Radio Frequency Interference Considerations in the TD-2 Radio Relay System

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Relationships are developed between the ratio of a desired RF carrier to an interfering co-channel RF carrier and the telephone channel interference that results therefrom. Objectives are set down in terms of permissible noise in a telephone channel for each individual RF interference on a hypothetical long system. Finally, systems applications of these interference considerations are discussed.

I. INTRODUCTION

The number of microwave systems that may be used on a particular frequency assignment in a given area is determined by the mutual interference between the systems. The Bell System is particularly conscious of this problem because of its extensive use of broadband microwave systems.

At the end of 1958 the Bell System had in operation approximately 215,000 one-way broadband channel miles of microwave systems in the United States, corresponding to approximately 7,000 transmitters and an equal number of receivers. A large portion of this extensive network makes use of the TD-2 radio relay system[1,2] operating in the 3700- to 4200-mc band. The TH system[3] operating in the 6-kmc range is under active development, and the TJ system operating in the 11-kmc common carrier band (10,700 to 11,700 mc) is now in commercial use. Equipments made by other manufacturers also operate in the 4- and 6-kmc bands.

In spite of the highly directive antennas now in use, a certain fraction of the transmitter power from any station will be radiated in directions other than that for which it is intended, and this becomes a potential source of intrasystem interference to itself and also to other systems operating in the same frequency band.

This paper is directed specifically toward the TD-2 system because of its extensive use and the experience gained with it. However, the philosophy developed herein may be applied directly to the study of interference arising in or from other systems.

It is sufficient for the purposes of this paper to point out that the TD-2 system, in common with many other microwave systems, uses frequency modulation. It can provide six two-way broadband channels, each of which can handle two one-way television channels or 480 or more two-way telephone channels.

The frequency arrangement at a repeater is shown diagrammatically in Fig. 1. The six channels in one direction operate on channel assignments whose midband frequencies are 80 mc apart. The six channels in the other direction are interlaced with the first six, and thus there are

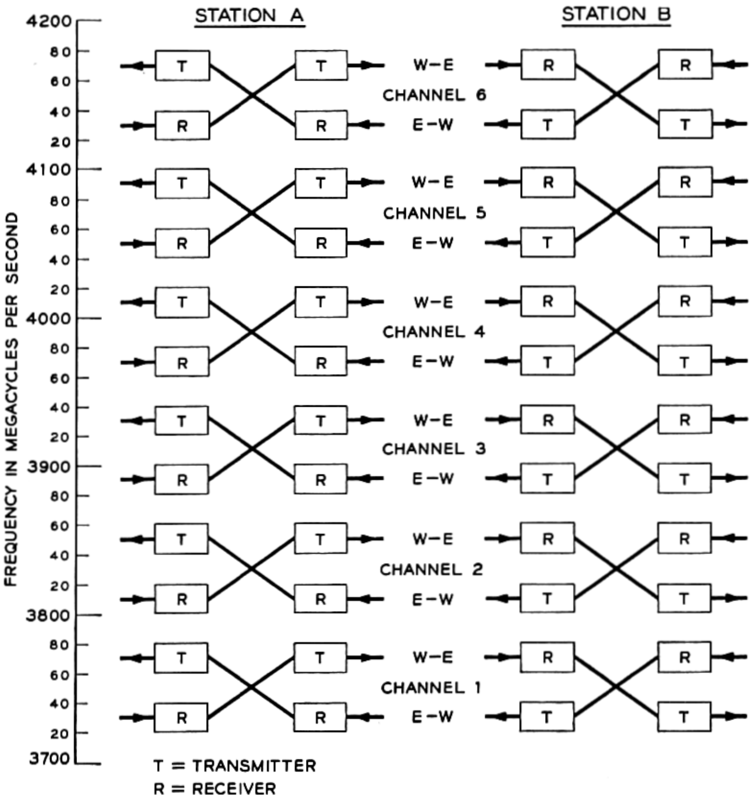

Fig. 1 — Frequency arrangement at a repeater.

40 mc between midband frequencies of adjacent channels in opposite directions. Thus, the potential interference from a transmitter at a tower is always separated by 40 mc or more from the closest receiving carrier frequency used at the same tower, and RF and IF filtering is sufficient to reduce such interference to a negligible magnitude.

When a two-way channel such as that shown in Fig. 1 is extended to include three consecutive repeaters, as in Fig. 2, it will be noted that two additional types of interference are involved. Similar interferences will exist, of course, on the other five channels.

For convenience in discussing these interference paths, let each antenna involved be given a number followed by a pair of letters designating the direction of transmission and whether the antenna is transmitting or receiving. Thus the sequence from west to east is 1E(T) to 2W(R) to 2E(T) to 3W(R), etc. At any particular receiving antenna such as 2W(R) there will be normally two important interferences. One is from 1W(T) into 2W(R), and the second is from 3W(T) into 2W(R). The first, for convenience, is designated "same section," since it transverses the same repeater section as the desired carrier from 1E(T); the second, 3W(T) into 2W(R), may be designated "adjacent section" for obvious reasons. Each antenna is normally subject to these same two interferences.

Of particular significance is the fact that the interference has the same nominal frequency as the carrier with which it interferes, and, hence, it cannot be discriminated against by filters. Therefore, the only protection lies in making the backward response of the antennas adequately low.

