TWO-WAY CATV SYSTEMS PERFORMANCE

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I. INTRODUCTION

The advent of full two-way cable systems has generated many claims as to the various services made possible. To evaluate the full potentialities for two-way communication in a given application the correct design approach must be selected and the resulting performance estimated. There are several performance trade-offs unique to two-way transportation that must be considered in system design and specification.

There are many specifications of importance to two-way systems. This paper will be concerned with the three major performance criteria -- carrier-to-noise (C/N), cross-modulation (XM), and group delay -- and how these are expected to vary with the system size, crossover frequency, and channel loading. Many systems are considering two-way operation, each with its own specific requirements. This leads to many different two-way configurations, including multiple cable approaches, each suitable for a particular type of application. It is beyond the scope of this paper to treat all of these configurations; rather several specific two-way CATV transportation designs will be reviewed and the resultant system performance estimated. Many of the design values used for these systems were arrived at employing considerations discussed in a previous paper "System Considerations in the Design of a Two-Way Transmission System" cited in Reference 1.

II. SINGLE CABLE SUB SPLIT

A. SYSTEM DESCRIPTION

This elementary cable two-way TV system employs a single cable trunk and a single feeder. The frequency spectrum is split below Channel 2 with the return information, which is destined for the headend, occupying the band 5-30 MHz. The outgoing signals at Channel 2 and above are distributed to the subscriber using the conventional assignments. A diagram of the system showing the layout of trunk and feeder stations is given in Figure 1. The operating principles of this configuration and several of the equipment design considerations are treated in some detail by Reference 1. This approach is an economical choice for applications requiring only a limited return bandwidth. Equipment for a two-way system of this configuration was designed and tested, the performance of which will be described in the first example. The outgoing system employs push-pull amplifiers designed for 27-channel operation utilizing the 12 standard VHF channels, 9 channels in the midband region, and 6 supers above Ch 13 in the region 216-260 MHz. Figure 2 illustrates the spectrum utilized. The feeder return and the trunk return amplifiers are also push-pull and are assumed to be located at every outgoing location. It is convenient to rate the return equipment in terms of TV channel capability although a large part of the spectrum may be occupied by data. The trunk return amplifiers are rated for four TV channels. It is felt by the author that this is a conservative method of rating because of the XM loading effect of data will be much less than a TV channel.

When the feeders are used to gather the return information, it is unlikely that any one feeder will have a significant percentage of the total return spectrum. It is tempting to rate the C/N and XM of the feeders on the basis of a single TV channel. However, some mathematical difficulties arise when considering single channel XM. In this presentation the feeder is rated for two TV channels which implies that a single TV channel may be returned via the feeder -- for community service or on-the-spot coverage -- and the cumulative effect of the rest of the data on the feeder is less than or equal to that of another TV channel. Table I gives the performance that can be expected of these amplifiers.

B. SYSTEM TOLERANCE

With the equipment performance defined, it is possible to estimate the performance of a typical CATV system that includes two-way as a part of the design. Assume a system of the following characteristics.

Total Cable Bearing Strand	350 miles
Feeder-to-Trunk Ratio	4
Maximum Trunk Cascade	25 amplifiers
Total Number of Trunk Amplifiers	250 amplifiers
Maximum Feeder Cascade	2 amplifiers
Total Number of Line Ext. (3.6/mile)	1250 amplifiers
Channel Capacity Outgoing	27 channels
Channel Capacity Return Trunk	4 channels
Channel Capacity Return Feeder	2 channels

The design goal for the distribution is -54 dB XM. This may be achieved with the levels assumed in Table 2. They are based on equal contribution between the bridger and each line extender amplifier. The outgoing trunk amplifier level is determined in the usual manner -- halfway between the XM and C/N limits. The levels for the return amplifiers were selected to put the return system halfway between XM and noise. The XM is determined using the maximum cascade, and the noise is determined using the total number of return amplifiers that return signals on a given cable. This aspect is discussed in Appendix A. The level of the return feeders is also designed on an optimum cascade basis as is the trunk -- in contrast to the design method for the feeders. Table 2 summarizes the levels used and the performance of each group of amplifiers. The performance of the outgoing and the return systems can be estimated using the performance given in Table 2. The outgoing C/N will be nearly that of the trunk 43 dB, and the XM will be -51.4 dB (-63, -65, -67). The return system will have 43.5 dB C/N (45 and 49), and -66 dB XM (-69, -77). Although there are a large number of return feeder amplifiers (1250), their operation at optimum cascade level +45 dBmV enables them to have 4 dB better C/N than the return trunk.

Multiple Return Trunk:

Figure 3 is a symbolic representation of a CATV layout where the headend is shown between two roughly equal areas. Consider the case where the return trunks from each area are not combined but are brought into the headend separately. Two benefits occur: 1. If the return levels were to remain the same, a 3 dB improvement in C/N would occur because only half the number of return amplifiers would add noise to a given cable. 2. Twice the return bandwidth is available because signals can be selected from either cable. This results in a complete return system performance of -68 dB XM and 45.5 dB C/N. The worst case round trip performance -- a signal gathered by the return feeders at the maximum trunk cascade and then turned around at the headend and distributed to the farthest outgoing subscriber -- would be -50.2 dB XM and 41.1 dB C/N representing a 1.1 tolerance improvement due to the use of the return split. These performances are summarized in Table 3.

System Size:

In tolerance calculations for the outgoing trunk only the maximum cascade is required. However, for the return trunk and return feeder amplifier performance both the maximum cascade and the total number of amplifiers to be served by a single cable must be known. For a proposed system the total number of return amplifiers may be estimated from the estimated strand miles using feeder-to-trunk ratios and amplifiers-per-mile.

Thus, when considering two-way for a given application, both the maximum cascade and the system size should be estimated.

Alternate Return Amplifier Spacing:

Although the maximum single span loss at 31 MHz is only 6.6 dB, inclusion of flat losses within the station and those due to trunk cable splitting will increase the return module gain requirement to a range of 11-16.5 dB. The average single span return gain assumed previously was 14 dB. A return amplifier at every other trunk station requires a gain of 20-31 dB. Assuming a nominal module gain requirement of 25 dB for alternate spacing, the same output capability and noise figure, this return amplifier would have 11 dB less tolerance than the "amp every" station. However, since there is half the number of return amplifiers adding XM and noise, the net result is a return trunk system with 5 dB less tolerance. A return feeder level matchup problem may occur at trunk stations where the return amplifier is "missing" because the required insertion level will be one span loss higher.

C. FILTER CONSIDERATIONS

Two-way operation is obtained by frequency splitting with filters. Gain flatness, stability, and isolation requirements will determine the required filter amplitude responses (see Reference 1). For these considerations it is desirable to make the filter "look like a cliff". However, this type of amplitude response implies very large group delay and chroma delay near the cutoff frequencies. In fact, higher stopband rejection, better passband match, and narrow guardband all imply higher group delay. Even the type of filter response selected (i.e., Butterworth, Elliptic) is of importance. A quantitative treatment of these factors on group delay variations is given by Reference 2.

Amplitude Requirements:

The amplitude requirements for the trunk line filters are given in Figure 4. The contiguous type high/low split filter (equal 3 dB cutoff frequencies) cannot be used as the 6 dB per filter isolation will be insufficient to prevent oscillation with the trunk amplifiers installed in the station. The 44 dB filter floor requirement is sufficient to keep the amplitude gain ripple to less than ±0.03 dB resulting from closed loop feedback effects. Filters for this requirement were designed and built with nominal cutoff frequencies of 45 MHz for the high pass section and 35 MHz for the low pass. Practical considerations of alignment and amplitude rounding near the cutoff limit the use in cascade to 49 and 32 MHz respectively.

