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Engineering Aspects of the TH Microwave Radio Relay System

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This paper gives a general description of the TH system, which is a long-haul system operating in the 5925–6425 mc band. It discusses the considerations governing the major design decisions, which lead to an FM system of eight channels in each direction, six working and two protection. Each channel has a 10-mc potential baseband width. The paper continues with a discussion of noise considerations, primarily from the viewpoint of telephone transmission. Fluctuation noise and modulation noise are the principal sources, with interference between radio channels a minor factor.

I. INTRODUCTION

The TH radio relay system is the most recent in the succession of radio facilities developed for use in the Bell System communication network. A point-to-point radio system was used as part of the commercial telephone network as early as 1920.[1] This and subsequent point-to-point radio installations were special cases using a single-hop, narrow-band system to carry one or a few telephone conversations across terrain where installation of wires or cables was impracticable. The use of radio relay as a general purpose facility in the Bell System network was inaugurated with the installation of the experimental TD-X system between New York and Boston in 1947. From this initial 220-mile route, the radio network had expanded by the end of 1960 to over 44,000 route miles carrying over twenty-nine million telephone circuit miles and 79,000 television channel miles.

The major portion of this network is provided by the long-haul broadband TD-2 system operating in the 4000-mc common carrier band. A relatively small amount is provided by short-haul feeder systems. Many of the TD-2 routes are now fully equipped and no more radio channels can be added within the assigned frequency band. The congestion is particularly acute where two or more routes cross or converge on cities. Additional circuit needs in these areas can be met only by the use of a different frequency band.

The TH radio relay system has been developed to provide the additional circuits. It is a broadband long-haul radio system operating in the common carrier band between 5925 mc and 6425 mc.[2] The basic design objective is to provide 4000-mile telephone and television circuits with transmission quality and reliability commensurate with the present system objectives. At the same time, maximum utilization of the available frequency spectrum is imperative, and the use of as much as possible of the existing TD-2 plant and engineering effort is economically desirable. Along with these requirements is the need to provide flexibility to meet changing conditions of usage, both in layout of routes and in types of signals to be carried. This paper gives a brief description of the system and discusses the over-all engineering aspects which led to the final system. Subsequent papers discuss in greater detail the design of the various component parts of the TH system.

II. THE TH SYSTEM

The TH system is shown in block diagram in Fig. 1. Each broadband circuit consists of an FM transmitter, a transmitting entrance link,

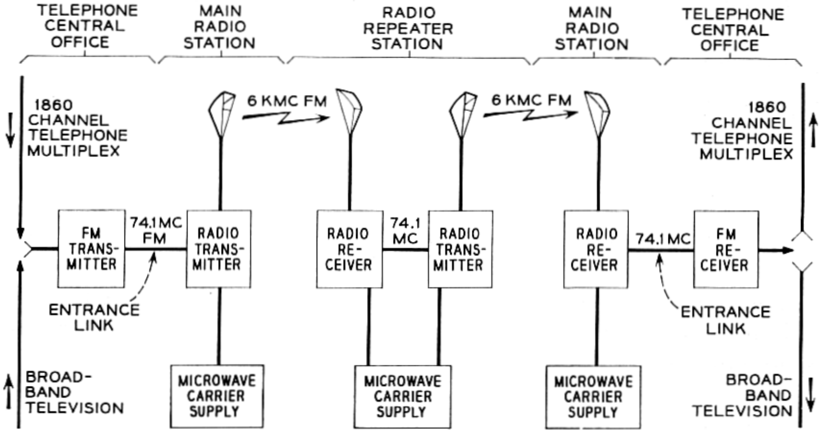

Fig. 1 — Block diagram of the TH system.

one or more radio repeater sections, a receiving entrance link and an FM receiver. The FM transmitter produces a 74.1-mc signal which is frequency modulated by the incoming baseband signal. This frequency-modulated signal is fed to a radio transmitter over a transmitting entrance link. The radio transmitter heterodynes the IF signal to the desired microwave frequency and amplifies it for radiation to the next station. The radio receiver at the next station heterodynes the microwave frequency back to the 74.1-mc intermediate frequency for amplification and equalization. The output of the radio receiver may then be connected to another radio transmitter for transmission farther down the route or may be connected through a receiving entrance link to an FM receiver. The FM receiver demodulates the signal and delivers the baseband signal to the terminating equipment.

Eight two-way, broadband radio channels and two two-way, narrowband radio channels (called the auxiliary channels) are provided in the assigned band as shown in Fig. 2. In each station, all the radio transmitters are grouped in one half of the assigned band and all the radio receivers in the other half of the band. Six of the broadband channels are used as working channels with the other two used as protection channels against equipment failures or fading. The auxiliary channels are located in the guard spaces between the broadband transmitters and receivers and at the edges of the band. These are used to provide circuits for voice order wires, for the automatic protection switching system, and for transmission of alarms from unattended stations. The two auxiliary channels in each direction are connected to provide a single transmission circuit with frequency diversity.

A fully equipped repeater station contains twenty radio receivers and twenty radio transmitters, each requiring a microwave beat oscillator signal. Rather than providing forty individual oscillators, a common carrier supply is used for all the receivers and transmitters in a station. Starting from a highly frequency-stabilized crystal oscillator operating at 14.8259 mc, the common carrier supply generates the 2nd, 4th, 408th and 425th harmonics to provide two VHF signals at 29.65 mc and 59.30 mc, and two microwave signals at 6049 mc and 6301 mc. The appropriate one of the ten beat oscillator frequencies shown on Fig. 2 is provided by either the 6049-mc or 6301-mc signals or is generated in the receiver or transmitter by combining one of the microwave signals and one of the VHF signals. Since the failure of the common carrier supply in a station would be catastrophic, it is supplied in duplicate with automatic switching to the standby unit when necessary.

The baseband signals to be carried by the TH system are shown in

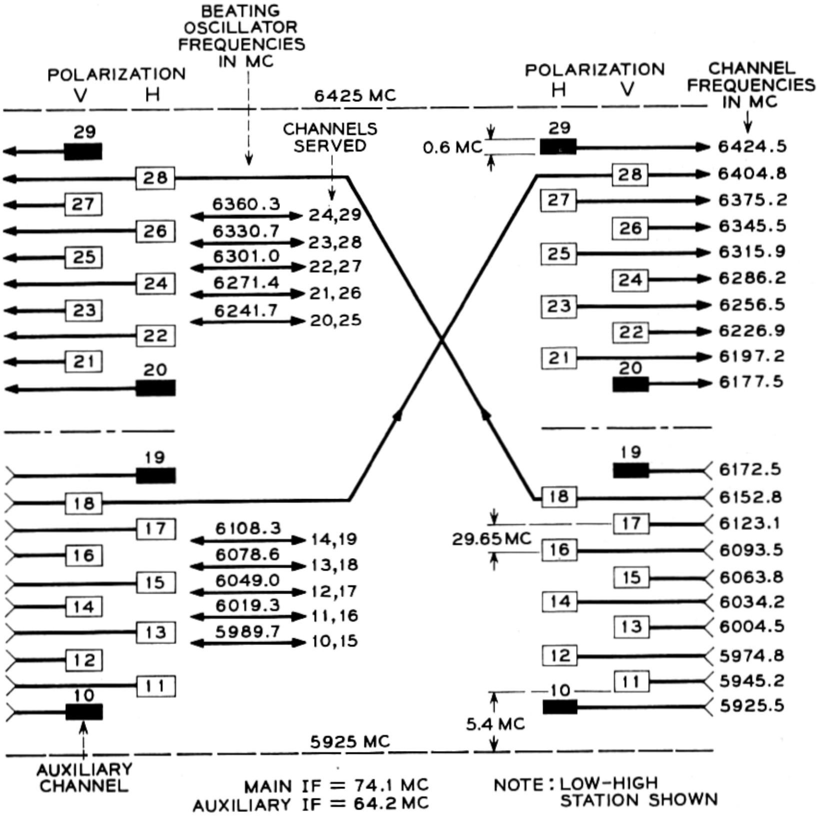

Fig. 2 — Frequency allocations and polarizations for the TH system channels.

Fig. 3. The telephone signals are derived by single-sideband multiplex equipment of the type used in the L-3 coaxial cable system.[3] The telephone signal for TH differs from the standard L-3 telephone signal only in the amount of pre-emphasis. High-definition theater television occupying the entire 10-mc baseband may also be transmitted.

III. SYSTEM DESIGN CONSIDERATIONS

The TH system as described above is basically similar to the existing TD-2 system but contains many refinements. This is accomplished through the use of newly developed components and through applying the experience gained from the TD-2 system. The design departs from that of the older system wherever an improvement is indicated and

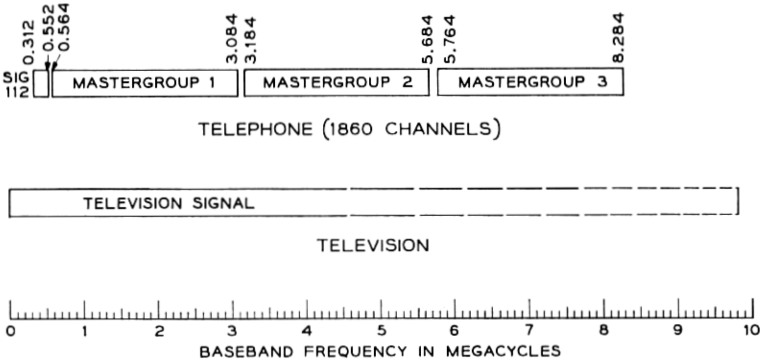

Fig. 3 — The baseband signals of the TH system.

follows that of the older system only if a review of the various possibilities showed that approach to be best.