The interference situation becomes increasingly complex at a point where a number of converging microwave systems operate on the same or nearly the same frequency. An extreme example of such a point is that which exists at New York, where the Bell System has two centers from which microwave systems radiate, as shown in Fig. 3. Here we have a total of five converging routes with angles ranging from 50° to 110°, with a sixth paralleling route.

II. RELATION BETWEEN RF INTERFERENCE AND BASEBAND INTERFERENCE

The relation between radio interference and baseband interference depends, among other things, on the kind of baseband signal being transmitted. In general, in Bell System use, this is either a video signal or a number of telephone channels arranged in frequency division. The latter case is emphasized herein, since it has been found to lead to a philosophy that provides adequate freedom from interference when either telephone or television signals are transmitted. For analytical and experimental

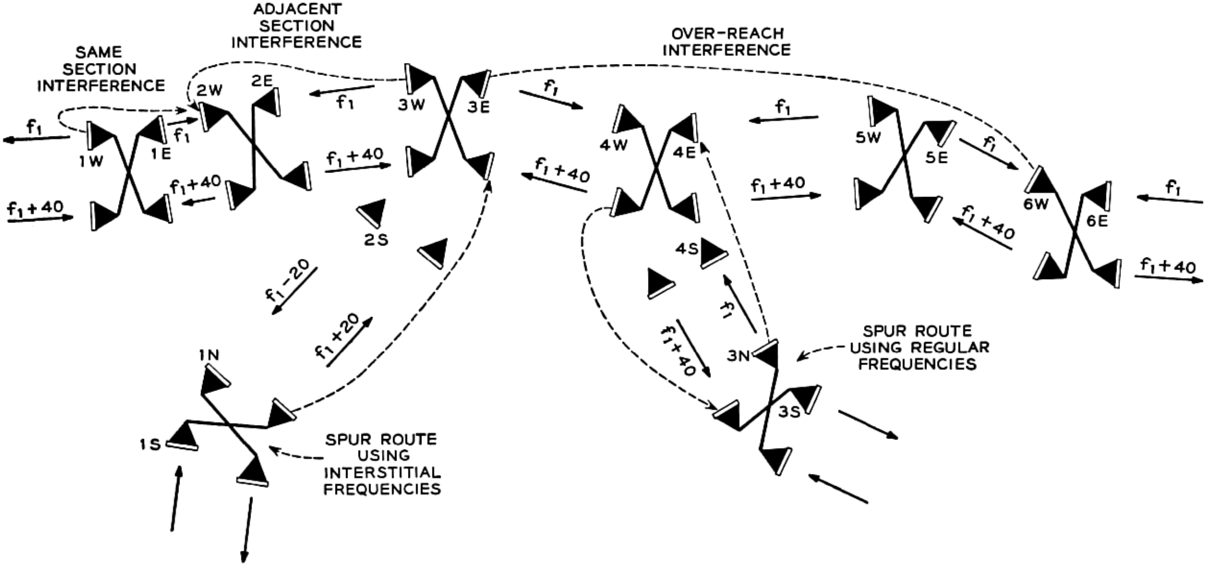

Fig. 2 — Radio frequency interferences on the TD-2 microwave system with typical paths as shown.

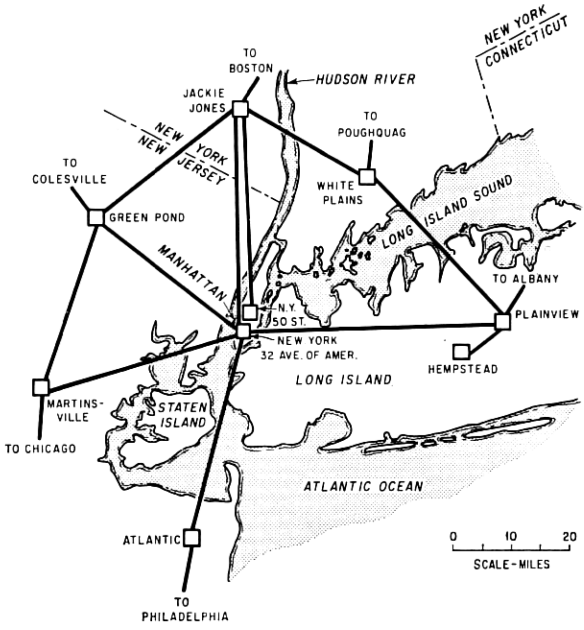

Fig. 3 — Microwave systems in New York area.

purposes a multichannel telephone signal can be adequately simulated by a band of random noise of the same average power and the same bandwidth as the multichannel signal.

The problem of intermodulation due to echoes in FM with noise loading has been treated in a previous paper,[4] which showed that the amount of intermodulation depends, among other factors, upon the echo delay.* It is of significance to the present problem that, as the echo delay becomes infinite, the correlation between the signal modulation on the echo carrier and that on the main carrier becomes zero. Hence, it may be reasoned that, in the limit, the interference problem discussed herein becomes analogous to the echo problem. An important difference is that here the carriers may be separated in frequency, whereas the echo must always have the same carrier frequency as the main wave.

This theoretical work, which is not reproduced here, leads to Fig. 4, which shows the relationship between the baseband signal-to-interference

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* During the preparation of this paper, a theoretical paper[5] on interference between noise-modulated FM carriers appeared, which gives a general expression for the interferences as a function of frequency deviation, top baseband frequency and frequency separation between carriers. The resulting equation is identical with the one from which Fig. 4 was computed.