Group Delay Requirements:

In color TV transmission it is not the group delay as such that is troublesome but rather the variation of group delay over the TV channel bandwidth that is of concern. Chroma information modulated on the color subcarrier may arrive at a different time than the luminance information modulated on the PIX carrier. This time differential is termed chroma delay and results in color misregistration and blurring. Chroma delay and how it occurs from amplitude filtering is explained in Reference 1.

Two questions are of direct concern: How much chroma delay can be tolerated? and How much will a given system produce? The former question requires a subjective evaluation. This has been answered in part by a recent study under laboratory viewing conditions and is cited in Reference 3. The delay introduced by the CATV transportation system falls in the "shaped delay" classification of this reference, and from Figures 1 and 6 we may draw the following conclusions from the expected comment for "expert observers" viewing of color TV monitors: 1. at 500 ns of chroma delay most would find the reception impaired but none would find it "definitely objectionable". 2. at 230 ns most would find a perceptible effect but none would find it even "somewhat objectionable".

Filter Chroma Delay:

The measured group delay response of the pair of high/low split filters used in the trunk station is shown in Figure 5 (Curve 2). Table 4 gives the chroma delay for these filters for the worst case channels. For the 25-amplifier cascade these filters will introduce -155 ns (-6.2 ns x 25) of chroma delay in Channel 2, 435 ns in T10 (25 MHz PIX), and 158 ns of chroma delay in T9 (19 MHz PIX). Channel 2 was deliberately favored over Channel T10 in terms of chroma delay by the selection of cutoff frequencies for two reasons -- color TV on Channel 2 is a definite requirement in most applications whereas it is not for T10, and it is relatively simple to delay equalize T10 at the IF frequency since it will be returned to the headend. The Channel 2 group delay that is delivered to the subscribers can be halved by including +77.5 ns of compensating chroma delay at the output of the Channel 2 processor at the headend.

Group delay scales inversely with the cutoff frequency. It is, therefore, possible to calculate the group delay and chroma delay that these filters would have if they had been designed for different dutoff frequencies (see Reference 2). The actual high/low cutoff frequencies are 45/35 MHz. The calculated values of group delay are plotted in Figure 5, and the calculated values of chroma delay are listed in Table 4 for the measured filter data scaled to the cutoff frequencies of 41/32 MHz, 48/37.4 MHz, and 51/39.6 MHz. It is observed that the raising of the high pass cutoff frequency to 51 MHz in order to obtain more return bandwidth nearly doubles the chroma delay in Channel 2.

D. CASCADE PERFORMANCE

A complete line amplifier cascade of the above design with cable and a.c. powering was tested. Tracings of the swept group delay performance are shown in Figure 6. Chroma measurements in individual channels are listed in Table 4. The chroma delay measurements of the 9-amplifier cascade for Channels T9, T10, 2, 3 and 4 are in excellent agreement with the expected values based on the individual filter measurements. For these channels the system chroma delay is determined by the filters used. At frequencies above 200 MHz there is a slight group delay rise caused by the amplifier response rolloff past 260 MHz.

In the return amplifier system a pronounced rise in group delay occurs below 10 MHz causing significant chroma delay. This is not due to the high/low split filter, but can be attributed to the return amplifier and a.c. choking. The return amplifier employs many capacitors, both bypassing and interstage coupling. Although the amplitude response is flat at 5 MHz, there is a pronounced rolloff at 3 MHz which generates this group delay behavior. The a.c. bypass chokes used in power inserters and trunk stations also have the same effect.

Figure 7 is tracings of the swept amplitude response of the 9-amplifier cascade employing standard amplifiers and equalizers. The peak/valley is considered satisfactory as no special "mop ups" were required to obtain the performance. As expected, there was no evidence of any gain ripples due to closed loop feedback.

E. SUMMARY

The system configuration can achieve broadband two-way communication on a CATV network. The required trunk and feeder stations have been built and tested, the resulting performance has been projected to a two-way system comprising 350 strand miles. It provides 27 outgoing channels, 12 of which are the standard V's; the return bandwidth can provide one TV channel and 19 MHz of data. Since the passive components, i.e. power inserters and directional taps, are also available, the results indicate that this two-way system is viable with today's technology.

III. SINGLE CABLE MID-SPLIT

A. SYSTEM DESCRIPTION

The next system to be considered has the same configuration (Figure 1) as the previous but employs a frequency split in the midband (Figure 2). Fourteen TV channels are available for outgoing distribution, and 14 channels + 9 MHz of data are available in the return path. This spectrum utilization provides two important advantages-much greater return bandwidth is available and the wide range provided for the filter crossover results in low envelope delay distortion.

Because only the 7 high VHF channels are available for distribution to a standard TV set without converter, this system must be regarded as special purpose. It can be used independently for private channel communications for either video or data by the school, civil, or business communities; or it can be used in conjunction with a regular one-way CATV plant to provide both private channel communications and two-way capability for all subscribers.

B. SYSTEM TOLERANCE

The performance of the mid-split approach will be calculated employing the previous 350-strand mile system example. The total number of return amplifiers adding noise is halved as in the previous example, by using two return cables near the headend. The amplifiers used in this system have the ratings listed in Table 5, and their operating levels were selected in the same manner as for the sub-split. The lower channel loading of the outgoing plant results in better tolerance than the previous example, and the low round trip XM allows sufficient for distribution systems such as schools that will utilize private-channel capability. The increased channel loading on the return path requires a better quality amplifier, and for systems of this size it may be desirable to consider an additional return cable.

C. CASCADE PERFORMANCE

Equipment for this configuration was built and tested in a 15-amplifier cascade that includes all cable and a.c. powering. The chroma delay was expected to be minimal because it varies inversely with the square of the filter cutoff frequency. Figure 8 includes tracings of the swept group delay for the outgoing and return paths and lists the chroma delay of the worst case channels. Channels 6A, 6B, 6C can occupy what is normally the FM band. The rise of group delay below 10 MHz is caused by the amplifiers and a.c. chokes which results in Channel T7 having larger chroma delay than any other channel, although this delay is not likely to require delay equalization. The chroma delay of the standard VHF channels is so small as to be inconsequential in a 25-amplifier cascade.

Figure 9 shows tracings of the amplitude response for the complete 15-amplifier cascade. This response is satisfactory as it was obtained by employing only the normal amplifier and equalizer adjustments. The peak/valley of the return path is attributed to the equalizer error which was of an early design.

D. SUMMARY

This approach provides a viable solution to systems that require large two-way communication bandwidth of high quality. The return channels may be distributed either on the outgoing path for private use or on the regular CATV system for public viewing. The resultant low value of chroma delay will not be of significant concern for CATV transportation.

IV. MULTIPLE CABLE APPROACHES

A. DUAL TRUNK, SINGLE FEEDER

This system employs two trunk cables, with trunk stations at congruent locations, and a single feeder cable. With reference to Figure 10 trunk cable A is one-way only and uses the outgoing frequency spectrum of 54-260 MHz for carrying 27 channels. The A cable distribution is two-way carrying the 54-260 MHz spectrum from the A trunk in the outgoing direction, and returning 5-30 MHz from the subscriber locations to the B trunk station.

