CONTRIBUTING SOURCES AND MAGNITUDES OF ENVELOPE DELAY IN CABLE TRANSMISSION SYSTEM COMPONENTS

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INTRODUCTION

Two-way transmission on a single cable system has focused attention on the cable system performance parameter group delay distortion (or variation), which previously was only of major concern in single channel head end equipment and off air signals. Group delay distortion is not the only important parameter which must be considered, but it is the topic of this paper. This paper covers the following topics:

1. Sources of group delay distortion in the single cable, 2-way cable system.

2. Examples of calculated and measured group delay of cable system components.

3. Methods of minimizing group delay distortion in the cable system.

It is well known that frequency division multiplex (FDM) filters are the primary cause of group delay distortion in a single cable, 2-way transmission system. The group delay characteristics of other cable system components were also investigated, however, since very little information has been published for these components. Permissable magnitudes of group delay distortion based on test results of subjective viewing are discussed in detail in Reference 1, and will only be mentioned in this paper.

Techniques for correcting or equalizing transmission path delay distortion which is considered unacceptable are discussed. The application of delay equalizing methods will require new products from CATV equipment manufacturers and the use of special test equipment by the system operator.

REVIEW OF IDEAL LINEAR SYSTEM CHARACTERISTICS

Signal information transmitted through a transmission system or device contains a finite band of frequencies. If the system or device has a flat amplitude response and a linear phase response over the band of signal frequencies, the output is an exact replica of the input, delayed in time, and directly proportional in amplitude to the constant gain factor A (See Figure 1, 2)

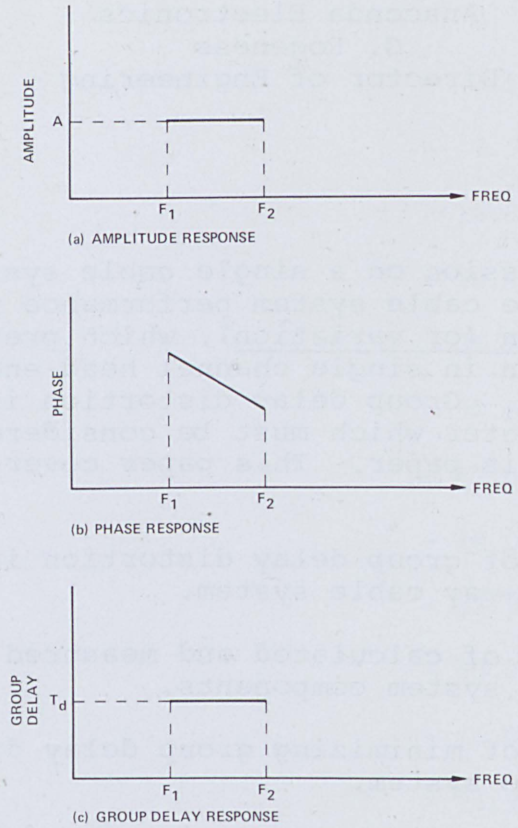


FIGURE 1 IDEAL SYSTEM OF BANDWIDTH (F_2-F_1) AMPLITUDE, PHASE, AND DELAY RESPONSE

Any device or component containing energy storage elements such as inductors and capacitors will produce phase shifts. Phase shift versus frequency is linear in the ideal system. Envelope delay (synonymous with group delay) is defined as the rate of change of phase shift with respect to frequency. Another way of saying this is that envelope delay is the incremental slope of the phase shift versus frequency curve of the transmission system. Linear phase means constant delay, as shown in Figure 1C.

The envelope delay response of cascaded systems or components is additive, just as is the decibel amplitude response of cascaded systems or components. Therefore, knowing the envelope delay of each individual piece of equipment in a cascade, the envelope delay of the total cascade can be determined by simple arithmetic addition. For example, a cascade of ten identical filters, each filter having an envelope delay of 3 nanoseconds, has an envelope delay of 30 nanoseconds. This principle is also helpful for designing delay equalizers.

In the non-ideal or practical situation, equipment will introduce amplitude distortion (response not perfectly flat over frequency band) and group delay distortion (response not constant at each signal frequency). An example of the effect of the delay response of practical hardware is shown in Figure 2C. In addition to waveform distortion caused by delay distortion, misregistration of chroma information in the television color signal will also result. Note that the output of an ideal system is a replica of this input signal, delayed in time, and modified by the constant gain factor A.

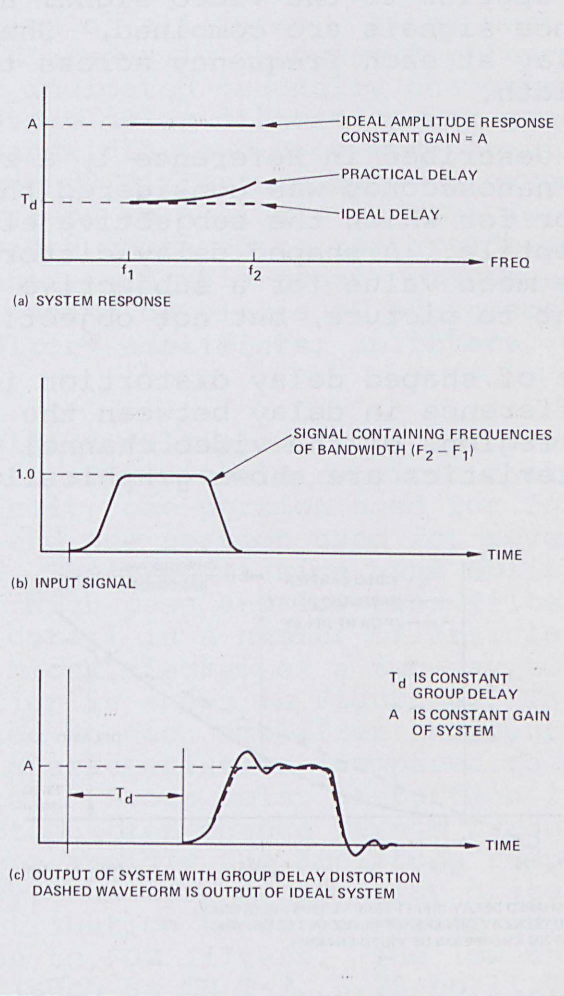


FIGURE 2 EXAMPLE OF SIGNAL TRANSMISSION THRU SYSTEM WHICH HAS IDEAL AMPLITUDE RESPONSE AND NON-IDEAL DELAY RESPONSE

TYPES OF DELAY DISTORTION

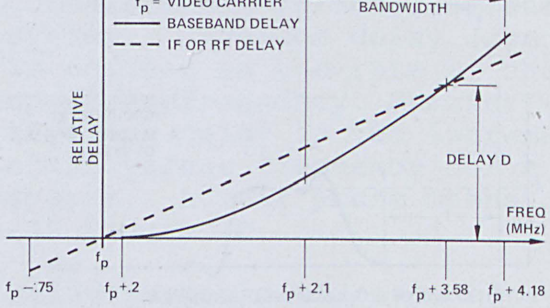
The NTSC color television signal consists of luminance and chrominance information. The delay difference between the chrominance and luminance signal will cause misregistration of color information, and, in addition will effect the transient response of the television signal. Chroma delay is defined as the difference between the chrominance and luminance carrier. Two types of delay distortion which are present in the transmission path between televised scene and subscriber television set picture are flat delay and shaped delay.

