RELIABLE DESIGN FOR FIELD INSTALLATION AND TESTS

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The Wilson, NC CATV system is analyzed demonstrating the successful design concepts for an overall system and its trunk stations. The signal path is traced from the head end, through the main trunks, and finally to the subscriber's TV set. A trunk amplifier station is analyzed demonstrating the interplay of electrical and mechanical design concepts. System performance tests verify the conceptual soundness of the design approaches described; the result is an environmentally stable, low maintenance CATV system yielding pictures of exceptional quality.

INTRODUCTION

Today's economics require a CATV system to provide more than just low initial cost. The system must be highly reliable, deliver high picture quality, and ensure low maintenance costs.

Also, adequate margins must be provided, through conservative design and specifications at all levels, to allow for an increase in channels carried, alignment errors, test equipment miscalibration, and system expansion.

AEL Inc. has recently installed a high-reliability low-maintenance CATV system in Wilson, North Carolina. The system is a single-cable sub-split type having a total cable length of 116 miles. It incorporates 80 bidirectional trunk stations and 300 line extender stations. Currently, over 4000 well satisfied subscribers are served by the system which is intended to serve up to 7000 subscribers.

The system's electronics installation was started in May 1976 and was completed and accepted by the customer in October of 1976. Careful system and equipment design ensured that installation was quickly accomplished and that a minimum of installation adjustments were required.

Since being installed, the system has provided outstanding performance in all critical parameters such as:

- Transmission response flatness
- Distortion levels
- Signal-to-noise ratio
- Hum modulation
- Stability with temperature variations.

The service record has shown that the system is highly reliable, is easy to maintain, and is stable under extremes of temperature and humidity variations, which have been very severe this year.

The following paragraphs present the basic concepts considered in the design of the hardware and the system. Also covered are the results of post-installation performance tests. The concepts presented will provide useful background information to system designers, field personnel, and system owners.

I. SYSTEM DESIGN CONCEPTS

The refinement of a CATV system is determined primarily by the requirements of picture quality and the need of stable, reliable performance under changing environmental conditions.

Among the major electrical parameters determining picture quality are the level of distortion products in the system, the overall signal-to-noise ratio, flatness of transmission response in a given channel, ghosting due to reflections (mismatches), and group delay.

Part of the Wilson, NC, system is shown in figure 1. The cable network consists of 0.750 in., Parameter 1 cables for the trunk spans and 0.500 in. Parameter 1 cables for the feeders. The RG-59/U cables (foam polethylene) are used for the tap-to-customer spans. Knowing the cable types used, transmission frequencies, and the ambient temperatures, the cable losses are easily determined. Typical cable losses at 68°F are:

Cable Type	Cable Length (ft.)	Loss at 270 MHz (dB)	Loss at 50 MHz (dB)
RG-59/U Foam poly-ethylene	100	4.15	1.73
0.500 in. Parameter-1	1490	21	8.3
0.750 in. Parameter-1	2120	21	8.2

The loss values vary by approximately 1.1 percent for each 10°F change in ambient temperature.

The cable spans on figure 1 are 21 to 22 dB at 270 MHz; these cable spans take into consideration final achievable performance results with minimum hardware used in the system.

System optimization requires evaluation of noise and distortion parameters; these parameters determine the number and types of amplifiers in the cascade, system cable spans, and optimum operating levels, as shown in the Appendix.