The B trunk cable is the mid-split two-way system previously considered. The 5-30 MHz portion of the B return spectrum is used by the A feeder return signals which are coupled over to the B station from a high/low split filter in the A station. The 30-108 MHz portion of the B return and the B outgoing have limited access and exit.

This approach has the following features:

Public Service:	54-260 MHz	27 Ch	Outgoing
(full distribution)	5-30 MHz	1 Ch + 19 MHz	Return

Private Service:	174-260 MHz	14 Ch	Outgoing
(limited access)	30-108 MHz	13 Ch	Return

The signals carried on the "A" cable suffer minimal chroma delay distortion in that the filters are only used in the feeders.

The high crossover frequency of the "B" cable filters result in low envelope delay distortion compared to the low frequency equivalent used in the "A" cable feeders.

Using the previous 350-strand-mile example the performance of this approach can be estimated. The private system will have the same performance as listed in Table 5, -56.5 dB XM and 42.7 dB C/N. The A system will have the same performance as in Table 3. The performance of a round trip channel using the B return trunk and distributed by the A system will be -49.4 dB (-63 and -51.4) XM and 41.3 dB (46 and 43) C/N.

The worst case path is the round trip "public service" TV channel that is gathered by the A return distribution and B return trunk and sent out the A outgoing system. Its performance would be -49.1 (-79 and -49.4) XM and 40.9 (51 and 41.3) C/N.

B. DUAL TRUNK, DUAL FEEDER

The last example is a dual trunk, dual feeder system. In this approach the A cable is a conventional one-way CATV system. The B cable is a full two-way system with 5-108 MHz trunk return, 5-30 MHz feeder return and 174-260 for the outgoing trunk and feeder.

This system has all of the advantages of the previous example with the feature of the additional channel capacity of the B outgoing distribution which is available to the subscriber by means of an A-B switch. In many cases enough channels would be available (19) by means of the switch that set converters would not be required for standard grade service.

Return:	5-30 MHz	1 Ch + 19 MHz	Public
	30-108 MHz	13 Ch	Private

Outgoing:	54-260 (A)	19 Ch	A-B switch only
	174-260 (B)	42 Ch	with converter

The tolerance of this system is the same as the previous example. (The B outgoing distribution is slightly better than A because of lower channel loading.)

REFERENCES:

1. H. B. Marron and A. W. Barnhart, "System Considerations in the Design of a Two-Way Transmission System", NCTA Official Convention Transcript, June 1970.

2. A. W. Barnhart, Group Delay Variations of Selected Filter Prototypes, Masters Thesis, University of Pennsylvania, Dec. 1970.

3. A. M. Lessman, Subjective Effects of Delay Difference Between Luminance and Chrominance Information of the NTSC Color Television Signal, Bell Laboratories, Homdel, N. J.

4. K. Simons, Technical Handbook for CATV Systems, Jerrold Electronics Corporation, Hatboro, Pa.

APPENDIX A

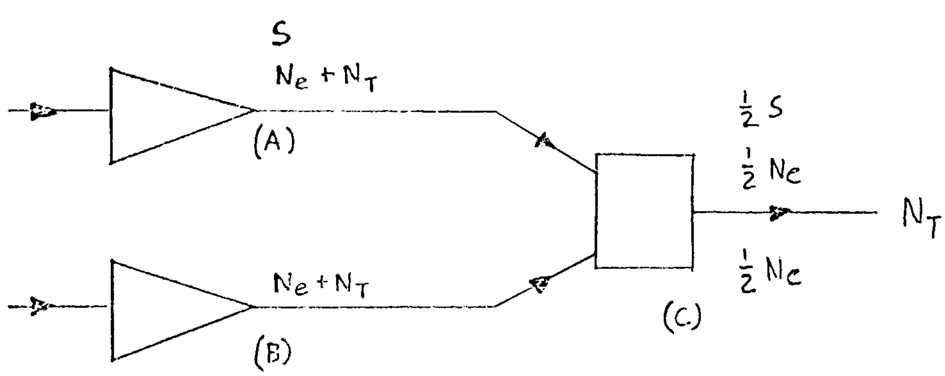
NOISE GATHERING EFFECT

Cable TV transportation systems are operated at unity gain; a signal introduced anywhere into the system, which is in the system bandwidth, will be maintained at approximately its original level. The output noise generated by any particular amplifier will also be transported by the system and maintained at its original level, and therefore the noise of all amplifiers returning signals to a given point will be present at that point. Since random noise adds in terms of power, the total noise will be the power sum of the noise output of each amplifier.

The noise referred to in the above discussion is the excess noise output, N_E, produced by the amplifier. Thermal noise, N_T, is ever present and does not build up. This is illustrated by the following example. Consider two trunk amplifiers whose outputs are combined by use of a 3-dB splitter, with a signal at the output of one amplifier having power S. The C/N ratio at this point (A) will be $S/(N_e + N_T)$. The C/N ratio at the output of the splitter (point C) will be $S/(2N_e + N_T)$. The excess noise at the output of the amplifier is usually at least a thousand times greater than thermal noise. We can thence say that the impairment in C/N ratio by combining two amplifier outputs is

$$\frac{(C/N)_C}{(C/N)_A} = \frac{S/(2N_e + N_T)}{S/(N_e + N_T)} = \frac{N_e + N_T}{2N_e + N_T} = \frac{1000 + 1}{2 \times 1000 + 1} = \frac{1}{2}\,\frac{1001}{1000.5} \doteq -3\text{ db}$$

and therefore the total noise can be considered to be the sum of the noise output of the two amplifiers.



Amplifier	Operational Gain	Noise Figure	Output Capability for -57 dB XM	
Outgoing Trunk	23 dB	10 dB	+48 dBmV	27 Ch
Outgoing Bridger	28 dB	12 dB	+47 dBmV	27 Ch
Outgoing Feeder	24 dB	12 dB	+42.5 dBmV	27 Ch
Return Trunk	14 dB	8 dB	+52 dBmV	4 Ch
Return Feeder	16 dB	8 dB	+58 dBmV	2 Ch

SINGLE CABLE SUB-SPLIT AMPLIFIER PERFORMANCE

Table 1

Amplifier Group	Operating Level dBmV	Number For XM	Cascade XM dB	Number For C/N	System C/N dB
Outgoing Trunk	+31	25	-63	25	43
Outgoing Bridger	+43	1	-65	1	62
Outgoing Feeder	+39.5	2	-57	2	59.5
Return Trunk	+32	25	-69	250	45
	+31	25	-71	125*	47
Return Feeder	+45	2	-77	1250	49
	+44	2	-79	625*	51

*Return Split Assumed

Sample Calculations (Ref. 4):

$$\text{XM Trunk Out} = XM_1 + 20 \log C = [-57 - 2\,(48 - 31)] + 20 \log 25 = -91 + 28 = -63 \text{ dB}$$

$$\text{C/N Feeder Return} = C - N - 10 \log C = +45 - [-59 + 8 + 16] - 10 \log (1250) = 45 + 35 - 31 = 49 \text{ dB}$$

SINGLE CABLE SUB-SPLIT AMPLIFIER TOLERANCE

Table 2

SYSTEM	XM	C/N
Outgoing Trunk and Distribution	-51.4	43.0
Return Trunk and Feeder	-66.0	43.5
Complete Round Trip	-50.0	40.2
Return Trunk and Feeder/2 Return Cables	-68.0	45.5
Complete Round Trip/2 Return Cables	-50.2	41.1