Flat delay difference may occur when the luminance and chrominance signal are processed separately at video frequencies, introducing a constant delay between the two signals. The broadcast studio and home receiver would be the most common source of this type of distortion. Flat delay distortion will not be considered in this paper.

Shaped delay applies to the video signal after luminance and chrominance signals are combined. Shaped delay is a change of delay at each frequency across the video or signal bandwidth.

In the tests described in Reference 1, a shaped delay error of 178 nanoseconds was considered the mean value of delay error for which the subjective effect was rated as just perceptile. A shaped delay distortion error of 477ns was the mean value for a subjective effect rated as "impairment to picture, but not objectionable".

The magnitude of shaped delay distortion is commonly taken to be the difference in delay between the 3.58 MHz and 0 to 200 KHz regions of the video channel Two shaped delay characteristics are shown graphically in Figure 3.



SHAPED DELAY DIFFERENCE VERSUS FREQUENCY.
D IS DELAY DIFFERENCE BETWEEN 3.58 MHz AND 0-200 KHz REGION OF VIDEO CHANNEL.

FIGURE 3

The dashed curve is representative of the type of delay distortion present in FDM filters and other broadband cable system components. The slope of the shaped delay curve can be either positive or negative, depending on the particular component properties. The solid curve is typical of those shown in the literature referring to baseband video, and, therefore, the delay characteristic does not extend below a carrier frequency. Articles, such as Reference 4, concerned with the design of narrowband RF and IF amplifiers, do address this problem of delay below a carrier.

ENVELOPE DELAY OR CABLE SYSTEM COMPONENTS

In the CATV Industry there was very little concern for envelope delay in cable system components until the study and development of two-way transmission on a single delay cable began a few years ago. The major sources of group delay were either already present in the signal received by the cable system, generated in the CATV head-end equipment, generated in the subscriber television receiver, or some combination of all three. Since most cable system components had gradually changing amplitude responses, which usually indicated gradually changing phase response, very little group delay distortion was generated. Also, the channel bandwidth, and even more specifically, the 3.58 MHz frequency difference between chrominance and luminance carriers in a single channel is a small percentage bandwidth compared to the broadband response of these components. In this paper, components are defined as functional units or pieces of equipment such as cable, equalizer, filter, amplifiers, splitters, directional taps, etc.

Frequency division multiplex (FDM) for 2-way transmission of signals on a single cable requires that the frequency spectrum be split, one portion used for forward (downstream) transmission and one portion used for reverse (upstream) transmission. The transmission band split is accomplished by the use of high pass and low pass filters and has been discussed in detail in a number of articles (References 6, 7, 8). A block diagram of a two-way transmission repeater amplifier is shown in Figure 4. The FDM filters must be located at each amplifier and must have relatively sharp cutoff characteristics (compared to other cable system components). Group delay distortion is proportional to rate of attenuation change versus frequency. In other words, the more rapidly the amplitude response changes with frequency, the more group delay distortion is present. The major contribution to cable system group delay distortion is due to FDM filters. The low end of the sub channel band (such as CH T-7, 5.75 to 11.75 MHz) delay distortion is due to sources other than FDM filters. To fully characteristize the system delay, each component in the transmission path should be evaluated.

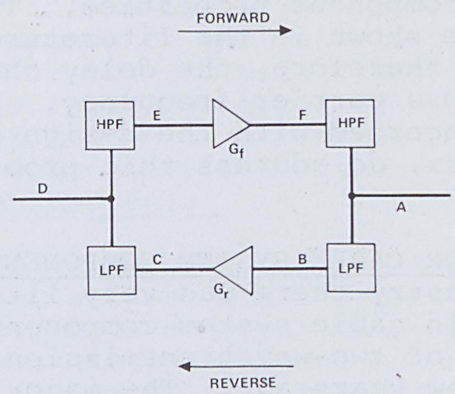


FIGURE 4 BLOCK DIAGRAM OF TWO-WAY REPEATER AMPLIFIER

The single cable system used for two-way transmission is actually split into two bandpasses and there are four cutoff frequencies as shown graphically in Figure 5. For the two bands shown in Figure 5, the FDM filters cause a sharp rate of attenuation beginning below 54 MHz for the downstream bandpass and above 30 MHz for the upstream bandpass.

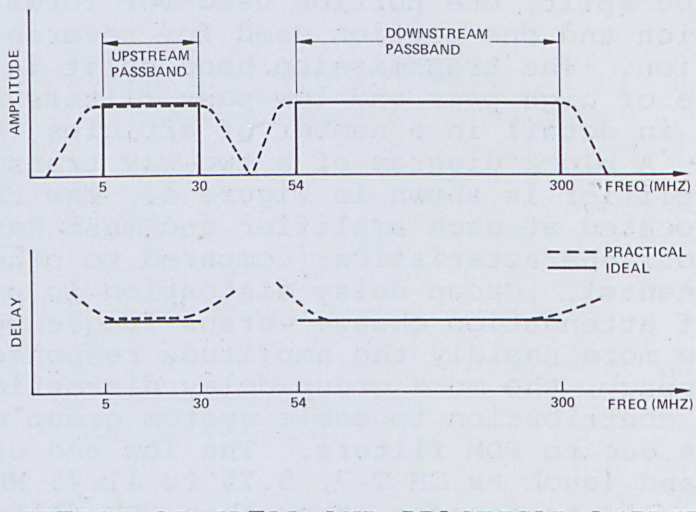


FIGURE 5 SKETCH OF IDEAL AND PRACTICAL AMPLITUDE AND DELAY RESPONSE OF SINGLE CABLE TWO-WAY TRANSMISSION SYSTEM

DOWNSTREAM PATH

The response above 300 MHz (or the highest frequency) in the downstream path will attenuate gradually due to amplifier gain roll-off and cable attenuation equalizer roll-off. Because of this fact and the fact that the ratio of 3.58 MHz/300 MHz is approximately one-sixth the value of the ratio of 3.58 MHz/55 MHz, delay distortion at the high end of the downstream across a 3.58 MHz will be very low. Therefore, the emphasis on delay distortion minimization in the downstream path is at the low end of the band and predominately attributable to FDM filters.

UPSTREAM PATH

The delay distortion problem in the upstream passband is accentuated because a 3.58 MHz bandwidth is a much higher percentage bandwidth ($\frac{3.58}{8.75}$ = .41 for channel T7, and $\frac{3.58}{26.75}$ = .134 for channel T10). Delay distortion at the high end of the upstream band will be caused mainly by the FDM filter design. However, the upstream cable attenuation equalizers also contribute delay distortion. The low end response of the upstream band is similar to that of a high pass filter. The high pass filter type response results from both the power frequency blocking capacitors and passing chokes plus response roll-off due to the magnetics used in line splitters and directional couplers.

GROUP DELAY OF LOW-LOSS CABLE

The equations used for the calculation of low-loss cable group delay are listed in Appendix I. The results of these calculations for two types of cable are summarized below. The chroma delay (delay of chroma carrier minus delay of channel carrier) is so small that it is negligible, as expected.