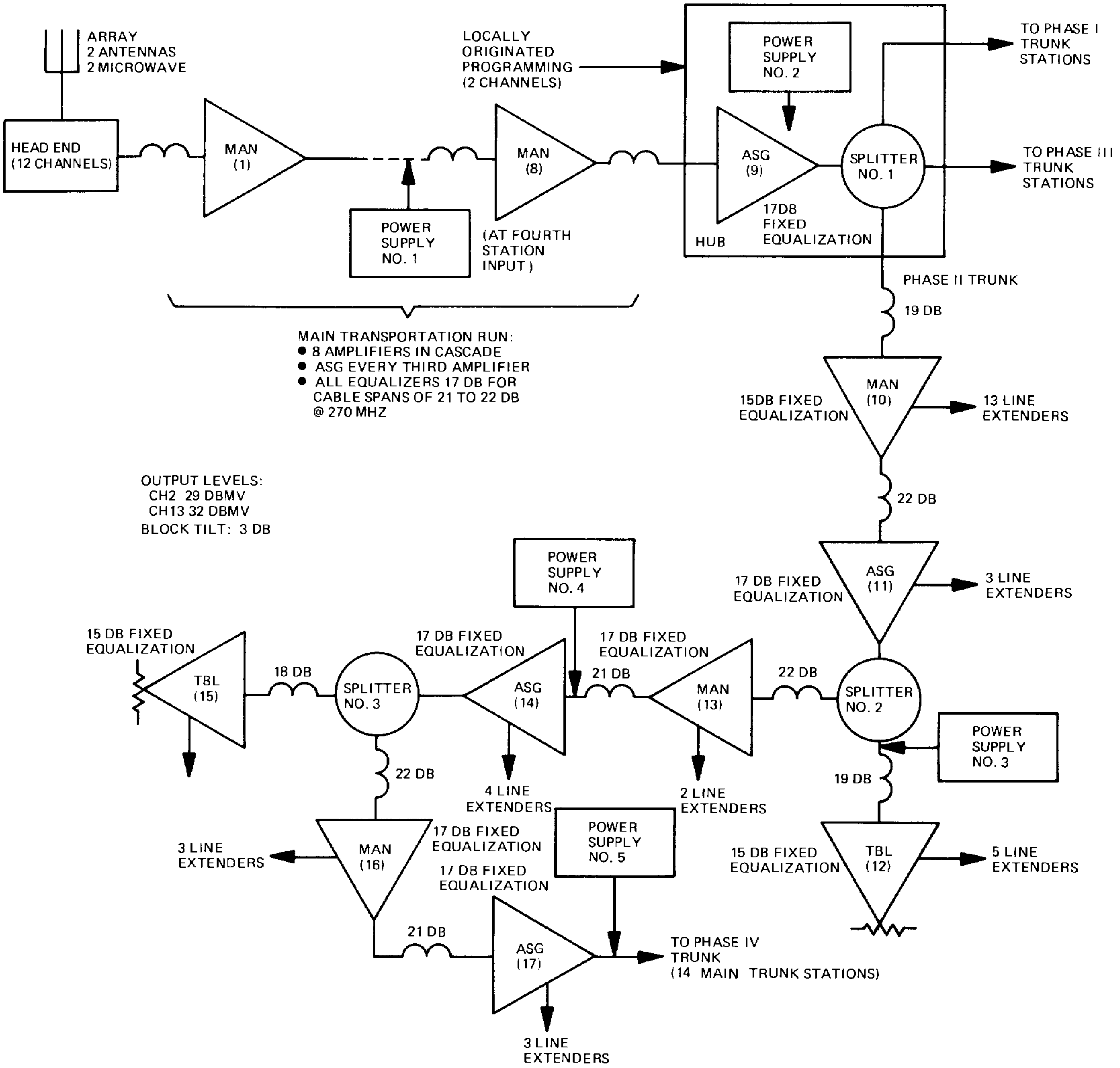

Figure 1. Typical Trunk Section of Wilson, NC System

On the average, a typical TV channel signal delivered to a subscriber in the Wilson, NC, system has the following characteristics: level from 3 to 6 dBmV, depending upon the customer's location in the local distribution system; cross modulation distortion level better than -56 dB; composite intermodulation levels better than -65 dB; flatness variation over a video channel better than 0.06 dB; gain variation to 0.5 dB maximum; slope variation ±0.25 dB. For a TV picture of excellent quality (no perceptible "snow") the signal-to-noise ratio must be at least 45 dB. Tests on the Wilson system have shown the signal-to-noise ratio to be 46 dB. Refer to the Appendix for derivations of the above parameters.

Refer again to figure 1. Twelve-channel air link television signals are received by the antenna array, processed at the head end and sent over the main transportation run to the hub. The main transportation cable runs are 2100 to 2220 ft. in length and represent cable losses of 21 to 22 dB at 270 MHz per run. The signal flow from the hub can be easily traced.

The system design specifications were achieved by employing an ASG (Automatic Slope Gain) station at every third trunk location. This limited use of the ASG stations is achieved by careful design of the automatic control circuitry resulting in a station that tracks cable with extremely good correlation over a wide temperature range as shall be shown in paragraph III. Good temperature compensation ensures stable performance.

The ASG uses Ch 5 and Ch 12 for the control carriers without any appreciable effects caused by sync or other modulation. This is achieved by employing the true peak detector combined with sync filtering in the detector circuits. Temperature stability of the control module is achieved by using temperature-stable capacitors in the tuned circuits. Also, other temperature compensating devices are used in the detectors to stabilize drift due to the diodes and the operational amplifier. The temperature stability of the circuits is ensured through proper compensation techniques. The time constants of the ASG circuits are such that short time variations in the signal do not noticeably affect the gain or slope of the system. Only the long-term variations, such as temperature effects, will cause the ASG circuits to respond; however, the detector design minimizes recovery time from large amplitude transients. The adjacent channel's interference to the control carrier has been minimized by using stable, highly-selective circuits and filters in the control modules.

The function of the ASG module is to compensate for effects of long term temperature variations of cable; it accomplishes this function in conjunction with the gain and slope circuits in the trunk module. The pin diode slope and gain circuits are designed to ensure excellent cable tracking for 10 dB of cable variation. This is accomplished by ensuring that these circuits, as well as all others, maintain at least 18 dB of input and output return loss. As a result, there is a minimum of deterioration in tracking characteristics over the entire adjustment range.

To compensate for cable characteristics each station uses fixed equalization 3 to 5 dB less than the cable being compensated. The additional equalization is provided by the slope control circuits manually or automatically.

To maximize station cascadability, it is essential that the amplifier module have as large a noise and distortion performance window as possible. The Mark IV station trunk module has achieved this by using a pin diode gain control attenuator at the amplifier's input. To accomplish this, two critical performance parameters must be optimized; namely, insertion loss and return loss.

The amount of insertion loss in this circuit is directly additive to the noise figure of the input hybrid in determining the overall noise figure of the module. In recognition of this requirement, the insertion loss of this pin diode circuit has been maintained at 0.5 dB. This slight compromise in noise figure is overshadowed by the improvement in distortion performance when compared to a circuit that would place the pin diodes after the input hybrid wherein, with higher levels present, the diodes would add significantly to the station's distortion.

The attenuator's second design parameter, return loss, is equally important since it directly affects response flatness, cable tracking performance, the characteristics of the station's input diplexing filter, and the return loss of the entire station. Observe that, as a result of locating the pin attenuator at the input, the station exhibits a constant carrier to noise. This simplifies carrier to noise calculations for temperature variations. Even more stringent controls on return loss are established for cascaded building blocks within the station in order to hold the very flat response which will be discussed later.

The AC power is inserted into the cable runs by corresponding AC power supplies as shown in figure 1. Programming of the AC power is accomplished at each station and is also discussed below.

The block diagram of figure 1 demonstrates the manner in which any similar system can be developed by using high-quality versatile stations.

Figure 2 shows local signal distribution in the Wilson system from a typical trunk station to the TV set. Local distribution from the ASG station no. 14 (on figure 1) is typical of the entire system.

Local distribution in this area is accomplished using 0.500 in. Parameter 1 coaxial cable and four AEL

CVT-5E line extender stations. Signal input to the line extenders is 19±2 dBmV; output levels are approximately 42 dBmV for high band signals and 39 dBmV for the low band. Signal taps to the subscribers are represented by the small rectangles. Distribution to the subscribers is accomplished by RG-59/U cable; tap loss for each subscriber circuit is noted in the rectangles. Other aspects of the distribution are marked on figure 2 (equalization, cable spans, etc.).

The CVT-5E extender stations with their low distortion and adequately flat transmission response will permit expansion of the distribution system as system expansion becomes necessary. The low distortion is achieved by using high-quality hybrid devices in the amplifiers.

The packaging approach in the CVT-5E station allows good thermal paths for the active devices in the station. This results in a relatively low temperature rise within the housing and subsequently high reliability.