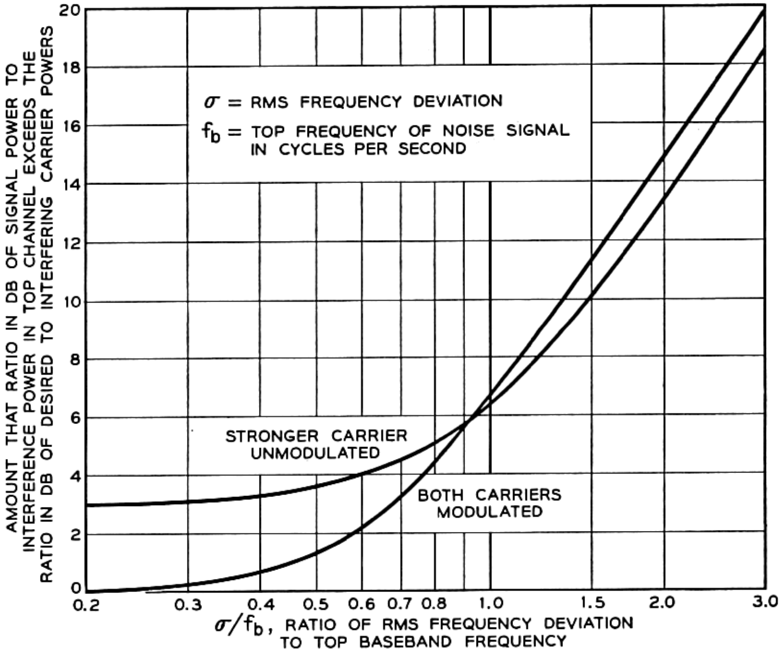

Fig. 4 — Co-channel interference from a multichannel FM system modulated with a flat band of noise.

ratio and the ratio in decibels of the desired-to-interfering carriers when the latter ratio is greater than about 10 db. This depends on the FM deviation ratio, which, in this case, is specified in terms of the ratio of the rms frequency deviation to the top baseband frequency. Furthermore, the relationship depends somewhat on whether both carriers are modulated with noise or only the weaker is so modulated. In the latter case, the baseband signal to which the interference is referred is assumed to be equal in magnitude to that applied to the interfering carrier.

In addition to the interference from the modulation on the carriers evaluated in Fig. 4, there is generated a beat note having a baseband frequency equal to the difference in frequency between the desired and interfering carriers. Since the beating oscillator frequencies in the TD-2 system are crystal-controlled, the carrier differences are held to within a few tens of kilocycles. Hence, the interferences between the carriers themselves fall below the lowest frequency used by the TD-2 system's channelizing equipment. Experience has shown that tone interference into systems carrying television service will be adequately low if the interference requirements imposed by multichannel telephone service are met.

With speech loading, the frequency deviation is generally specified in terms of the peak value, in contrast to noise loading, where it is convenient to refer to it in terms of the rms frequency deviation. Fig. 5 shows the sine wave power, at a point of 0-db transmission level, which has the same peaks as a multichannel telephone system, assuming an activity factor of one-quarter. This is taken from a paper by Holbrook and Dixon.[6] Also shown in Fig. 5 is the power of a multichannel load, based on talkers whose volumes correspond to the mean power of the assumed talker volume distribution curve, an activity factor of one-fourth being included. This curve is derived from constants given in Ref. 6.

The TD-2 system with a 480-channel load normally uses a peak deviation with speech of ±4 mc. Fig. 5 shows that, for this channel load, the ratio of the rms frequency deviation with equivalent full sine wave modulation to the rms deviation with noise loading is 11.5 db. This ratio referred to peak sine wave deviation is 3 db greater, or 14.5 db. Accordingly, the rms deviation with a noise load can be seen to be 0.7 mc. Therefore, since the top baseband frequency is approximately 2 mc in the example, the ratio of rms frequency deviation to top baseband frequency would be approximately 0.35. Hence, Fig. 4 shows that, in this case, the baseband signal-to-interference ratio in a telephone channel at the top

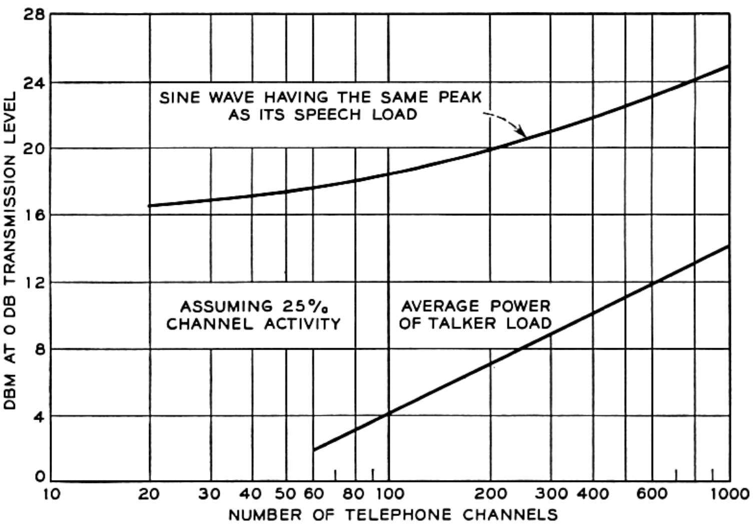

Fig. 5 — Multichannel telephone load, assuming 25 per cent channel activity.

baseband frequency is $\frac{1}{2}$ db greater than the ratio in decibels of the "desired" carrier to an interfering carrier when both carriers are modulated with noise. Thus, by rounding this value to 1 db, we may write, in db:

$$S_{\mathrm{dbm}} - N_{\mathrm{dbm}} = C - I + 1. \tag{1}$$

It has been found useful in the Bell System to express noise power in a telephone circuit in dba.* This implies a specific frequency weighting characteristic, and 1 milliwatt (0 dbm) of flat noise in a 3-kc band reads 82 dba. For a measurement of noise power to have meaning, it must be referred to the signal power at the same point in the circuit, or else the transmission level at which the measurement is made must be specified. Noise in dba is often specified at the 0-db transmission level, the point of reference being the toll transmitting switchboard.

