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11–GHz Radio:

Application of Rain Attenuation Data to 11-GHz Radio Path Engineering

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This paper describes the procedures adopted at Bell Laboratories for using rain attenuation data to engineer 11-GHz microwave radio hops and routes. Rain outage time charts, which show the rain outage time as a function of rain attenuation and hop length, are the basic tools in engineering the hops. The charts, their formulation, and the procedures for using the charts are described and illustrated with several examples. The procedures are used to demonstrate and quantify the sensitivity of allowable hop lengths to the available rain attenuation margin, the effects of a limited rain attenuation margin, and the effects of the variation in the outage in a single year from the 20-year average outage. Guidelines for judging if a hop or route is performing as engineered are developed.

I. INTRODUCTION AND SUMMARY

In engineering a microwave radio system, as in engineering any system, one of the major concerns is the amount of time that the system will not be usable or that its performance will be below an acceptable level; this is known as outage time. For a system to be reliable, the amount of outage time must not exceed some objective and should be controllable and predictable.

In microwave radio systems, outages can be separated into two classes according to source: failure of the system equipment, and anomalous propagation conditions. In modern systems, the equipment outage time can be made negligibly small by using standby equipment and automatic protection switching systems. Protection against some propagation outages can also be achieved by providing an alternate path or channel and automatic switching; multipath fading protected by space or frequency diversity is an example. However, at frequencies above about 10 GHz, attenuation by rain can cause an outage which is not easily protected by providing an alternate path or channel because rain attenuation is relatively constant with frequency across the common carrier bands, attenuates both polarizations, and covers a fairly large area. The use of route diversity to provide an alternate propagation path has been considered, but because of the cost of providing a complete standby system and the uncertainty of the amount of joint fading on the two routes, this has not been practical.

Therefore, the only practical way of achieving a reliable radio system at those frequencies where there is substantial rain attenuation is to engineer the system in such a way that the expected amount of rain outage is below some outage objective. However, reduction of the amount of rain outage is primarily achieved by reducing the radio repeater spacing, which in turn means increasing the number of radio repeaters. Because radio repeaters are very expensive, this can greatly increase the cost of a system. Conversely, in order to reduce the cost of the system as much as possible, the system must be engineered for the longest hops, and consequently the fewest repeaters, for which the rain outage will meet the outage objective. The unavoidable dependence of the economic-versus-reliability trade-off on a statistical occurrence of nature is peculiar to radio systems operating at frequencies above about 10 GHz, and makes a reliable practical method of path engineering crucial to the future use of 11-GHz radio systems.

Prior to the availability of the data described in these papers, most radio paths were engineered using data and methods developed by Hathaway and Evans and published in 1959.[1] While this work did provide a methodology, it was based on only six months of data on two hops in one city which was then related by not-well-established relationships to rain data in other parts of the U.S. By the mid-1960s, as the future use of more and higher-capacity 11-GHz radio systems became apparent, descrepancies and problems with rain attenuation theory in general were pointed out,[2] and complaints of excessive outage in some existing systems were reported, it became obvious that better design information was needed.

Collectively the companion papers in this issue describe the current theories for predicting the amount of rain outage, the underlying substantiating data, and the methodology for engineering 11-GHz radio systems limited by rain attenuation. The paper by Hogg et al.[3] reviews the factors involved in developing the rain attenuation theory and the work which led to the present understanding. The paper by Lin[4] describes the source and processing of the basic rain rate data, and the algorithm for converting the rain rate data to rain attenuation data.

This paper describes the procedures which have been adopted for using the rain attenuation data to engineer 11-GHz microwave radio hops and routes. Section II describes the rain outage charts which are used for radio path engineering. Section III describes, and illustrates with examples, methods of using the rain outage charts to estimate annual outage time and allowable hop length to meet a given objective. The methods are then used to demonstrate the sensitivity of allowable hop lengths to the available rain attenuation margin and the effect of a limited rain attenuation margin. Section IV uses the methods of Section III to demonstrate the effects of the variation in the outage in a single year relative to the 20-year average. Section V discusses the geographical coverage of the rain attenuation data and considerations in estimating rain outage in areas where no data exist.

In addition to the methodology just described, some quantative data is derived and is summarized as follows.

(*i*) The differential attenuation between the horizontal and vertical polarization is 8.0 to 8.5 dB for 50 dB of attenuation on the vertical polarization and hop lengths from 60 km to 10 km respectively (Section 3.2).

(*ii*) A 5-dB difference in rain attenuation margin results in a 16 to 18 percent difference in allowable hop length, and a 10-dB difference results in a 30 to 35 percent difference in allowable hop length (Section 3.4).

(*iii*) For midcontinental cities in the U.S., the factors by which the maximum 1-year outage exceeds the 20-year average outage range from 2.5 to 7.1; the variability for the western cities is slightly more. Factors are also given for the maximum 5-year averages (Section 4.1).

(*iv*) Guidelines are developed for judging if a system rain outage performance is as engineered. For example, if the route outage time of a route containing three or more hops exceeds the engineered value by more than a factor of 5 in any one year, or by a factor of 2 for any 5-year average, the outage time is excessive and the reason should be determined. (Section 4.1).

(*v*) If hops were engineered on the basis of the maximum 5-year average outage time, 9 to 27 percent more repeaters would be required than if they were engineered on the basis of the 20-year average. From 25 to 77 percent more repeaters would be required to engineer on the basis of the maximum one-year outage time (Section 4.2).

This paper addresses the problem of outage caused by rain attenuation only. In some cases there may be significant amounts of outage due to other causes such as multipath fading or equipment failure. In such cases, the basic procedure is to allocate only part of the total allowable outage to rain attenuation. Detailed considerations of the allocation and computation of outage time from other effects is outside the scope of this paper.

II. RAIN OUTAGE CHARTS

The generation of rain attenuation statistics as described by Lin[4] is a two-step process. First, long-term appropriately averaged, point rain rate distributions are derived from weather bureau data at a given location. These distributions show the number of minutes per year, T, that the 5-minute point rain rate, R, exceeds a given value, and can be described by the functional relation

$$T = g(R) \tag{1}$$

Secondly, the radio path attenuation, α, for a given hop length, L, and polarization is related to the 5-minute point rain rate, R. From eqs. (14) through (19) in Lin's paper,[4] these relations for vertical and horizontal polarizations are

$$\alpha_V = \frac{.0153R^{1.1909}L}{1 + L\left(\frac{R-6.2}{2636}\right)} \qquad \alpha_H = \frac{.0170R^{1.2012}L}{1 + L\left(\frac{R-6.2}{2636}\right)} \tag{2}$$

where α is in dB, R is in mm/hr, and L is in km.

In radio path engineering we are interested in the amount of time the path attenuation exceeds the rain attenuation margin, M_R, on the radio path. This can be determined by setting α equal to M_R and solving eq. (2) for the rain rate which gives the marginal attenuation, then using the rain rate distribution to find the amount of time that rain rate is exceeded. Functionally, the solution of (2) for R can be represented by

$$R = f_V\,(M_R, L) \tag{3a}$$

$$R = f_H\,(M_R, L) \tag{3b}$$

for the vertical and horizontal polarizations respectively. Figure 1 and 2 show the rain rate R as a function of rain attenuation margin with hop length as a parameter for $12 \text{ dB} \le M_R \le 70 \text{ dB}$ and $10 \text{ km} \le L \le 60$ km.