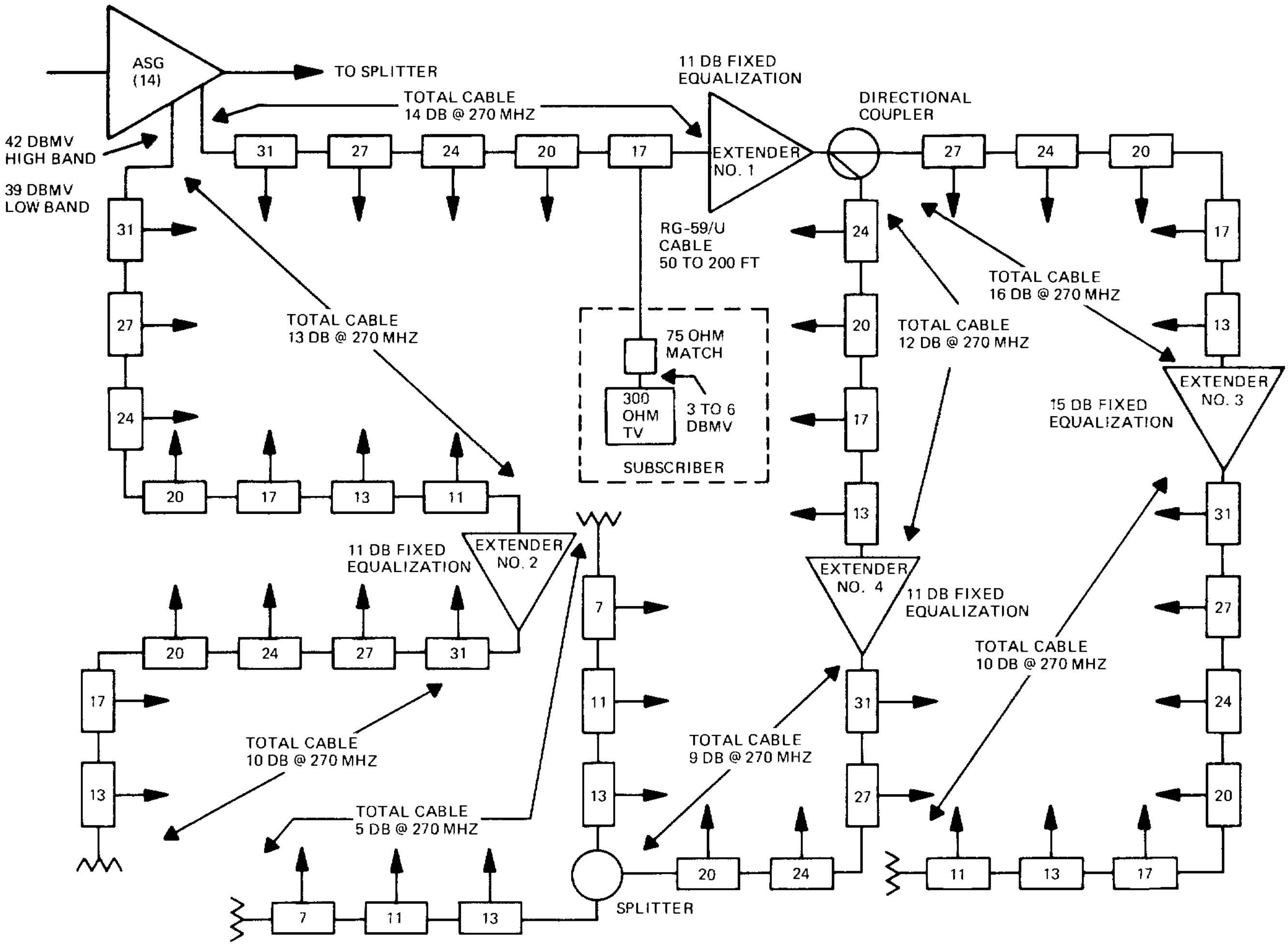

Figure 2. Wilson, NC CATV System (Local Distribution from Trunk Station No. 14)

II. TRUNK STATION DESIGN CONCEPTS

The AEL Mark IV trunk station is the subject of this design evaluation. The station's design features greatly affect the system's performance. To ensure high-quality station performance, the pin diode slope circuit and its control circuitry must precisely track cable slope while maintaining an excellent match to surrounding circuits.

Several aspects of the Mark IV stations design are considered; namely, the rf signal paths, base plate, passive devices, rf modules, power supply, protection circuits, and packaging principles.

The rf signal flow paths are presented in figure 3, "Mark IV Functional Block Diagram," and are self-explanatory: they represent a two-way station with signals from the Trunk Input to the Trunk Output port and also to the feeder cables (54 to 300 MHz); the return path (5 to 32 MHz) is from the Trunk Output port to the Trunk Input port; also from the Feeder Cables to the Trunk Input port. The station may have either Manual or ASG control of gain and slope.

