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TV Bandwidth Compression Techniques Using Time-Companded Differentials and Their Applications to Satellite Transmissions

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This paper describes various methods to compress the bandwidth of a National Television System Committee (NTSC) color TV signal. The methods are based on taking differences between adjacent or successive scan lines and then performing time companding on these differential signals. In the three specific methods outlined, a 4.2-MHz TV signal can be bandwidth-reduced to 3.34 MHz, 2.9 MHz, and 2.5 MHz, respectively, without loss of picture quality. When these techniques are used with time-compression multiplexing in satellite transmissions, high spectral efficiency can be obtained. Examples are shown where the transmission of two or three broadcast-quality TV's per 36-MHz transponder are possible with existing technology.

I. MOTIVATION

There has been considerable interest in recent years in transmitting two or more broadcast-quality TV signals through a single satellite transponder (usable bandwidth of 36 MHz). The difficulties of doing this with the conventional frequency-division-multiplexing (FDM) approach are due to the effect of transponder nonlinearities such as intermodulation and intelligible cross talk. To alleviate these problems, time-compression multiplexing (TCM) can be employed whereby the scan lines from different, but synchronized, TV signals can be time compressed and time multiplexed into the duration of an ordinary scan line for transmission via a single frequency-modulated (FM) carrier. The concept of TCM is not new,[1,2] but the recent commercial availability of fast analog/digital (A/D) converters, digital/analog (D/A) converters, charge-coupled devices (CCD), and memory devices makes it economically feasible for implementation. The bandwidth efficiency of TCM/FM outweighs that of FM/FDM whenever time division between different signals can be achieved more efficiently than frequency division. In the case of satellite transmission, this is generally true. Therefore, TCM is advantageous from both viewpoints of avoiding transponder nonlinearities and achieving higher spectral efficiency.

Haskell[3] recently demonstrated that a differential signal derived from two adjacent or successive scan lines of a National Television System Committee (NTSC) color TV has significantly lower bandwidth occupancy than the original 4.2-MHz composite signal. When this differential signal technique is used in combination with the concept of TCM, i.e., time companding (time compression or expansion), significant bandwidth compression on a TV can be obtained (see Sections II and III). When TCM is further exploited by application to different bandwidth-compressed TV signals, high spectral efficiency can be obtained in a satellite link. We discuss examples illustrating this idea in Section IV, where examples for two or three TV's per transponder are shown. Since all the techniques discussed are easy to implement with existing hardware, we conclude with an encouraging outlook into the foreseeable future when multiple high-quality TV transmissions through a single satellite transponder may become possible.

II. LINE AND FIELD DIFFERENTIAL SIGNALS

NTSC color TV pictures have an interlacing scan pattern whereby the scan lines are presented in the order of the odd-number lines (the odd field) first, followed by the even-number lines (the even field). The bandwidth of such a TV signal is assumed to be 4.2 MHz. A block diagram for generating a line differential signal is shown in Fig. 1. Consider an odd field where the scan lines are labeled 1, 3, 5, and so on. As line 1 arrives, it is stored. As line 3 arrives, it is stored while line 1 is read out simultaneously. When line 5 arrives, an output is formed

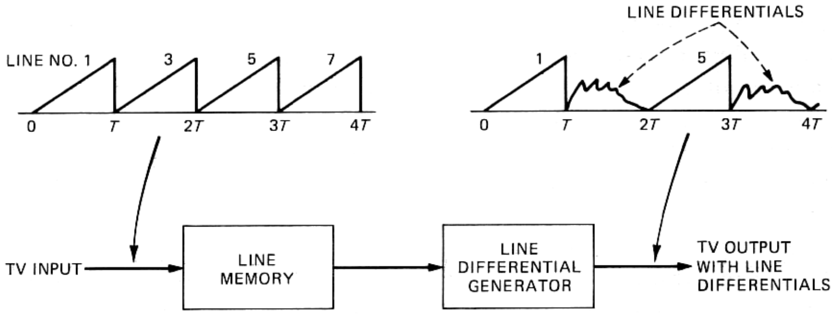

Fig. 1—Generation of a TV signal with line differentials.