For engineering purposes, a rain outage chart should show the annual expected rain outage time as a function of the rain attenuation margin and hop length for both vertically and horizontally polarized transmission at a given location. Such charts have been devised by solving eqs. (3) and (1) graphically by juxtaposing the rain rate scales of Figs. 1 and 2 with the rain rate scale of the point rain rate distribution. Examples of the resulting charts are shown in Figs. 3 to 9; Fig. 3 shows the rain rate scale for illustration only.

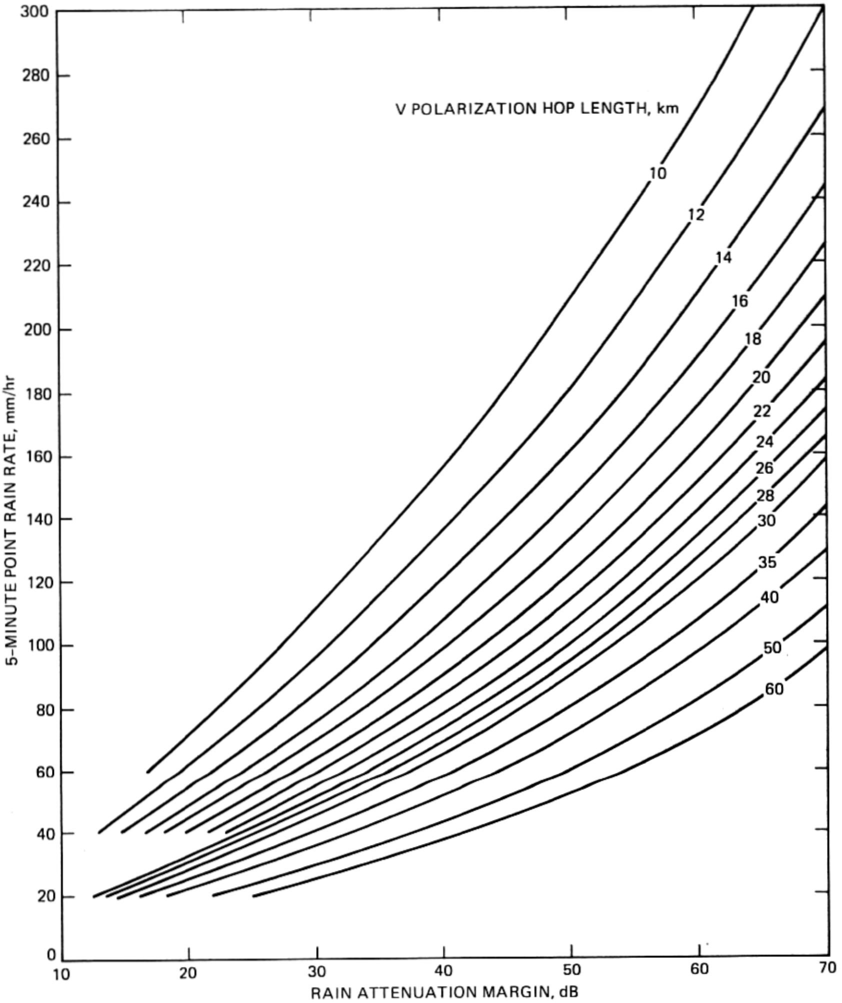

Fig. 1—Graph of the empirical relation between the annual distribution of 5-minute point rain rates and the annual distribution of rain attenuation of the vertical polarization on a radio hop with the hop length as a parameter.

The advantages of this type of rain outage chart are: (*i*) the rain rate distributions are displayed explicitly; (*ii*) the graphical solutions of eqs. (1) and (3) are kept independent, which simplifies the work required in changing the charts should new or revised data become available; (*iii*) the rain rate values are available if needed although not explicitly shown; (*iv*) both horizontal and vertical polarization data is shown on the same chart; (*v*) the rain attenuation margin-hop length scales are the same for every chart.

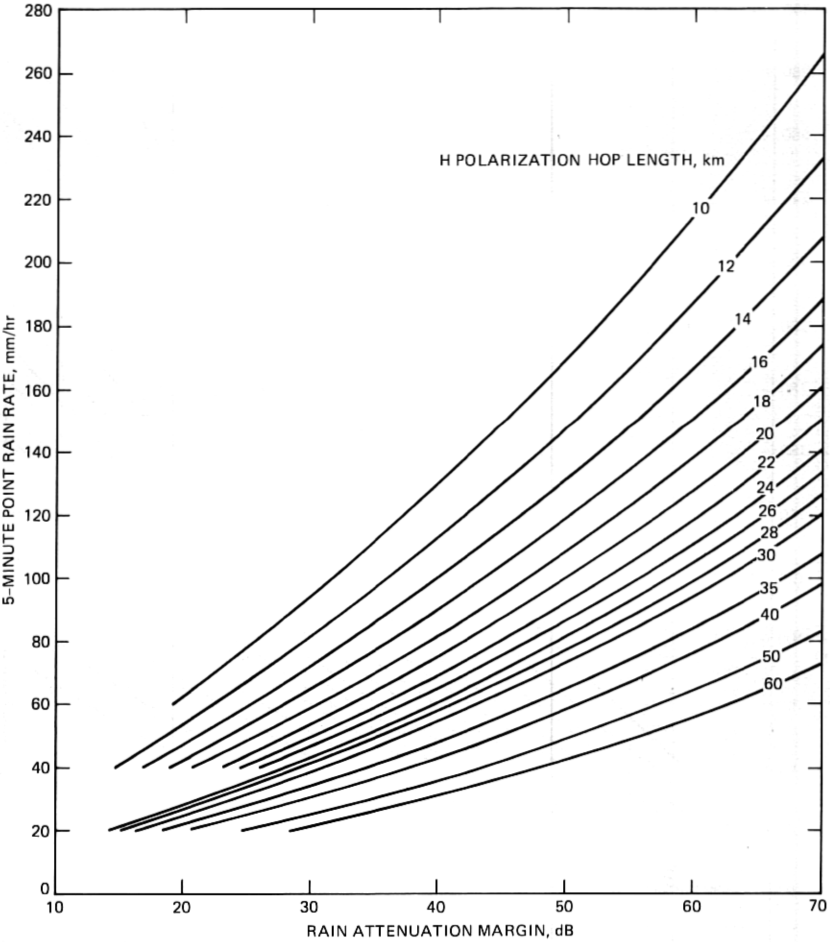

Fig. 2—Graph of the empirical relation between the annual distribution of 5-minute point rain rates and the annual distribution of rain attenuation of the horizontal polarization on a radio hop with the hop length as a parameter.

III. USE OF RAIN ATTENUATION CHARTS

3.1 Determination of rain attenuation margin from system parameters

The first step in using the rain attenuation charts for engineering a radio route is to determine the available rain attenuation margin from the specifications of the equipment used on each hop. This section describes the procedure and gives an example using typical values.