TABLE 1

		CHROMA DELAY NSEC/10,000 FEET	
CHANNEL	FREQ (MHZ)	500 CABLE	750 CABLE
T7	10.58	-.0297	-.0137
2	58.83	-.00071	-.00033

GROUP DELAY OF BRIDGED-T EQUALIZER

A cable attenuation equalizer is a form of band pass filter. The attenuation slope of this band pass filter is used to equalize the cable attenuation. A type of cable equalizer which is common in many CATV amplifiers is referred to as a constant resistance bridged-T equalizer. A schematic of such an equalizer is shown in Figure 6.

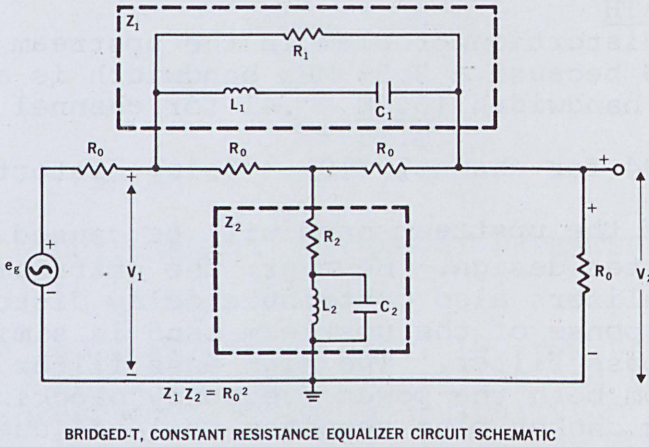


FIGURE 6

Assuming a constant source and load impedance of Ro (Ro = 75 ohms for CATV applications) the expression for its insertion loss is:

$$\frac{V_1}{V_2} = 1 + Z_{1/Ro} \tag{1}$$

The term Z_1 is a function of frequency and is a complex number, so it therefore contains a real and imaginary term. The expression for the equalizer phase shift is

$$\text{Phase}\left(\frac{V_2}{V_1}\right) = P = \text{Arctan}\left(\frac{\text{imaginary part of } Z_{1/Ro}}{1 + \text{real part of } Z_{1/Ro}}\right) \tag{2}$$

The expression for phase shift is needed to calculate the group delay which is

$$\text{Group Delay}\left(\frac{V_2}{V_1}\right) = D = \frac{-dp}{dw} \qquad (3)$$

where $w = 2\pi f$

Expression (3) was evaluated for an equalizer similar to that shown in Figure 6. An equalizer response for the 5-30 MHz frequency band and the 50 to 300 MHz band was calculated and also breadboarded. The cable loss plus equalizer loss was flat within 1.0 dB peak to valley over the passband. Delay values were measured using a General Radio Type 1710 Analyzer system. The delay magnitude of the 50-300 MHz equalizer was calculated at less than 2 ns across the band, so that a meaningful measurement could not be obtained. However, the delay magnitude measured on the 5-30 MHz equalizer was within the resolution of the test equipment and agreed well with the calculated values.

Calculated delay values for the two equalizers are summarized in Table 2. The equalizers were designed based on the Anaconda SLM 750 cable attenuation characteristic. The dB value of equalizer shown refers to the dB loss of cable at either 30 MHz or 300 MHz.

TABLE 2

5-30 MHZ 6 dB EQUALIZER				50-300 MHZ 17 dB EQUALIZER			
FREQ. (MHZ)	CABLE + EQU. LOSS (dB)	PHASE (DEG)	DELAY (NSEC.)	FREQ. (MHZ)	CABLE + EQU. LOSS (dB)	PHASE (DEG)	DELAY (NSEC.)
7.0	-6.2	4.8	-1.78	55.25	-10.8	17.3	-.24
10.58	-6.7	7.0	-1.58	58.83	-10.8	17.6	-.21
19	-6.9	10.7	- .70	211.25	-10.9	19.4	+.28
22.58	-6.6	10.9	+ .68	214.83	-10.9	19.0	+.31
25	-6.3	9.5	+2.67	295.25	-10.9	1.33	+.78
28.58	-5.9	3.5	+6.51	298.83	-11	.33	+.78

Group Delay of Downstream Flat Gain Repeater Amplifier

The group delay variation versus frequency of flat gain broadband hybrid integrated circuit amplifiers (for use over 50-300 MHz band) now in production is very low. One reason for this is that the amplitude response of these IC amplifiers (two types manufactured by Hewlett Packard) is flat from approximately 20 MHz to greater than 330 MHz. The response roll-off at the band edges is also gradual, so that very little group delay variation occurs in a passband of 54 to 300 MHz. In addition, it is possible to reduce the effect of circuit parasitics, so that the appropriate element values can be used.

Using the same principle of extending the bandwidth beyond the passband frequencies, the upstream amplifiers will also have low values of chroma delay in the passband. Care must be taken to insure that the low frequency cutoff extends well below the lowest frequency of 5 MHz and yet rejects the power frequency of 60 Hz.

Channel T-7 and T-8 Chroma Delay

Much attention has been given the FDM chroma delay problem at the upper edge of the upstream band and lower edge of the downstream band. However, the low frequency delay response of components in the upstream path can have a considerable effect on channels T-7 and T-8. As an example of the occurrence of this chroma delay, two fundamental circuit arrangements are analyzed. These circuits, plus variations of these circuits appear many times in an amplifier and/or passive component. More specifically, these circuits are the cause of low end upstream channel chroma delay in the following cable system equipment.

- Directional Couplers
- Line Splitters
- Intermediate Bridger (Thru Path)
- Directional Taps
- Upstream Repeater Amplifiers
- Repeater amplifier motherboard (or module interconnect chassis) in 60 Hz power feed and tapoff circuit.

The number of such components in cascade can cause T-7 chroma delay which is equal to or greater than that due to FDM filters in other channels.

Typical networks which appear in these components are shown in Figure 7.

As an example of the values of delay resulting from these types of networks, calculations using some sample values are summarized in Table 3.

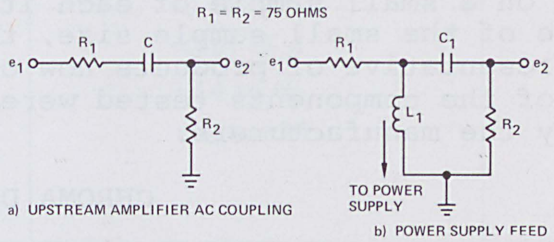


FIGURE 7

Figure 7 Circuits which can be source of group delay distortion in low subchannels.

TABLE 3

CIRCUIT (A) C = .01 uf			CIRCUIT (B) L_1 = 5uh C_1 = .02 uf	
FREQ MHZ	e_2/e_1 dB	DELAY NSEC	e_2/e_1 dB	DELAY NSEC
7	-6.02	1.37	-6.13	4.08
10.58	-6.01	0.60	-6.07	1.78
13	-6.00	0.40	-6.05	1.18
16.58	-6.00	0.25	-6.04	.72

Unfortunately, a conclusion on specific delay values for each of the components listed on page 10 cannot be reported at this time because a large enough sample of each component was not available. However, delay measurements made on each item available indicated that the chroma delay through a cable system could be significant in channel T-7 (picture carrier 7 MHz, chroma carrier 10.58 MHz). Typical values of channel T-7 chroma delay measured on a small sample of each item is listed below. Because of the small sample size, these numbers may not be representative of products now on the market. The bandwidth of the components tested were specified as 5-300 MHz by the manufacturers.