Holbrook and Dixon give the power of an rms talker at a point of 0-db transmission level (0-db T.L.P.) as −9.9 dbm. With a channel activity factor of one-quarter, the equivalent noise load per 4-kc channel is −15.9 dbm. The noise in a 3-kc band is 1.2 db less, or −17.1 dbm. This amount of noise power would measure very nearly, 65 dba. From this it follows that, given a measurement of signal power and of noise power in the same narrow band, the equivalent noise in dba at a point of zero transmission level can be obtained from the following relationship:

$$N_{\mathrm{dba}} = 65 - S_{\mathrm{dbm}} + N_{\mathrm{dbm}} . \tag{2}$$

By combining (1) and (2), the relationship between interference in a telephone circuit and the RF carrier-to-interference ratio can also be obtained.

Thus, for the TD-2 system,

$$N_{\mathrm{dba}} = 64 - (C - I), \qquad \text{in db,} \tag{3}$$

provided $C - I$ is greater than about 10 db. This relationship is plotted in Fig. 6.

III. OBJECTIVES

Experience has shown that long-haul telephone circuits will give excellent transmission performance if the rms noise from all sources is 38 dba or less at a point of zero transmission level (0-db T.L.P.). On a radio relay circuit, noise in the more general sense may arise from many

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* A discussion of this unit and its relation to other units of noise power is given in some detail by Franke.[7]

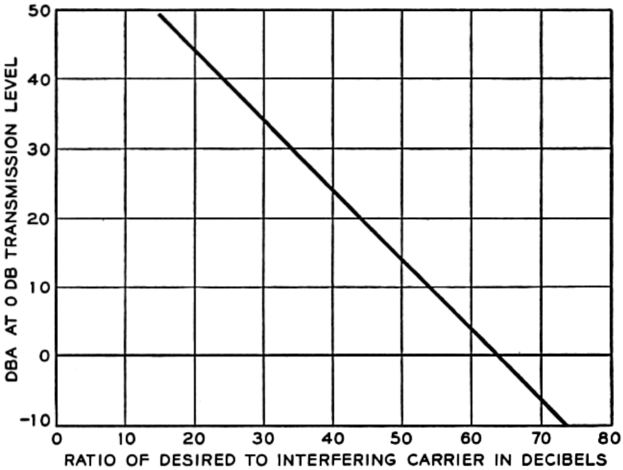

Fig. 6 — Telephone channel interference due to an interfering co-frequency radio channel in TD-2 and TH microwave systems, all-telephone case.

sources. A portion will be in the form of fluctuation noise arising in the converters; some will be intermodulation due to amplitude and phase distortion in the IF and RF circuits, as well as from echoes in the waveguide runs and the interconnecting IF cables. It is necessary to divide the total permissible noise among all the known contributors, alloting to each source an objective consistent with its importance and the feasibility of meeting it. Of particular concern here is unintelligible crosstalk due to RF interference; a reasonable allocation for this last source of impairment is 24 dba at the 0-db T.L.P. for a 4000-mile system.

Provision must be made for both the interference within the main route itself and interference to the main route from other systems that converge. Of the total of 24 dba given above, it appears reasonable to allot 22 dba to main route interference. As mentioned above, there will be two main-route RF interferences of major importance at each repeater: "same section" and "adjacent section" interference.

In order to arrive at a "per interference" allotment, it is necessary to discuss the antenna directivity patterns. The measured directivity pattern of an individual sample of a given antenna at a particular frequency will exhibit numerous maxima and minima, as shown by Fig. 7. It is not practical to make use of the sharp nulls to reduce converging route interference, because their angular position varies with frequency and is apt to differ from one particular antenna to another. Also, the nulls are usually sharper than the angular stability of the tower used to sup-