The basic equipment specification is the *system gain*, G_s, for a given performance threshold, which is defined as the dB difference in signal levels between the transmitter bay output and the receiver bay input for the given performance threshold, where the channel combining

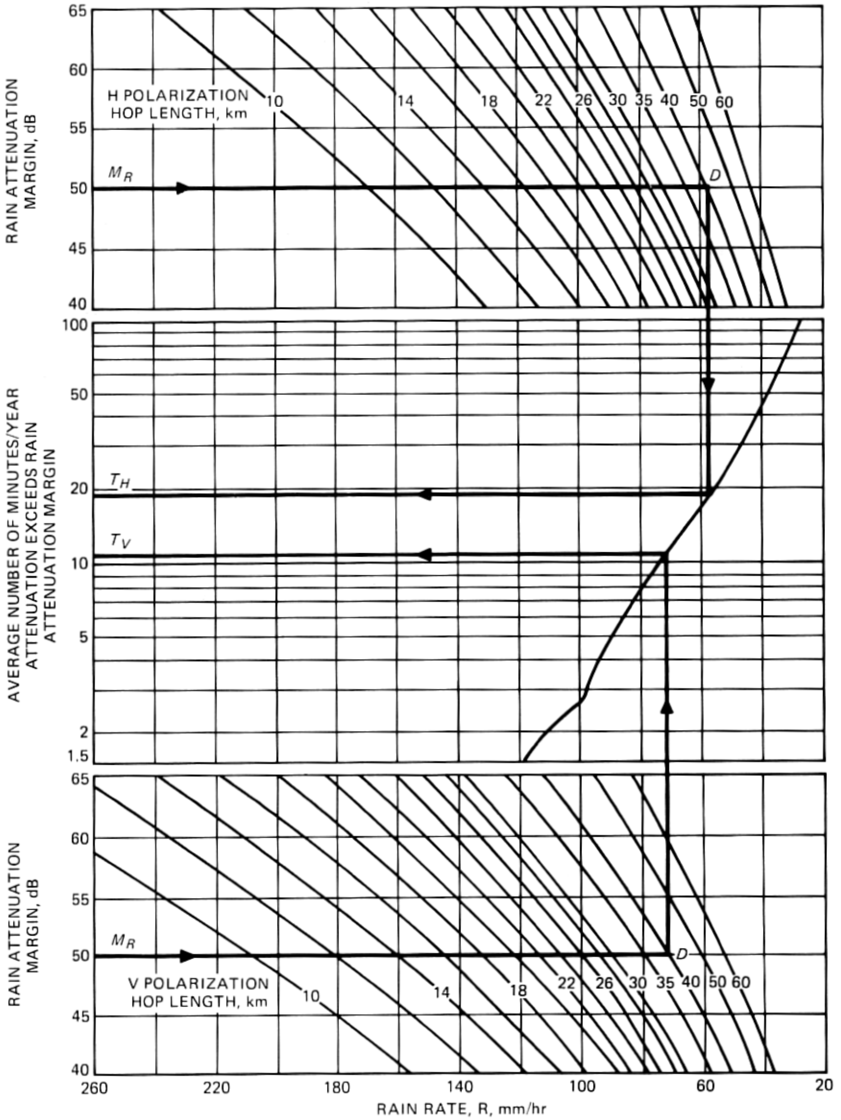

Fig. 3—Illustration of the use of a rain outage chart to find the outage time on the vertical and horizontal polarizations from a known rain attenuation margin and hop length.

networks are assumed to be inside the bays. In digital radio systems the performance threshold is usually specified in terms of bit error rate (BER), whereas in analog radio systems it is specified in terms of voice frequency channel noise. The *total fade margin, M_T,* against rain fading is the amount of flat signal loss that degrades the system performance

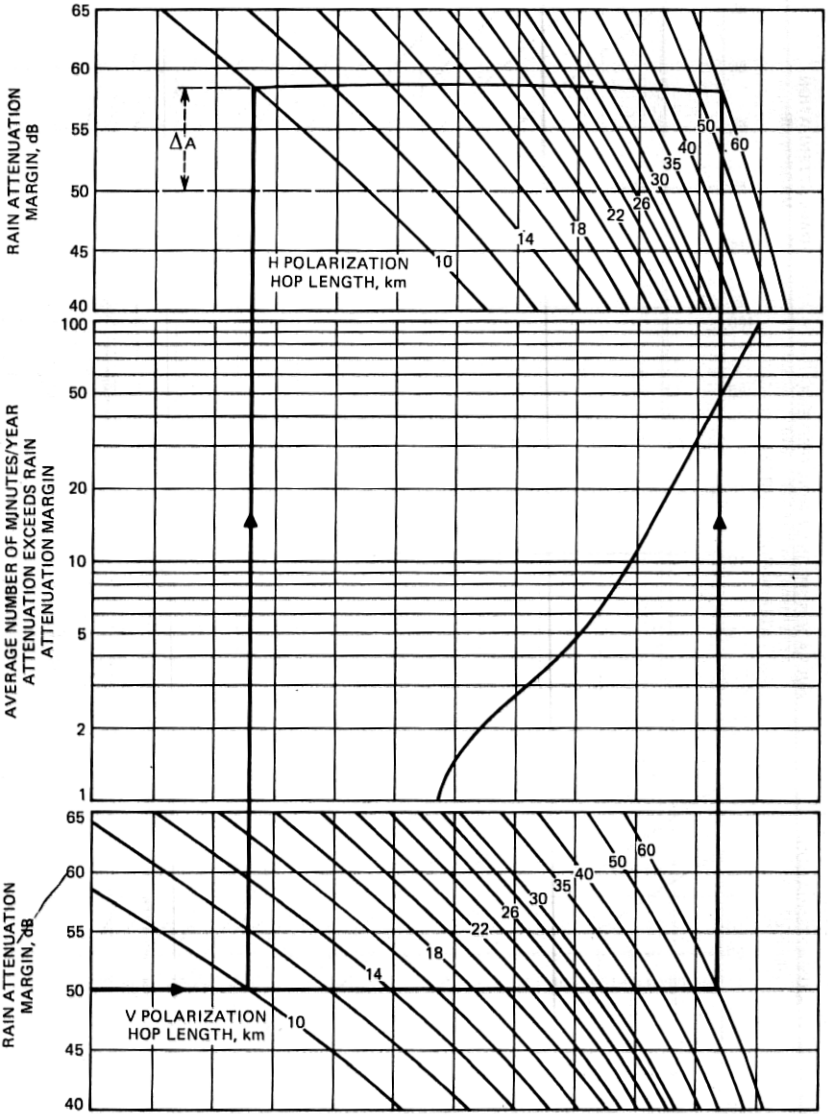

Fig. 4—Illustration of the differential attenuation between the horizontal and vertical polarizations for hop lengths from 10 km to 60 km and an attenuation of 50 dB on the vertical polarization.

to a given threshold in the absence of any other degradations. It can be found from the system gain for the same threshold by subtracting the section loss, L_s, which is the sum of the waveguide, antenna system, and free-space path losses less the antenna gains.

