6-GHZ DIGITAL SYSTEMS
RADIO ENGINEERING
MICROWAVE RADIO

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1. INTRODUCTION

A. General

1.01 This section provides guidelines to assist companies in engineering digital microwave radio routes. The guidelines are applicable to any manufactured equipment that meets the performance objectives defined. Areas of particular importance include:

(a) AT&T network outage objectives

(b) Maximum length of short-haul systems

(c) Outages due to multipath fading

(d) Interference considerations

(e) Outages due to upfades.

Following the theory presentation, examples serve as summary demonstrations illustrating the proper use of data in this section.

1.02 This section is reissued to provide a general updating, to return to the historical outage time objective, and to introduce the concept of a composite fade margin.

B. Digital Advantage

1.03 The prime advantage of digital systems resides in what has been called the "ruggedness" of the digital signal. This arises from the fact that digital systems are regenerative and, assuming a certain threshold of degradation has not been exceeded, can be retransmitted with a quality equal to that at the point of origin. In this sense, a properly operating transmission system can be regarded as "transparent" to propagation.

1.04 The economics of digital terminals and multiplexers for relatively short systems has led to their widespread use in urban areas. These economic advantages are being extended to provide digital interconnecting paths between isolated areas of common interest in the range of 25 to 150 miles, and occasionally longer.

C. Further Characteristics

1.05 In seeming contrast to the advantage of ruggedness (with respect to noise and interference tolerance) as stated above, digital systems are also considered to be "brittle" in that radio line failure will tend to be abrupt—rather than continuous or gradual as in analog systems—when certain limits (often within a few dB) are exceeded. Multipath fading, for example, has a greater destructive impact on digital transmission. Here, in addition to the familiar long path—short path phase cancellation (and depolarization) which are significant in thermal noise limited systems, an additional dynamic known as distortion or dispersion operates on digital modulated signals. This results from the deleterious interaction of differentially delayed frequency components arriving at the point of reception via multiple paths. As a result of the increased influence of such induced amplitude, phase, and envelope delay distortions, digital fade margins are somewhat less than the typical 40 dB or more allowed by thermal noise criteria alone.

1.06 Interference in digital systems must also be treated distinctly from analog methodology. In analog systems (which are not regenerative), interference noise is cumulative, and therefore is assigned a minimal (below the thermal noise) allowance per exposure. Because the abruptness of digital systems will allow greater total noise below the critical threshold, C/I ratios can allow interference to exceed the thermal noise under certain conditions.

1.07 The maintenance of digital systems represents a major consideration, the importance of which should not be underestimated. Digital systems are inherently more subject to hard-to-find transient problems than are analog systems. While regeneration per se can obscure fault localization, regenerative operations provide an opportunity to measure performance criteria such as reframes and BER on a per-hop basis. If fault detecting and alarm equipment is provided, troubles may more easily be traced to individual stations. Without such means for trouble isolation, maintenance of digital systems can become an almost insurmountable task.

2. FCC RULES AND GENERAL GUIDELINES

A. FCC Rules

2.01 The FCC Rules as amended under Dockets 18920 and 19311 allow high-speed digital transmission in the 6-GHz common carrier band under the conditions of a minimum digital capacity of one bit per hertz of bandwidth and a minimum loading of 1152 voice grade circuits (VGC) in a 30-MHz channel. The latter requirement coupled with economic factors has led to the development of several 6-GHz systems in the 78- to 135-Mb/s range capable of interfacing with one or more of the hierarchical rates: DS1 at 1.544 Mb/s, DS2 at 6.312 Mb/s, and DS3 at 44.736 Mb/s. Figure 1 illustrates the digital hierarchy and locates 6-GHz radio among the transmission facilities. The 6-GHz modulation techniques are typically 8-phase PSK or 16 QAM (quadrature amplitude modulation). While available 6-GHz designs at the time of writing were single polarization per frequency transmission (SPF), dual polarization per frequency (DPF) systems employing 4-phase PSK are also accommodated by FCC requirements. The following topics provide the transmission engineer with a review of certain FCC regulations that may influence selection and use of 6-GHz digital radio systems. This information, however, is not intended to replace AT&T Western Electric Practices or engineering letters (ELs) written to provide specific guidance, and questions should be directed to the appropriate headquarters FCC coordinator. The rules regarding digital radio systems fall within two basic categories:

(a) Those which specify necessary equipment parameters and characteristics for type acceptance (manufacturer)

(b) Those which specify distance and loading criteria for common carriers using the 6-GHz band (licensees).