consisting of line 3 minus some average of lines 1 and 5. This output is called a line differential signal. The operation is carried out for all subsequent lines. Therefore, the output of the line differential generator as shown in Fig. 1 consists of alternate lines of the original signal and a line differential signal. This composite output has a bandwidth of 4.2 MHz. However, if only the line differential signal is considered, its bandwidth can be reduced to 3 MHz without affecting picture quality.[3]

A block diagram illustrating the generation of a field differential signal is shown in Fig. 2. The scan pattern of the input TV signal is first changed from interlacing to sequential, i.e., line 1, line 2, line 3, ··· and so on. In doing so, there is at least a delay of one field for the signal. This sequential signal is processed as follows: As line 1 arrives, it is simultaneously stored and read out. When line 2 arrives, the difference between lines 1 and 2 is taken and is output in the duration following line 1. This difference signal is called the field differential signal because it is derived from two adjacent lines of two successive fields. The same operation is repeated for all successive pairs of input (sequential) lines. The resulting composite output consists of alternate lines of the original input signal and a field differential signal. This composite output again has a bandwidth of 4.2 MHz. If the field differential signal is considered by itself, the bandwidth can be reduced to 2 MHz without affecting picture quality.[3]

It should be pointed out that there are several ways to derive a line (or field) differential signal. One way is to take the difference between the current line and the average of the preceding and succeeding lines. This would, of course, involve more than a two-line memory, and hence, an additional delay. We digress from the detailed discussion on how to take these line and field differences.

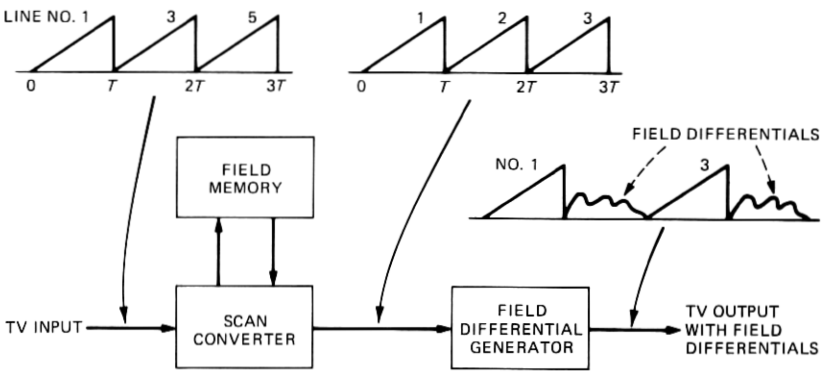

Fig. 2—Generation of a TV signal with field differentials.

III. BANDWIDTH COMPRESSION USING TIME COMPANDING

As we mentioned previously, it is straightforward to implement time companding (time compression or expansion) with readily available A/D and D/A devices (or CCD). The use of time companding in combination with the differential signals described in the preceding section can lead to significant bandwidth reduction in the TV signal. For instance, using time companding and the line differential signal the TV bandwidth can be reduced to 3.31 MHz. Similarly, it can be reduced to 2.9 MHz with the field differential signal, and to 2.5 MHz with the line plus field differential signals. Various ways to achieve these reductions are discussed below.

3.1 Line differential signal

For simplicity, let us restrict our attention to a pair of successive scan lines at the output of a line differential generator, say the intervals $(0, T)$ and $(T, 2T)$, where T is a scan line duration. As shown in Fig. 3, the interval $(0, T)$ contains the original 4.2-MHz signal; the interval $(T, 2T)$ contains the 3-MHz line differential signal whose horizontal blanking interval (about 17 percent of T) is identically zero and need not be transmitted. We perform a time expansion on the line $(0, T)$, resulting in an output in the interval $(0, T')$, $T' > T$ (neglecting actual delay for simplicity); and we perform a time compression on the input $(T, 2T)$, resulting in an output $(T', 2T)$. The time expansion factor α and compression factor β, both >1, are chosen such that the bandwidths of the signals in the output intervals $(0, T')$ and $(T', 2T)$ are equal. This can be written mathematically as

$$\frac{f_1}{\alpha} = \beta f_2, \tag{1}$$

where f_1 and f_2 are the maximum frequencies of the signals in the input

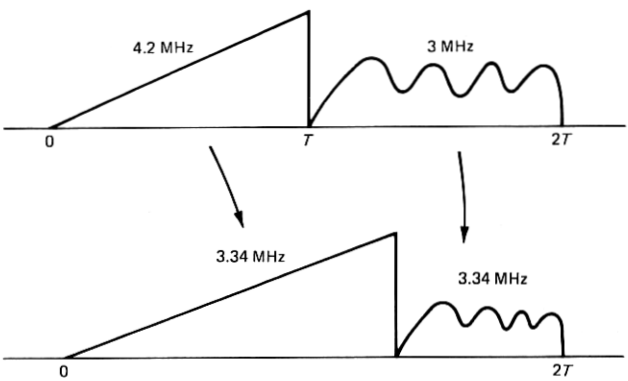

Fig. 3—Time companding of a line differential signal in $(0, T)$.