ITEM	CHROMA DELAY (NSEC)
2-output line splitter	2.5
4-output line splitter	10
Directional Taps	3
Intermediate Bridger	5
Trunk Amp Motherboard	3
Upstream Amplifier (IC, no equalizer)	Negligible

FDM FILTERS

FDM Filters for the sub-low frequency split (5-30 MHz, upstream, 54-300 MHz downstream) must simultaneously meet a number of performance parameters. The filter design is a compromise of the following parameters:

- rate of cutoff
- minimum stop band attenuation
- minimum ripple in passband
- minimum insertion loss in passband
- high return loss in passband
- constant group delay in passband

The group delay characteristic of the FDM filter will depend not only on what design compromise is made, but also on the filter alignment and practical filter component values. Estimated ranges of chroma delay values which might be expected from a pair of FDM filters (one pair per amplifier station) are listed in Table 4. The group delay will depend on the specific filter design, which each manufacturer must specify. The estimated delay values are based on filter designs which are necessary to simultaneously realize performance for each of the six parameters listed above.

TABLE 4
RANGE OF CHROMA DELAY VALUES IN NSEC
FOR PAIR (2) OF FDM FILTERS

CHANNEL	LOW PASS FILTER (2)	HIGH PASS FILTER (2)
T-7	+1 to +2.0	
T-8	+3 to +5.4	
T-9	+3.4 to +6	
T-10	+10 to +20	
2		−4 to −8
3		−3 to −5

System Chroma Delay

The system chroma delay of a channel can be estimated by adding the chroma delay of the channel due to each component in the transmission path between sending and receiving location. As discussed in previous pages, the chroma delay of each channel can be caused by a number of different components. A summary of the sources of chroma delay and the channels affected is shown below.

CHANNEL	FREQUENCY	MAIN SOURCES OF CHROMA DELAY
T-7 T-8	7-10.58 13-16.58	Directional Couplers Directional Taps Line Splitters AC Coupling to Upstream Amplifier Intermediate Bridgers Repeater Station Motherboard Power Supply Coupling
T-9	19-22.58	FDM Filters
T-10	25-28.58	Cable Equalizers
2	55.25-58.83	
3	61.25-64.83	FDM Filters
4	67.25-70.83	

Testing for Chroma Delay

One method of testing for chroma delay is the use of a modulated 20T or 12.5T pulse as described in Reference 8. This is a single channel test which requires use of a demodulator, since the test equipment is designed to operate at baseband video frequencies. Waveform testing, in addition to the modulated 20T or 12.5T pulse, may be necessary to insure that a given channel delay characteristic (equalized or not), does not impair the total channel waveform beyond an acceptable limit.

Swept delay measurements of a transmission path would be desireable if the test equipment was available. Further discussion of testing for chroma delay is beyond the scope of this paper.

System Delay Distortion Correction

Each component in the 2-way cable system should be designed to minimize its contribution of delay distortion. However, constant group delay per television channel, per system component, many times cannot be met simultaneously with all of the other required operational characteristics of the system component. A given amount of delay distortion will therefore be present in a transmission path after the compromises of cost effective component design and design tradeoffs between delay distortion, frequency response, insertion loss, etc., have been selected. So the next question is "what methods or techniques can be used to reduce transmission path delay distortion from that caused by the components in the transmission path, when these components are considered to be optimum from a total performance and cost standpoint?". Two methods will be considered. Either one, or both, may be required to solve a specific delay distortion problem. One method requires selection of channel frequencies in the forward and reverse transmission path and the second method requires the addition of delay equalizers in the transmission path.

Method One - Channel Frequency Selection

Channel frequency selection may be effective when downstream low band channels are available and can be used to transmit any upstream channel which has suffered delay distortion back into the downstream system path. If low band channels are not available, then some other method of delay equalization may be used.

Consider the delay characteristics of a single low pass filter and high pass filter as shown in Figure 8. As an example of how channel frequency selection can reduce total transmission path delay distortion, the simple system of Figure 9 will be analyzed. An upstream channel, T-9, applied to the low pass filter, acquires the delay characteristic of the low pass filter over its channel bandpass.

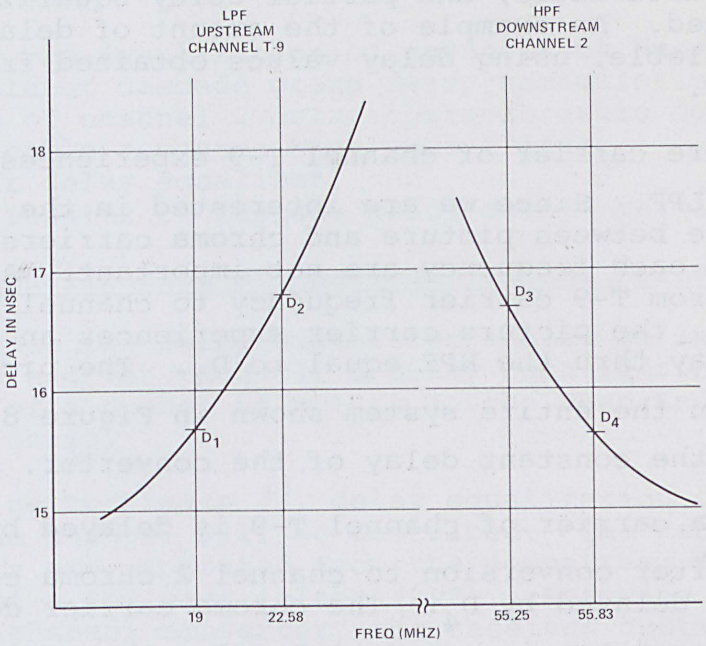


FIGURE 8 GROUP DELAY OF C06-05-44 FDM FILTER PAIR

Channel T-9 is then converted to Channel 2 in a converter located at a hub or the headend. The converter is assumed to have a constant delay versus frequency characteristic over the channel bandwidths. The delay of the video and color subcarrier frequencies passing through the high pass filter have an inverse delay characteristic compared to the low pass filter as shown in Figure 8. That is, the relative delay at the

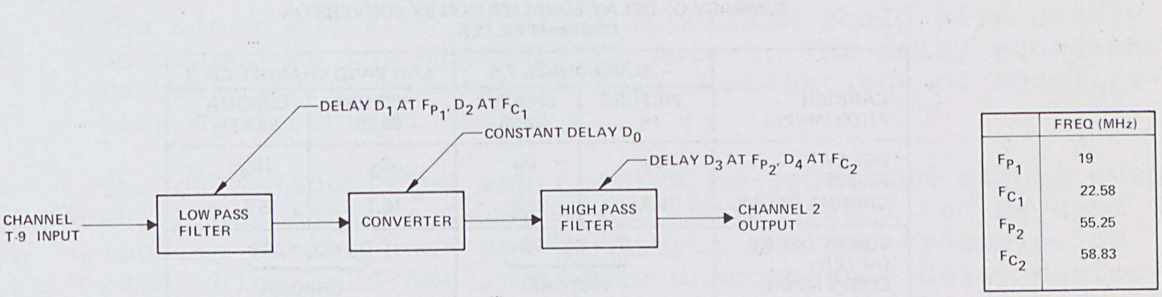


FIGURE 9 TRANSMISSION PATH DELAY DISTORTION REDUCTION BY CHANNEL FREQUENCY SELECTION

luminance and chrominance carrier frequencies are reversed between the low pass and high pass filter. The inverse characteristics will match in much the same manner that a cable loss equalizer matches the cable loss characteristic, and partial delay equalization can be obtained. An example of the amount of delay equalization available, using delay values obtained from Reference 2 follows.