3.1 *Antenna System*

A large portion of the expense of any radio relay route is the cost of repeater sites, access roads and towers to support the antennas. Any new radio system should be designed to utilize the repeater sites and towers of older systems if at all possible. Furthermore, the same antennas should be used for as many systems on any route as possible. The cost penalty for using separate antennas for each system involves provision of heavier, more expensive towers and additional waveguide runs as well as the additional antennas themselves. In anticipation of the use of TD-2 (4 kmc), TH (6 kmc) and possibly TJ (11 kmc) systems on the same route, the horn-reflector antenna was developed.[4,5] This antenna, with its circular waveguide feed, can transmit cross polarized signals in all of these bands. Polarization is used to help separate two signals which are too close together in frequency to be separated completely by practicable filters. The cross polarization discrimination of a repeater section, including the antennas, round waveguides and system combining networks, is expected to be at least 25 db for the TH system. The performance of the antennas is one of the factors permitting the close spacing of adjacent channels as shown in Fig. 2.

The horn-reflector antenna is designed to have approximately the same gain in the 4-kmc band as the delay lens antenna originally used with TD-2. This in turn sets the antenna gain at 6 kmc as 43 db. The average spacing of TD-2 repeaters is about 30 miles. The 6-kmc path loss between isotropic radiators spaced 30 miles apart is 142 db. Thus the requirement for maximum utilization of existing TD-2 plant determines the loss between the transmitter output and the receiver input of the TH system. With an allowance of 8 db for losses in the waveguide components, this is 64 db.

The connections to the antenna are shown diagrammatically in Fig. 4, which shows only one side of the TH repeater station. The system combining networks[6] at the bottom of the round waveguide accept signals

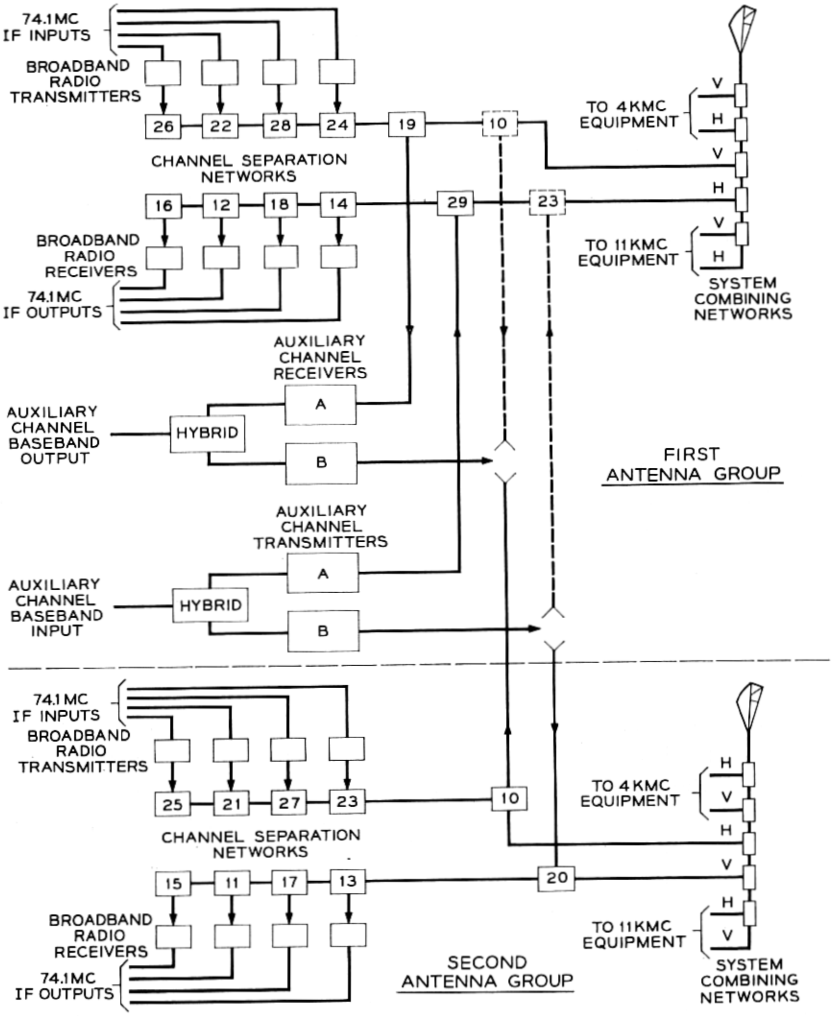

Fig. 4 — Diagram of antenna connections.

in two rectangular waveguides for each frequency band and combine them into cross polarized signals in the round waveguide. The individual channels of the TH system are combined in the tandem connected channel separation networks.

The use of the same antenna for transmitters and receivers permits improved reliability against failures in an antenna or its round waveguide on a heavily developed route, since failure of any one antenna does not shut down all radio channels. The initial installation of TH normally consists of one working and one protection broadband channel. By the standard growth plan, these are channels 4 and 8 (channel 4 designates the alternate sections of channels 14 and 24 required to make up a continuous transmission path, etc.). As additional broadband channels are required, a second pair is added to provide a second working and a second protection channel. These may be either the other two even-numbered channels or a pair of odd-numbered channels (normally 3 and 7). If the first four are all even-numbered channels, they operate on a single pair of antennas as shown in the upper part of Fig. 4, and the installation of the second pair of antennas may be deferred until an odd-numbered channel is required. Where the second pair of antennas is available initially, as when TH is added to a TD-2 route already equipped with horn reflector antennas, odd-numbered channels are used for the second pair to utilize the added reliability of the extra antennas. Additional channels are then added as needed until all channels are equipped as shown in Fig. 4.

Normally, channels 1 and 5 are equipped last to leave two slots in the band which may be used by nearby light-route equipments as long as possible.

3.2 *Frequency Allocation*

The frequency allocation plan of TH provides maximum utilization of the assigned band consistent with the transmission objectives. Interference between transmitters and receivers in the same station is minimized by grouping all the transmitters together in one half of the band and all the receivers together in the other half, as shown in Fig. 2. This, together with the use of cross polarization, permits the guard bands to be reduced to one at the center of the band between the transmitters and the receivers, and one at each edge of the band between the TH signals and any services in adjacent bands. Because of the excellent back-to-back discrimination of the horn-reflector antenna, the same frequency may be used to transmit in both directions at each station, and the full band may be utilized in both directions.

As shown in Fig. 2, each channel is shifted in frequency (or frogged) by 252 mc as it passes through a repeater station. Frequency frogging is necessary to prevent feedback from the repeater output into the input. In TH, if a transmitter and a receiver are operated at the same frequency in the same station, the loss between the transmitter and the receiver has to be greater than 118 db to keep interferences at a tolerable level. Only ideal locations with tall towers and practically no nearby reflective surfaces can be made to meet such a requirement.

Minimum channel spacings are determined by adjacent channel interference considerations. With low index frequency modulation, the interference increases sharply when the channel spacing is reduced to the point that the second-order sidebands of one channel overlap the first-order sidebands of the other. Thus the minimum channel spacing is set at three times the top baseband frequency. For the 10-mc nominal top baseband frequency of TH, the channel spacings must be about 30 mc. These considerations determine the general frequency allocation plan of TH. The exact choice of frequencies is discussed in connection with the common carrier supply, later in this paper.

3.3 *Type of Modulation*

The type of modulation to be used in a system is chosen to give the best compromise between noise and distortion performance on the one hand and practicable design limitations on the other. For example, pulse modulation systems can be made to give excellent noise and distortion performance through many repeaters in tandem, but they are not suitable for use in the TH system because of the large bandwidths they require. High index frequency modulation is unsuitable for the same reason since it too trades bandwidth for noise performance. At the other extreme, single sideband suppressed carrier transmission makes the most efficient use of radio spectrum and of transmitter power, but it requires a high degree of amplitude linearity in the amplifiers to reduce distortion. At the present state of the art, 6-kmc power amplifiers of the required degree of linearity would be prohibitively large and expensive, if they could be built at all. The compromise chosen for TH is low deviation frequency modulation. This requires a relatively narrow band (approximately three times the top baseband frequency) and will tolerate compression in the amplifiers.

The optimum frequency deviation to be used is related to many factors, among which the more important are the transmitter power, the noise figure of the radio receiver, the system delay distortions, and the baseband signal to be transmitted. At the time TH was being planned, a traveling-wave tube in a reasonable size with 5 watts output became a practical possibility. This was chosen as the output stage for TH, and the tube was developed as the Western Electric Type 444A.[7,8] New modulator crystals and the use of an isolator in the modulator input combine to give a receiver noise figure of 10 db. All components of TH are designed for low delay distortion by using the most stable elements available in circuit configurations having minimum delay distortion. The traveling-wave tube amplifier is designed to be essentially flat over the entire 500-mc TH band with only minor tuning adjustments required for each channel. The IF amplifier uses factory adjusted, fixed-tuned interstage circuits designed to minimize effects of changes in tube parameters. The radio repeater room is temperature controlled to minimize temperature effects on waveguide filters. When these parameters are considered in terms of the 1860 telephone channel load, the optimum frequency deviation is found to be ±4 mc peak, which is about the same as that used in TD-2.

3.4 *Type of Repeater*

Three general types of radio repeaters might be used. These are the baseband repeater, in which the signal is demodulated to baseband and remodulated on the radio frequency at each repeater; the IF repeater, in which the modulated radio frequency signal is heterodyned to an intermediate frequency for amplification and equalization and then heterodyned back to radio frequency without demodulation; and the RF repeater, in which the signal is amplified and reradiated with only the frequency shift required for frogging. An RF repeater may be either a single radio channel repeater in which the radio channels are separated and amplified in individual amplifiers, or a multichannel repeater in which all radio channels in one direction are amplified in a single amplifier.