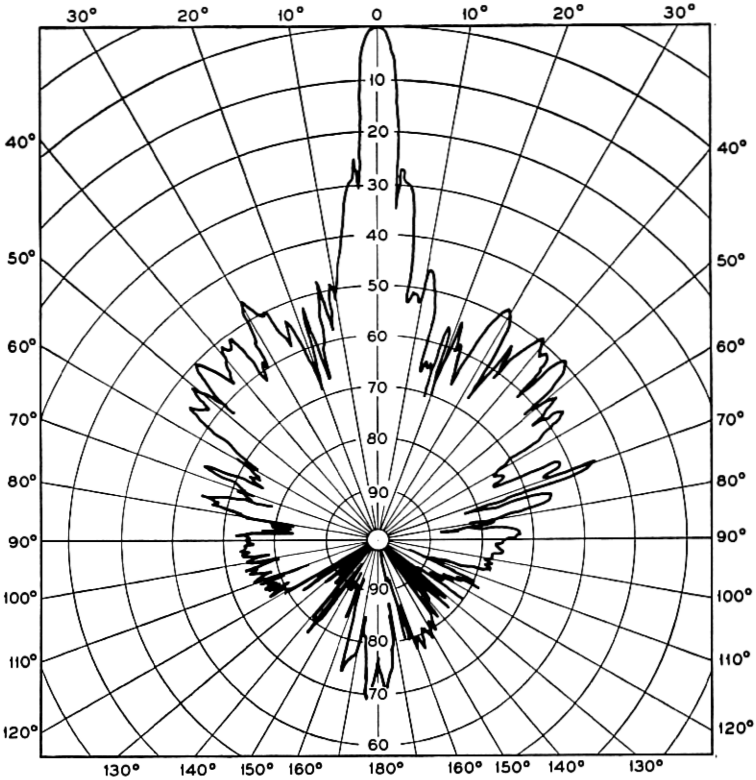

Fig. 7 — Measured directivity pattern of an individual antenna (horn-reflector, horizontal directivity, vertical polarization, 3740 mc, 3-db beamwidth 2.5°).

port the antenna. Therefore it is desirable to use smoothed directivity patterns, as shown in Figs. 8, 9 and 10, in designing particular systems. The smoothed patterns were obtained by drawing a more or less smooth curve through the peak (or poorest) values of the measured patterns. Therefore, these effectively are "worst" values rather than "rms" values.

In a multirepeatered system where there is a sizable number of exposures involving random angles, a substantial percentage of these exposures will contribute less interference than would be indicated by the work presented here. Therefore, the total rms interference is somewhat less than would be expected by simple power addition of the individual interferences. An examination of various measured directivity patterns indicates that it is reasonable to assume that straight power addition is perhaps too conservative by about 6 db. This factor can be introduced into the allotment either by altering the antenna characteristics or by altering the allotment. Since the antenna characteristics describe what was actually measured, we have chosen not to modify them; instead, we have modified the allotment.

Furthermore, considering one exposure alone, intelligible crosstalk can appear only if the two carriers involved are within a few hundred cycles of each other; the chance of this is very small. Actually, the two

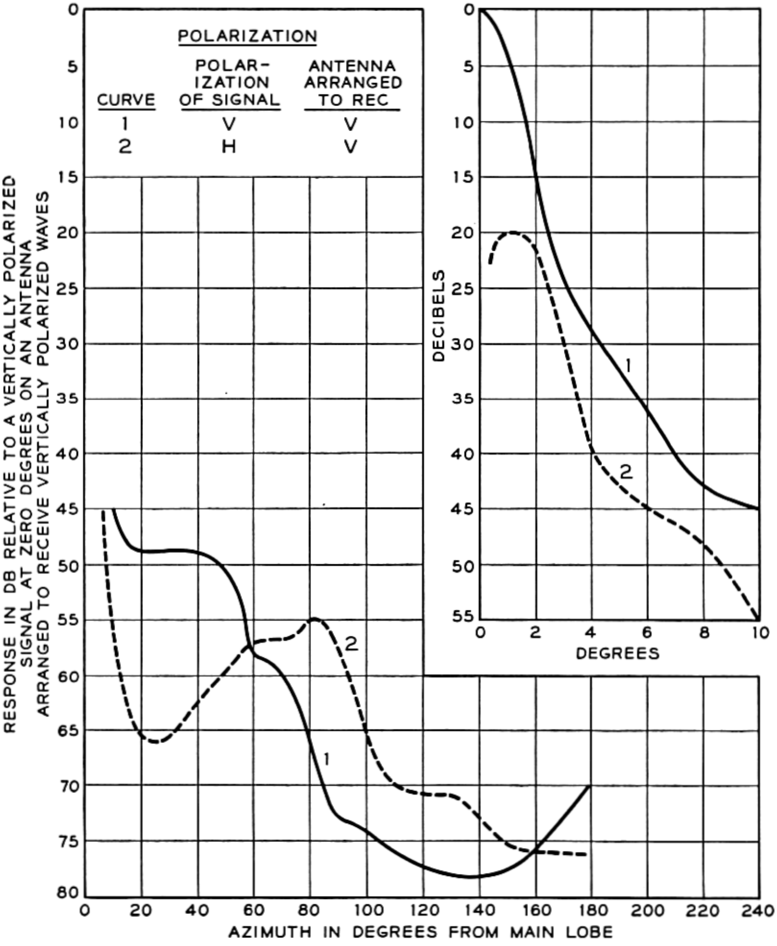

Fig. 8 — Smoothed directivity in the horizontal plane for a horn-reflector antenna at 4 kmc.