The following topics first cover equipment parameters and characteristics which will have been specified by the manufacturer prior to receiving FCC type acceptance. (Transmitters must be type accepted in accordance with the FCC Rules, Part 21.) Distance and loading rules are then presented, followed by the stated requirement for annual modulation and frequency checks. A discussion of additional guidelines then concludes the topics of this part.

B. Equipment Characteristics and Requirements

2.02 Following are the FCC definitions for bit rate, symbol rate, and modulation:

Bit Rate:	The rate of transmission of information in binary (2-state) form in bits per unit time.
Symbol Rate:	Modulation rate in bauds. The term "baud" is derived from telegraphy and describes the symbol or information pulse rate. For example, if the four permutations available in two bits 00, 10, 01, and 11 are each represented as one of four carrier phase states 0°, + 90°, – 90°, and 180°, each baud will, in this case, represent two bits.
Digital Modulation:	The process by which some characteristic (frequency, phase, amplitude, or combinations thereof) of a carrier frequency is varied in accordance with a digital signal; e.g., one consisting of coded pulses or states.

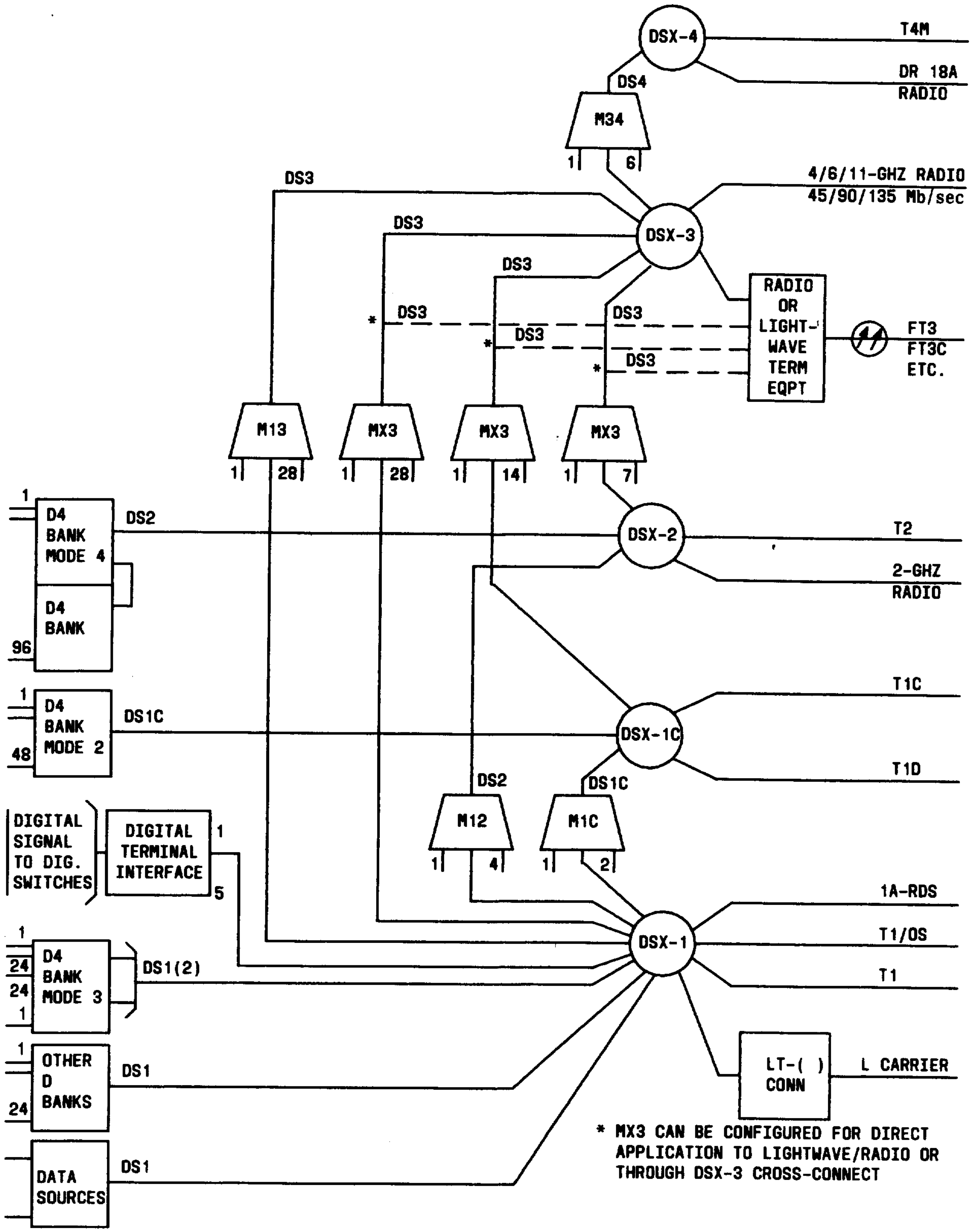


Fig. 1—Digital Hierarchy and Transmission Facilities

Emission Limitation

2.03 Emission limitations for analog and digital radio equipment are different. For 6-GHz digital radio equipment, the modulated transmitter emission limitations are: the mean power emitted in any 4-kHz band outside the authorized bandwidth shall be attenuated below the mean power in any 4-kHz band within the authorized bandwidth in accordance with the following formula. The attenuation should not be less than 50 dB, although attenuation greater than 80 dB is not required. (See Fig. 2.)

$$\boldsymbol{A} = 35 + 0.8(\boldsymbol{P}\text{-}50) + 10 \log_{10} \boldsymbol{B}$$

where:

$\boldsymbol{A}$ = Attenuation (in dB) below the mean output level

$\boldsymbol{P}$ = Percent of authorized bandwidth removed from the carrier frequency

$\boldsymbol{B}$ = Authorized bandwidth in MHz.