The total fade margin must be allocated to the various losses and

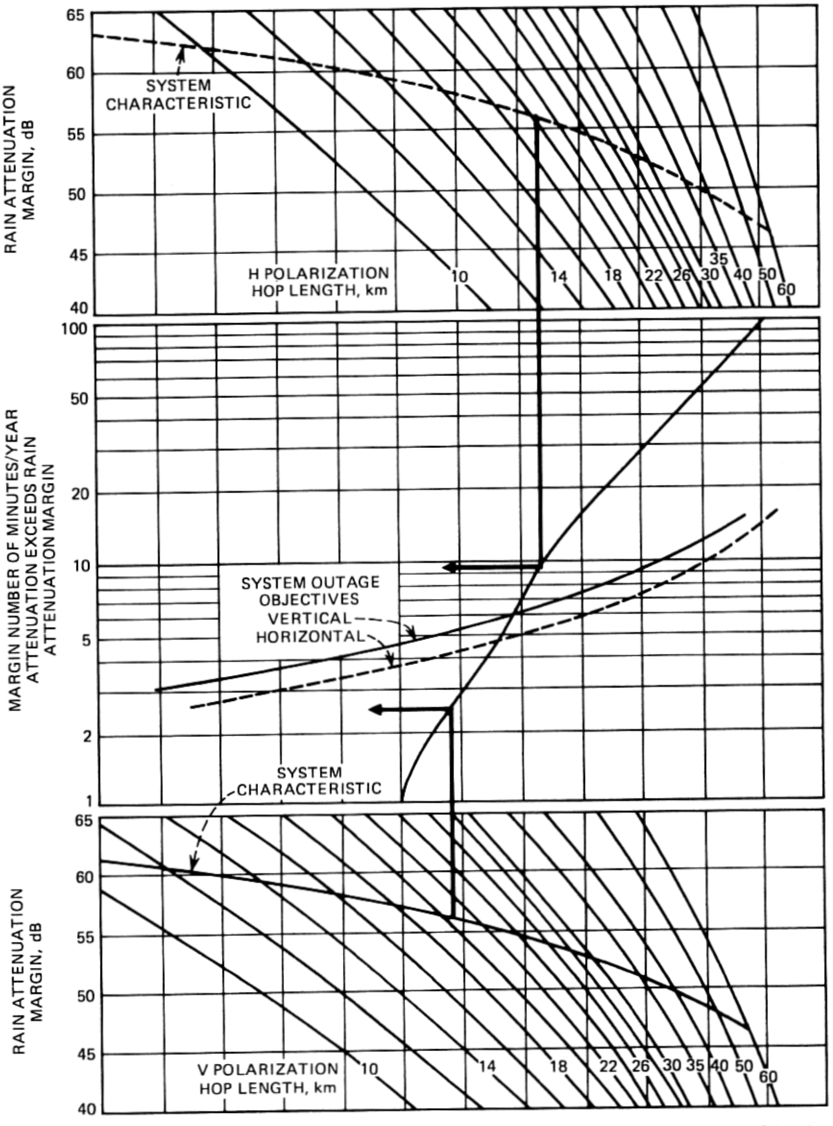

Fig. 5—Illustration of the use of the system characteristic curve and the system objective curves in finding the maximum allowable hop lengths for a particular system.

degradations that occur during rain fading, such as rain attenuation in the aerial path, wet radome loss, depolarization performance degradation, and foreign system interference degradation. The rain attenuation margin, M_R, is that margin which is allowed for *aerial attenuation only,* and is not necessarily equal to the total fade margin.

Wet radome losses have been discussed by Hogg et al.[3] For engineering

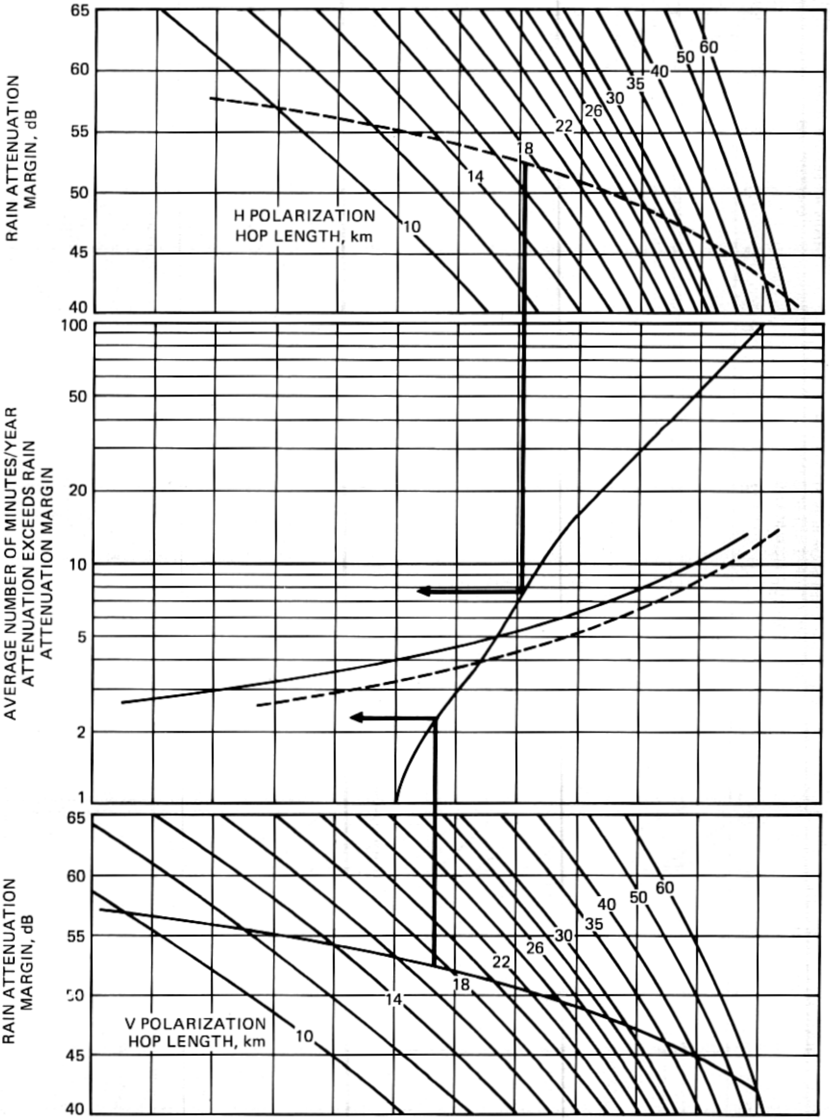

Fig. 6—Illustration of the vertical and horizontal polarization outage times for a system engineered to meet a weighted average outage time.

11-GHz radio systems using antennas with flat vertical radomes, a total loss of 4 dB for both antennas is normally assumed.[5] In digital radio systems using dual polarized frequency channels, depolarization by heavy rain can cause cochannel interference to degrade the system performance by about 2 dB.[5] Foreign system interference can cause a