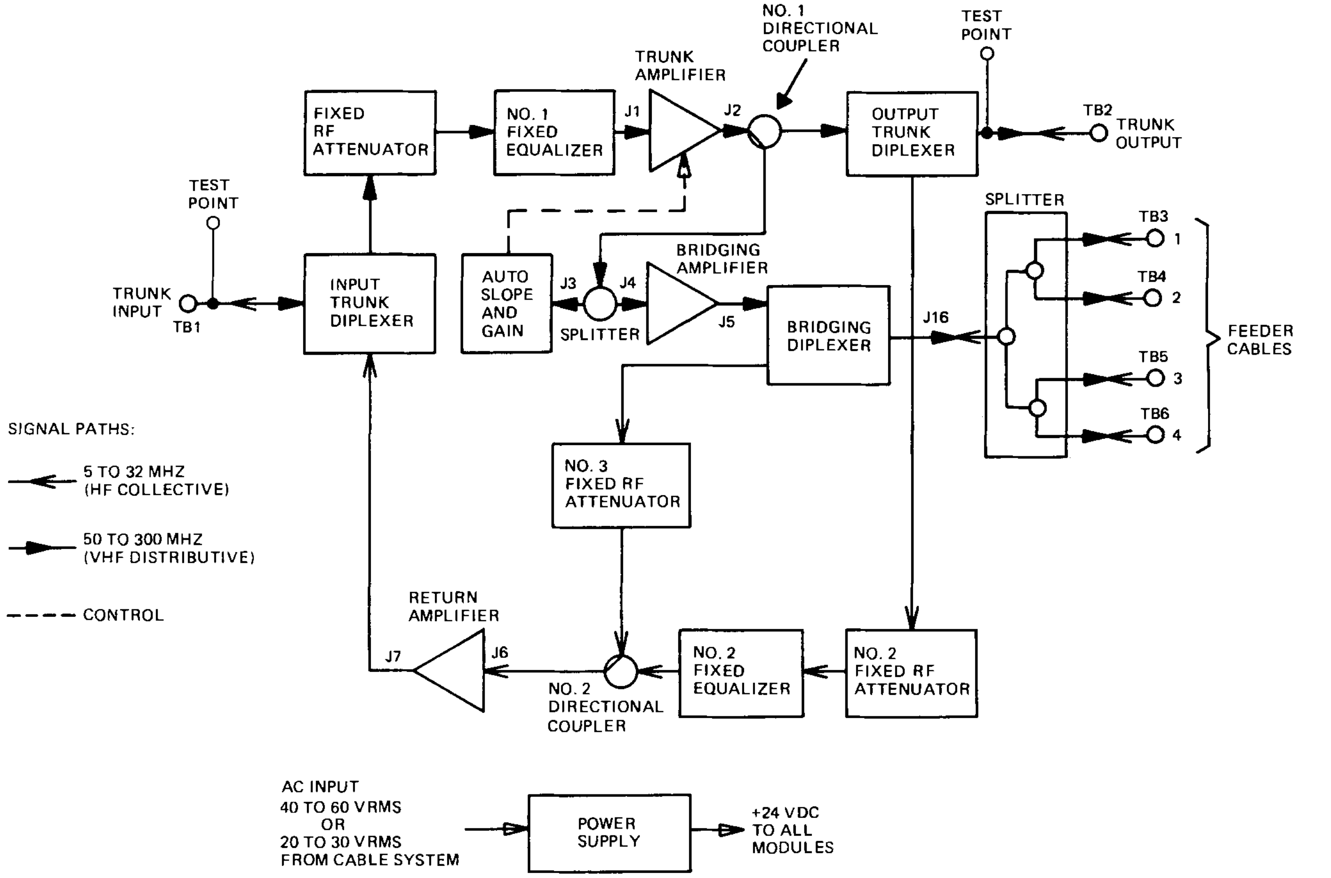

Figure 3. Mark IV Station Block Schematic

In the Wilson, NC, system, the return path of 5 to 32 MHz capability is not used at the present time, but it is an integral part of the installed and tested equipment. Plug-in untuned modules will complete the upstream path with only level setting required.

In addition to wide design margins for electrical parameters, all station modules must be considered in terms of mechanical design criteria. Factors to be considered, in addition to the temperature rise contribution of each module are: ease of handling, ease of adjustment, plus ease and economy of repair.

The temperature rise contribution of each module is minimized by substantial heat sinking of components within the module and by careful attention to the design of the mechanical interface of the module with the station housing. Good mechanical interfaces ensure that heat generated by each module will be rapidly conducted to the station housing and then to the surrounding air. Low temperature gradients within the housing preclude the detrimental effects of local hot spots on electronic components.

The Mark IV station contains the base plate, power supply, and all signal modules within a cast aluminum housing designed to provide a low packaging density environment. This environment ensures that temperature changes within the housing are relatively moderate and provide good electrical stability and freedom from failures related to thermal effects. The hottest area temperature within the housing (heat sinks) is 84°C maximum at 60°C still air ambient test.

All station modules are considered in terms of mechanical design criteria; temperature rise within modules is minimized by adequate heat sinking within the module and from the module to the housing areas from which heat conduction to the surrounding air is good.

The base plate contains all passive devices such as: diplexers for two-way operation, directional couplers, splitters, plug-in fixed attenuators, plug-in fixed equalizers, fusing, surge protection devices, and ports for plug-in modules.

Overall rf signal flow has been carefully planned to guarantee logical signal flow resulting in ease of field installation, structural isolation of the high level bridger output from the trunk input, and structural isolation of all upstream-from-downstream signals.

Feeder maker modules are of such a design that they effectively do nothing to the signal other than split it, which is, in fact, their sole function.

The reliability and efficiency of the station's power supply deserves extensive treatment. The station is not only dependent on the power supply's performance, but also on its location in the cascade; the inability of the power supply to function properly can result in a catastrophic system failure.

The power supply is an area of major concern for the station designer as it contains most of the heavy current circuit elements and, therefore, is the major site of heat generation and the major contributor for circuit element failures related to thermal effects.

Good efficiency combined with low packaging density and adequate heat sinking to the housing surfaces ensure markedly reduced failure probability of all elements comprising the station.

This approach to power supply design suggests the selection of conventional series regulators rather than switching-type regulators. Switching-type regulators provide good efficiency with low dissipation (necessary for high-density packaging designs) for a wide range of ac input voltages in the system. The switching-type regulators, however, are more subject to damage than the series-type when subjected to the transients frequently encountered in operational systems. Transient safeguards for switching-type regulators are very often designed to handle the worst case of a given geographical or local area of installation. The transients that must be considered (for any type of the voltage regulator) include power line turn-on or turn-off induced surges, induction due to adjacent power lines with abrupt load changes, and lightning strikes. The quality of the station's grounding system, both within the housing and at the local site (earth ground return) can not be overstressed. All module grounds must converge into a common station ground. According to regulations, all ground returns from the cable and wire systems on a utility pole (telephone, CATV, power lines of low and high voltage) must have common conductor to ground (earth); this conductor presents a major problem when its impedance is high. Also, the ground impedance from the return conductor to earth may contribute to the common high impedance path; soil type, presence of moisture and the return conductor surface area in soil determine quality of the earth ground. For good reliability, all local grounds should utilize heavy conductors and provide adequate and reliable contact with a good earth ground. The transients mentioned above may also damage any module in the station as well as the power supply.

In most power supply designs, the series-path power transistors and associated components are the first circuit elements to be damaged by heavy transients. The series-path transistors of a switching-type regulator are, however, more susceptible to transient damage. Since switching operation occurs at about 20kHz and the transients apt to cause transistor damage are of millisecond (or less) duration, heavy transients imposed on switching-type regulators during the off period (when input impedance is high) are likely to damage the device. Improvements in the area of transient protection for transistors operating in this manner will be necessary before switching regulators can operate with the same immunity to transients as series pass regulators.