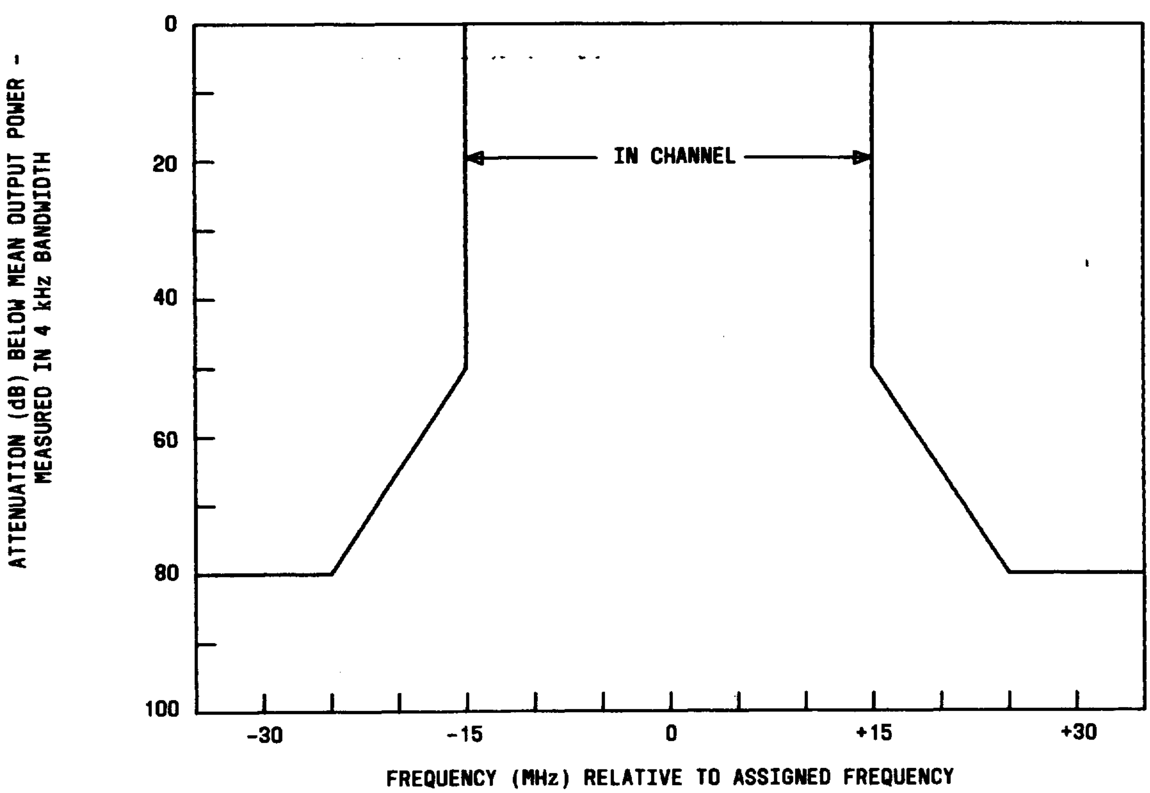


Fig. 2—FCC Emission Limitation Mask

Necessary Bandwidth Calculations

2.04 Formulas for calculating the necessary bandwidth (Bn) for digital modulation are contained in Part 2 of the FCC Rules. The symbol "Y" at the end of the emission designator, 30000F9Y, indicates digital modulation.

Occupied Bandwidth

2.05 The occupied bandwidth shall be measured at the output of any filter network, pseudorandom generator, or other device required in normal service. Additionally, the occupied bandwidth shall be shown for any spectrum-modifying device that is operated at the equipment user's option.

Required Transmitter Capacity (Digital Traffic)

2.06 The minimum transmitter bit rate, in bits per second, shall be equal to or greater than the bandwidth specified by the emission designator in hertz; i.e., to be acceptable, equipment must transmit one or more bits per second per hertz.

Required Transmitter Capacity (Voice Traffic)

2.07 Equipment to be used for voice transmission shall be capable of satisfactory operation within the authorized bandwidth when loaded with at least 1152 voice channels.

C. Distance and Loading Rules

2.08 The following topics highlight those items which must be taken under consideration by the users (operating companies) of 6-GHz digital radio systems.

Maximum Authorized Bandwidth

2.09 The maximum authorized bandwidth for the 6-GHz common carrier band is 30 MHz.

Path Length

2.10 For the 6-GHz band, the minimum path distance is 17 kilometers (10.6 miles). However, the FCC may waive this requirement if a showing (with supporting facts) can be made justifying a shorter path length.

Loading