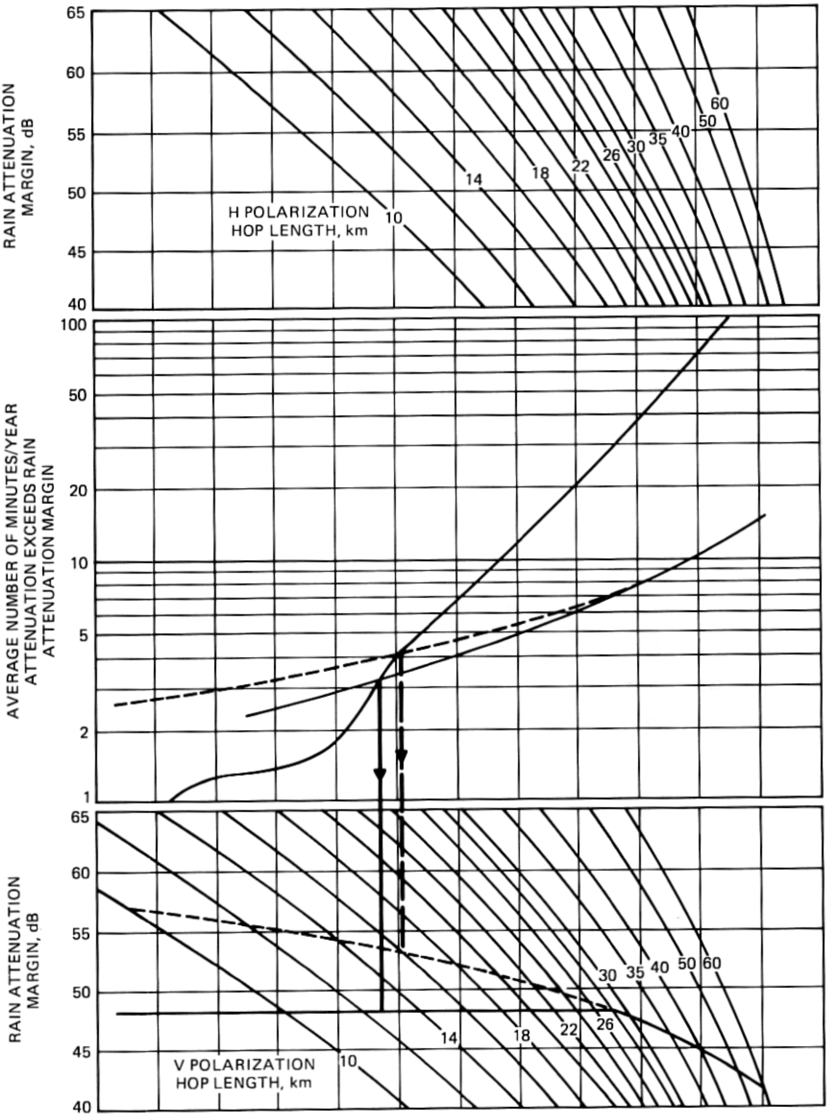

Fig. 7—Illustration of the effect of a rain attenuation margin which is limited by the radio receiver AGC range.

performance degradation during rain fading if the carrier-to-interference (C/I) ratio approaches the fade margin plus the system carrier-to-noise ratio at the performance threshold, and the interference does not fade with the desired signal. Normal frequency coordination practices require C/I ratios so high that this effect is negligible. However, if the desired

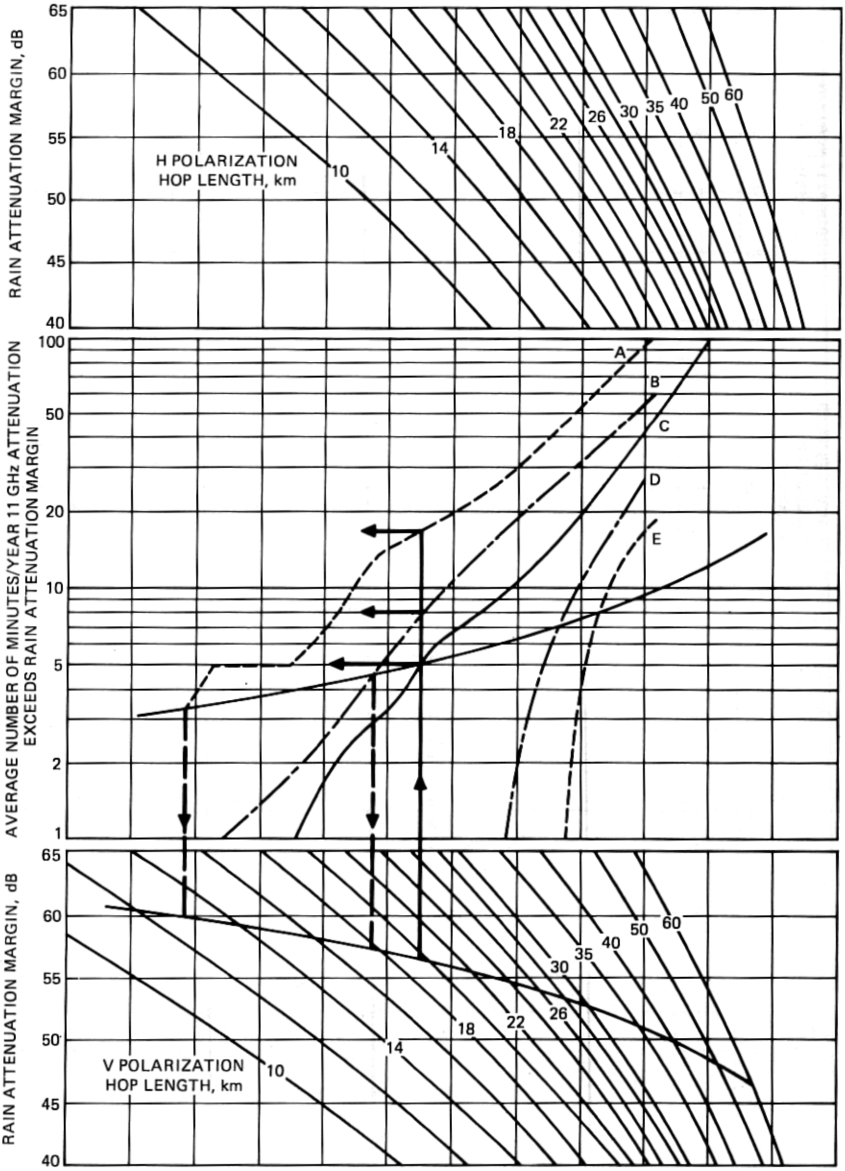

Fig. 8—Illustration of the outage times based on a 20-year average, a maximum 5-year average, and a maximum 1-year average outage time; and of the maximum hop lengths which will meet an objective for the maximum 5-year average and maximum 1-year outage times.

C/I ratio cannot be achieved, then the reduced *C/I* ratio can be tolerated by engineering with a reduced rain attenuation margin.