The trapezoidal waveform ac input voltage, of either 40 or 60 Vrms or 20 to 30 Vrms, is taken directly from the cable system. System dc voltage is isolated in the station by an input transformer which has multiple primary winding taps. One of the taps is selected during installation to match the individual station's ac voltage. The six taps provided on the transformer provide an effective and inexpensive way to maintain high efficiency (70 percent). The voltage drop in the series-path transistor of the regulator is kept to a minimum, and the temperature rise within the housing is minimized, assuring higher reliability and stable performance of all modules within the housing.

Standard features of this supply include input and output overvoltage protection as well as short circuit protection. When the power supply senses an overvoltage condition, a crowbar circuit fires thus opening a fuse and thereby protecting the station from damage due to prolonged overvoltages. The short circuit protection is of such a nature as to protect the power supply from damage. Resumption of normal power supply operation occurs after the short has been removed.

Both the chokes and the copper paths of the trunk power passing circuit are capable of carrying the full current output capability of the 60-volt square-wave power supply.

To be able to establish which tap to use at a given cascade station, a conveniently located dc test point is provided in the station's power supply. This test point will show the dc voltage in the voltage regulator before regulation. This voltage value is primarily a function of the ac rms value of the trapezoidal voltage applied to the isolation transformer's primary. A regular dc voltmeter can be used to select the tap for lowest heat dissipation in the series path transistor. The rms value of trapezoidal voltages measured in the field is speculative at best.

Ac power programming flexibility is achieved by the incorporation of an additional fuse circuit; this fuse allows independent powering of the trunk from the distribution ports, or it permits the trunk and distribution lines to be tied together for powering purposes.

Protection from the surge voltages is achieved by using ruggedized, fast-firing surge protectors at each port of the station.

With a primary design objective for the trunk station being the minimization of performance degradation for the broadband, extremely flat, low distortion hybrids, it is necessary that all circuitry in the station be flat, have good return loss, and minimize loss and distortion. As seen earlier in this paper, not only is the design of the circuit important but also the circuit's location is important in determining the station's performance. Maintaining at least an 18 dB return loss not only ensures a minimum deterioration in flatness of the hybrids but also limits the number of controls necessary to optimize that flatness. As a result of all these considerations, the number of "pooch" adjustments in the trunk and bridger modules has been held to two. These two controls take corrective action at the extreme ends of the bandpass only, not in the middle of the band.

Some of the station's features which affect the flexibility of the system and its quality are worth restating:

(a) Fixed plug-in cable equalization is of a split type: one plug-in equalizer is at trunk amplifier input, and the second plug-in equalizer is in the interstage area.

(b) The same approach is taken for the fixed plug-in attenuators. These approaches allow the optimization of carrier-to-noise ratio and low distortion for a great variety of cable spans; it accommodates a variety of block tilt and slope combinations required in different system designs.

(c) The diplexer design approach results in an exceptionally flat frequency response and match, low insertion loss, and a cross-over point attenuation and selectivity which eliminate interaction between the forward (trunk) and return paths. The group delay is kept at very low values.

(d) The directional couplers, splitters and rf cabling are of reliable high quality type (low losses, good match and flat overall frequency response).

(e) Match at all ports is extremely flat over the frequency band of interest with monotonic rising characteristics at the band edges. This is achieved by careful rf layout and trimming techniques.

(f) Low density distribution of the rf circuits and passive devices ensures good isolation between the housing ports.

(g) Rf and/or ac test point areas are easily accessible.

(h) The housing construction is solid and of high quality. The temperature rise within the housing is rather small when compared with high density packaging concepts.

To eliminate infant mortality and ensure quality performance, all tested modules are subjected to a burn-in process for at least 48 hours. The station with installed modules is retested for all main specification parameters as a final check.

III. TEST RESULTS

The Wilson system represents 116 miles of operational one-way cable television transmission. The system is capable of operating from 54 to 300 MHz, and from 5 to 32 MHz; the actual operating range is from 54 to 270 MHz.

Test results for the longest cascade (phase III, 19 stations) are as follows:

(a) Transmission Response: see figure 4.

(b) Signal-to-Noise Ratio (system specification, 44 dB):

Ch 2, 47 dB
Ch 7, 47 dB
Ch 13, 46 dB.

(c) Cross Modulation Distortion (system specification, -58 dB):

Ch 2, -62 dB
Ch 13, -60 dB.

(d) Second Order Distortion: -68 dB.

(e) Hum Modulation: less than 1 percent.

(f) Composite Intermodulation Distortion: -60 dB (worse case).

(g) Mark IV Trunk Station Performance Curves: see figures 5 through 14.

(h) Mark IV Trunk Station Group Delay Curves: see figures 15 through 19. These tests were made using the GR 1710 RF Analyzer.

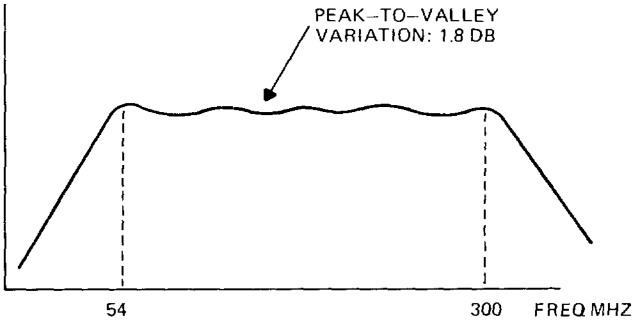

Figure 4. Phase III Simulated Trunk Transmission Response (19 Stations Cascade)

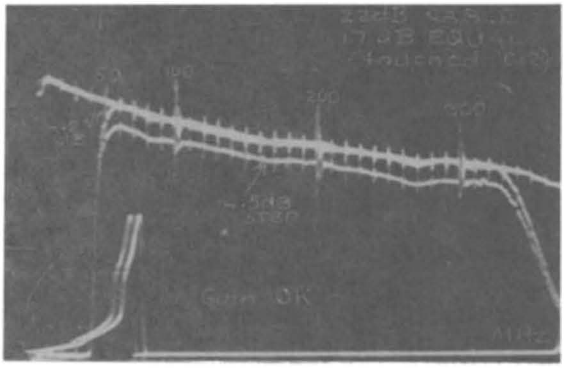

Figure 5. Mark IV Station Frequency Response - Forward Trunk with 22 dB of Cable and 17 dB Plug-in Equalization