The picture carrier of channel T-9 experiences a delay D_1 thru the LPF. Since we are interested in the delay difference between picture and chroma carriers, constant delays at each frequency are not important. After conversion from T-9 carrier frequency to channel 2 carrier frequency, the picture carrier experiences an additional group delay thru the HPF equal to D_3. The picture carrier delay thru the entire system shown in Figure 8 is now D_1 $+D_3$ plus the constant delay of the converter.

The chroma carrier of channel T-9 is delayed by D_2 in the LPF and after conversion to channel 2 chroma carrier frequency is delayed by D_4. The chroma carrier delay thru the entire system is now $D_2 + D_4$ plus the same constant delay of the converter.

The chroma delay of the channel 2 (converted from T-9) signal is equal to $(D_2 + D_4) - (D_1 + D_3)$. The delay values are summarized in Table 5.

The low pass filter and high pass filter designs are referred to as C06-05-44 in Reference 2. The delay values for D_1, D_2, D_3, D_4 were derived from a graph on Page 176 of Reference 2. The LPF cutoff frequency is 35MHz and HP cutoff is 45 MHz. Note that delay equalization for this example greatly reduces the chroma delay of the transmission path.

TABLE 5
SUMMARY OF DELAY EQUALIZATION BY CONVERSION
CO6-05-44 FILTER

	SUBCHANNEL T-9		LOW BAND CHANNEL CH. 2	
CARRIER FREQ (MHZ)	PICTURE 19	CHROMA 22.58	PICTURE 55.25	CHROMA 58.83
DELAY (NSEC) CHROMA DELAY	D_1 15.7	D_2 17.3	D_3 16.7	D_4 15.5
SUM OF DELAY (AFTER CONVERSION)	$\underbrace{D_1 + D_3 = 32.4}_{\text{PICTURE}}$		$\underbrace{D_2 + D_4 = 32.8}_{\text{CHROMA}}$	
CHROMA DELAY AFTER EQUALIZATION BY CONVERSION	$(D_2 + D_4) - (D_1 + D_3)$ = CHROMA DELAY 32.8 − 32.4 = 0.4 NSEC			

Proceeding on to further methods of transmission path delay equalization, the following items will be discussed:

Delay Equalization of upstream channel received at Head End.
Delay Pre-Equalization of channels at Head End and example of cascade group delay accumulation.
Shape of channel 2 delay characteristic due to broadband cable repeater high pass filter.
Linear delay equalizer.
Test results of cascade group delay equalization.

Delay Equalization of Upstream Channel Arriving at Head End

To correct the delay distortion caused by an upstream signal path on a given channel, a delay equalizer can be placed at any of a number of points in the Head End signal processor chain.

Referring to Figure 10, delay equalization of a single upstream channel will be described. The received upstream channels are separated from the downstream channels by means of a low pass filter (LPF). Assuming use of a single channel converter, the received upstream channel is converted to a standard television channel, such as channel 2 or channel 3. The signal can now be applied to a standard heterodyne signal processor. Delay Equalization can be accomplished either at i-f frequencies or at r-f frequencies. Delay equalization at i-f frequencies is convenient, since a single set, or family of delay equalizers can be designed to accommodate all channels, rather than a set of delay equalizers for each channel. Delay equalization at i-f frequencies is shown in Figure 10, where the heterodyne i-f amplifier output is fed to a delay equalizer rather than directly to the upconverter input. On the other hand, since only a few channels should need delay equalization, it can be done at the actual channel frequencies.

The block entitled IF DELAY EQUALIZER could alternately be placed at the UPCONVERTER output. The delay equalizer is designed to provide various combinations of equalization as discussed next.

The delay equalizer can provide an equalized signal output which has minimum delay error. This signal can be used locally at the head end or fed to another transmission path which does not introduce unacceptable delay distortion. Signal output #1 of Figure 10 would be used for this purpose.

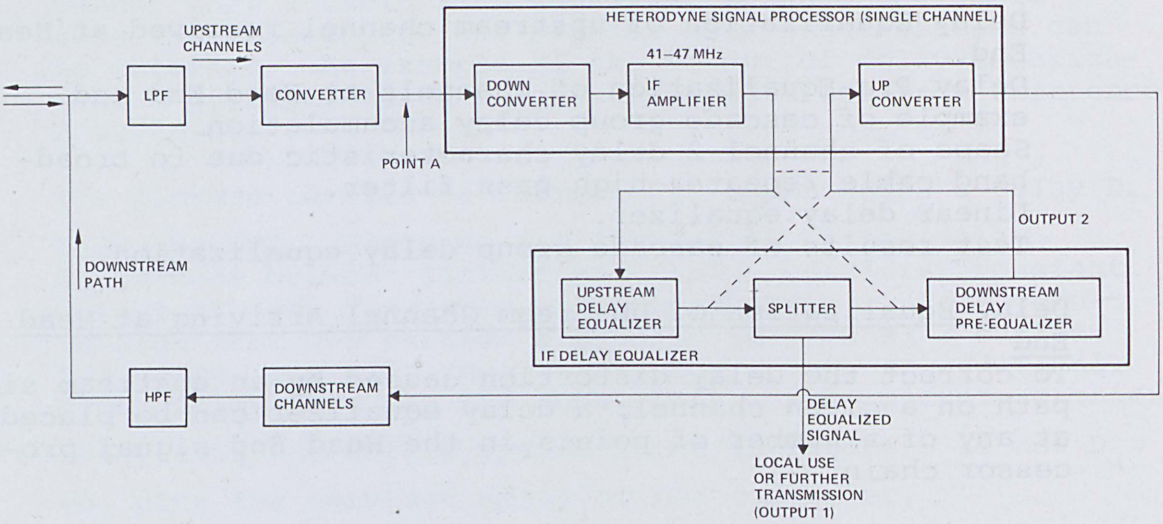


FIGURE 10 BLOCK DIAGRAM OF HEAD END, DETAILING ONE ARRANGEMENT OF ROUND TRIP GROUP DELAY EQUALIZATION

After the received channel has been delay equalized, it can then be fed thru a delay pre-equalizer for transmission back into the system on the downstream path. Output #2 of Figure 10 refers to this signal.

If desired, the upstream delay equalizer can be bypassed and the delay equalizer used for pre-equalization only. This arrangement can be used to provide delay pre-equalization for channels received off-the-air.

<u>Delay Pre-Equalization of Channels at the Head End</u>
The use of delay pre-equalization was mentioned in the last section. Delay pre-equalizations means that a predetermined amount of delay distortion is added to a channel at the head-end or at a signal input point. The sense, or shape of the pre-equalization delay curve is the negative of the delay curve which the signal will experience in passing through the system. An example of the results which can be expected by the use of delay pre-equalization are shown in Figure 11.