The baseband repeater provides the highest degree of route flexibility by making the baseband signal available at all repeater points along the route. However, in a long-haul system such as TH, the large number of modulators and demodulators connected in tandem would require each modulator to meet extremely stringent distortion requirements. The multichannel RF repeater is not suitable for applications where polarization is used to separate the signals of adjacent radio channels. This leaves only the single channel RF repeater and the IF repeater as possible choices for TH. The latter was chosen because of the greater ease of separating and equalizing channels and of switching between working and protection channels at IF.

The use of IF-type repeaters leads to the use of the intermediate frequency as a common interconnection between the various portions of the system. The output of the FM transmitter and the input of the FM receiver are made to operate with the same IF signal as is used in the radio repeaters. Entrance links, when required to connect widely separated radio equipment and multiplex terminals, are also operated at IF. Good route flexibility results, since all route reassignments or additions are made by IF interconnections.

Tone interference due to leakage of the beat frequency oscillators into the radio channels can be minimized by the proper choice of the intermediate frequency. If the IF is made equal to an odd multiple of half the channel spacing, the leakage tones fall midway between two channels and are least disturbing to both. Past experience with other microwave systems has indicated that an IF of about 70 mc is a good compromise in the IF amplifier design between electron tube input conductance and broadband coupling network design. This leads to the use of $2\frac{1}{2}$ times the channel spacing (74.1 mc) for the TH intermediate frequency. This IF is not compatible with the 70-mc IF of TD-2. However, regular use of direct IF interconnections of the two facilities would be extremely unlikely, since the use of the 10-mc bandwidth of TH to carry the 2.25-mc to 4-mc signal of TD-2 would be economically wasteful and since the use of the TD-2 system to carry the wider signal of TH is impossible. For emergency restoral of service, the wider IF bandwidth of TH will permit transmission of the offset TD-2 signal although at the expense of possible interchannel interferences of the type discussed later as "tertiary interference".

3.5 *Common Microwave Carrier Supply*

Forty microwave beat oscillator signals are required in a fully equipped radio repeater station. The use of a common carrier supply rather than individual supplies reduces the active equipment required, reduces maintenance efforts, eases stability requirements, and permits better control of tone interferences.

The frequency stability objective of the TH system (derived from interference and distortion considerations) is that at no point in a 4000-mile circuit shall the transmitted frequency be in error by more than 280 kc (one per cent of the transmitted bandwidth). Of this tolerance, 100 kc is allocated to the FM transmitter with the remaining 180 kc available for errors in the carrier supplies of 133 tandem radio repeaters. If individual supplies were used, the 180 kc would have to be divided among 266 supplies. Assuming random addition of the errors, this permits about 11 kc error per supply or less than 2 parts per million. However, if a common carrier supply is used for both the receiver and the transmitter of a channel, only the error in the shift frequency need be considered in that station. This is true whether the transmitter and receiver beat oscillators are derived from different harmonics of the same oscillator or from the combination of a microwave oscillator and a shift oscillator. This reduces the error sources in a 4000-mile route to two 6-kmc carriers in the end stations in tandem with 132 shift oscillators operating at 252 mc. Again assuming random addition and that the stability of the shift oscillators is the same as that of the carrier supplies at the ends of the route, the permissible error becomes 20 parts per million. The actual oscillators used in TH have approximately an order of magnitude better frequency stability than required above.

The frequency stability discussed above can be attained either with a common carrier supply of the type used in TH or with carrier supplies individual to the channels as is done in TD-2. In either case, the stability requirement calls for use of a crystal oscillator as the basic frequency-determining circuit, with frequency multipliers to generate the microwave frequency. In a fully equipped station, individual channel supplies of the TD-2 type would require about three times as many electron tubes as does the common carrier supply. Since the number of electron tubes can be taken as a rough index of the total number of components required and of the failure rate, the common carrier supply should be considerably less expensive and require considerably less maintenance effort in a fully equipped station. In the minimum size station (two two-way channels) the individual carrier supplies would have fewer components, but since the cross-over point occurs at only three two-way channels, the advantages of the common carrier supply outweigh any initial cost advantage for such minimum routes.

The beat oscillator (BO) frequencies are shown in the center of Fig. 2. The upper five radio channels in each half of the band (including the upper auxiliary channel) use BO frequencies lower than the signal frequencies, while the lower five channels use BO frequencies higher than the channel frequencies. Since the IF has been chosen to make the BO frequencies fall midway between channels, each BO frequency serves two channel assignments, and only five BO frequencies are required in each half of the band, or a total of ten in each station. These ten frequencies are derived from four frequencies generated in the common carrier supply. The center BO frequency in each half of the band (6049 and 6301 mc) may be used directly or may be shifted up or down by one or two channel spacings (29.65 or 59.30 mc). These four frequencies are distributed from the common carrier supply as needed to the transmitters and receivers, where individual carrier shift modulators and microwave filters generate and select the desired frequency.

Tone interference requirements, which are very stringent in the TH system, are discussed later in this paper. They lead to severe requirements on the microwave filters following the shift modulators. However, if the basic frequencies fed to the shift modulators are all harmonics of the same oscillator, the leakage tones will all fall exactly on the BO frequencies or between channels where the requirements are most lenient. Another argument for a coherent common carrier supply (one in which all frequencies are harmonics of a single oscillator) is that of maintenance. If independent oscillators are used, maintenance facilities must be provided for measuring and adjusting all the various oscillator frequencies to close tolerances; whereas in the coherent supply, only one oscillator frequency need be measured and controlled.

A coherent common carrier supply, although desirable, is not necessarily feasible. A number of independent requirements must be met, and the oscillator frequency is the only variable which may be adjusted to satisfy them all. The basic oscillator frequency must be an integral submultiple of the channel spacing. The two microwave frequencies generated in the carrier supply must be obtainable from the basic oscillator by simple multiplication chains and a minimum of shift modulators. Multiplication factors must be no more than two or three to aid in rejection of spurious harmonics. A center guard band must be provided. The BO frequencies must be symmetrical about the center of the assigned band (6175 mc). And finally, the channel spacing must be approximately 30 mc. Fortunately, a reasonable solution was found for TH as shown in Fig. 5. The oscillator frequency is 14.82593 mc, which sets the channel spacing at 29.65 mc and the intermediate frequency at 74.13 mc. This also determines the exact broadband channel frequencies as shown in Figs. 2 and 5.

In comparing the reliability of the common carrier supply with that of individual channel carrier supplies, both single channel failures and complete route failures must be considered. The failure of any one tube in an individual channel carrier supply will cause the failure of one radio channel. As a result, failure of one or two radio channels due to carrier supply failures is not particularly rare. However, failure of an entire route due to carrier supply failure is almost unthinkably improbable. A common carrier supply provided with one complete standby generator with automatic switching reduces the single channel carrier supply failures to negligibility but does introduce the possibility of

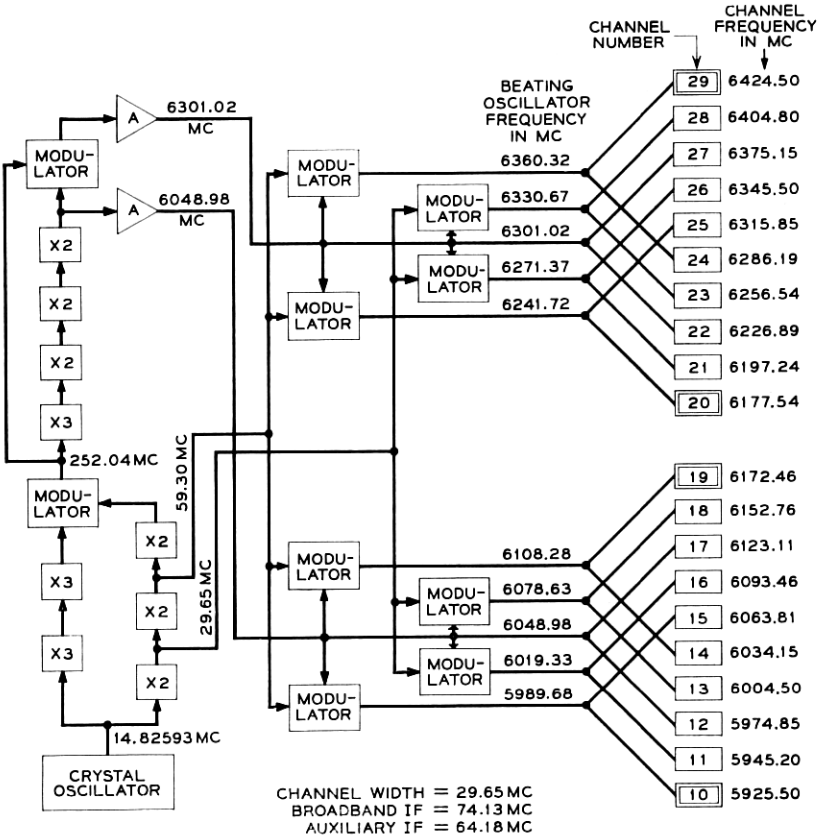

Fig. 5 — Generation of beat-oscillator frequencies from single crystal oscillator.

complete route failure. A study based on anticipated tube and component failure rates gave an expected route failure rate of from 0.007 to 0.015 failure per year per 1000 miles. The addition of a second standby generator would reduce this rate by several orders of magnitude. However, this predicted failure rate with one standby is comparable to failure rates in other currently used broadband systems, and the second standby generator does not appear to be warranted.