SINGLE CABLE SUB-SPLIT SYSTEM TOLERANCE

Table 3

Channel	Chroma Delay of Trunk Station Filters with Varying Cutoff Frequencies: High/Low (MHz)				Chroma Delay of 9-Amplifier Cascade	Chroma Delay Feeder Amp.
	41/32*	45/35	48/37.4*	51/39.6*		
T7	2.2	1.4	0.9	0.6	-90	<1
T8	5.3	3.1	2.1	1.4	$\sim$0	1.0
T9	10.4	6.3	4.4	3.1	58	2.6
T10	46.9	17.4	11.1	7.7	155	6.8
2	-4.2	-6.2	-9.2	-12.3	-55	-4.6
3	-2.8	-3.4	-4.0	-6.1	-31	-2.4
4	-1.9	-2.3	-2.7	-3.0	-21	-1.2

*Calculated Values

SUB-SPLIT CHROMA DELAY (NANOSECONDS)

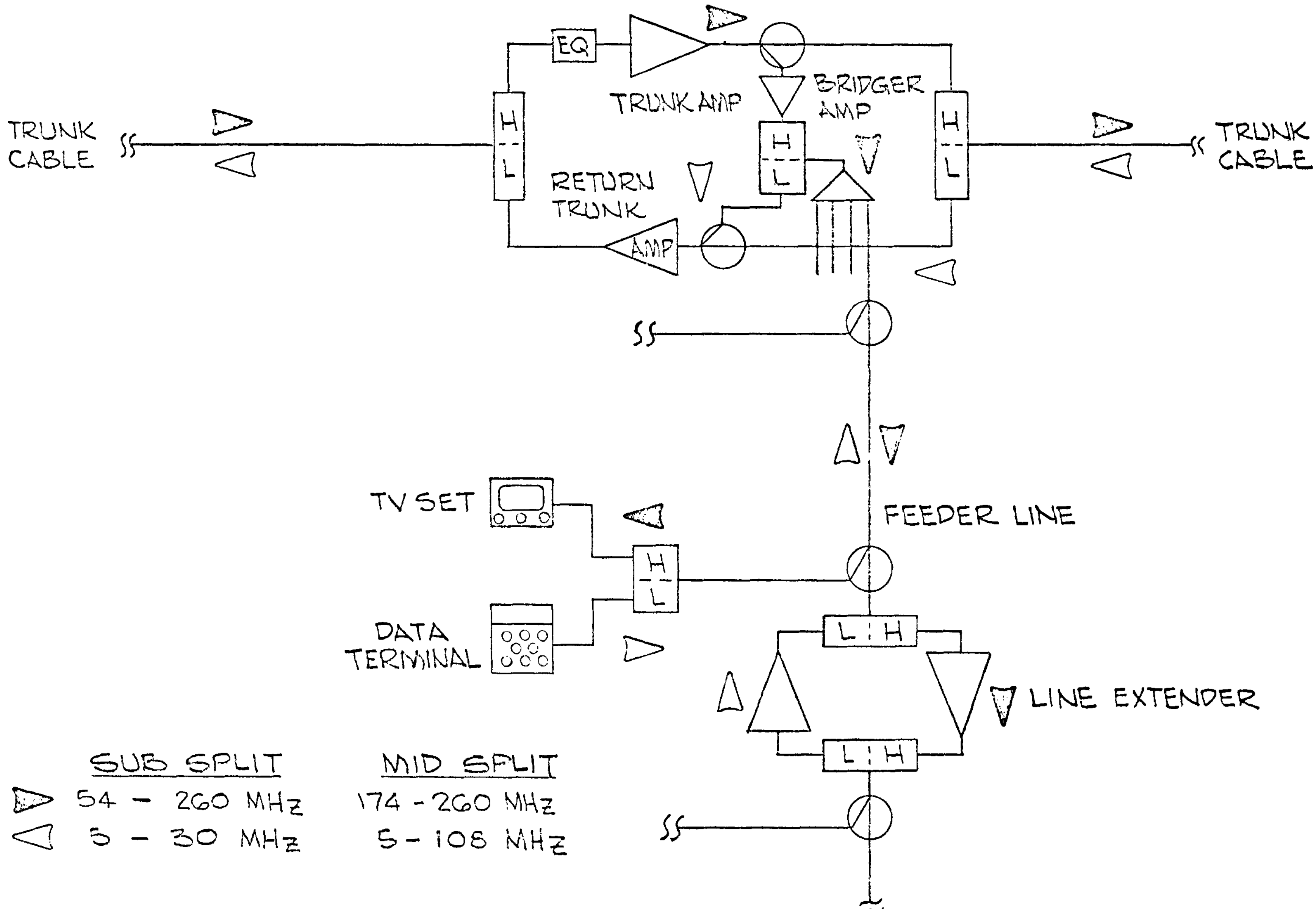
Table 4

Amplifier	Level dBmV	S_{MAX}* dBmV	Gain dB	NF dB	Cascade	Noise Total	XM dB	C/N dB
Outgoing Trunk	33.5	+50	23	10	25	25	-62	45.5
Return Trunk	35	+52	19	8	25	125	-63	46.0
Round Trip							-56.5	42.7

*Output Capability for -57 dB XM for 14 Ch Low Band for Return
High Band for Outgoing

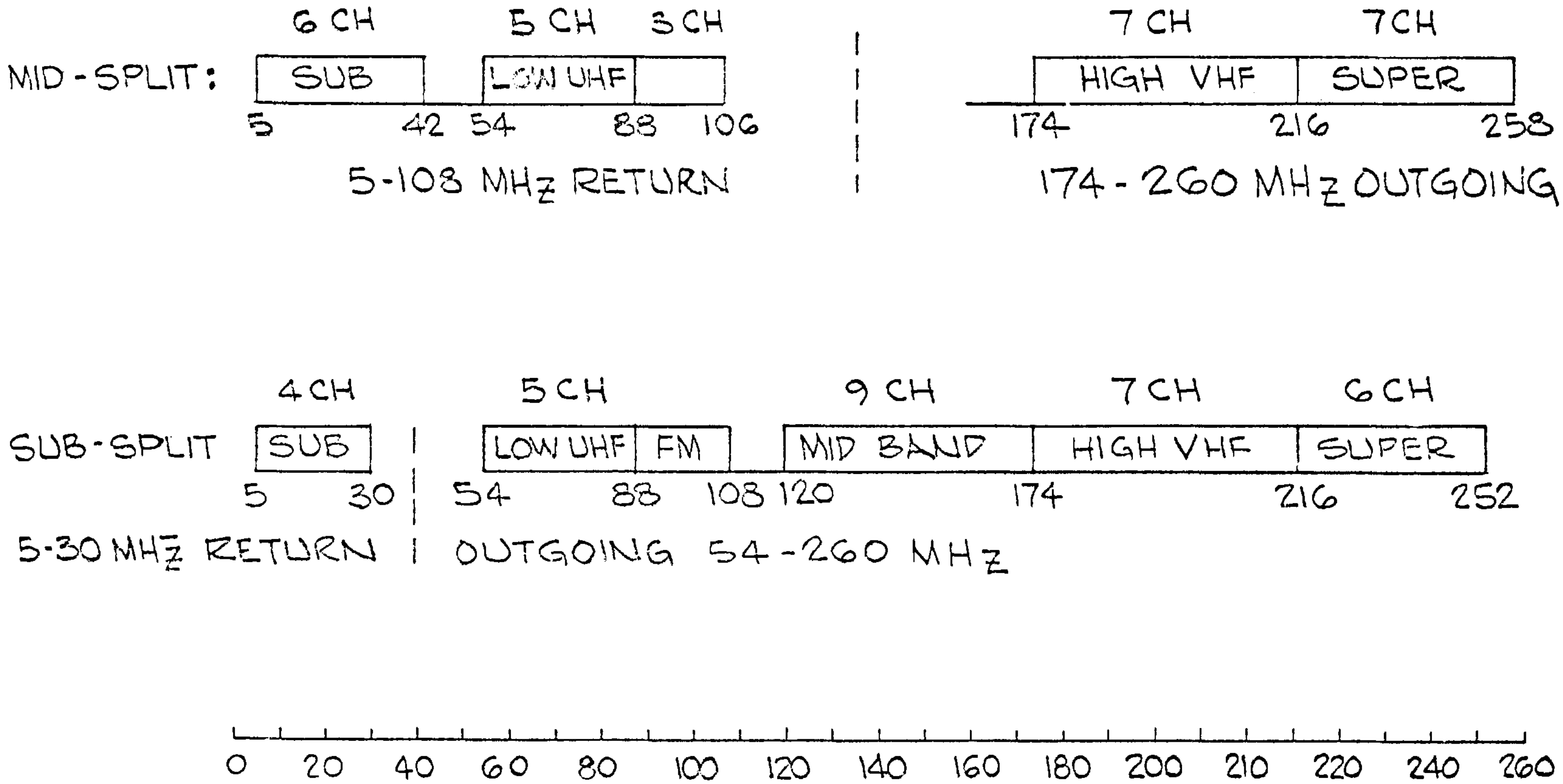
SINGLE CABLE MID-SPLIT AMPLIFIER PERFORMANCE