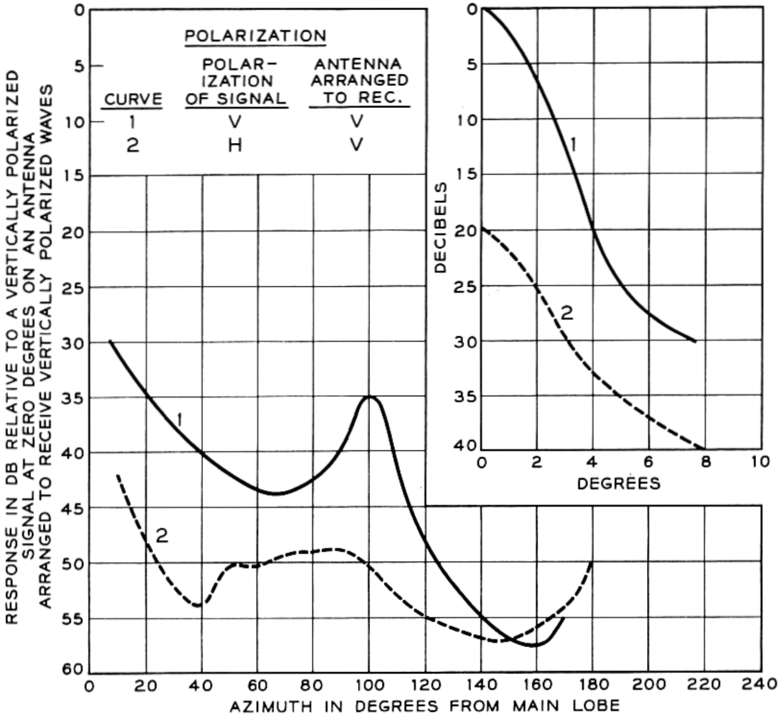

Fig. 9 — Smoothed directivity in the horizontal plane for a delay lens antenna at 4 kmc.

carriers may be as much as several tens of kilocycles apart in frequency; hence, an observer would more probably hear crosstalk from two telephone channels simultaneously with a random amount of frequency staggering. Since the frequency differences between carriers in a large number of exposures will be quite randomly distributed about an average, the telephone interference will appear as babble and may be treated as noise. Therefore, on the basis of 140 repeaters (4000 miles), two interferences per repeater, and a factor of 6 db as mentioned above, the per-repeater allotment in dba for either the same-section or the adjacent-section interference is: $+22 - 10 \log 280 + 6$, or approximately $+4$ dba at the 0-db T.L.P.

Since this allotment is slightly below that for first circuit noise, the sideband power per cycle of allowable RF interference is slightly below the fluctuation noise per cycle in the receiver converter in which the RF interference falls.

It is then evident that, during a fade of the "desired" carrier entering any particular receiver converter, the converter noise and the RF interference contributions, as observed in any telephone channel at the terminal of the system, will rise together and always stay in balance. Obviously, if the interfering carrier fades it becomes increasingly weaker than the fluctuation noise, and the effect then becomes entirely negligible.

Pertinent features of a long main route such as may extend across the continent are the spurs by means of which television and telephone channels are brought to cities situated off the main route.

At each point where a spur joins a main route four RF interferences

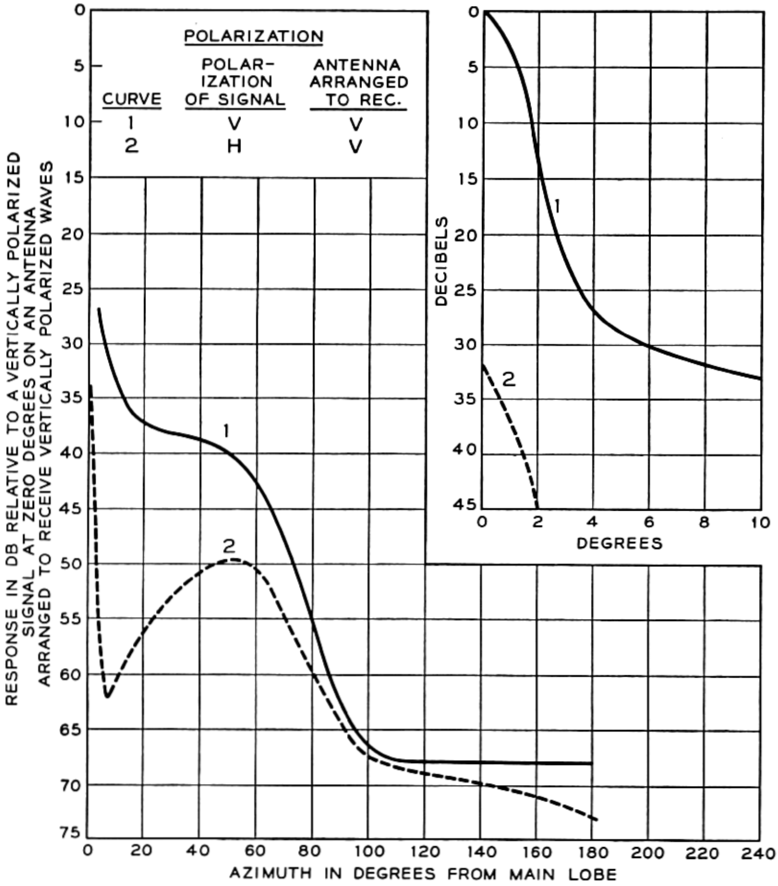

Fig. 10 — Smoothed directivity in the horizontal plane for an 8-foot parabolic antenna at 4 kmc.

will occur, as shown in Fig. 2. Two of these will appear finally as telephone channel babble at the west end of the backbone route, and similarly two will appear at the east end. Thus, assuming 64 spurs per 4000 miles, there will be a maximum of 128 such interferences at either end.

However, the angles of the spurs may be expected to be distributed at random, with presumably no angle less than a value consistent with the objectives developed below. Hence, many interferences may be expected to contribute substantially less baseband noise than the alloted value. In view of this it is probably not unreasonable to assume that only one-half of these interferences will contribute significantly to the total.