3.6 *Power System*

A high reliability radio system, must, of course, have a highly reliable power source. In other radio systems, reliability is attained by operating the electronic equipment from batteries which in turn are kept charged from commercial ac or from emergency engine-alternators. However, the traveling-wave tubes of TH require voltages of up to 3000. Both the size of battery plant required and the personnel hazard involved in distributing such high voltages rule against batteries for this service. The safer and more practical approach is to generate the high voltage dc in each bay containing a traveling-wave tube. While individual high voltage supplies could be built for operation from either ac or dc inputs, an ac input supply is simpler and more reliable. If a reliable, or "firm," ac source is to be developed for the high voltage supplies, a logical extension is to operate all electronic components from local supplies powered from the firm ac.

A bank of from four to seven generators provides 230-volt, 60-cycle ac power for the TH system. These generators are normally driven by ac motors operating from commercial ac. In the event of power failure, dc motors mounted on the same shaft are switched on, and the ac output is uninterrupted. If the power failure persists long enough for the emergency diesel engine-alternator to pick up the ac load of the station, the ac motor is again activated, this time operating from the engine-alternator. After restoral of commercial ac, the ac motor is automatically switched back to normal. While the dc motor is normally intended to operate only the few minutes required for the engine-alternator to be activated, several hours' battery reserve is provided in case the diesel engine fails to start.

A minimum of two generators is operating at all times to provide the firm ac. The regular and standby common carrier supplies, the two auxiliary channels, and other critical loads are divided between these two machines so that failure of either can not cause total failure of the station. As more channels are installed, generators are added to a maximum of five required to carry a fully equipped TH station. Loads are distributed among these generators for maximum reliability. In addition to the normally working generators, a running spare and a nonrunning spare are provided in each station. The running spare is automatically switched in place of any working machine that fails. The nonrunning spare may be manually patched to replace any of the running machines to permit maintenance or repair without loss of reliability.

3.7 *Auxiliary Channels**

Communication facilities between the various stations of the system are necessary for voice communications between maintenance personnel,

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* Material contributed by A. V. Wurmser.

transmission of alarm indications from unattended stations, and operation of automatic protection switching. These services were originally provided for TD-2 routes by wire line networks. However, radio repeater stations are normally located on the tops of hills while cable or wire line routes tend to follow valleys, so that expensive and difficult-to-maintain spur lines are usually required to connect the individual radio stations to the wire networks. Many of the more recently installed TD-2 routes are equipped with light-route radio systems to provide the maintenance circuits. The TH auxiliary channels are provided as an integral part of the system, to carry maintenance circuits.

The auxiliary channels must be inexpensive but reliable: inexpensive so they can compete economically with wire lines or separate light-route radio systems, and reliable so they will be operable when needed to transmit vital control information for the broadband circuits. These needs, together with the requirement that the auxiliary channels operate in a frequency band assigned to common carrier use, resulted in the decision to integrate the auxiliary channel into the TH system and make maximum use of the performance and reliability of the high gain antenna system and the common carrier supply.

The auxiliary channels must be protected against transmission failures due to either equipment failures or fading. To reduce interruptions of this nature to a minimum, twin channel transmission on a frequency diversity basis is used. Statistical data indicate that, for frequency diversity to be as effective as possible, the two channels carrying duplicate signals should be at least 160 mc apart. The location of the auxiliary channels at band edges and band center, as shown in Fig. 2, gives nearly 250 mc frequency diversity.

The type of modulation used on the auxiliary channels is determined primarily by the need to demodulate to baseband at each station. A study indicated that either AM or FM is practical but that the AM system would be considerably more economical because of the complexity of FM terminals, particularly in comparison to double sideband AM terminals.

In addition to the maintenance circuits of TH, the auxiliary channel accommodates the TD-2 maintenance circuits on routes common to both systems. Voice communication and alarm and control channels to intermediate stations can be common to TD-2 and TH. These functions require two two-way telephone channels. Automatic protection switching control signals, however, require different channels for TD-2 and TH because of the frequent differences in the locations of the switching terminals as well as the dissimilarity between the switching signals.

The TD-2 switching signals are modulated tones and require one two-way telephone channel. The TH switching signals consist of 16 single-frequency tones in each direction and occupy a bandwidth of 16 kc. One additional voice channel is provided for use where needed for direct communication between terminals or other purposes. Thus the minimum capacity provided by the auxiliary channel is equivalent to four telephone channels plus a 16-kc band for TH automatic switching tones.

The design also allows expanding the auxiliary channel to provide a small number of short-haul telephone channels in conjunction with the basic four channels. The ON carrier system, in which the basic group consists of four telephone channels, lends itself to this use. The 16 TH switching tones are spaced 1 kc apart between 20.5 kc and 35.5 kc. The ON operating frequency range begins at 40 kc, just above the tones, and terminates at 264 kc. With this future possibility in mind, the top baseband frequency was set at 300 kc, resulting in a required radio frequency bandwidth of 0.6 mc, for a double sideband AM system.

The transmitting power for the basic auxiliary channels can be obtained directly from the common carrier supply, but if any short-haul telephone channels are added, a traveling-wave tube (TWT) amplifier is required in the transmitter output. This conclusion is based on noise and crosstalk requirements for a 10-repeater system, this length being considered typical of short-haul telephone service. Since the TWT amplifier would add considerable cost to systems that do not need this service, the development of that portion of the circuit has been deferred. The basic radio channel circuits are designed to handle a 300-kc baseband signal, and space is provided in the radio terminal bays for future installation of the TWT equipment if the need develops.

Studies of performance of the basic system showed that objectionable interchannel cross-modulation can occur between the TH switching tones and the four voice channels. To avoid this problem, the basic four voice channels are assigned to the ON group operating in the 80- to 96-kc baseband range.

The auxiliary channels are operated on the same antenna system with the broadband channels. In the fully equipped system, maximum equipment diversity is obtained by connecting one auxiliary channel receiver and one auxiliary channel transmitter to each antenna as shown by the solid lines of Fig. 4. If, during the early growth stages of a route, only two antennas are provided per station, the auxiliary channel B transmitter and receiver must be connected to the first antenna. This temporary connection is shown dotted in Fig. 4. During this period, the separation between channels 19 and 20 is insufficient, so channel 20 is temporarily shifted to the channel 23 frequency allocation. When the route grows to the point that the second set of antennas is installed, auxiliary channel B is restored to its normal frequency and antenna connection.

The auxiliary channel separation networks are connected on the antenna side of the broadband separation networks to facilitate the addition of broadband channels after the initial installation without interrupting the working auxiliary channels. The auxiliary channel transmitters are connected with the broadband receivers to relieve some interchannel interferences. These are discussed in Section V of this paper.

IV. NOISE AND EQUALIZATION

In the early stages of system design, the noise objective for the system is customarily divided among various sources as experience and judgment indicate, and efforts are then made to meet the allocations. As the design progresses to final hardware and as natural limitations appear, the original allocations become more or less historical in nature. Accordingly, the noise performance of TH is discussed herein from the viewpoint of expected performance rather than early allocations. The over-all objective for 4000 miles of TH is an rms telephone circuit noise during busy periods from all sources no greater than 39 dba at the 0-db transmission level (TL) in the worst telephone channel.

The sources of noise may be divided loosely into three groups: fluctuation, modulation and interference.

4.1 *Fluctuation Noise*

There are three contributors to fluctuation noise: the amplifiers in the signal path of the radio repeaters, the microwave carrier supplies, and the FM terminals. The radio repeater amplifier noise is generally controlling above 2 mc, the FM terminal noise controls below 0.1 mc, and all three sources contribute in the region between 0.1 and 2 mc. Fig. 6 shows the anticipated values of these sources for 4000 miles of TH radio referred to a 0 dbv point.* The circles are values extrapolated from measurements on the initial installation, without the FM transmitter.

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* A 0 dbv point in the TH system is defined as one where a 1 volt peak-to-peak baseband signal corresponds to 8 mc (±4 mc) swing of the FM carrier. The TH baseband circuit impedance is 124 ohms balanced, and a sine wave of 0 dbm is also 0 dbv. The input to the FM transmitter is a 0 dbv point, and the output of the FM receiver is a +8 dbv point.

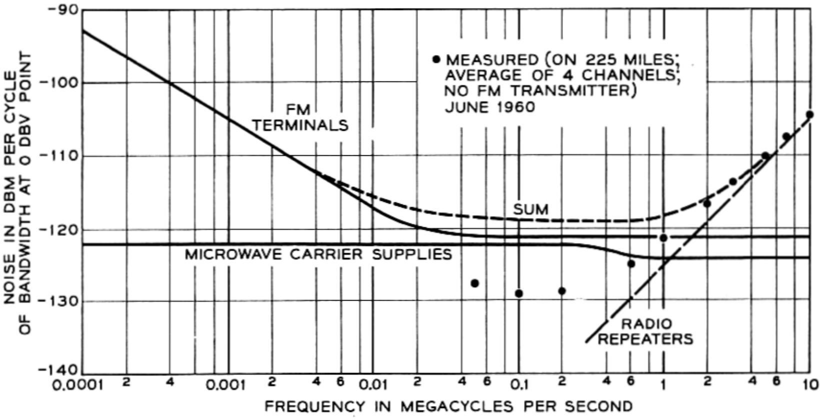

Fig. 6 — Anticipated values of fluctuation noise for 4000 miles of TH radio.

The radio repeater noise in Fig. 6 is based on the normal transmitter power of +37 dbm, received carrier power of −27 dbm (section loss of 64 db) and 10-db repeater noise figure. The 10-db repeater noise figure includes the contribution of the TWT amplifier. The section loss figure is based on study of the 477-mile initial TH installation between Prospect Valley, Colorado, and Salt Lake City Junction, Utah.

The section loss includes channel separation networks, systems combining networks, waveguides and antennas as well as the path loss itself. The section loss for each broadband channel in each of the 15 repeater sections of the initial installation was calculated from the plot plans and building layouts. These losses ranged from 51 db to 66 db, with an rms value of 62.7 db. The channels farthest from the antennas have about 1.3 db more loss than those nearest to it, and will thus have 1.3 db more radio repeater noise. The rms of the actual measured section losses for the channels of the initial installation is 62.4 db.