Table I shows an example calculation of the rain attenuation margin

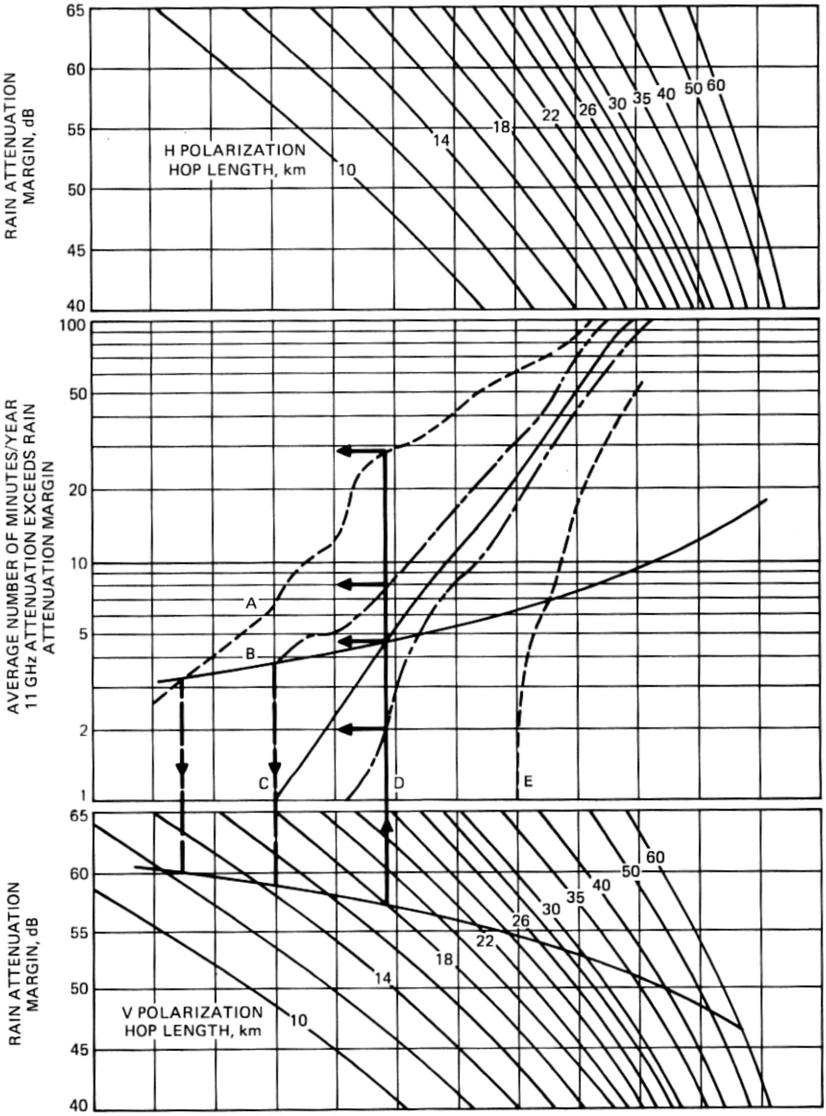

Fig. 9—Illustration of the outage times based on a 20-year average, a maximum 5-year average, and a maximum 1-year average outage time; and of the maximum hop lengths which will meet an objective for the maximum 5-year average and maximum 1-year outage times.

for a typical 11-GHz digital radio system path with a length of 40 km. For this example the rain attenuation margin is 50 dB.

Since the rain attenuation margin for a given type of equipment depends on the components of the section loss, these components can be

Table I — Calculation of rain attenuation margin (example)

Parameters	Decibels
System gain at 10^{-3} BER, G_s	112.0
Waveguide loss, total	6.6
Free-space path loss, 40-km path	145.6
Antenna gain, total for two 10-foot dish antennas	96.6
Section loss, L_s	55.6
Total fade margin available for rain fading ($M_T = G_s - L_s$)	56.4
Wet radome loss, L_r	4.0
Depolarization performance degradation, L_{XPD}	2.0
Foreign system interference degradation, L_{FI}	0.4
Rain attenuation margin, ($M_R = M_T - L_r - L_{\mathrm{XPD}} - L_{\mathrm{FI}}$)	50.0

chosen to give the optimum reliability versus economic tradeoff for each path. For example, if a path is constrained to be short because of terrain or the need for dropping a channel, then cost can be reduced by using less expensive but more lossy waveguide, or smaller antennas.

However, as is shown in Section 3.4, the allowable path length is quite sensitive to the rain attenuation margin. Because radio repeater site costs are so large in comparison to waveguide and antenna costs, it is usually least expensive to engineer for the longest path possible.

3.2 Determination of per-hop outage from rain attenuation margin

Once the rain attenuation margin and hop length are known, the expected number of minutes per year the hop performance will be below the performance threshold can be read directly from the rain chart. Figure 3 illustrates the use of the chart for the system used in the previous example. The lower scale is used for the outage on the vertical polarization and the upper scale for the outage on the horizontal polarization. For this example, the vertical polarization outage time, T_V, is 11 minutes and the horizontal polarization outage time, T_H, is 19 minutes.

The difference between vertical and horizontal polarization outage times is caused by the differential attenuation between the two polarizations. For 50 dB of attenuation on the vertical polarization, the differential attenuation ranges from 8.0 dB to 8.5 dB for hop lengths from 60 km to 10 km as illustrated in Fig. 4. The differential attenuation is relatively insensitive to hop length but varies substantially with absolute attenuation as shown in Hogg et al.[3]

A short-haul radio annual outage objective of 0.02 percent for a 250-mile system is often used in the Bell System. This amounts to 105 minutes per year for a 400-km system, or 10.5 minutes for a 40-km hop. Thus the expected annual outage for the vertical polarization is just over the objective, while the outage for the horizontal polarization is substantially higher than the objective.

In medium to highly loaded systems, both polarizations must be used and the hops must be engineered to give adequate reliability with both polarizations utilized. Because some form of polarization frogging can usually be used to average the outage of both polarizations on any one trunk, and because it is almost always possible to use the vertical polarization more than the horizontal, the hop outage is usually taken to be the weighted average outage, weighted 60 percent for the vertical and 40 percent for the horizontal polarization. In this case the weighted average outage is $T_{\mathrm{AV}} = 0.6\ T_V + 0.4\ T_H = 14$ minutes, which is still above the objective.

In order to meet the objective the rain attenuation margin must be increased. This can be done by changing the section loss or by shortening the hop length. From this point on, the procedure is by trial and retrial. The next section describes a method for finding the maximum allowable hop length by graphical construction.

The allocation of an objective on a per-hop basis by prorating the route objective on the basis of hop length implicitly assumes that the fading events on each hop are mutually exclusive. Since some simultaneous fading of adjacent or nearly adjacent hops is expected, this procedure leads to pessimistic estimates of the total outage time for tandem hops. However, there is as yet no adequate data for engineering otherwise.

3.3 Determination of allowable hop length to meet an objective

It is often desirable to be able to determine the maximum allowable hop length, for a given set of system parameters and location, for which the expected outage just equals the objective, without doing it by trial and error. This section describes a graphical procedure for determining the allowable hop lengths for the individual polarizations and approximately for the weighted average.

As mentioned in the previous section, it order to reduce the outage time the rain attenuation margin must be increased either by changing the equipment parameters or by changing the hop length or perhaps both. As can be seen from Fig. 3 by using the vertical polarization scale, increasing the fade margin by 3 dB by changing equipment parameters but keeping the hop length at 40 km reduces the outage time from 11 minutes to 8.5 minutes. This is not a significant reduction considering the difficulty involved in gaining 3 dB of margin by changing the waveguide loss or antenna size. The more effective way of increasing the margin is to decrease the hop length because changes in both margin and hop length act together to decrease the outage time. Therefore, in cases where the hops are rain-limited, the best procedure is to use the best practical system parameters and adjust the outage by changing the hop length.

If the system parameters are fixed, the rain attenuation margin varies with hop length according to the equation

$$M_R = M_{Ro} + 20 \log \frac{D_o}{D} \tag{4}$$

where M_{Ro} is the rain attenuation margin on a hop length D_o. The values of M_{Ro} and D_o therefore become a measure of the equipment performance of a hop, dependent on how that particular equipment has been engineered. In the previous examples, we have shown that $M_{Ro} = 50$ dB on a 40-km hop is typical of the Western Electric 3A-RDS radio system. A plot of eq. (4) on the vertical or horizontal scales of a rain chart is called the *system characteristic curve* for the system with M_{Ro} at D_o. Figure 5 shows such curves for $M_{Ro} = 50$ dB at $D_o = 40$ km. The system characteristic displays the rain outage time as a function of hop length by reading vertically upward from the system characteristic at the desired hop length to the rain outage curve.

The outage objective for a given hop length, assuming the objective is prorated proportionally to the hop length, is

$$T_{\text{OBJ/HOP}} = T_{\text{OBJ/ROUTE}} \left(\frac{D}{\text{route length}} \right) \tag{5}$$

Using an objective of 0.02 percent per 400-km route, eq. (4) becomes

$$T_{\text{OBJ/HOP}} = .26\, D \text{ minutes} \tag{6}$$

when D is in km. If eq. (6) is plotted on the outage time scale of a rain chart as a function of hop length D *along the system characteristic* on either the vertical or horizontal scales, it becomes the *system objective* curve for the system. Figure 5 shows system objective curves for both polarizations and a system with $M_{Ro} = 50$ dB at 40 km.