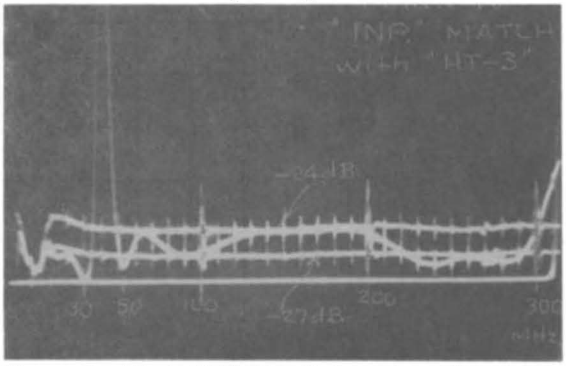

Figure 6. Mark IV Station Return Loss Response at Housing Trunk Input Port

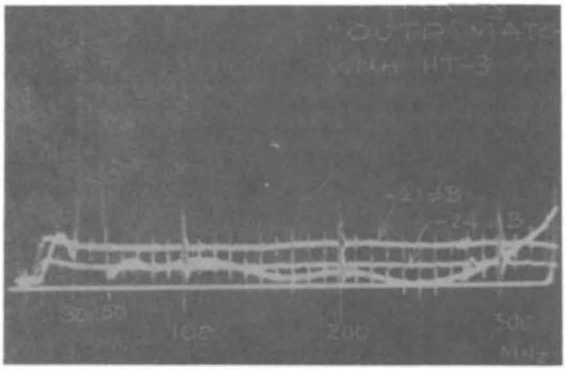

Figure 7. Mark IV Station Return Loss Response at Housing Trunk Output Port

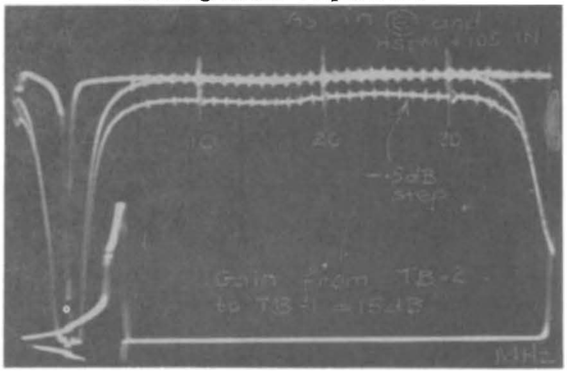

Figure 8. Mark IV Station Sub-band Frequency Response from Housing Output Port to Input Port

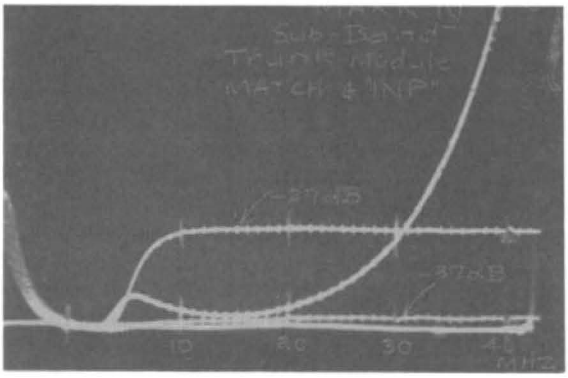

Figure 9. Mark IV Station Return Loss Response at Housing Input Port for Sub-band Frequency Range

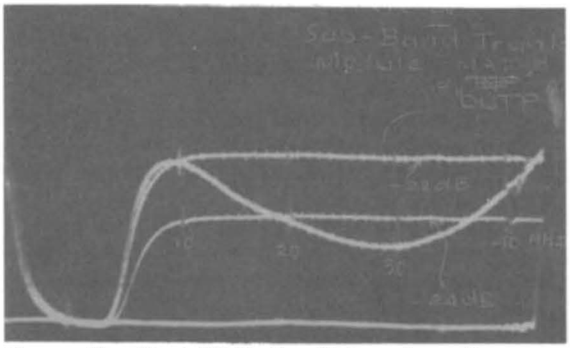

Figure 10. Mark IV Station Return Loss Response at Housing Output Port for Sub-band Frequency Range

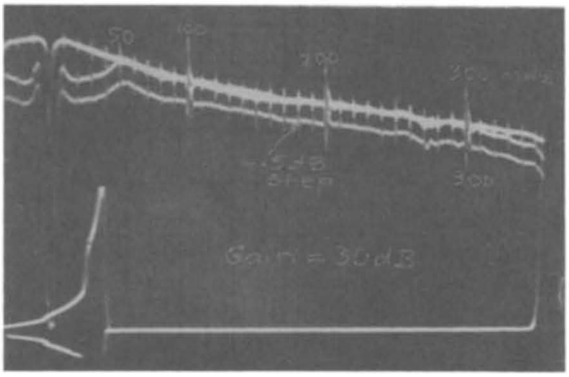

Figure 11. Bridger Amplifier Frequency Response (HB-3)

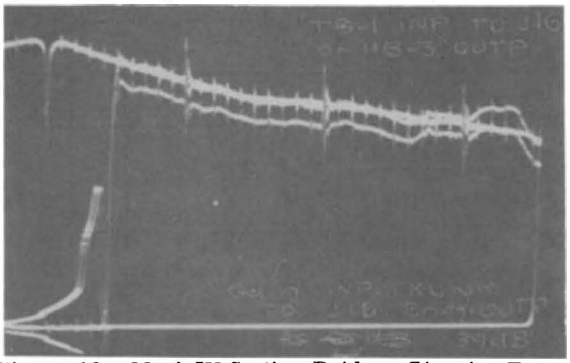

Figure 12. Mark IV Station Bridger Circuits Frequency Response from Housing Input Port to J16 Bridger Output

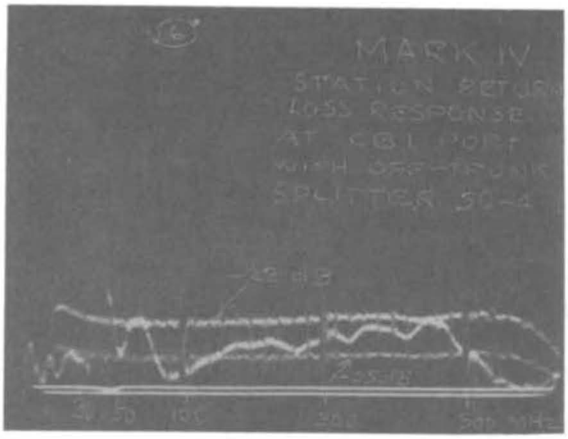

Figure 13. Mark IV Station Return Loss Response at Housing Port CB-1 with SO-4 Off-trunk Splitter