Table 5



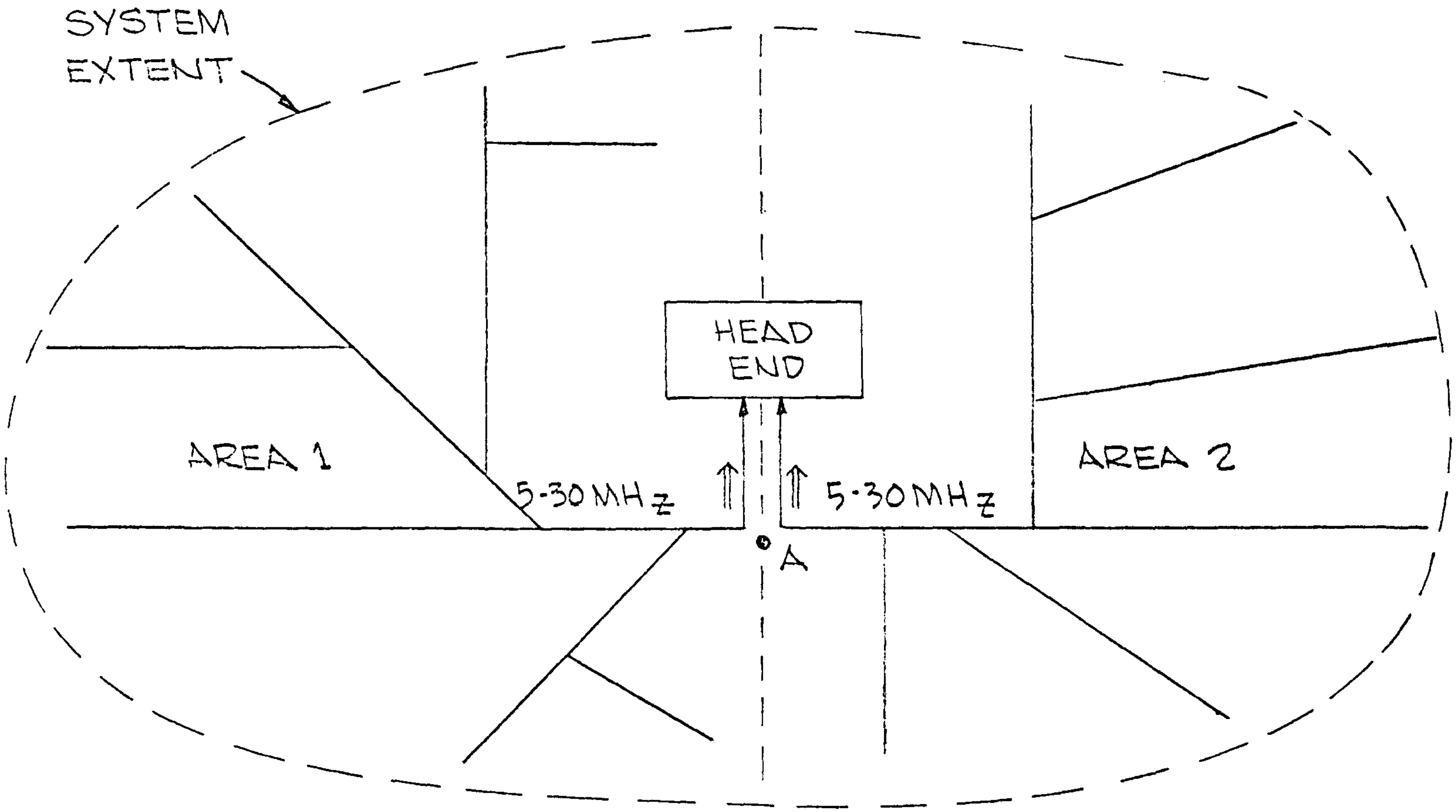
TRUNK STATION & LINE EXTENDER LAYOUT

FIGURE 1



SPECTRUM UTILIZATION OF SINGLE CABLE SYSTEM

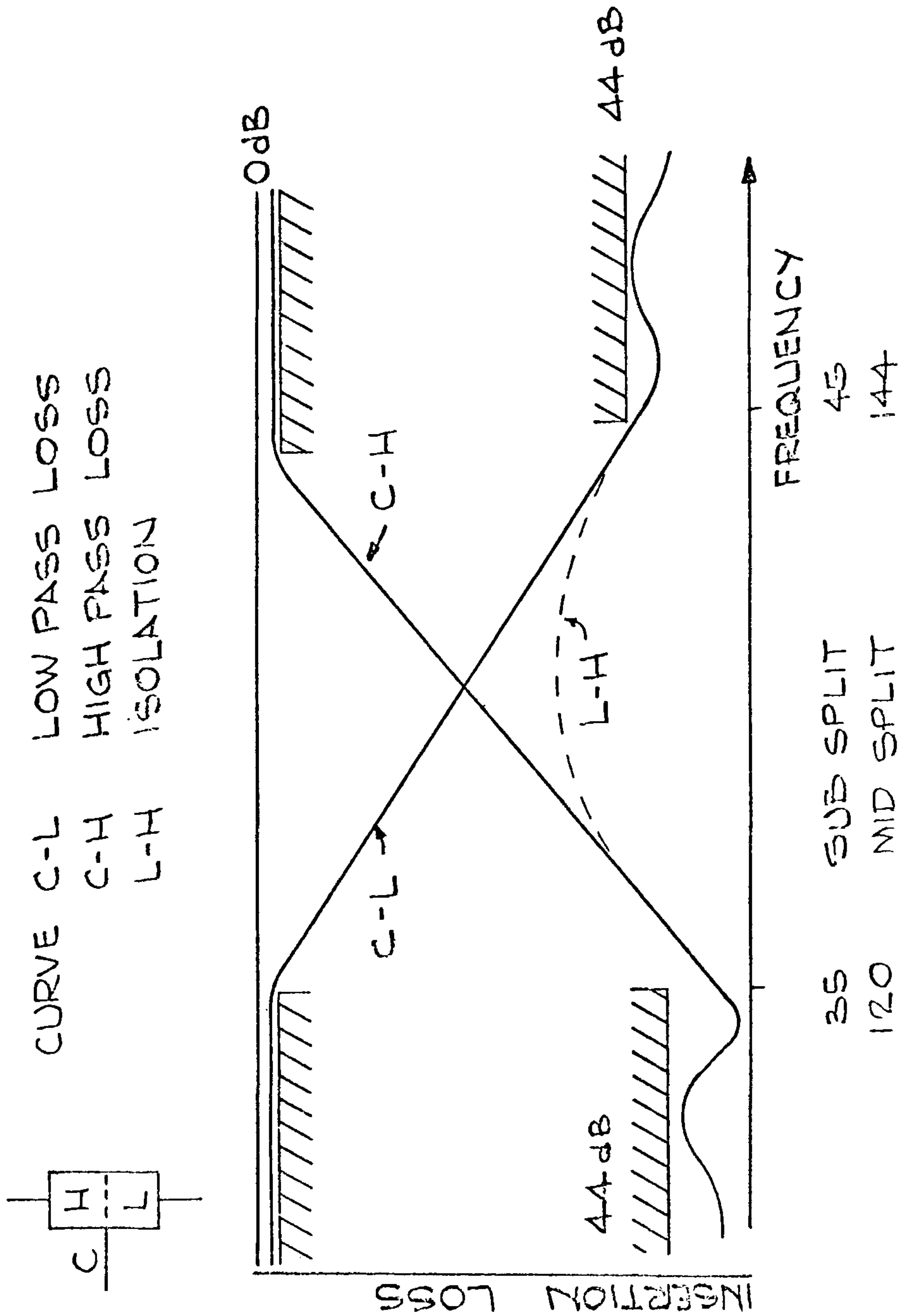
FIGURE 2



If two return cables are employed from point "A" to the Head End, and the areas are approximately