This particular route was designed with great care to keep waveguide runs as short as possible. Most of the towers are very short and the buildings are very close to the towers. The average future installation will probably include longer waveguide runs. The addition of only 50 feet of rectangular waveguide in each transmitter and receiver connection would increase the section loss by 1.3 db. Thus 64 db is taken as a more representative value for section loss. As an example of how section loss accumulates, Table I gives a detailed breakdown of the extreme channels in a typical repeater section. The importance of short waveguide runs is clearly shown by this tabulation.

TABLE I — SECTION LOSS ANALYSIS, GREEN RIVER TO CHURCH BUTTES

Channel number	26	23
Green River:		
Trans Monitor directional coupler	0.03	0.03
Channel Separation Network	(Ch. 26) 0.40	(Ch. 23) 0.40
Channel Separation Network	(Ch. 22) 0.08	
Channel Separation Network	(Ch. 28) 0.14	
Channel Separation Network	(Ch. 24) 0.14	
Interchannel waveguide	0.55	
Aux Chan Sep Net	0.06	0.06
Indoor Rect waveguide	0.49	0.56
Outdoor Rect waveguide	0.62	0.61
System Combining Network	0.56	0.33
Circular waveguide	0.04	0.04
Sum	3.11	2.03
Path Loss	142.60	142.47
Antenna Gains (2)	−86.16	−86.45
Sum	56.44	56.02
Church Buttes:		
Circular Waveguide	0.24	0.24
System Combining Network	0.56	0.33
Outdoor Rect Waveguide	1.35	1.41
Indoor Rect Waveguide	0.64	0.71
Aux Chan Sep Net	0.06	0.06
Interchannel Waveguide	0.03	
Channel Separation Network	(Ch. 24) 0.14	
Channel Separation Network	(Ch. 28) 0.14	
Channel Separation Network	(Ch. 22) 0.08	
Channel Separation Network	(Ch. 26) 0.40	(Ch. 23) 0.40
Sum	3.64	3.15
Total	63.19	61.20

Green River tower 37.5 feet high, 13 feet from waveguide entrance to building.

Church Buttes Tower 112.5 feet high, 30 feet from waveguide entrance to building.

Path length 31.5 miles.

At the radio receiver input, thermal noise is −174 dbm per cycle of bandwidth (denoted dbm/cbw). With the repeater noise figure of 10 db and the receiver input carrier power of −27 dbm, the repeater noise is $(-174 + 10 + 27)$ or −137 db relative to unmodulated carrier per cbw. The FM deviation constant is such that 0 dbm (single frequency) at a 0 dbv point corresponds to a 4-mc peak deviation. Then by ordinary FM theory, noise at 4 mc at 0 dbv is −137 dbm/cbw, per noise sideband, or −134 dbm/cbw for two noncoherent noise sidebands. The 133 tandem repeaters add 21 db for a total 4000-mile repeater noise at 0 dbv point of −113 dbm/cbw at 4 mc. The noise follows the 20 db/decade FM law, and is shown as the "Radio Repeater" curve on Fig. 6.

4.2 *Noise From FM Terminals*

FM terminal noise comes primarily from frequency modulated noise present in the output of the klystrons in the FM transmitter. At frequencies above 25 kc the noise is essentially flat with frequency at a level of four db below 1 cps rms deviation per cycle of bandwidth. This is equivalent to −133 dbm/cbw at a 0 dbv point. Below 25 kc, klystron noise rises at about 10 db/decade with an estimated value of −117 dbm/cbw at 1 kc. A 4000-mile TH route is customarily assumed to include 16 pairs of terminals. Thus the "FM Terminals" curve of Fig. 6 is drawn 12 db above the values given above for a single pair of terminals.

4.3 *Noise From Microwave Carrier Supplies*

Microwave carrier supply (MCS) noise appears in the broadband channels in two ways. In one, the noise components at signal frequency (which is 74 mc from carrier supply frequency) add directly to the signal. This source is controlled by carrier supply filtering and by balance (about 20 db) in the channel modulators. The second, more serious, form of noise injection from the MCS is at the carrier supply frequency itself. This noise is equivalent to random amplitude and phase modulation of the carrier supply frequency. The modulators, as frequency shifters, are completely transparent to this noise, and the phase modulation appears as noise at the output.

Some of this noise, generated in the low frequency multiplier chain, is reduced by a narrow-band filter in the 252-mc input to the high frequency multiplier chain. In a repeater station, the low frequency noise within the pass band of the 252-mc filter is further reduced by cancellation between the receiver and transmitter modulators. An additional contribution is from the TWT amplifier used to amplify the carrier supply for the transmitter modulator.

From laboratory measurement, the MCS noise in a repeater station is approximately uniform with frequency, at −145 dbm/cbw at a 0 dbv point. It is assumed that there are 116 such repeaters in 4000 miles. For terminals, and other special locations where cancellation does not occur, the noise rises below 1 mc to a value of −138 dbm/cbw at 200 kc and flattens off there. It is assumed that there are 16 such stations in 4000 miles. Combining the two types yields −124 dbm/cbw above 1 mc and -122 dbm/cbw below 0.2 mc as the MCS contribution in 4000 miles, as shown in Fig. 6.

Noise contributions from the FM receiver and ion oscillations in the TWT amplifier have been neglected in Fig. 6. The contribution of 16 FM receivers is believed to be about -136 dbm/cbw, flat across baseband. Ion oscillations, which can occur in the region of 3 mc, may be extremely bad, but normally occur only immediately after a new TWT is installed and vanish rapidly as the TWT ages.

4.4 *Pre-emphasis*

It is clear from Fig. 6 that if all message channels are transmitted at the same transmission level (TL) at a 0 dbv point, the noise in the channels at the top edge of MG 3 (8.3 mc) is 12 db greater than that in channels at the bottom of MG 1 (0.3 mc). The object of pre-emphasis is to equalize this difference. Usually the contribution from second-order modulation products is taken into account also.

The TH system uses step-type pre-emphasis in which the various master groups of the telephone multiplex signal are transmitted at different levels. This avoids the need for careful match of pre-emphasis and de-emphasis networks, since the pre-emphasis is obtained by a hybrid tree in the multiplex terminal and a match can be attained by adjustment of flat gain controls. A limit on the amount of pre-emphasis is set by the nonlinearity of the baseband amplifiers, whereby second-order difference products between the higher level components fall back on the lower level part of the band.

If the pre-emphasis steps are chosen to make fluctuation noise about the same in the top channels of each master group, these steps would be 4.5 and 7.5 db. As a result of minor practical considerations, the steps used are actually 4.7 and 7.2 db.

The "load capacity" of an amplifier handling multichannel carrier telephone signals has been defined by Holbrook and Dixon[9] as the power in dbm at 0-db transmission level (TL) of the single frequency sine wave whose peaks are exceeded by the complex modulating signal only a very small percentage of the time. The same load capacity is customarily used to relate the nominal peak deviation of an FM signal to the actual complex modulating signal. Fig. 7 of Ref. 9 gives the required load capacity for various numbers of telephone channels. When extrapolated to 1860 telephone channels and modified by adding approximately a db of extra safety margin, this gives 28.8 dbm as the load capacity used in TH calculations.

Without pre-emphasis the TL at the 0 dbv point for 1860 channels would be simply −28.8 db, since a sine wave of 0 dbm at that point causes rated peak frequency deviation. But with step pre-emphasis, the TL's of the three mastergroups are different. For the same total power at the 0 dbv point, the pre-emphasized TL's are: −33.6 db TL for MG 1, −28.9 db TL for MG 2 and −26.4 db TL for MG 3.

The noise at the top of MG 1 (3084 kc) is shown in Fig. 6 as −114 dbm/cbw or −79.2 dbm in a 3-kc band. Since −82 dbm of fluctuation noise in a 3-kc band is 0 dba, MG 1 noise is +2.8 dba at −33.6 db TL or +36.4 dba at 0-db TL. This assumes implicitly that a voice channel travels the full 4000 miles on the same baseband frequency assignment. Since this is unrealistic, a more appropriate noise value is given by the rms noise across the whole baseband. This corresponds to the result that would be obtained by extensive frogging of voice channels. The rms noise is about 1.6 db less than the maximum value, or +34.8 dba at 0-db TL. Some noise margin is thus available for other sources between this value and the over-all objective of +39 dba at 0-db TL.

4.5 *Modulation Noise*

Modulation noise in the TH system is expected to be chiefly second order, arising from residual unequalized linear envelope delay distortion (EDD). The modulation produced in an FM system by linear EDD of 1 mμs/mc is:

$$M_d = \frac{10^{-15}}{2\pi} MM'$$

in which M is the baseband modulation function and M' is the time derivative of M. It is easily shown that M_d contains second harmonic terms and sum and difference frequency terms of all the modulating frequencies.

In the conventional simulation of a telephone system by noise loading, M is considered to be a large number of incommensurate frequencies of random phase, one for each unit of baseband width. The total modulation power M_d, at any given frequency is obtained by summing the powers of the individual modulation products arising from all possible combinations of fundamentals which give that frequency.