The maximum amount of baseband noise each of these RF interferences may be permitted to contribute can then be obtained by using the same line of reasoning as was followed above. Thus, assuming 64 spurs per 4000 miles, the per spur allotment is: $+20 - 10 \log 64 + 6$, or +8 dba at the 0-db T.L.P.

It is recognized that the above can at best be only a guide, since any tentative layout may call for spur angles ranging from zero (which may introduce excessive interference) to 180°. Hence, each specific spur contribution must be examined in the light of the over-all spur allotment, bearing in mind that cases will arise where there may be no practical alternative but to exceed the pro-rated allotment.

IV. SYSTEMS APPLICATION

The previous sections have (a) set down objectives in terms of permissible noise in a telephone channel for each individual RF interference on a hypothetical long system and (b) developed a relationship between the ratio of a desired RF carrier to an interfering co-channel RF carrier and the telephone channel interference that results therefrom.

The ratio of the desired carrier to the interfering carrier at any point depends on the transmitted powers, antenna gains, path losses of the two carriers involved and the discrimination of the receiving antenna against the interfering carrier. The first three factors are readily computed and need not be elaborated on here. The antenna's gain and discrimination are, of course, functions of its size and design. Figs. 8, 9 and 10 show smoothed discrimination curves for the antennas normally used in the TD-2 system: the horn-reflector antenna, the delay lens antenna and a simple 8-foot parabolic antenna.

Since the response of the 8-foot parabolic antenna to a signal from the rear is only 45 db below the main lobe response, both the "adjacent section" and "same section" interference would be on the average +19 dba, or a total of +22 dba per repeater. This would be regarded as intolerably high for a long-haul circuit. For this reason, the parabolic antennas have been used mostly on short-haul spur or secondary routes. Both the delay lens and horn-reflector provide in excess of 65 db discrimination in the rearward direction, which is entirely adequate even for systems of 4000 miles in length.

The minimum angle between a spur route and a main route on the basis of a given permissible interference is determined by the discrimination of the antennas involved. This, for a given pair of antennas, depends on whether the interference is polarized similarly or at right angles to the plane of polarization of the desired carrier.

Table I gives the minimum angle between the disturbed and disturbing paths based on the interference into the receiving antennas at the point of convergence, with the inherent assumption that the disturbed and disturbing signals are equal in strength; i.e., they originate from similar equipments and traverse paths of equal length.

In general, the Bell System does not operate separate microwave routes in close enough proximity for mutual interference to become a consideration. However, where it is suspected, the baseband interference can be computed on the basis of the principles laid down above. In general, disturbing transmitters and the disturbed receivers on separate

TABLE I — MINIMUM ANGLE BETWEEN DISTURBED AND DISTURBING PATHS FOR CO-CHANNEL INTERFERENCE

Disturbed Antenna Type	Polarization		Minimum Angle (Degrees)
	Disturbing (Transmitting) Antenna	Disturbed (Receiving) Antenna	
Delay lens	V	V	80
	H	V	72
Horn-reflector	V	V	58
	H	H	26
	H	V	10
	V	H	11
Parabolic, 8-foot	V	V	144
	H	H	*
	H	V	130
	V	H	26
Parabolic, 10-foot	V	V	122
	H	H	*
	H	V	110
	V	H	*

* The objective cannot be met at any angle with these conditions.

routes do not point at one another, and the discrimination advantage of both antennas is obtained. The combinations and possibilities are so great for such cases that generalization becomes useless and each case should be treated individually.

In the standard frequency arrangement for the TD-2 system, transmitting and receiving carriers are separated by 40 mc. Ahead of the receiver converter, RF filters provide 20 db of discrimination to the transmitter. This and the IF selectivity are more than adequate to eliminate interference between transmitters and receivers at the same site.

It is possible under certain conditions to operate channels in the 20-mc slots between an adjacent transmitter and receiver in the standard frequency arrangement. These interstitial or so-called "slot" channels are used at converging points or spurs where co-channel interference considerations would limit the minimum angle of convergence to an undesirably large angle.*

When interstitial frequencies are used, each channel may have interferences separated only 20 mc from the normal carrier frequency, i.e., at 50 mc and 90 mc in the IF band. This separation is not sufficient to provide any appreciable suppression of the interfering carriers by RF filtering. Furthermore, the IF discrimination to such interferences is only of the order of 5 to 10 db.

If the FM receiver could be assumed to consist of a perfect limiter and a perfect demodulator, FM theory would indicate that the resulting interference at baseband frequencies would be infinitesimal in magnitude in the frequency range occupied by the normal signal. Furthermore, any such interference would be incoherent with the modulating signal on the disturbing channel. Actually, experiment has shown that the signal on the weaker carrier is transferred to the stronger carrier. The crosstalk increases 2 db as the ratio between the desired carrier and the interfering carrier decreases 1 db, provided that the interfering carrier is weaker than the desired carrier; beyond this point, the baseband interference rises still more rapidly. No completely satisfactory explanation has been advanced, other than the generalized one that physical amplifiers, limiters and discriminators are frequently not ideal devices.

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* Developments subsequent to the preparation of this paper indicate that additional discrimination applied at each repeater at the intermediate frequency of 70 mc reduces the crosstalk from the adjacent microwave channels 20 mc offside so as to allow the minimum angle between converging routes to become zero degrees. This is equivalent to saying that six interstitial two-way microwave channels can also be operated in the 3700- to 4200-mc band, making a total of 12 broadband channels. The technical problems relating to the possible use of these six additional two-way channels are now being studied at Bell Telephone Laboratories.