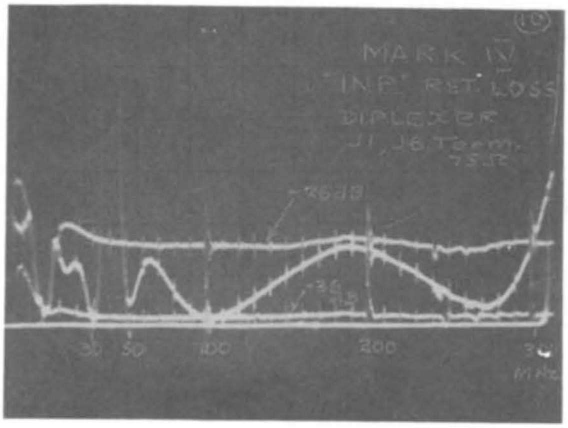

Figure 14. Mark IV Station Input Port Diplexer Return Loss Response with J1 and J6 Terminated

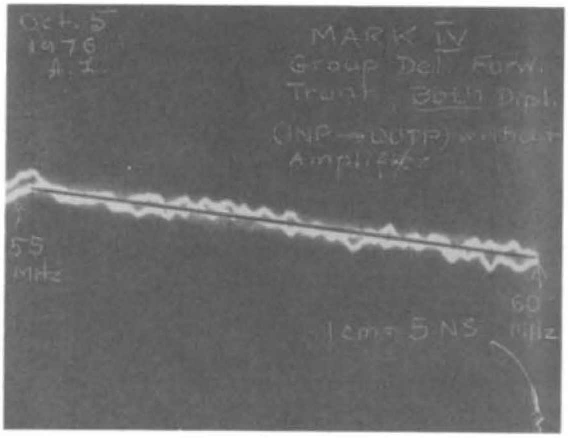

Figure 15. Group Delay from Input to Output (Both Diplexers Combined) from 55 to 60 MHz, 1 cm = 5 ns

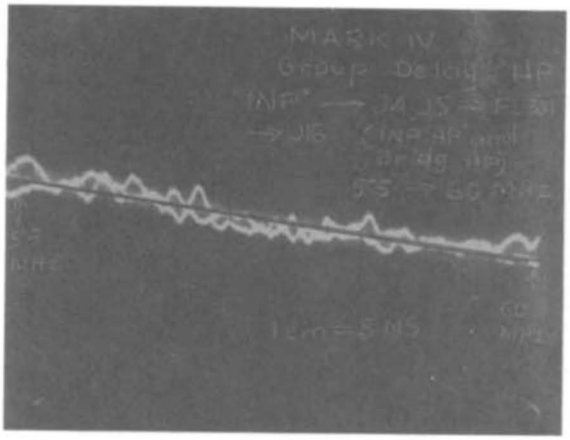

Figure 16. Group Delay from Input to J4, J5 to FL301 J16 (HP Input and HP Bridger Combined) from 55 to 60 MHz, 1 cm = 5 ns

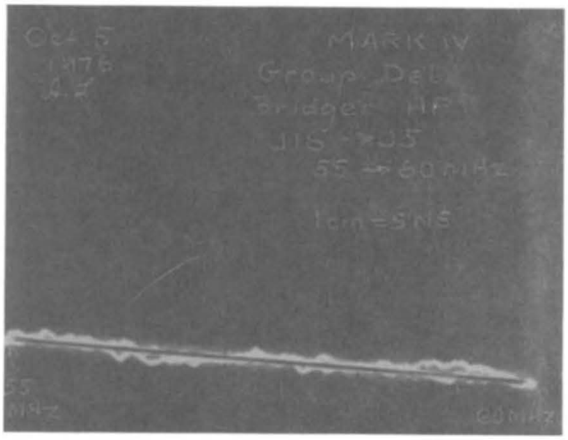

Figure 17. Group Delay for Bridger HP Section (J16 to J5) from 55 to 60 MHz, 1 cm = 5 ns

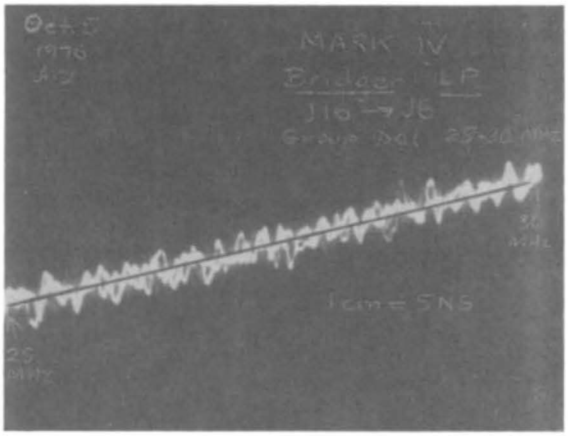

Figure 18. Group Delay for Bridger LP Section (J16 to J6) from 25 to 30 MHz, 1 cm = 5 ns

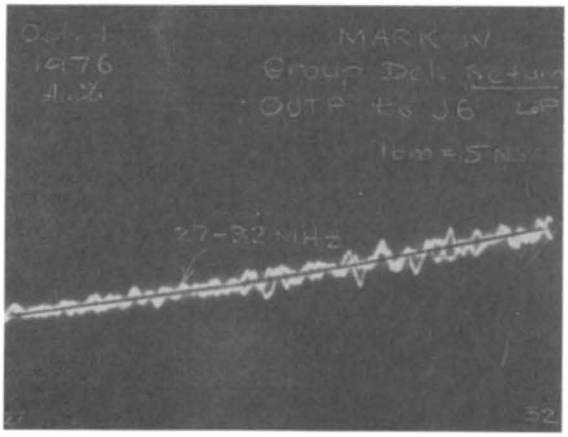

Figure 19. Group Delay for Output Diplexer LP Section (Output to J6) from 27 to 32 MHz, 1 cm = 5 ns

CONCLUSIONS

Reliable design for field installation and test involves a properly designed cable system and reliable equipment which is easy to install and to service.