At present, in addition to a basic equalizer for each repeater section, blocks of delay slope equalization of +1 mμs/mc or −1 mμs/mc are provided for distribution along each switching section, as determined by over-all EDD measurements. Mop-up equalization will be added at the end of each switching section to permit over-all delay slope equalization to $\pm\frac{1}{8}$ mμs/mc. It is expected that, with final equalization, variations with time will be such that on the average the linear EDD of a switching section will be no greater than $\frac{1}{4}$ mμs/mc. Assuming 25 switching sections in 4000 miles, the computed 4000-mile modulation noise is shown on Fig. 7 together with the sum of the fluctuation noises from Fig. 6. This, however, neglects other factors such as intermodulation from other sources: for example, waveguide echoes and second-order sideband clipping because of restricted bandwidth (this latter is essentially a third-order modulation effect). The circles and triangles on Fig. 7 show an extrapolation of measurements (in 1960) on the initial installation. Noise loading simulating 1860 channels, pre-emphasized, was used. Fig. 8 shows the over-all EDD of 60 hops in tandem (1900 miles) obtained by looping two two-way channels. The residual EDD slope of this characteristic is the accumulation from the eight switching sections, which are individually equalized to $\pm\frac{1}{2}$ mμs/mc only. The coarse structure is the systematic deviation of the basic equalizer from the radio repeater and is about $\pm\frac{1}{2}$ mμs/repeater. The

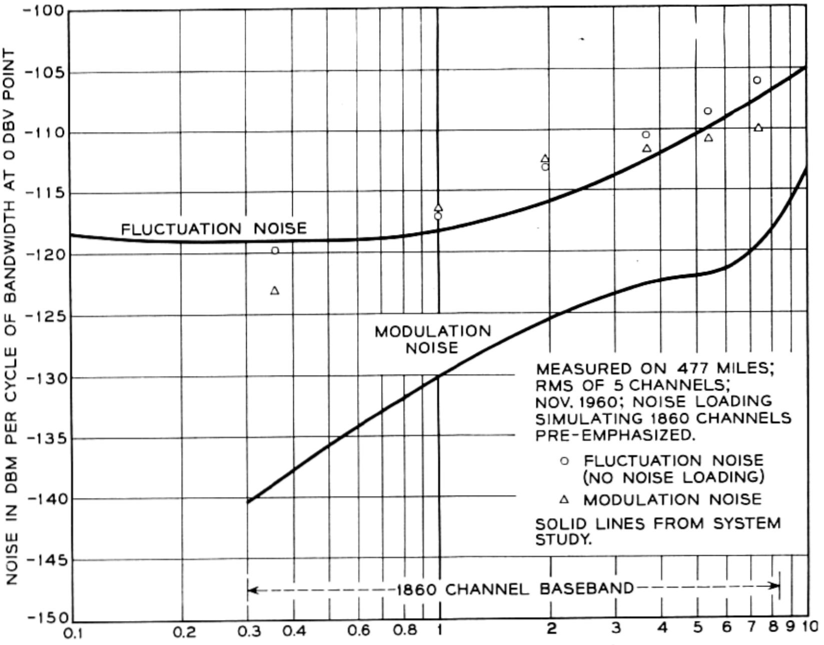

Fig. 7 — Modulation and fluctuation noise for 4000 miles of TH radio, as calculated in system study and as extrapolated from field measurements.

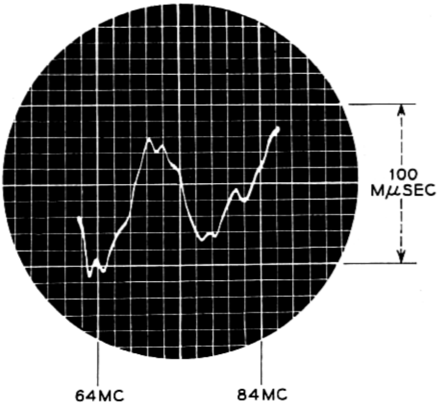

FIG. 8 — Typical over-all envelope delay distortion of 1900 miles (60 repeater sections in tandem) of TH radio.

fine structure (small ripples) is probably due to echoes in waveguide or IF cabling. The continuing work on equalization is expected eventually to reduce the EDD and the modulation noise substantially.

4.6 *Limiters and Mop-up Equalization*

Limiters are used in each radio transmitter to reduce conversion of amplitude modulation to phase modulation. AM/PM conversion is defined as 20 log (x/a), where x is the index of PM at the output and a is the index of AM at the input. Without a limiter, the conversion in a TH transmitter is around −10 db; the limiter improves this to around −30 db. In itself, AM/PM conversion is basically just another source of transmission distortion and is indistinguishable from other sources. However, when produced by active devices, such as limiters and TWT amplifiers, it is variable with time. The success of any nondynamic equalization plan requires that deviations stay put. Although dynamic equalization (regulation) has been considered, it has not yet been the object of development effort for microwave radio systems. Hence the use of the limiter in TH, to reduce the magnitude of this variable.

The ideal in any system is to equalize each individual repeater over the needed transmission band. Thus, each repeater in the TH system includes a basic gain and delay distortion equalizer. Since this equalization can not be perfect, a variable IF equalizer is provided in each switching section to mop-up the remaining distortions. Previous experience with TD-2 showed that many factors reduce the effectiveness of mop-up equalization, a principal one being the inherent instability of the system. Considerable effort has been taken in all parts of the TH system to improve transmission stability.

The use of a limiter in each station tends to "freeze-in" the distortion occurring in that repeater section. Since it is easy to postulate exaggerated examples which demonstrate that mop-up equalization through tandem limiters is impossible, extensive calculations were made to determine feasibility. These calculations, using digital computer techniques, showed that substantial benefits are potentially realizable from mop-up equalization when nominal distortions are considered.

Envelope delay distortion can be measured through limiters by the two-frequency sweep method.[10] Thus mop-up equalization to minimize the over-all EDD would apply the exact inverse of the EDD of the system. With individual repeater characteristics representable by a simple cubic power series, use of the inverse EDD correction at the end of ten sections gave a computed improvement of the order of 15 db in cross-modulation noise. The EDD correction increases the video gain roll-off, an effect typical of systems with limiters. This may be corrected with a symmetrical (with respect to the carrier) gain equalizer. The computations showed it to be essential to have a limiter between the delay mop-up and the gain mop-up equalization.

The calculations further indicated that mop-up equalization is ineffective for ripples in the transmission characteristic, i.e., for echoes. Accordingly, no provision is made for mop-up ripple equalization. Instead, one of the design objectives of TH is to keep all echoes less than -60 db, and hence not require equalization. This 60-db echo requirement is obtained from the Bennett, Curtis, Rice paper.[11] Using the TH constants of 0.7-mc mean rms deviation, 10-mc top baseband frequency, 3-db improvement from pre-emphasis and 4000 random echoes, the effect of 60-db echoes can be determined from Fig. 5.7 of Ref. 11 as 28 dba at 0-db TL, i.e., about 9 db below fluctuation noise. All return losses in the TH system have design limits of 30 db to maintain the 60-db echo limit.

It is not yet known how much of the potential benefit of mop-up equalization shown by the calculations can be realized in practice. Tests of mop-up equalization made in 1960 on the initial installation were inconclusive, possibly because of the presence of a large delay distortion, as shown on Fig. 8, which was not equalizable by a cubic power series.

V. INTERFERENCE BETWEEN RADIO CHANNELS

The design approach for TH has been to make this general source of noise small compared to fluctuation and modulation noise. With twenty radio channels packed tightly in the allocated frequency band, there are numerous possibilities for interchannel interferences. Some of these are well known from experience with the earlier TD-2 microwave system.[12] Others are peculiar to TH.

5.1 *Classifications*

In the study of interchannel interferences, it is useful to distinguish between interference produced by the ordinary crossmodulation effect in transmitter, receiver and shift modulators, and interference inherent in limiter action. True, this is in reality a form of intermodulation due to the nonlinear characteristic of a limiter, but it is distinct from the first in that the performance of a limiter is predictable (ideal limiters are assumed) but that of modulators has to be determined by measurements.

The expression for limiter interference* has been derived repeatedly.[13] The interference at baseband due to the adjacent channel is a tone of the frequency of the channel spacing (29.65 mc), frequency modulated with the baseband signals of both channels. The tone itself falls outside baseband, but the spectrum of the interference covers a wide range and part of it falls within baseband, causing interference which is treated as noise. A consequence of limiter action is that if the input to the limiter consists of the carrier and a relatively weak interference tone, say x dbC (db relative to the carrier), on one side of the carrier, then in the output spectrum there are frequencies on both sides of the carrier, at $(x - 6)$ dbC.

According to the character of the interference as observed at baseband, interferences fall into three classes: tone, noise, and intelligible crosstalk. Tone interference rises from combinations of the various fixed frequencies in the system. The noise-like interferences arise from combinations of various signal sideband components with each other and with the carriers. The combinations are usually quite involved, and there is considerable uncertainty regarding the soundness of the computation techniques for long systems. Most measurements of this class of interference are unsatisfactory and the experimental difficulties are large. The third class (intelligible or clear crosstalk) is given the special name of "direct adjacent channel interference," and has recently been given much attention.[14]

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* The phase distortion in the wanted channel is

$$u_d = r \sin(\omega_D t - u_t + v_t)$$

where r = carrier ratio ($r \ll 1$),
ω_D = difference between carrier frequencies,
u_t = phase modulation of wanted carrier, and
v_t = phase modulation of unwanted carrier.

5.2 *Objectives*

Objectives for interferences depend on their class: tone, noise, or clear crosstalk. The allocations made in the earliest engineering studies were, for 4000 miles,

Co-channel	24 dba at 0 db TL
Adjacent Channel	21 dba at 0 db TL

No specific allocations for other types of interchannel interference were made. The general policy has been adopted of applying a 21-dba objective to new noise sources as they are found.