From a systems engineering viewpoint, when interstitial frequencies are used the interfering carrier must be sufficiently weaker than the desired carrier during free-space transmission that, when the desired carrier fades, the crosstalk remains below the fluctuation noise as long as the circuit is useful.

Fig. 11 shows how the fluctuation noise theoretically increases with depth of fade on a single typical repeater section. Also in Fig. 11 is a curve showing how the crosstalk from an interstitial channel increases

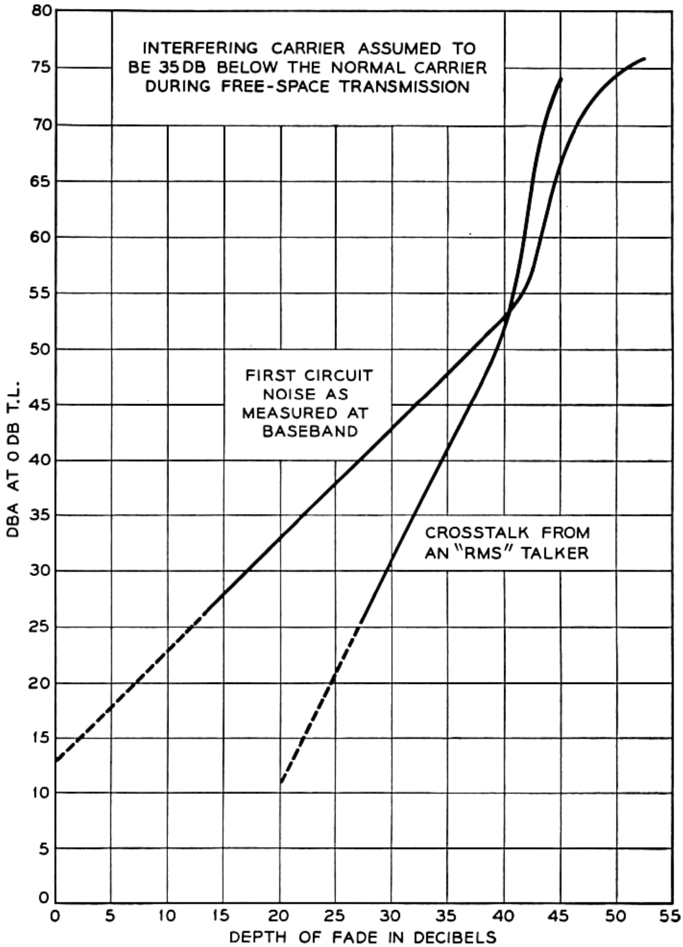

Fig. 11 — First circuit noise and adjacent channel crosstalk, with interfering carrier assumed to be 35 db below normal carrier during free-space transmission.

with a fade, assuming that the interfering carrier is 35 db weaker than the interfered-with carrier during periods of free-space transmission. It is assumed, in this case, that the interfering channel is modulated with average power talkers.

This figure indicates that, with a carrier ratio of 35 db, the crosstalk remains below the noise for fades up to about 35 db. Arrangements are provided automatically to switch the faded channel to a protection channel when the depth of fade exceeds 35 db.

Since this carrier ratio is about 20 db less than the requirement for tolerable co-channel interference, the minimum angle at which two routes may converge is greatly reduced when interstitial frequencies are used at the point of convergence. Table II illustrates the minimum angles of convergence that are practical when interstitial frequencies are used.

In a linear system it would be expected that additional IF selectivity would reduce the effect of interstitial interference. Experiment has shown that the TD-2 system is so nonlinear that added IF selectivity is effective only when applied at each repeater where interference may enter the system.

For this purpose IF filters are available that have no appreciable loss and phase distortion in the frequency range from about 60 to 80 mc, and about 30 db loss in the frequency regions of 50 mc and 90 mc. When these filters are employed in a TD-2 system using an interstitial frequency plan, the angles between converging routes need be such as to provide an antenna discrimination of only 25 db during periods of free-

TABLE II — MINIMUM ANGLE BETWEEN DISTURBED AND DISTURBING PATHS USING SLOT FREQUENCIES

Disturbed Antenna Type	Polarization		IF Filter, Minimum Angle (Degrees)	
	Disturbing (Transmitting) Antenna	Disturbed (Receiving) Antenna	Out	In
Delay lens	V	V	12	3.5
	H	V	*	*
Horn-reflector	V	V	6	3.1
	H	H	9	5.5
	H	V	4	2.5
	V	H	6	2.4
Parabolic, 8-foot	V	V	20	5
	H	H	20	7.2
	H	V	5	1.8
	V	H	8	4.9

* Less than 2°; a minimum of 2° is suggested.

space transmission. Table II gives the minimum angles necessary for adequate protection from interference when IF filters are used.

When the suggested minimum angles are very small, as when filters are used, allowance must be made for the mechanical stability of the towers and for the precision to which the antennas can be oriented. The former depends on the design of the tower structure and on the loads to which it is subjected. The latter depends on the methods and skill used in orienting the antennas. No safety factors for these considerations have been included in the suggested minimum angles.

Also for these same reasons, with the delay lens antenna and a cross-polarized interfering carrier, it is suggested that the minimum permissible angle between converging routes be 2 degrees rather than 0 degrees, as would be indicated by the discrimination pattern for the delay lens antenna.

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