intervals (0, T) and (T, $2T$), respectively. Since the expanded and compressed line lengths are assumed to add up to $2T$, we have another constraint on α and β:

$$\alpha T + \frac{0.83T}{\beta} = 2T,$$

or

$$\alpha + \frac{0.83}{\beta} = 2. \tag{2}$$

Solving (1) and (2) with $f_1 = 4.2$ MHz and $f_2 = 3$ MHz, we obtain $\alpha = 1.255$ and $\beta = 1.115$. The bandwidth of the time companded output is given by (1), i.e.,

$$f_{\max} = \beta f_2 = 3.34 \text{ MHz}. \tag{3}$$

Therefore, the final output consists of successive pairs of scan lines. Within each of these pairs, one is a time-expanded version of the original line, and another is a time-compressed version of the line differential signal, resulting in a bandwidth reduction from 4.2 MHz to 3.34 MHz. Reconstruction of the original is accomplished by the inverse of the above operation.

3.2 Field differential signal

It is obvious that the above bandwidth reduction technique can also be used with the field differential signal in place of the line differential signal. The mathematical descriptions are the same, i.e., (1) and (2) also hold. With $f_1 = 4.2$ MHz and $f_2 = 2$ MHz, we obtain $\alpha = 1.433$ and $\beta = 1.465$. The maximum frequency of the final time-companded

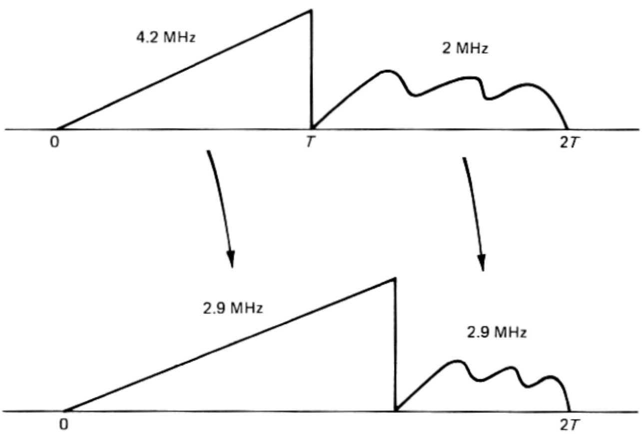

Fig. 4—Time companding of a field differential signal in (0, $2T$).

output is (see Fig. 4)

$$f_{max} = \beta f_2 = 2.9 \text{ MHz}. \tag{4}$$

The use of the field differential signal thus reduces the TV bandwidth from 4.2 MHz to 2.9 MHz.

3.3 *Line plus field differential signals*

Further bandwidth reduction is yet possible with a combination of line plus field differential signals. We first convert the scan pattern of a 4.2-MHz input TV signal from interlacing to sequential. For easy understanding, we visualize that this sequential TV signal is to be processed by two tandem processors, say I and II (see Figure 5). Processor I works as follows: As line 1 arrives, it is simultaneously stored and read out. When line 2 arrives, a field differential signal derived from lines 1 and 2 is read out in the duration following line 1. This field differential signal can be bandlimited to 2 MHz without affecting picture quality, as previously mentioned, and its horizontal blanking interval (about 17 percent) is again not transmitted. As line 3 arrives, a line differential signal is taken for output. The line differential signal has a bandwidth of 3 MHz, and its horizontal blanking interval is not transmitted. When line 4 arrives, the field differential signal derived from lines 3 and 4 is read out. These operations in four consecutive line durations are repeated for all subsequent lines. As a result, processor I output consists of 4-line blocks, each of which contains a line of the original signal, a field differential signal, then a line differential signal, and finally another field differential signal. Within each of these 4-line blocks, processor II performs either time compression or expansion to each of the lines in a manner similar to that discussed above, so as to equalize the resulting bandwidths of the