The objective for tone interference used in systems analysis and design is shown on Fig. 9. In the derivation, which is too lengthy to give here, −70 dbm at 0-db TL has been used as the basic requirement on single frequency interference into a voice channel. With minor exceptions, no pure tones have been observed in the 0- to 10-mc baseband due to interference from other channels or to spurious frequencies on the microwave carrier supply. This is because of the inherent instability (jitter) of an FM carrier produced by beating two 6-kmc klystrons. A steady FM carrier with a steady interference tone results in a steady baseband tone. When the FM carrier has jitter, the energy at baseband, instead of being concentrated at a single frequency, is smeared over a frequency band. Rather than the tone requirement, then, a 10-db more lenient noise requirement may be used. The noise, as heard on telephones when demodulated to voice, has an unpleasantly harsh

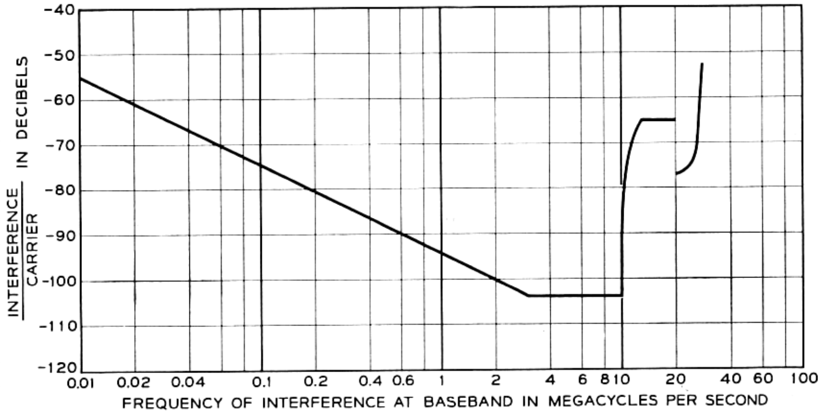

Fig. 9 — Objective for single-tone interference at IF at limiter input.

and burbling quality, completely different from the steady hiss of thermal noise.

For clear, intelligible crosstalk, as produced by direct adjacent channel interference, the objective is quite severe. Its derivation, due to H. E. Curtis, is given in the Appendix. In terms of the coupling loss per repeater, as measured at baseband, the objective is 94-db average during free space transmission, and 40-db for the minimum during a 27-db fade. Laboratory data on the TH system and field data on the TD-2 system indicate that the coupling increases (loss goes down) two db for one db of fading. Therefore, the second objective also corresponds to 94-db minimum loss under free space conditions.

5.3 *Laboratory and Field Observations*

The results given here are a combination of calculations, laboratory measurements of single exposures, and data obtained on the initial installation of TH between Prospect Valley, Colorado, and Salt Lake Junction, Utah, in 1960. The classification below is based primarily on the source of interference and is arranged roughly according to the separation between the wanted and unwanted channels.

5.3.1 *Co-channel Interference*

This refers to interference from other repeater sections using the same carrier frequency. Basically the only protection against this is antenna directivity and physical separation. The former has its limitations. In particular the inherent directivity of an antenna can be, and is, spoiled by reflections of the transmitted microwave energy by objects (e.g., large buildings, mountain ridges) along the transmission path, usually in the general neighborhood of the antenna. The front-to-back ratio of horn-reflector antennas at 6 kmc will therefore show a statistical distribution which is not presently available. However, calculations show that if the rms of this is 65 db, the co-channel interference objective will be met with 2-db margin. Measurements on the initial installation of twenty F/B ratios gave two values of 61 db, all others 66 db to 85 db.

5.3.2 *Direct Adjacent Channel Interference*

This is interference in which a signal on the unwanted channel appears unchanged on the observer's channel. Extensive laboratory tests of direct adjacent channel interference (DACI), made on a single radio repeater, result in the following views on DACI production:

i. The adjacent channel carrier and its sidebands produce in the limiter sidebands around 74 mc which are roughly half AM and half PM. The limiter is the chief source of DACI.

ii. The limiter has a "DACI constant," analogous to a modulation coefficient, which permits the calculation of the PM component of the interference sidebands near the carrier and at the limiter output from the known adjacent channel interference spectrum at the limiter input. However, the physical mechanism of the sideband production is not yet understood.

iii. Any amplifier in compression acts like a poor limiter and can contribute to DACI production.

iv. DACI increases 2 db (very closely) for 1-db increase in carrier ratio. Carrier ratio is defined as the level in db of the unmodulated carrier of the unwanted channel with respect to that of the wanted channel at the input to the latter's receiving channel separation network. An increase in carrier ratio corresponds to an increase in unwanted signal.

v. The interference is affected by the selectivity of the radio receiver, determined in part by microwave filters and in part by the IF amplifiers. Thus DACI is worst at high baseband frequencies.

vi. The laboratory measurement gives 40 db as the equal-level coupling-ratio per radio receiver at 8 mc for 0-db carrier ratio. With 25-db cross-polarization discrimination, the per exposure coupling is 90 db, or quite close to the objective derived in the Appendix.

Measurements made on the initial installation at −3-db carrier ratio on five repeater sections showed considerable variation in equal-level coupling ratios, ranging from 40 db to 58 db. On the whole it appeared that the laboratory value of 40 db at 0-db carrier ratio at 8 mc is representative. It was quite definitely established that voltage addition in tandem sections [see Appendix, 1e] does not hold, in which case the controlling requirement is probably the 40-db value during a 27-db fade [Appendix, 2d]. With 40 db at 0-db carrier ratio, 27 db of cross-polarization discrimination is needed, a value generally obtained on this installation. Fig. 10 shows the distribution of cross-polarization discrimination.

A few measurements were made with normal couplings over the whole route (15 hops). Here it was necessary to use a very strong drive to find the interference in the noise. Depending on the selection of unwanted and wanted channels, the over-all 8-mc coupling varied between 73 db and 95 db. Even the 73-db value meets the free-space transmission requirement of the Appendix.

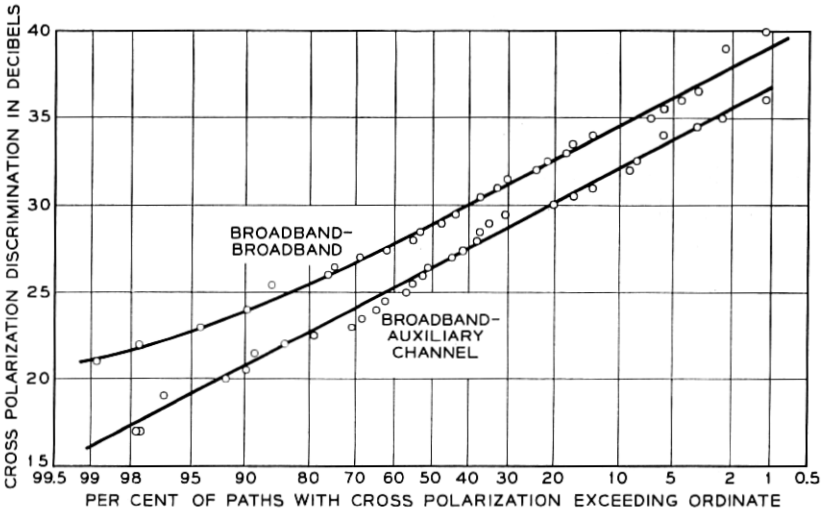

FIG. 10 — Distribution of cross-polarization discrimination, as measured on the initial installation.

5.3.3 *Adjacent Channel Interference*

This type includes the effects of (1) cross-modulation in the receiver modulator and (2) the inherent cross-modulation produced by ideal limiting. In the first case the chief possibility for interference arises from intermodulation between the carrier spikes, which produces "tones" at low baseband frequencies (typically 100 kc or less) or around 15 mc. Cross-modulation of the sideband energy is negligible. On the basis of the single-tone requirement and using the measured modulation performance of a very early model of the TH receiver modulator, requirements were calculated on unwanted tones at the modulators, and these were used to establish requirements on filters in the microwave carrier supply and in the signal path.

With regard to limiter action, elaborate computations on this indicated that the interference would meet the allocation of 21 dba with 20 db of cross polarization discrimination, provided the top baseband frequency was less than $\frac{1}{3}$ channel spacing, or 9.88 mc. This condition is satisfied in TH. The chief components of interference are, in order, due to (a) each adjacent carrier with first-order sidebands of the other adjacent channel, (b) second-order sidebands of adjacent channels with first-order sidebands of the center channel and (c) direct interference from third-order sidebands of adjacent channels. The "tone" due to interaction of the two adjacent carriers was dismissed as being below the lowest telephone channel. The chief uncertainty about the calculations is with respect to the addition of interferences in tandem sections; the calculations assume power addition.

Both laboratory and field measurements of this type were unsatisfactory because of measurement difficulties. Such data as were taken indicate that it is extremely unlikely to be an appreciable source of interference.

5.3.4 *Lost Carrier*

If the unwanted channel loses its carrier, the TWT amplifier saturates at full power with noise spread over a wide band (normally about 98 per cent of the total radiated power is concentrated in the carrier). In the adjacent channel, 30 mc away, this noise power is very much greater than the sideband energy usually present, and if no action were taken would make the channel uncommercial. Protection against this is given by providing an automatic carrier resupply circuit in each radio transmitter.

5.3.5 *Tertiary Interference (Limiter transfer)*

The basic mechanism of this is shown in Fig. 11. The limiter in channel 27 transmitter transfers the interference due to channel 18 to the other side of the channel 27 carrier, producing interference into channel 26 receiver. By this mechanism, a 5-mc baseband tone on channel 18 becomes a 24.65-mc interference on channel 27, which in turn becomes a 5-mc interference on channel 26. The interference frequency on channel 26 differs from the original frequency on channel 18 by only a small amount, due to variations of the actual carrier frequencies of channels 18, 17, 27 and 26 from their theoretical values.