equal, the C/N will be 3 dB better than if the return cables were combined at "A".

SYSTEM EMPLOYING MULTIPLE RETURN CABLES

Figure 3



FILTER AMPLITUDE REQUIREMENTS

FIGURE 4

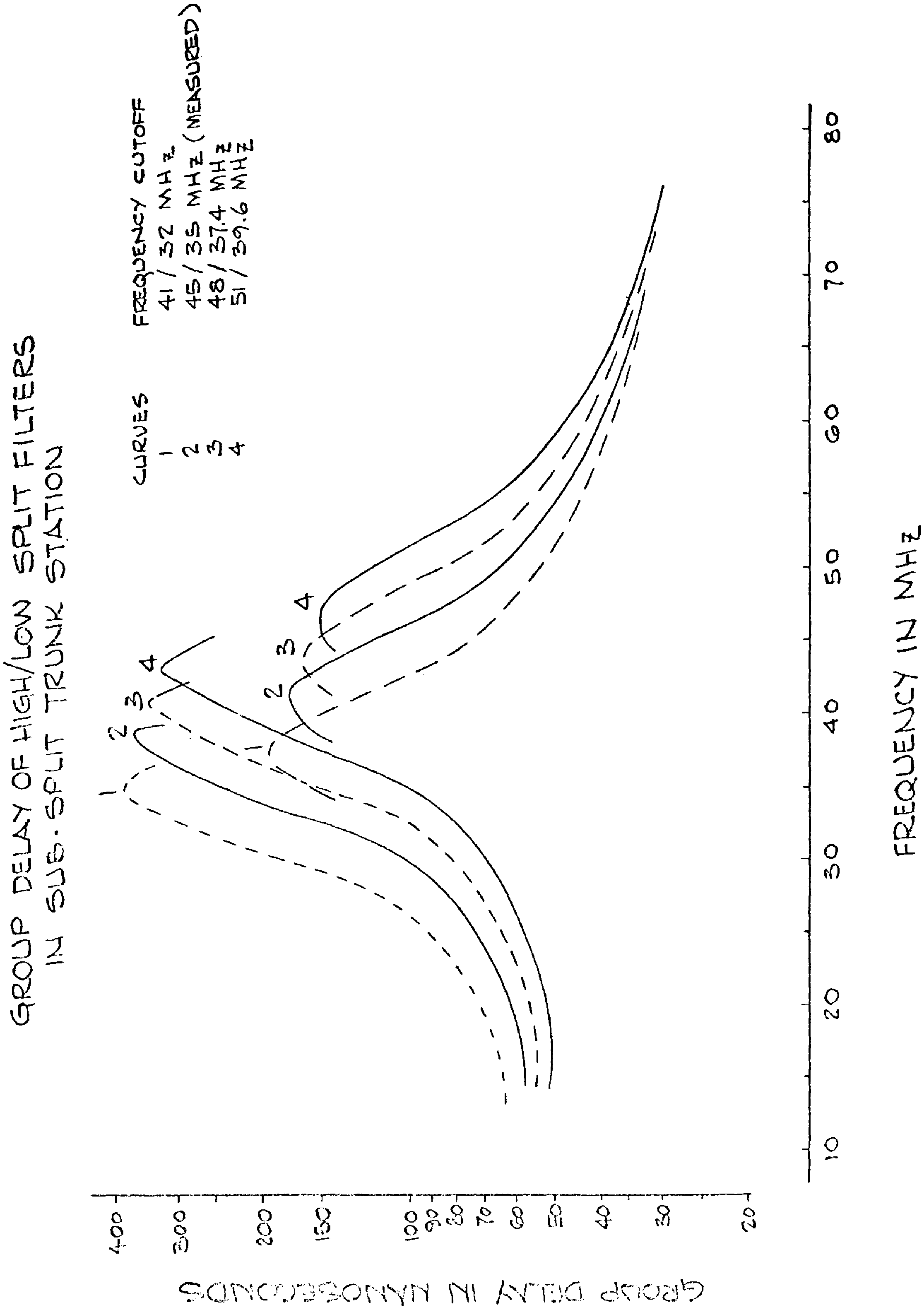
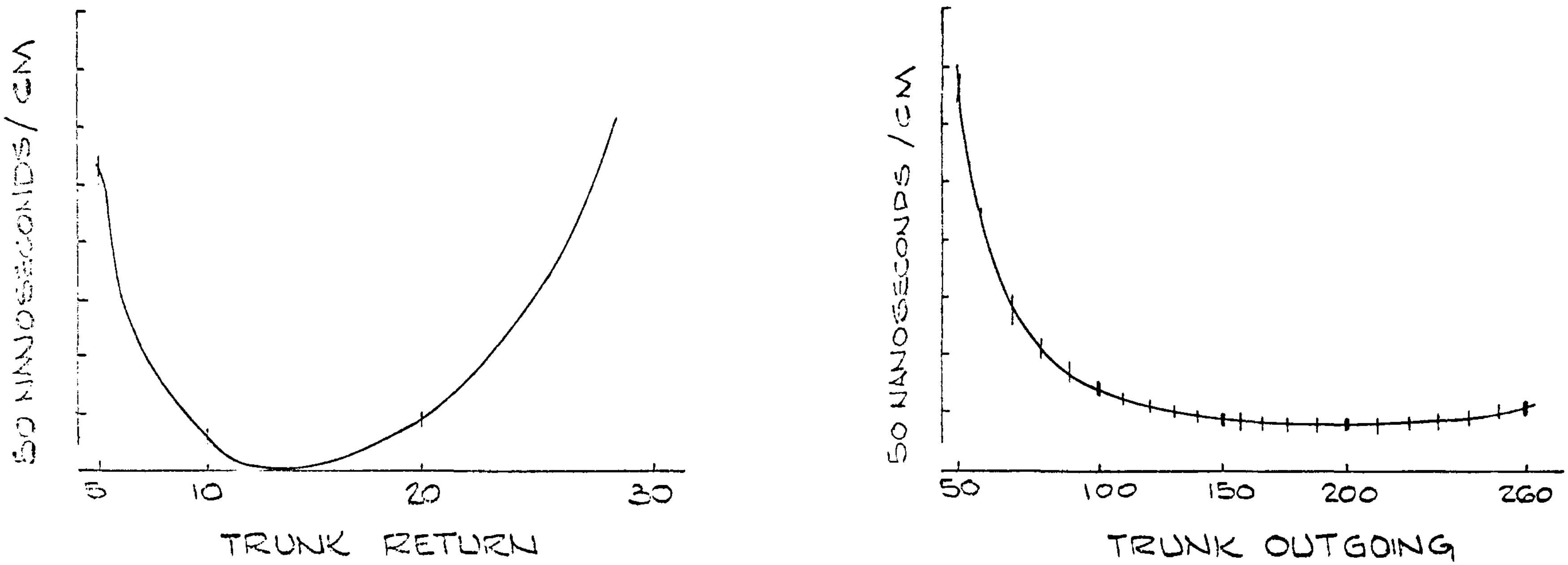
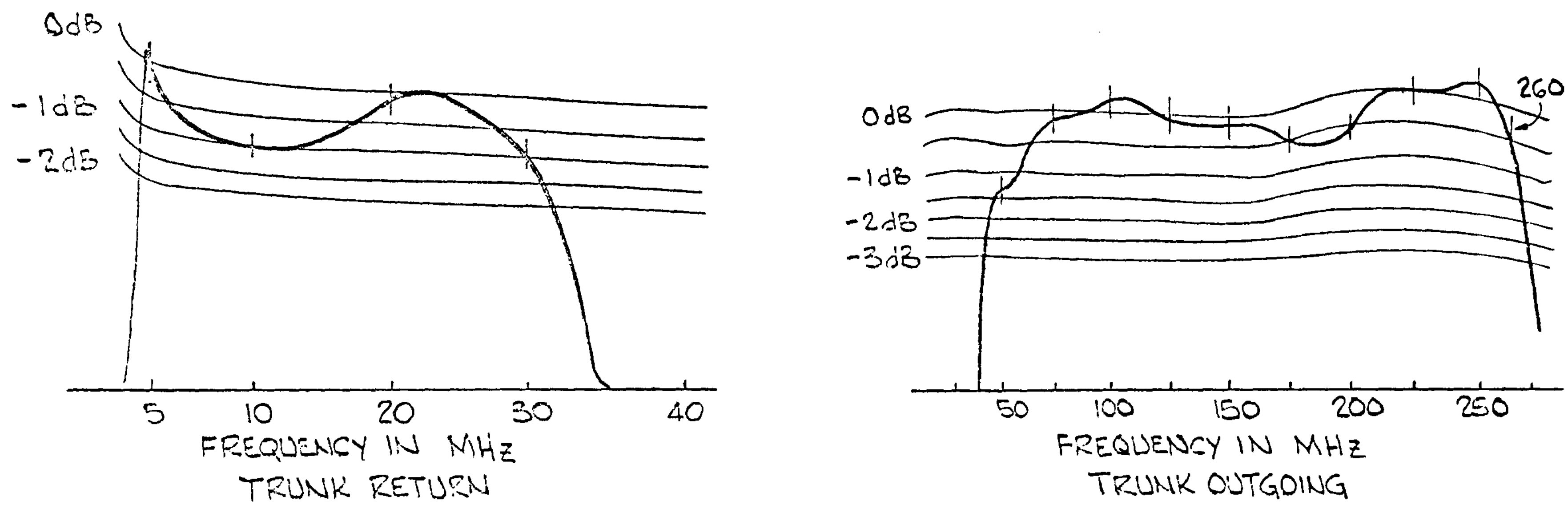