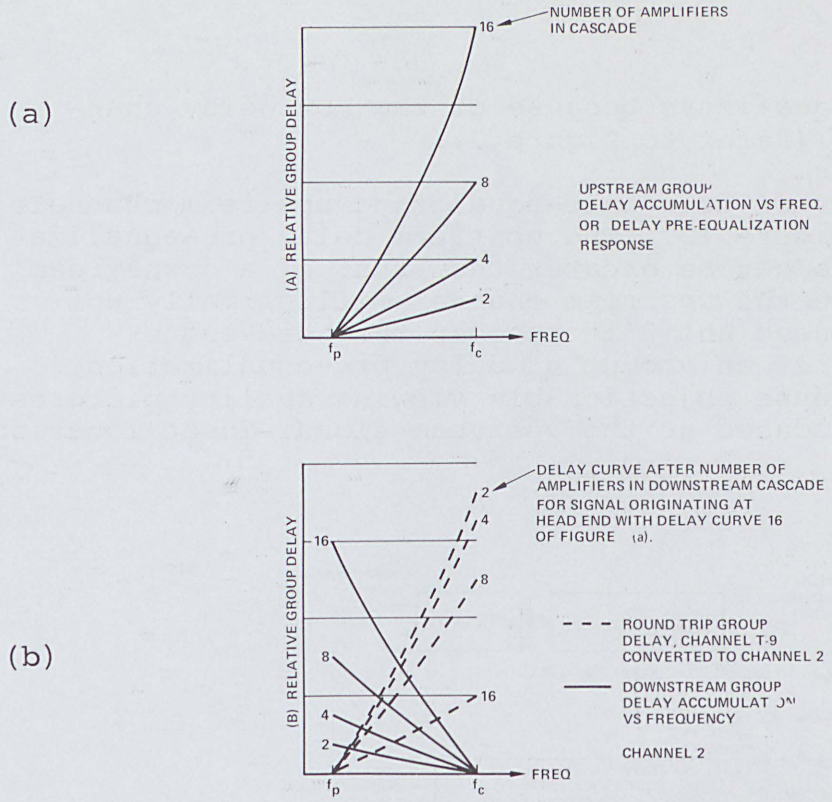


FIGURE 11 PRINCIPLE OF DELAY EQUALIZATION THRU 2-WAY TRANSMISSION AMPLIFIER CASCADE

A set of single channel delay curves is shown in Figure 11 (a). These delay curves could be the delay generated in a channel passing through the upstream path, or, they could be a set of delay curves generated by a delay pre-equalizer in the head end at the downstream channel frequency. If it is due to the upstream path delay, then this channel can be converted to a set of downstream channel frequencies. The delay curve is preserved thru this frequency conversion.

In Figure 11 (b), the dashed delay curve represents the channel delay as the signal proceeds thru a downstream path which introduces delay which is shown by the solid curve in Figure 11 (b). Note that after the 16th amplifier in the downstream path, the delay variation of the downstream channel as shown by the dashed curve is reduced compared to the delay variation caused by the downstream transmission path alone.

Block diagrams of methods to delay pre-equalize channels originating at the head end are shown in Figure 12. Delay pre-equalizers can be designed at video, if, or the actual r-f frequency of the desired channel. Equalization at if or rf frequencies may be more effective than video delay equalizers because of the FDM delay characteristics. (Refer to Figure 3).

Block diagrams of delay pre-equalizing upstream channels are shown in Figure 13. The upstream delay pre-equalization magnitude can be greater than that of a downstream channel, since the upstream channel will normally not be viewed or used until it reaches the head-end or hub. Therefore, an amount of delay pre-equalization which would cause objectionable viewing quality pictures could be introduced at the upstream signal input location.

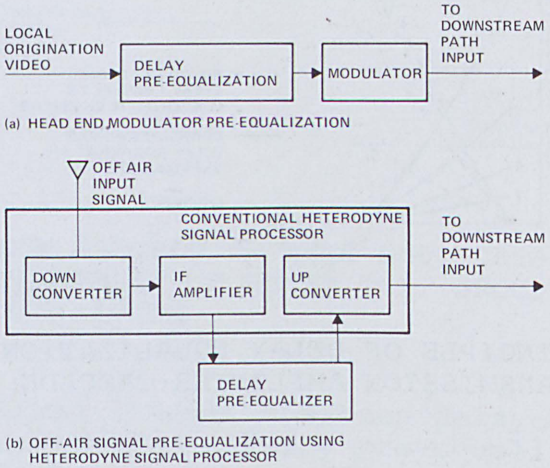


FIGURE 12 BLOCK DIAGRAM SHOWING METHODS OF DELAY PRE-EQUALIZATION OF SIGNALS ORIGINATING AT HEAD END

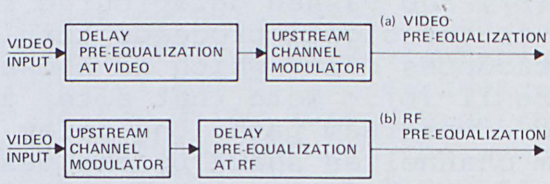


FIGURE 13 BLOCK DIAGRAM OF DELAY PRE-EQUALIZATION AT UPSTREAM SIGNAL INPUT LOCATION

Channel 2 Group Delay Characteristics
A group delay characteristic over channel 2 frequency band is shown in Figure 14. This curve was calculated by a circuit analysis program developed by Anaconda Electronics.

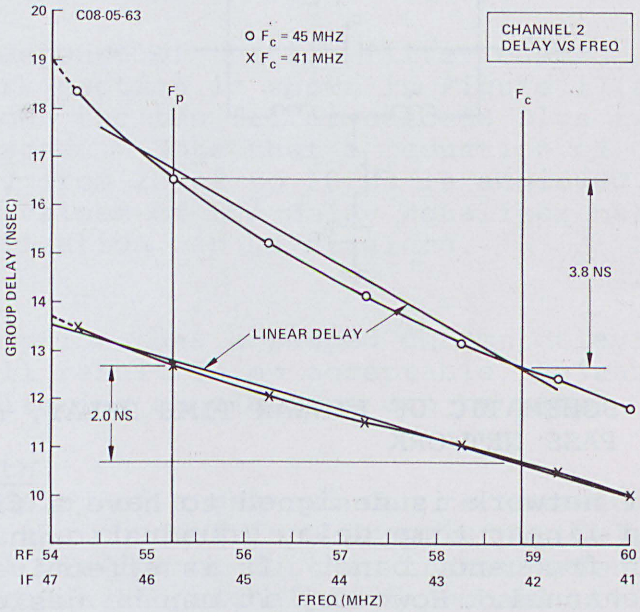


FIGURE 14 CALCULATED GROUP DELAY IN CHANNEL 2 FOR TWO FILTERS OF SAME DESIGN BUT DIFFERENT CUTOFF FREQUENCY

The filter analyzed is referred to as C08-05-63 and was taken from page 286 of Reference 5. It is an eighth order filter with design values to realize a 26dB pass-band return loss. Inductor Q's = 200 were used and the cutoff frequency of the filter was 41 MHz for curve A and 45 MHz for curve B. The Anaconda Electronic Model 2153 FDM filter has a delay characteristic which falls between the two shown.

A straight line is drawn thru both curves to show how well the delay characteristic of a single filter approximates a straight line. The straight line, or linear, approximation of the delay curve is significant, since linear time delay network designs have been in use for other applications for many years. By using a linear time delay network with a slope equal in magnitude and opposite in sign to the filter characteristic, excellent delay equalization is obtainable.