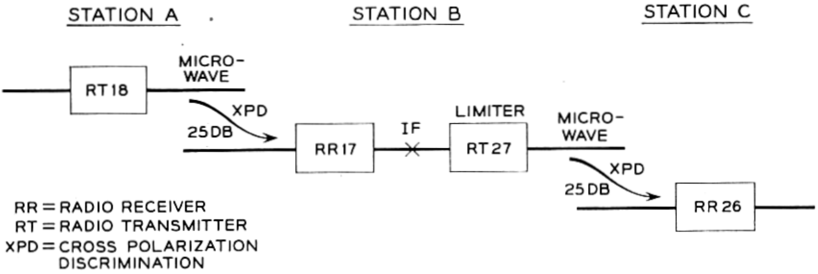

FIG. 11 — Basic mechanism of tertiary interference.

Laboratory tests show that limiter transfer action is perfectly straightforward and in exact accordance with elementary FM theory. The seriousness of limiter transfer action was first noted in dealing with interference from the auxiliary channels into broadband channels. Eventually the antenna connections of the auxiliary channels were changed to minimize the tertiary interference from them; see Section 5.3.8, below.

In a slightly different type of tertiary interference, the auxiliary channel carrier is picked up by the broadband receiver of the adjacent channel, amplified and reradiated by the broadband repeater; here the channel separation is only 20 mc. This reradiated signal is picked up by the auxiliary channel receiver in the next station. Slight differences in the frequencies of the various crystal-controlled oscillators involved cause interference between the carriers to appear as a tone which may fall into the band assigned to TH switching signals. The interference is normally not objectionable, but during a fade of the broadband channel (or worse yet, when the preceding broadband transmitter is shut down for maintenance), the AGC of the broadband receiver brings up the spurious signal to the point where the interference is comparable in level to the switching tones. This situation is treated by the insertion of a narrow-band cavity resonator absorption trap at 94 mc in broadband channels 1 and 8, and by holding the frequency tolerance of the crystal oscillators to values which cause the interference to fall at a frequency below that of the switching tones.

The chief protection against interferences of types 2 to 5 is cross polarization discrimination, and it is thus important to avoid its deterioration. Some discrimination is realized from the selectivity characteristics of the channels.

5.3.6 *Image Interference*

The image suppression given by microwave filter selectivity (channel separation plus channel bandpass) is about 100 db, and in addition 25 db of cross polarization discrimination is effective. This much discrimination makes image interference completely negligible, since it is of the same nature as co-channel interference for which 65-db coupling loss is considered acceptable.

5.3.7 *Carrier Supply Interferences*

Interferences which are basically of the tone type are produced by interactions among the various high level carriers used to drive the various modulators. The most difficult problems here were solved by the adoption of the coherent carrier supply. Due to slight variations of the actual frequencies from their theoretical values, both as generated in FM transmitters and as modified by repeated frequency shifts up and down in successive repeater sections, the interferences from various sources will be spread out over relatively narrow bands, at most a few hundred kc wide, centered on the carrier and on 14.82 mc. When the TH system is operating properly, the interferences near the carrier and the second-order difference products between those at 14.82 mc will all fall below the lowest telephone channel at 300 kc.

Interference arises from carrier leak through the transmitter shift modulators on channels 1 and 3, which results in those channels transmitting also on channel 2; channels 6 and 8 similarly interfere into 7. The channel 2 spectrum is badly distorted by the channel filters, but with high modulating frequencies, one set of sidebands gets through fairly well and modulates with the regular channel 2 carrier to form the interference. Field measurements indicate that this interference will be about 11 dba at 0-db TL, provided 20-db or more carrier balance is maintained in the shift modulators.

In the field excessive interference at 59.3 mc was observed in channel 8; this turned out to be direct radiation at 6 kmc from the standby microwave carrier supply into the channel 8 receiver modulator; these are in adjacent bays, and the radiation path bypasses the carrier supply filter. This is remedied by proper shielding.

Spurious tones at 420 kc and 5.08 mc were observed on all channels at baseband. The source of these was eventually located in occasional units of the 14.8-mc crystal oscillator in the microwave carrier supply. The tones occur as the result of a beat between the third and fifth mechanical overtones of the crystal, which frequency modulates the normal output. Slight modification of the circuit remedied this.

These last two interferences are classic examples of the need for extensive testing on a commercial installation, since neither was anticipated in systems design or found in laboratory testing.

5.3.8 *Auxiliary Channels*

These channels were a troublesome source of interference because their frequency assignments are not harmonics of 14.82 mc. Interference into the broadband channel is considered under control except possibly where bad building reflections reduce antenna side-to-side coupling loss. The controlling interference here is tertiary, from channel 20 transmitter into channel 17 receiver, via channel 18, producing 4.87

mc in channel 17. To meet the interference requirement, 90 db separation is required between channel 20 transmitter and channel 18 receiver. The only way to meet this is to put these channels on separate antennas; furthermore, channel 20 has to be cross-polarized with respect to channel 21; this establishes the channel assignments of Fig. 4. Fig. 12 shows a distribution curve of antenna couplings.

The chief potential source of interference into auxiliary channels from the broadband channel is sideband energy in the adjacent broadband channel. Under normal conditions, the cross polarization discrimination puts this sideband energy at least 10 db below fluctuation noise level.

5.3.9 *Envelope Delay Sweep*

This test signal, used for the measurement of envelope delay distortion at IF, puts large amounts of signal energy at the band edges, and experience on the initial installation shows it to be a potential source of severe interference. For the purposes of collecting data, a sweep of ±14 mc (60 mc to 88 mc) was used, but this creates intolerable conditions on the auxiliary channel. To avoid trouble with an operating system, the sweep has to be limited to ±10 mc.

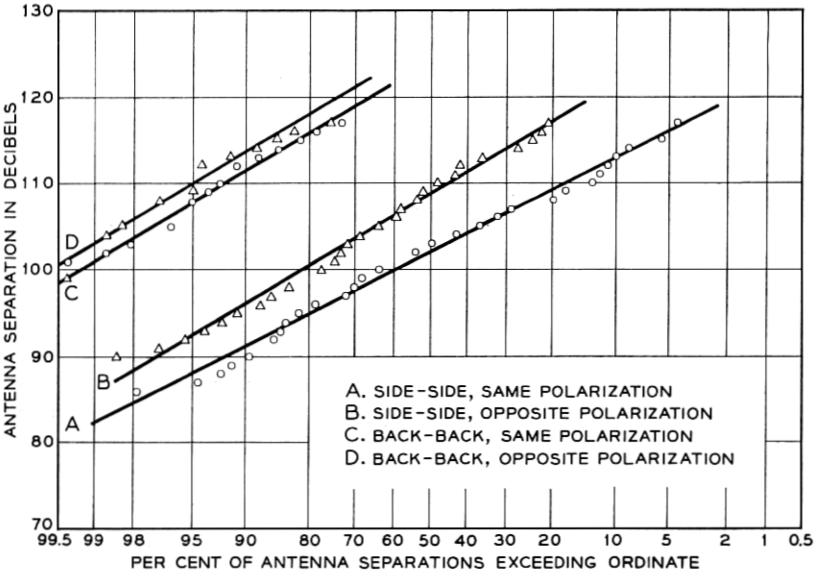

Fig. 12 — Distribution of antenna coupling loss, as measured on initial installation.

5.4 *Conclusion*

The initial installation revealed a few unanticipated sources of interchannel interference. When remedial measures for these have been installed, interchannel interference will not normally be a problem in TH with careful maintenance, and with antenna separations as good as obtained on the initial installation.

VI. ACKNOWLEDGMENTS

The development of a system as massive as TH, with its complex of subsystems, requires the contributions of literally hundreds of individuals, creating, adapting, building and polishing both electrical and mechanical designs. The authors of this paper, and of the other papers in this issue, as reporters of the results, acknowledge these contributions without attempting to list every individual by name.

APPENDIX

*Objective for Direct Adjacent Channel Interference**

During periods of free-space transmission, all repeaters contribute more or less equal amounts of crosstalk to the over-all system. On the contrary, during fading periods it is uncommon for more than one repeater at a time to fade 30 db or more. During such a period, then, nearly all the crosstalk will come from one repeater. Consequently it is reasonable to set up two objectives, viz., one for free space transmission and another for a 27-db fade (the point at which the system switches to the protection channel).

Telephone Crosstalk

1. *With Free-Space Transmission*

a. System noise – 4000 miles, 0 db TL = 39 dba

b. Assume that crosstalk from a "1 per cent talker" must be 10 db below the noise, or = 29 dba

c. A 1 per cent talker reads at 0 db TL = 86 dba

d. Coupling at baseband (4000 miles) = 86 – 29 = 57 db

e. Assume voltage addition for each repeater contribution up to 1000 miles and power addition for each 1000 mile portion; correction to a "per repeater basis" is then = 37 db

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* Original derivation is due to H. E. Curtis.

f. Allowable average coupling per exposure, as measured at baseband = 94 db

2. *During a 27-db Fade.*

Assume that the controlling amount of crosstalk comes from the faded section. It would be extremely rare to have a 1 per cent talker and a 27-db fade simultaneously; therefore it will be assumed that only the "rms" talker must be maintained well below the noise. Proceeding as before,

a. Noise due to one section during a 27-db fade = 44 dba
b. Assuming the "rms" talker must be 8 db below noise, or = 36 dba
c. An "rms" talker reads at 0 db TL = 76 dba
d. Allowable maximum coupling per exposure for a 27-db fade, as measured at baseband = 76 −36 = 40 db

Television Crosstalk

The 4-mc coupling loss at which 50 per cent of the observers in subjective tests rated television crosstalk "just perceptible", was 58 db for flat coupling and 40 db for coupling with 3 db per octave slope. Since the latter corresponds more nearly to the observed coupling, the TV requirement is less severe and is not controlling.

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