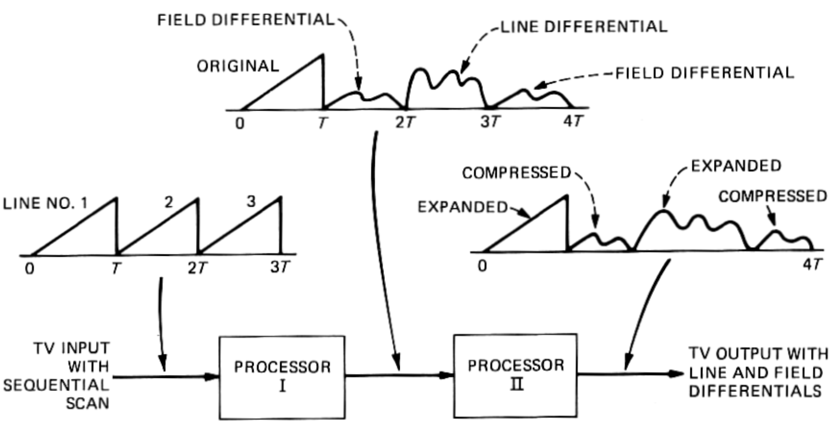

Fig. 5—Generation of a TV signal with line and field differentials.

four lines. It is briefly shown below that the bandwidth can be reduced from 4.2 MHz to 2.5 MHz.

Again, let T be a line duration (Fig. 6). In the interval $(0, 4T)$, we have one line of the original signal ($f_1 = 4.2$ MHz), a field differential signal ($f_2 = 2$ MHz), a line differential signal ($f_3 = 3$ MHz), and finally another field differential signal ($f_4 = 2$ MHz). The equations to equalize bandwidths and to adjust time durations are:

$$\frac{f_1}{\alpha} = \alpha_2 f_2 = \frac{f_3}{\alpha_3} = \alpha_4 f_4, \tag{5}$$

and

$$\alpha_1 T + \frac{0.83T}{\alpha_2} + 0.83\alpha_3 T + \frac{0.83T}{\alpha_4} = 4T, \tag{6}$$

where α_1 and α_3 are time-expansion factors for bandwidths f_1 and f_3, respectively; α_2 and α_4 are time-compression factors for bandwidths f_2 and f_4, respectively; and the factor 0.83 accounts for the deletion of the horizontal blanking interval. The solution for the above is: $\alpha_1 = 1.68$, $\alpha_2 = 1.25$, $\alpha_3 = 1.20$, and $\alpha_4 = 1.25$. The overall bandwidth is then

$$f_{\max} = \alpha_2 f_2 = (1.25)(2) \text{ MHz} = 2.5 \text{ MHz} \tag{7}$$

The preceding descriptions outline the system operations conceptually. In an actual implementation, the various functions of scan conversion, taking differences, and time companding need not be done separately as presented. For instance, once the input TV signal is digitized, all the functions can be realized in an integrated manner.

IV. APPLICATIONS TO MULTIPLE TV TRANSMISSIONS THROUGH SATELLITES

In this section we discuss some applications of the various bandwidth compression techniques (outlined in Sections II and III) to multiple TV transmissions through satellites. We assume that TCM is to be

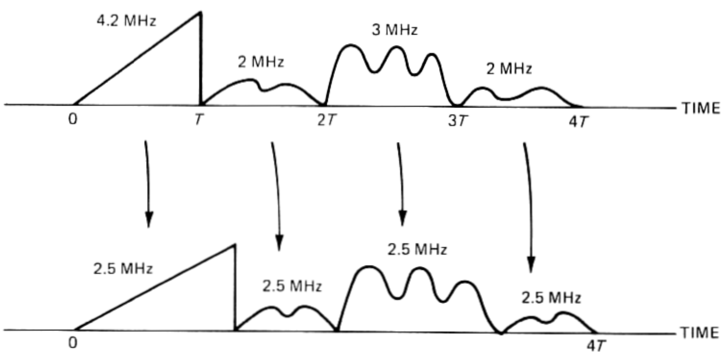

Fig. 6—Time companding of line and field differential signals in $(0, 4T)$.

employed for multiplexing different but synchronized TV signals before transmission via a single FM carrier. The performance of a simplified TCM/FM satellite link is shown in Fig. 7, where the following assumptions are made:

(*i*) Only the downlink is considered.