LINEAR TIME DELAY EQUALIZER
A linear time delay network or section is shown in Figure 15. The total delay correction or pre-equalization required will determine the number of sections required.

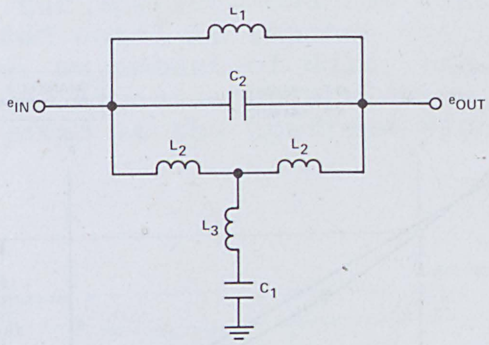


FIGURE 15 SCHEMATIC OF LINEAR TIME DELAY, ALL PASS NETWORK

This type of network is designed to have a flat amplitude response and linear time delay (quadratic phase) response over a given frequency band. It is effective over a single television channel. However, it can be designed to cover more than a single television channel. Calculated delay values for a single section of network similar to that shown in Figure 15 are listed below. This network was used to equalize the group delay variation of the channel 2 band through a cascade of ten FDM filters (5 amplifier cascade). The delay characteristic of the network built was shifted slightly in frequency from those values in the Table 6.

TABLE 6

CALCULATED DELAY EQUALIZER RESPONSE

FREQ (MHZ)	PHASE (DEGREES)	DELAY (NSEC)
54.25	39.5	13.5
55.25	44.9	17.0
56.25	51.8	21.8
57.25	60.8	28.6
58.25	72.8	38.6
59.25	89.2	53.1
60.25	111.6	72.5

Test Results of Delay Equalizer Network

Ten Anaconda Electronics Model 2153 filters were connected in cascade and the group delay versus frequency response measured on a General Radio Type 1710 analyzer system. The response of this cascade is shown in Figure 16(a). The vertical scale is 10 ns per large division and the horizontal scale is 1.0 MHz per large division. The center of the horizontal scale is 55 MHz. Two delay network sections (networks similar to that shown in Figure 15) were constructed. The delay response of these two sections is shown in Figure 16(b).

The delay response of the ten filter cascade plus a single delay network section is shown in Figure 17(a) In Figure 17(b) is shown the ten filter cascade plus two delay sections in cascade. Note that a reduction of Channel 2 chroma delay from 28 ns to 10 ns is achieved. By varying element values of the delay equalizer networks even better equalization can be attained.

Conclusion

If the assumption that a shaped chroma delay of 178 nanoseconds will result in an acceptable, saleable, picture, then the following conclusions can be made.

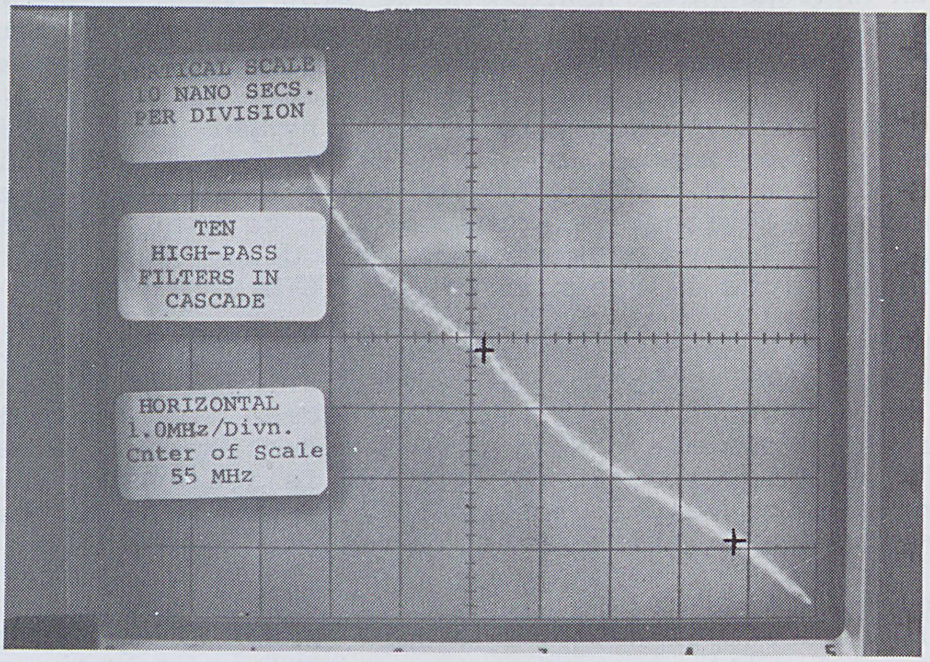
Upstream Path

The chroma delay of a channel can far exceed 178 nanoseconds if the channel is appropriately delay equalized before final viewing or further transmission. This is possible because the signal will probably be received at a single, or at most, a few locations, so that delay equalization at the receiver is practical. Chroma delay of the upstream cable path will be negative for Channel T7 (chroma carrier has less delay than picture carrier) and positive for Channel T-10 (chroma carrier has more delay than picture carrier). Chroma delay of Channels T8 and T9 may be either positive, negative, or U-shaped, depending on components used in system.

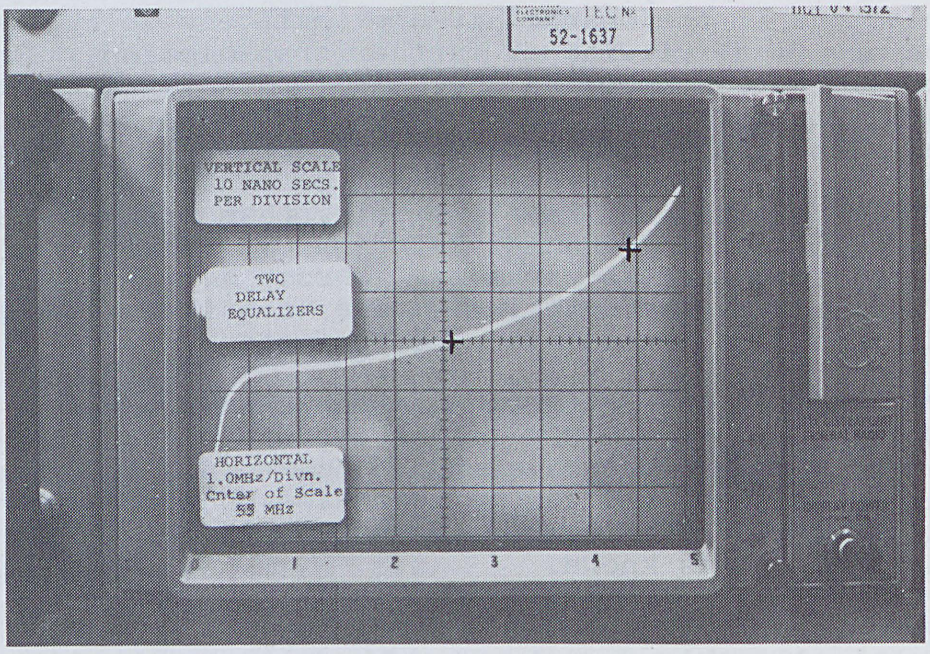
To estimate the upstream delay on Channels T-8, T-9, and T-10, the upstream FDM filter chroma delays and upstream amplifier chroma delays should be known. The chroma delay of Channel T-7 can be estimated when the chroma delays of the total number of components (listed on Page 10) in the path is known.