GROUP DELAY OF HIGH/LOW SPLIT FILTERS
IN SUB-SPLIT TRUNK STATION
CURVES
1
2
3
4
FREQUENCY CUTOFF
41 / 32 MHz
45 / 35 MHz (MEASURED)
48 / 37.4 MHz
51 / 39.6 MHz
GROUP DELAY IN NANOSECONDS
400
300
200
150
100
90
80
70
60
50
40
30
20
10
20
30
40
50
60
70
80
FREQUENCY IN MHz

FIGURE 5

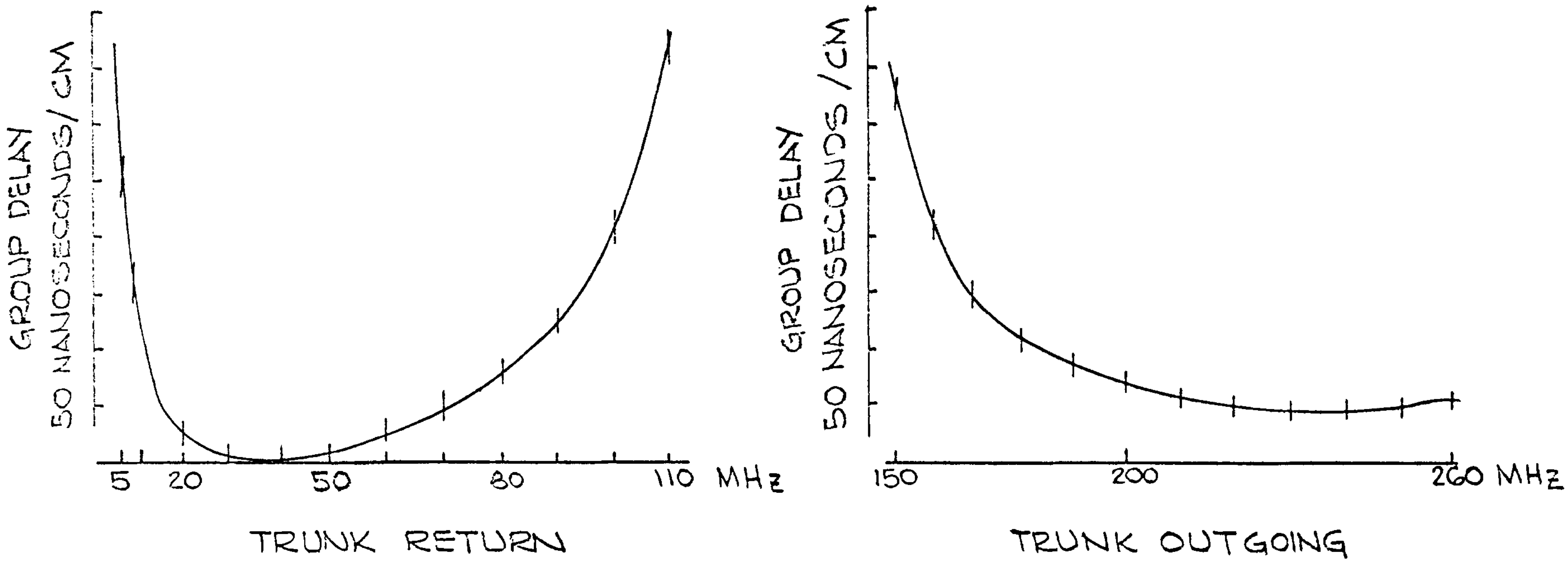


RELATIVE GROUP DELAY FOR COMPLETE CASCADE OF 9 TRUNK STATIONS (SUB-SPLIT)