(*ii*) Time compression and expansion are ideal.

(*iii*) Satellite Effective Isotropic Radiated Power (EIRP) = 34 dBW; satellite usable channel bandwidth = 36 MHz; receive earth station elevation angle = 15°; frequency = 4180 MHz; maximum receive flux density = -152 dBW/m^2/4 kHz.

(*iv*) The peak-to-peak signal to weighted rms noise ratio (in dB) is

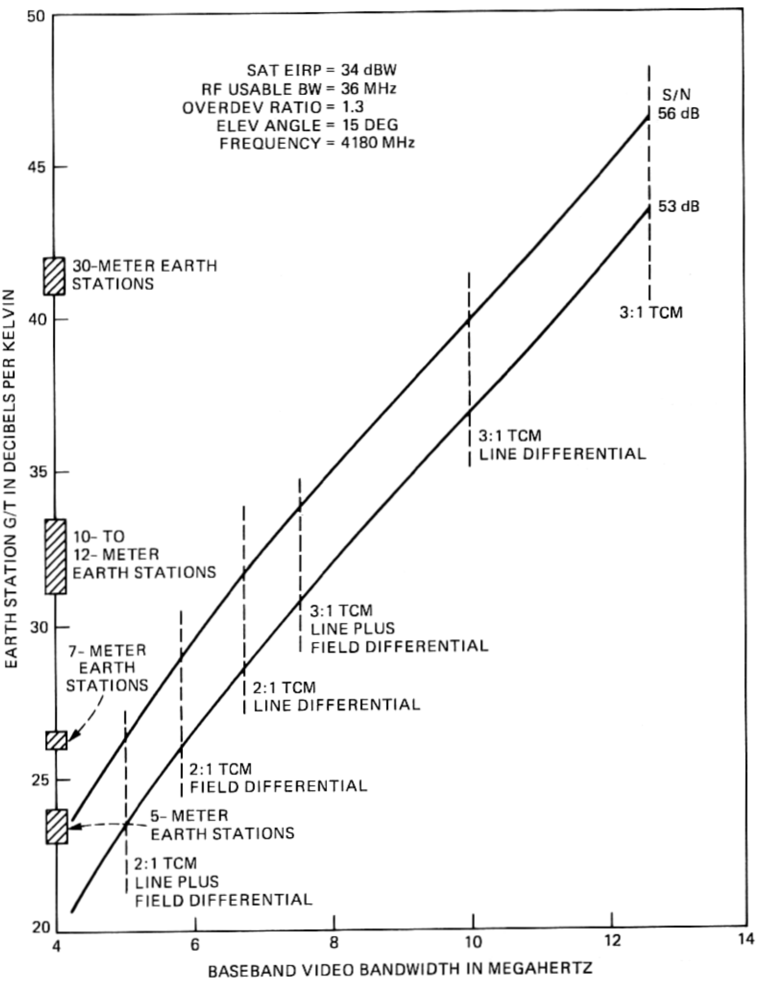

Fig. 7—Performance of a color TV transmission via TCM in a satellite link.

calculated by the well-known formula

$$s/n = \text{CNR} + 10 \log \left[12 \frac{(0.7\Delta f)^2 B}{f_m^3} \right] + 12.8, \tag{8}$$

where

CNR = received IF carrier-to-noise ratio (dB);

Δf = peak frequency deviation (MHz);

B = IF bandwidth (MHz);

f_m = baseband video bandwidth (MHz).

When Carson's rule is used, $B = 2(\Delta f + f_m)$. However, we assume that overdeviation* is permissible, and $\Delta f = 1.3(B/2 - f_m)$.

(*v*) The baseband bandwidth, f_m, would be equal to the bandwidth of an ordinary TV (i.e., f_t = 4.2 MHz) if it were a single TV/FM case. However, we let f_m vary over the range from 4.2 MHz to 12.6 MHz in the calculation to account for TCM.[4] The corresponding values of receive earth station figure of merit (G/T) for signal-to-noise ratio (s/n) = 53 and 56 dB are evaluated and plotted in the figure.