Downstream Path

Total allowable downstream path delay can be 354 nsec if 178 nsec of delay pre-equalization is inserted in the signal path at the head end. Because of the multi-receiver locations along the downstream path, delay equalization at the receivers is not practical at this time.

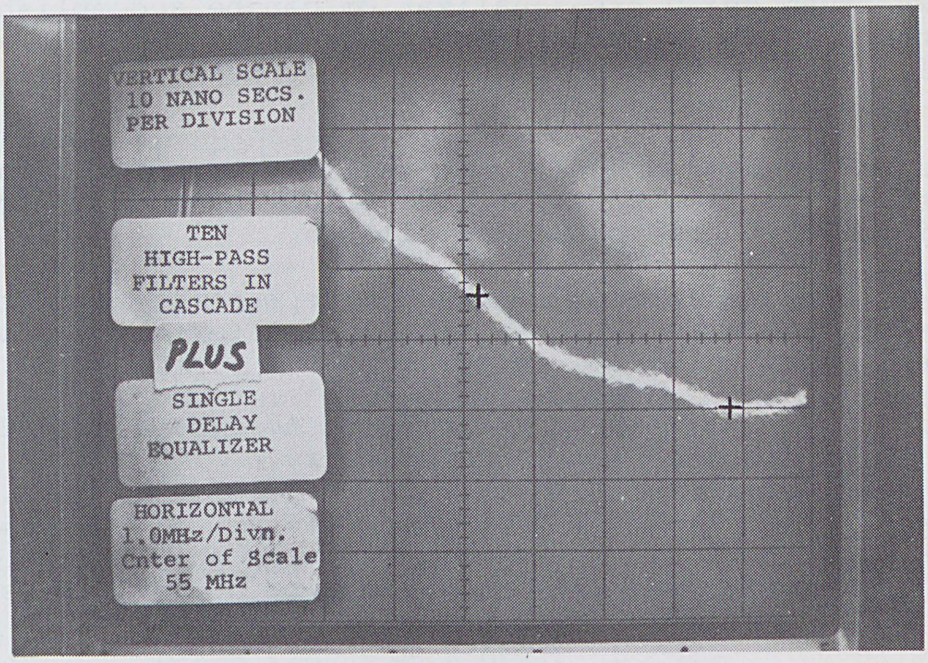


(a)

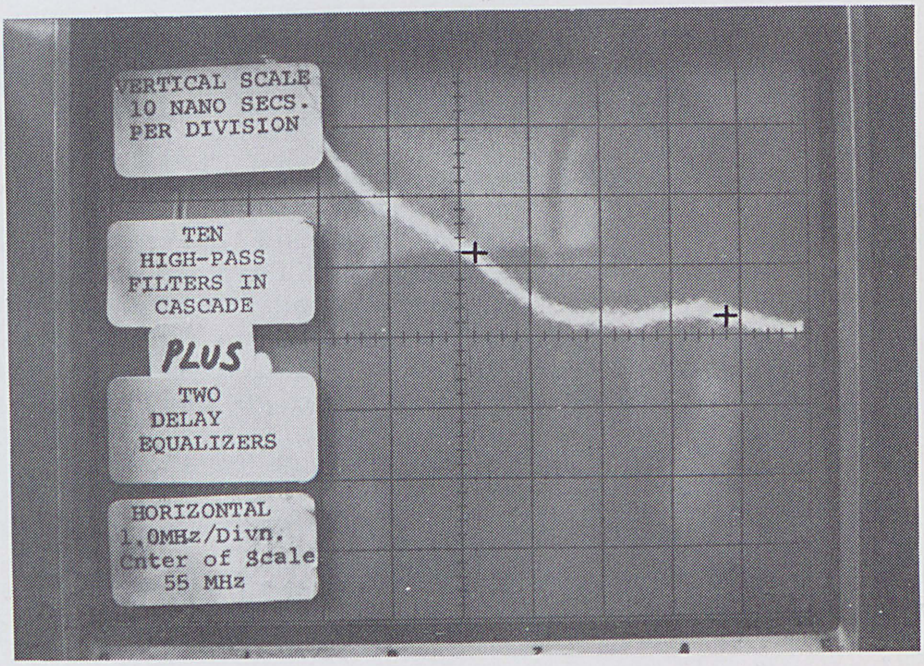


(b)

FIGURE 16 a) Group delay versus frequency of cascade of ten (10) high pass FDM filters
b) Delay response of two delay equalizer sections



(a)



(b)

FIGURE 17 a) Delay response of 10 filter cascade plus single delay equalizer section
b) Delay response of 10 filter cascade plus two delay equalizer sections

Downstream delay pre-equalization can be accomplished either by conversion of the upstream channel with suitable delay characteristic or a delay network equalizer, or a combination of both.

The downstream path delay is easier to predict than the upstream path delay, since the predominant delay contribution is due to the FDM filters.

If delay equalization is used, care must be taken to insure than an acceptable delay characteristic across the channel bandwidth is attained.

Video waveform testing in addition to a modulated 20T or 12.5T pulse test may be necessary.

Acknowledgement

The efforts of Jere Friske in building and testing numerous circuits and CATV products were helpful in gathering information for this paper.

APPENDIX I

Delay Characteristics of Low Loss Cable

The complex propagation constant of a transmission line is

$$\gamma = (R+jwL) \quad (G+jwC) \qquad (1)$$

The quantity (R+jwL) is the equivalent series impedance per unit length, and (G+jwC) is the equivalent shunt admittance per unit length. The real part of γ is the attenuation constant per unit length, and the imaginary part of γ is the phase shift per unit length.

For a low loss line, $R \ll wL$ and $G \ll wC$. Using these approximations and the binomial expansion, the imaginary part of (1) becomes:

$$B = W\sqrt{LC}\left[1+ 1/8\left(\frac{R}{WL}\right)^2\right] \qquad (2)$$

Equation (2) is the phase shift constant of a low loss line. By taking the derivative of B with respect to W, the group delay of the low loss cable becomes:

$$T_d = \frac{dB}{dw} = \sqrt{LC}\left[1 - 1/8\left(\frac{R}{WL}\right)^2\right] \qquad (3)$$

Note that this term is not independent of frequency, and therefore all frequencies are not delayed by the same amount. However, the variation in delay over a 4.2 MHz bandwidth is so small for the cable presently used in CATV systems that the effects of this delay distortion can be ignored. As a numerical example, equation (3) is evaluated for a sub-low and low band channel. The results are listed on page 8. Typical cable constants are:

Velocity of Propagation

$$V_c = .82V_o = \frac{1}{\sqrt{LC}} = 7.87 \times 10^8 \text{ft/sec}$$

V_o is the velocity of propagation for free space.

Capacity per foot $C = 16.5$ pf/ft (Both 500 and 750 cable)

Cable attenuation at 68°F

500 Cable .243dB/100ft at 10 MHz, .59dB/100ft at 55 MHz
750 Cable .166dB/100ft at 10 MHz, .41dB/100ft at 55 MHz

Reference List

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9.0 Envelope Delay, Phase Delay, Group Delay, Chroma Delay, What Does It Mean, How Is It Measured, Fred J. Schulz, NCTA Official Convention Transcript, July 1971, pp. 294-313.