FIGURE 6



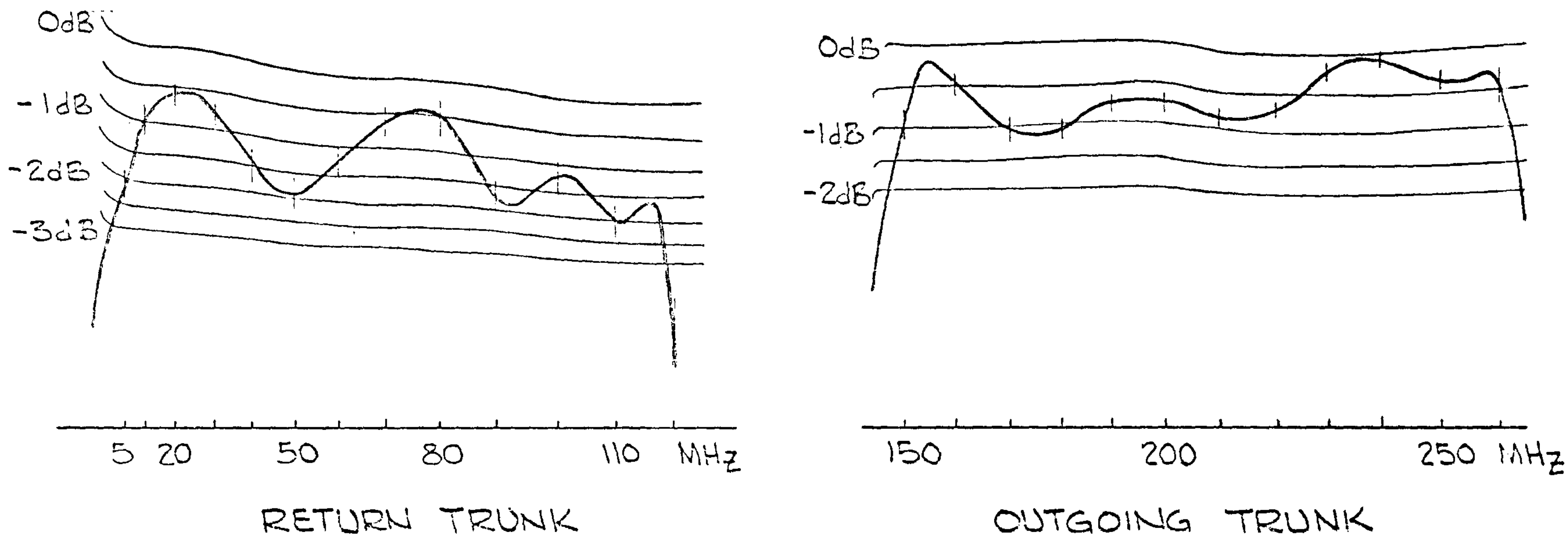
AMPLITUDE RESPONSE OF 9 AMPLIFIER CASCADE
FIGURE 7



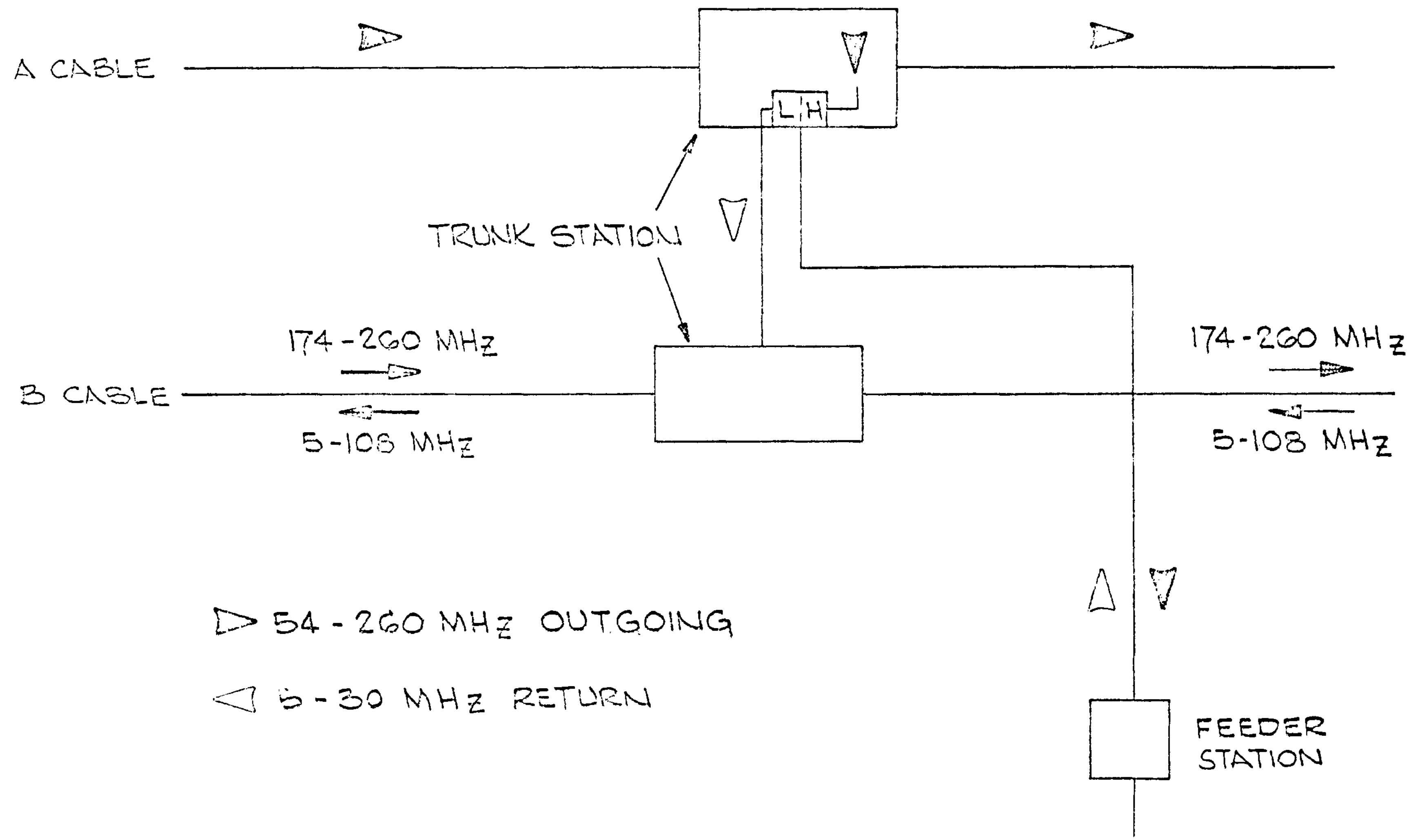
Channel #	T7	T8	T9	5	6	6A	6B	6C	7	8
Chroma Delay, nanoseconds	135	40	11	12	15	23	32	50	13	9

GROUP AND CHROMA DELAY 15-STATION CASCADE

Figure 8



AMPLITUDE RESPONSE 15 AMPLIFIER CASCADE MID-SPLIT
FIGURE 9



DUAL TRUNK SINGLE FEEDER SIGNAL FLOW

FIGURE 10