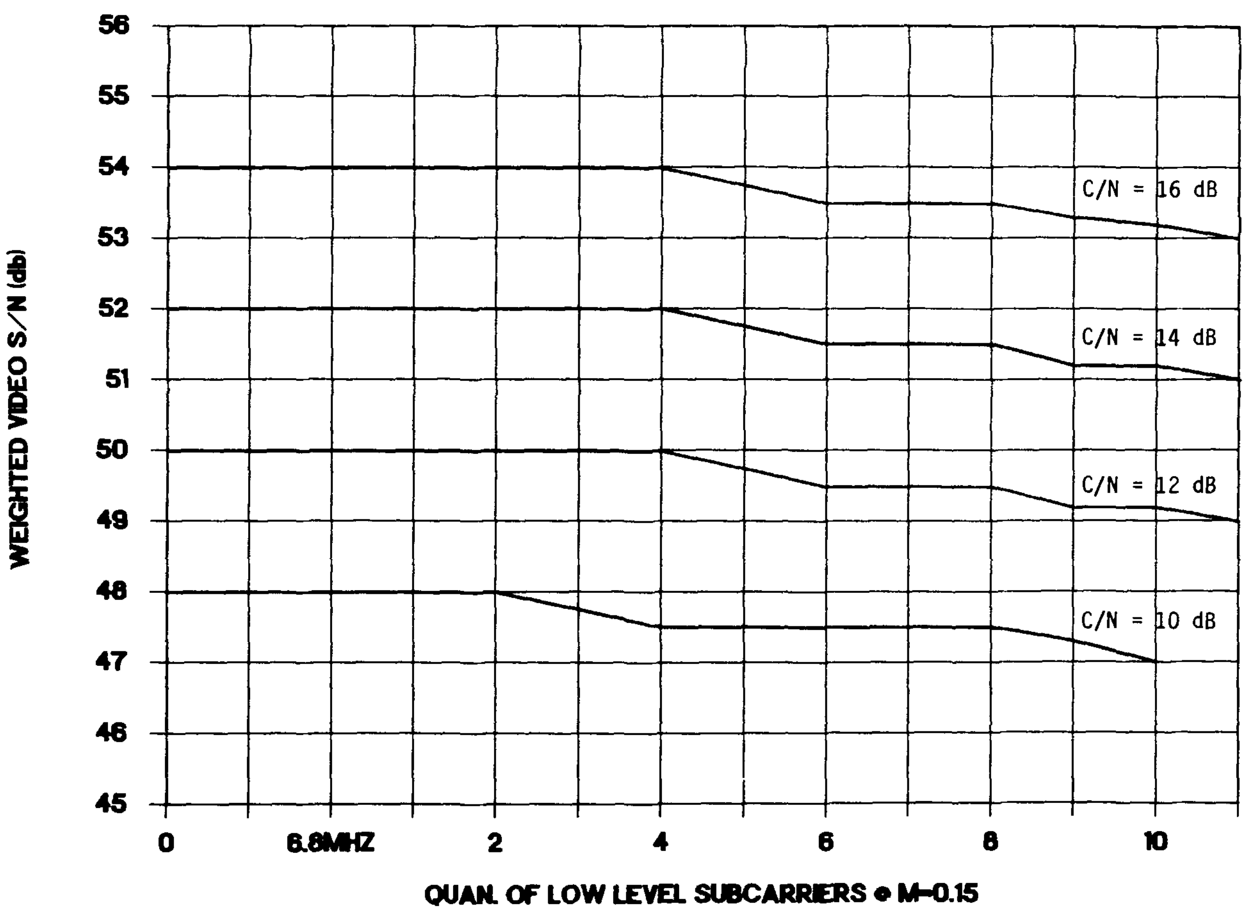
Fig.1- LOADING VS. VIDEO S/N



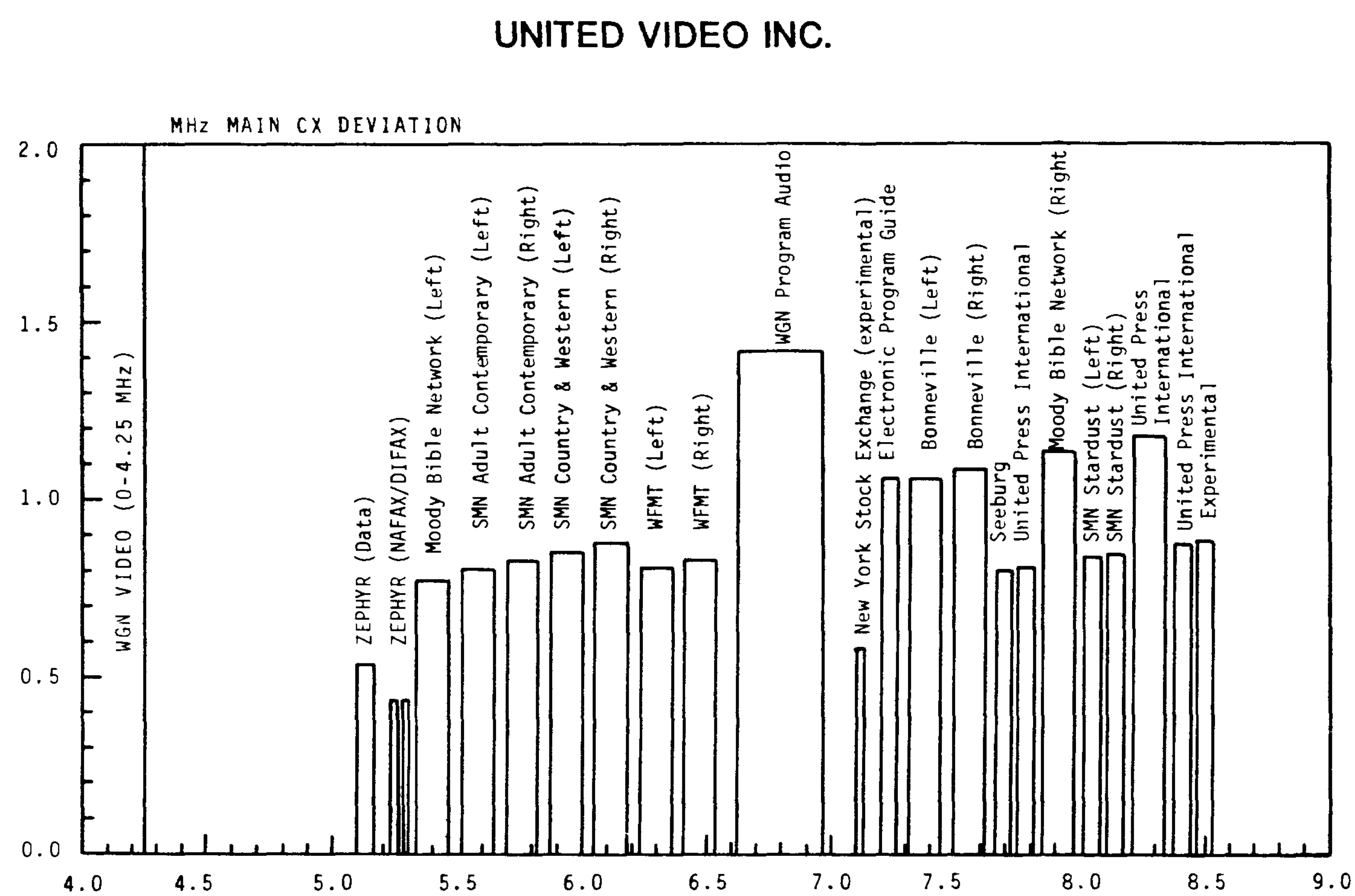


FIGURE 6 - An Example of Aggressive Subcarrier Loading
(COURTESY OF UNITED VIDEO, INC.)