Referring to Fig. 7, we interpret the baseband video bandwidth f_m as the total baseband bandwidth of the combined time-compressed TV signals. For instance, the baseband bandwidth of a time-compressed TV coded with a line differential signal is 3.34 MHz (Section III). Time-compression multiplexing three such TV signals yields a total baseband bandwidth of 10.02 MHz. Using f_m = 10.02 MHz, we read from Fig. 7 that the G/T required to receive these three TV's at s/n = 56 dB is 39.8 dB. We recognize that this kind of calculation is not strictly valid because of the unknown subjective noise effects on the differential signals. However, these calculations do indicate the approximate performance to be expected and are suitable for the present feasibility study.

Along the vertical axis of Fig. 7, we also show some typical G/T's for differential types of earth stations. For easy reading we tabulate the baseband bandwidths for various cases of interest in Table I. Using Table I and Fig. 7, we derive various G/T's for the various cases, and the results for s/n = 56 and 53 dB are tabulated in Table II. If we assume that s/n = 53 dB is acceptable,[5] then the following observations can be drawn:

(*i*) Using 30-meter receive earth stations, we should be able to get

* Overdeviation with respect to the receiver noise bandwidth is sometimes used in satellite TV transmission to trade off waveform distortion for signal-to-noise performance. In this case, the modulator output would have to be filtered to ensure that the allocated bandwidth is not exceeded. In addition, the overall effect of the small amount of overdeviation used would have to be evaluated further.

Table I—Total baseband bandwidth for various combinations of bandwidth compression methods and TCM

Bandwidth Compression	Total Baseband Bandwidth (MHz)		
	1 TV	2 TV/TCM	3 TV/TCM
No Compression	4.2	8.4	12.6
Line Differential	3.34	6.68	10.02
Field Differential	2.9	5.8	8.7
Line and Field Differential	2.5	5.0	7.5

Table II—Receive earth station G/T required for various combinations of bandwidth compression methods and TCM

s/n	Bandwidth Compression Method	G/T(dB/K)	
		2 TV/TCM	3 TV/TCM
56	No Compression	35.9	46.4
	Line Differential	31.5	39.8
	Field Differential	28.9	36.7
	Line plus Field Differential	26.4	33.7
53	No Compression	32.9	43.4
	Line Differential	28.5	36.8
	Field Differential	25.9	33.7
	Line plus Field Differential	23.4	30.7

three TV's per transponder with the line differential compression method.

(*ii*) Using conventional 12-meter earth stations, or 10-meter earth stations with very sensitive low-noise amplifiers (LNAs) we should be able to get three TV's per transponder with the field or line plus field differential compression method, and two TV's per transponder with a straightforward TCM without baseband TV bandwidth reduction.

(*iii*) Using conventional 10-meter earth stations, we should be able to get two TV's per transponder with the line differential method.

(*iv*) Using 7-meter earth stations, we should be able to get two TV's per transponder with the field differential method.

(*v*) Using 5-meter earth stations, we should be able to get two TV's per transponder with the line plus field differential technique.

It is obvious that the above five results involve progressing bandwidth efficiency at the expense of increasing bandwidth reduction hardware.

The problem of adjacent satellite interference was not included in the above, and if the satellite spacing were to be reduced to 2° in the future, then the use of the 5- and 7-meter earth stations might not be appropriate. Finally, let us note that although the transmission of TV audios was not addressed, it could be included easily by virtue of the time-multiplexing characteristic in the system and the ease of digitizing audios today. A number of possibilities exist. Just to name one example, each TV line could be time compressed a little more to create sufficient time space for accommodating the digital audios.

V. CONCLUDING REMARKS

We have outlined three bandwidth compression techniques that can reduce the bandwidth of a 4.2-MHz NTSC color TV signal into 3.34, 2.9, and 2.5 MHz, respectively. These methods can be implemented with existing high-speed digital processing hardware. When these techniques are used in combination with TCM for multiple TV transmissions through a single satellite transponder, high bandwidth efficiency can be attained without the conventional problems owing to transponder nonlinearities (such as intermodulation and intelligible cross talk). We show in a specific example that up to three TV signals may be transmitted simultaneously with acceptable quality in a 36-MHz transponder with a 10-meter receive earth station, and with simpler hardware, two TV's per transponder may be transmitted with 7- or 10-meter earth stations. We conclude that these bandwidth compression techniques plus TCM are promising approaches to maximize the use of future satellite transponders for high-quality TV distribution.

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