Since the rain outage curve relative to the system characteristic curve is the hop outage as a function of hop length, and the system objective curve relative to the system characteristic curve is the hop objective, the maximum hop length, outage time, and corresponding fade margin can be found from the intersection of the two curves. Thus from Fig. 5, the values listed in Table IIA are found for the example system.

The maximum allowable hop length for which the weighted average outage time (0.6 T_V + 0.4 T_H) meets the objective can be found approximately by taking a weighted average of the vertical and horizontal allowable hop lengths:

$$D_{\text{MAX-AVG}} \approx 0.4\, D_{\text{MAX-V}} + 0.6\, D_{\text{MAX-H}} \tag{7}$$

Note that the weighting is reversed because the higher outage of the horizontal polarization contributes more to the weighted average outage even with the 60–40 weighting. Once the maximum hop length has been calculated, the corresponding fade margin can be read from the system

Table II — Allowable hop length calculations*

A. Calculations for V and H polarizations

	Polarization	
	V	H
Maximum hop length	24 km (15.0 mi)	18 km (11.3 mi)
Rain outage time	6.2 min	4.7 min
Rain attenuation margin required	54.5 dB	57.0 dB

B. Calculations for weighted average outage

Approximate maximum hop length [eq. (7)]	20.4 km (12.8 mi)
Rain attenuation margin [eq. (4)]	55.9 dB
Vertical polarization outage	2.5 min
Horizontal polarization outage	9.5 min
Weighted average outage	5.3 min
Objective for 20.4-km hop	5.3 min

* For a system with a rain attenuation margin of 50 dB on a 40-km hop using the rain outage chart in Fig. 5.

characteristic or calculated from (4), and the horizontal and vertical outage times can be read from the rain outage curve. Continuing the previous example gives the results listed in Table IIB, which are indicated in Fig. 5.

3.4 Sensitivity of allowable hop length to rain attenuation margin

Different types of radio systems have different attainable rain attenuation margins not only because the waveguide losses or antenna gains are different, but also because of inherent system performance capabilities. In this section we illustrate the sensitivity of the maximum allowable hop length to the rain attenuation margin by comparing the maximum allowable hop lengths of systems with different rain attenuation margins on a 40-km hop.

Table III and Fig. 6 show the results of calculations paralleling those of Section 3.3 but for a system with $M_{Ro} = 45$ dB on a 40-km hop. For both systems, the weighted average outage is equal to the outage objective.

The results show that a 5-dB decrease in rain attenuation margin requires a 16 percent decrease in hop length relative to the average of the two hop lengths. Calculations for other values of fade margins and other locations have shown that for fade margins ranging from 40 to 55 dB on a 40-km hop and for all cities where the maximum allowable hop lengths are 50 miles or less, a 5-dB difference in rain attenuation margin results in a difference of 16 to 18 percent in allowable hop length, and a 10-dB difference gives a difference of 30 to 35 percent in allowable hop length. Thus relatively small differences in margins can give substantial savings in system costs by reducing the number of repeaters required.

3.5 Effect of dynamic-range limited rain attenuation margin

Reducing the hop lengths decreases the rain outage time for two reasons: because the rain attenuation margin increases, and because the amount of rain attenuation incurred decreases. In order to actually realize that part of the decrease due to the rain attenuation margin increase, the AGC range of the radio system receiver must be adequate. If the AGC range is inadequate, it will be unable to maintain a constant signal level in the receiver and an outage will be caused by loss of signal level rather than degraded signal-to-noise ratio. In such cases the system characteristic curve does not show a continual increase in margin as the hops are shortened, but remains constant at some limiting value.

Figure 7 shows an example of a system with 45 dB of rain attenuation margin on a 40-km hop, but with a maximum rain attenuation margin of 48 dB, limited by the receiver AGC range. Figure 7 uses the vertical polarization only, but the same principles apply for both horizontal polarization outages and weighted-average outages.

The limited AGC range decreases the maximum allowable hop length substantially. For example, in Fig. 7 if the AGC range were not limited, the maximum allowable hop length would be 15 km (10 miles) and a rain attenuation margin of 53 dB would be required. With the rain attenuation margin limited to 48 dB, the maximum allowable hop length is 12.5 km (7.8 miles), or a decrease of 22 percent relative to 16 km. This would require a 28 percent increase in the number of repeaters.

This effect is much more substantial in the Southeastern U. S. where the hops must be short with correspondingly large margins required.

IV. EFFECTS OF THE VARIATIONS IN THE ANNUAL OUTAGE TIMES

Lin[4] has discussed the variability of the rain rate distributions from year to year and has emphasized the need for stable statistics on which to engineer radio systems. In this section we discuss the implications of this variability on the reliability of systems engineered by the proposed methods and show the penalty for engineering for worst case statistics.

4.1 Estimate of variability of annual outage times

Figures 8 and 9 show rain charts with the worst (A) and best (E) annual distributions, and worst (B) and best (D) 5-year average distributions, in addition to the 20-year average distribution (C). Figures 8 and 9 also show the system characteristic and system objective curves for the example system with 50-dB rain attenuation margin on a 40-km hop. For simplicity, only the vertical polarization will be considered; similar conclusions would be drawn for engineering based on the horizontal polarization outage or the weighted-average outage.

Table III — Allowable hop length calculations*

A. Calculations for V and H polarizations

	Polarization	
	V	H
Maximum hop length	20 km (12.5 mi)	15.5 km (9.7 mi)
Rain outage time	5.2 min	4.0 min
Rain attenuation margin required	51.0 dB	53.2

B. Calculations for weighted average outage

Approximate maximum hop length [Eq. (7)]	17.3 km (10.8 mi)
Rain attenuation margin [Eq. (4)]	52.3 dB
Vertical polarization outage	2.3 min
Horizontal polarization outage	7.8 min
Weighted average outage	4.5 min
Objective for 17.3-km hop	4.5 min

* For a system with a rain attenuation margin of 45 dB on a 40-km hop using the rain outage chart in Fig. 6.

First assume that the system has been engineered for the maximum allowable hop length for which the outage on the vertical polarization will meet a 0.02 percent per 400 km objective. The resulting hop length in Fig. 8 is 19.5 km (12.2 mi) and the average annual outage is 5 minutes per year based on the 20-year average distribution.

The curves shown on the rain outage chart are actually those distributions which were measured over the 20-year base period, 1953 to 1972. Thus the outage times read from the rain chart are those outage times which would have been measured if a system had been operating during the 20-year base period (assuming the rain theory is correct); but they are probably *not* the outage times that will be measured in the next or any other 20-year period. They are, however, the *best estimate* of what similarly averaged outages would be for any 20-year period. Furthermore, the outage time indicated by the 20-year average curve is the *best estimate* of what the annual outage time will be in any one year although we know that it probably will not be that value.

The annual outage times indicated by curves A and E in these figures give some indication of the extreme values that can be expected over a 20-year period. In Fig. 8, the largest outage time is about 17 minutes, a little over 3 times the design value; the smallest outage time is much less than one minute. The largest annual outage time averaged over any 5-year period is expected to be about 8 minutes; and again the smallest is much less than 1 minute. Similar results are obtained from Fig. 9.