The CATV system and equipment designs covered in this paper give a basic understanding of "how" and "why" such a system functions.

The Wilson, North Carolina CATV system design aspects were discussed. By using an approach which avoids marginal designs, one can produce a high quality reliable system.

It is important, also, that the equipment design criteria require an absolute minimum of external adjustable controls. This eliminates costly errors and wasted rework time, especially during initial installation and test of the system. With modules having many accessible controls, it is easy to obtain an incorrect combination of the control settings with subsequent deterioration in performance.

The minimization of service and test adjustments also permits the use of persons with limited technical training, thus shortening maintenance efforts and reducing costs.

REFERENCES AND ACKNOWLEDGEMENTS

References

Simons, Ken, "Technical Handbook for CATV Systems," Jerrold Electronics Corporation, Third Edition.

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APPENDIX
CATV CASCADED TRUNK LINE AMPLIFIER SYSTEMS CONCEPTS

For the purpose of this document we will assume that all cascaded amplifiers are identical, have similar performance characteristics, and are separated by identical cable lengths each of which has a loss equal to an amplifier gain. From this, two basic quantities may be obtained: noise and distortion; these characteristics determine the quality of the resultant TV picture and the final length of the system.

a. NOISE RELATIONSHIPS

The noise output of a single amplifier with a terminated input is

$$N_1 = -59 + G_1 + F_1 \text{ (dBmV)} \quad (1)$$

where,

G_1 = operating gain of amplifier in dB

F_1 = noise figure of amplifier corresponding to G_1 gain (in dB).

The lowest allowable signal output is:

$$S_{min(1)} = N_1 + R_{min} = -59 + G_1 + F_1 + R_{min} \text{ (dBmV)} \quad (2)$$

where,

R_{min} = lowest acceptable signal-to-noise ratio (S/N) in dB. See Table 1.

Table 1. Acceptable Signal-to-Noise Ratio (S/N) Levels

TASO Picture Rating	S/N
1. Excellent (no perceptible snow)	45 dB
2. Fine (snow just perceptible)	35 dB
3. Passable (snow definitely perceptible but not objectionable)	29 dB
4. Marginal (snow somewhat objectionable)	25 dB

The system noise figure is determined as:

$$F_m = F_1 + C \text{ (dB)} \quad (3)$$

where,

$C = 10 \log m$ (cascade factor)

m = number of amplifiers in cascade.

The noise output of the last amplifier is:

$$N_m = N_1 + C \quad (4)$$
$$= -59 + G_1 + F_1 + C \text{ (dBmV)}.$$

Therefore, the lowest allowable signal output from the last amplifier is:

$$S_{min(m)} = N_m + R_{min} \quad (5)$$
$$= -59 + G_1 + F_1 + C + R_{min}$$
$$= S_{min(1)} + C$$
$$= S_{min(1)} + 10 \log m \text{ (dBmV)}.$$

b. CROSS MODULATION RELATIONSHIPS

$$XM_m = XM_1 + 2C \quad (6)$$

where,

XM_m = system cross modulation

XM_1 = cross modulation of one amplifier

$C = 10 \log m$ (as shown in equation 3).

To determine the system maximum output, with system cross modulation expressed as XM_{max}, use the relationship:

$$S_{max(m)} = S_{max(1)} - 10 \log m \quad (7)$$
$$= S_{max(1)} - C$$

where,

m = number of amplifiers in cascade

$S_{max(1)}$ = output in dBmV from one amplifier where cross modulation XM_{max} is on the worst channel with the other channels measured at the operating gain.

The system cross modulation $XM_m = XM_1 + 2C = XM_1 + 20 \log m$

c. SYSTEM NOISE AND CROSS MODULATION EFFECT

To relate noise and cross modulation on system length, the term tolerance (T_S) will be used as the allowable variation in level that does not produce objectionable picture degradation. This is expressed as the difference in dB between the lowest permissible output (determined by noise) and the highest permissible level (determined by cross modulation).

For a single amplifier this is expressed as:

$$T_{(1)} = S_{max(1)} - S_{min(1)} \quad (8)$$
$$= S_{max(1)} + 59 - G_1 - F_1 - R_{min} \text{ (dB)}$$

where,

$S_{max(1)}$ as in (7).

For a cascaded system, the system maximum output is expressed as:

$$S_{max} = S_{max(1)} - C; \quad (9a)$$

system minimum output is expressed as:

$$S_{min} = -59 + G_1 + F_1 + C + R_{min}; \quad (9b)$$

and system tolerance is expressed as:

$$T_S = S_{max(m)} - S_{min\ (m)} \quad (9c)$$
$$= S_{max(1)} + 59 - G_1 - F_1 - R_{min} - 2C$$
$$= T_{(1)} - 2C \text{ (dB)}.$$

d. MAXIMUM NUMBER OF AMPLIFIERS

From equations 8 through 9c we may derive the value of tolerance equal to zero as:

$$T_1 = 2C; \; T_1 - 2C = 0 \quad (10)$$

With the value of T_S equal to zero for the maximum number of cascaded amplifiers, the tolerance of a single amplifier approaches the value 2C. During the state of zero tolerance only one operating level is possible.

e. OPTIMUM SYSTEM OPERATING LEVEL

The optimum system operating level is defined as the operating level that is halfway between the maximum and minimum output (i.e., this is the midpoint between the level at which cross modulation becomes objectionable and the level at which noise becomes intolerable).

From equation 7 we have the formula:

$$S_{max(m)} = S_{max\ (1)} - C$$

where,

$$2C = T_{(1)} \text{ for zero tolerance.}$$

Therefore,

$$S_{max(m)} = S_{max(1)} - \frac{T_{(1)}}{2} \quad (11)$$

In order to find the optimum operating level for each amplifier in a cascaded chain, subtract one half the single amplifier tolerance from the single amplifier maximum output. At zero tolerance:

$$S_{min(m)} = S_{min(1)} + \frac{T_{(1)}}{2} \quad (12)$$

f. TRIPLE BEAT DISTORTION, SECOND ORDER DISTORTION

The occurrence of composite triple beat distortion is due to the third order distortion in the active devices of the system. The visible threshold level of the triple beat distortion is 46 dB below the peak carrier with 30 channels. However, AEL amplifier performance specifications far exceed these requirements and perform exceptionally well for this criterion.

The second order distortion levels also are very low (-68 dB or better).