A similar ananysis was done for each of 13 representative cities including those in Figs. 3 to 9 and the results are listed in Table IV. Table IV is divided into two parts. For those cities listed in part B the allowable hop lengths are so long, and the corresponding rain rates so low, that meaningful short-term distributions at high rain rates could not be

Table IV Factors by which the 20-year average outage time on the vertical polarization is exceeded*

Rain Outage Chart	Hop length, km	Hop length, miles	20-yr averge outage time, minutes	Factor by which outage time exceeds 20-yr average outage time: 1-yr max	5-yr max	5-yr min	1-yr min
			(A)				
Fig. 4	32.3	20.2	8.4	2.6	1.3	0.6	†
Figs. 5, 6	23.9	14.9	6.2	7.1	1.9	0.3	0.0
Fig. 7	19.2	12.0	5.0	4.8	2.4	0.1	0.0
Fig. 8	19.5	12.2	5.1	3.2	1.6	0.0	0.0
Fig. 9	17.7	11.1	4.6	6.3	1.7	0.5	0.0
(Not shown)	30.8	19.2	8.0	5.0	1.8	0.5	†
(Not shown)	23.1	14.4	6.0	2.5	1.7	0.6	0.0
			(B)				
Fig. 3	36.2	22.6	8.2	3.9	2.3	0.3	†
(Not shown)	36.2	22.6	5.9	5.8	1.8	0.5	†
(Not shown)	36.2	22.6	3.7	4.1	1.8	†	†
(Not shown)	36.2	22.6	2.0	10.0	2.2	†	†
(Not shown)	36.2	22.6	2.8	7.1	2.1	†	†
(Not shown)	36.2	22.6	1.4	7.1	3.4	†	†

* By the maximum and minimum 1-year outage times and 5-year average outage times. Part A uses representative cities for which the hop length listed is the maximum allowable to meet the outage objective. Part B uses representative cities for which the hop length is shorter than the maximum because data was not available at the maximum allowable hop length. The outage time allowable at the 36.2-km hop length is 9.4 minutes. A system with 50-dB margin on a 40-km hop is assumed.

† Data not available.

generated. Consequently, the calculations were made at the longest hop length for which data was available—36.2 km.

The data in Table IV show that for the midcontinent cities in part A the factors by which the maximum 1-year outages exceed the engineered value range from 2.5 to 7.1. Factors by which the maximum 5-year average annual outages exceed the engineered value range from 1.3 to 2.4. At every location there should be at least 1 year out of 20 for which there is no outage. The variability in the outage for the cities in part B is slightly more, the maximum 1-year factors ranging from 3.9 to 10, and the maximum 5-year factors ranging from 1.8 to 3.4.

The question of whether a hop or a route is performing as engineered inevitably arises. Two additional factors which affect the observed outages of a route must be considered. First, as demonstrated by Lin,[4] the outage of a route consisting of several hops should not be as variable as the individual hops themselves. Lin's Fig. 16 shows roughly a factor-of-2 reduction in his $\Delta t/\bar{t}$ factor, which is equivalent to the factor listed for the 1-year maximum in Table IV,* for a route consisting of three

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* In Lin's paper Δt is the worst-year minutes less the best-year minutes. However, the best-year minutes are negligible, so the ratio is essentially worst year minutes divided by the 20-year average which is the same as used in Table IV.

hops. Secondly, the route outage should not be as large as the sum of the individual hop outage because of joint fading on tandem hops. This effect should be more important in the midcontinent cities where the hops are shorter.

Based on the foregoing, the following guidelines seem reasonable. First it must be definitely established that the outage in question is caused by *aerial attenuation by rain.* Then, if the route outage time of a route containing three or more hops exceeds the engineered value by more than a factor of 5 in any one year, or by a factor of 2 for any 5-year average, the rain outage is excessive and the reason for the excessive outage should be determined. If the outage time of a single hop or two tandem hops exceeds the engineered value by more than a factor of 10 in any one year, or a factor of 4 for any 5-year average, the reason for the excessive outage should be determined.

4.2 Engineering for worst-case outages

To avoid exceeding the outage objective for any one year, or for any 5-year average, would require that the hops be engineered so that the objective is met for the estimated maximum 1- and 5-year average annual outages respectively. Figures 8 and 9 illustrate the procedure for the example system using only the vertical polarization outage.

In Fig. 8 the hop length is 19.5 km (12.2 miles) based on the 20-year average, 17.7 km (11.1 miles) based on the maximum 5-year average annual outage time, and 12.9 km, (8.1 miles) based on the maximum 1-year annual outage time. These hop lengths are 9.2 and 33.9 percent reductions in hop length, which in turn mean 10.1 and 51.3 percent increases in the number of repeaters, respectively.

Table V lists similar percentages for eight Eastern and Midwestern cities. Such comparisons are not meaningful for the far Western cities because the allowable hop lengths based on 20-year average outage times are much longer than are used in practice. (In other words, the hops are not rain-attenuation limited.) Table V shows that the percentage increase in number of repeaters ranges from 9 to 27 percent if the hop lengths are based on maximum 5-year average outage times, and from 25 to 77 percent if the hop lengths are based on the maximum 1-year outage times. Because radio repeaters are so expensive, such increases in the number of repeaters could make rain-attenuation-limited radio systems very uneconomical.

V. GEOGRAPHICAL COVERAGE

Although charts have been produced for many cities, there are still areas a few hundred miles on a side for which no rain data exists, and so the problem of how to engineer radio systems in these areas still exists.

Table V—Percentage decrease in allowable hop lengths and resulting percentage increase in number of repeaters*

Rain outage chart	Hop length for 20-year average		Percentage decrease in hop length for hops engineered to indicated distributions		Percentage increase in number of repeaters for hops engineered to indicated distributions	
	km	miles	5-yr max	1-yr max	5-yr max	1-yr max
Fig. 3	36.5	22.8	21.1	39.0	26.7	63.8
Fig. 4	32.3	20.2	8.3	40.5	9.1	68.0
Figs. 5, 6	23.9	14.9	11.3	43.6	12.7	77.1
Fig. 7	19.2	12.0	—	20.0	—	25.0
Fig. 8	19.5	12.2	9.2	33.9	10.1	51.3
Fig. 9	17.7	11.1	19.8	30.5	24.7	43.9
(Not shown)	30.8	19.2	16.3	32.5	19.4	48.2
(Not shown)	23.1	14.4	18.1	33.4	21.7	50.2

* Resulting from engineering the maximum 1- and 5-year average outage times to meet a 0.02 percent per 400-km objective.

At the present time there is no definitive proven solution to this problem, but the following approaches seem reasonable.

The problem can be approached in two basic ways: interpolation between locations where data exists, or identification of the unknown location with a known location based on consideration of climates and local judgment. Usually some combination of these two approaches is the most satisfying intuitively.

There is no reason to suppose that other than linear interpolation should be used. Linear interpolation can be used by calculating the outage times for a given system at different locations and interpolating between them, or by calculating the allowable hop lengths and interpolating them. The main advantage interpolation has over judgment is that it is consistent and reproducible.

In using judgment of climatological conditions it is of the utmost importance to remember that it is the *rainfall rate* that determines outage time and *not* the total amount of water that falls. The northwest coast of the United States is the primary example of a very wet region where there is virtually no rain-attenuation-caused outage. Large scale climatological factors which seem to bear some relation to high rain rates are number of thunderstorms, late summer humidity, and total July precipitation. These are probably related because most of the rain rates which are large enough to cause an outage are due to thunderstorms. For example, total July precipitation is related to thunderstorms because in July most of the precipitation is from thunderstorms. Terrain should also be considered, especially in the lee of mountains, because rough terrain and mountains contribute to the formation of thunderstorms.

Finally, local knowledge and judgment should be used in comparing the area in question to a location where data is available.

VI. ACKNOWLEDGMENT

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