2.11 In the 6-GHz band, the initial working channel must have an anticipated loading (within 5 years or other period subject to reasonable projection) of at least the following:

Voice Channels (4 kHz)—900

or

Digital Data—10 Mb/s

Frequency-diversity channels will be authorized only if the anticipated system growth will reach three working channels within 3 years.

D. Check of Modulation and Frequency Characteristics

2.12 The modulation characteristics of digital radio equipment must be measured annually. The manufacturer's equipment-type acceptance filing contains the parameter(s) which, if measured and found to be in tolerance, will ensure that the modulation characteristic remains within limits. The user should determine these parameters from the manufacturer and measure them during the annual check. Frequency sources which can affect the transmitted carrier must also be periodically checked, with intervals dependent on stability. Both modulation and frequency checks are further discussed in conjunction with maintenance considerations in Part 3.

E. Additional Guidelines

Frequency Plan

2.13 It is recommended that 6-GHz digital radios be operated on the regular 6-GHz T channels; i.e., 29.65-MHz channel spacing with 5945.2 MHz the center frequency of the lowest channel (Fig. 3). Other frequency plans have been used for analog radio systems in this band; e.g., splitting the frequency assignment of a channel to obtain two frequency assignments for short-haul radio systems. At this time, the only available systems meeting the FCC requirements outlined in Part 2A, B, and C above require a full 30-MHz channel. The 6-GHz band can be used best with the regular 6-GHz T channels, both for all-digital and combined analog and digital routes.

Single Versus Dual Antennas

2.14 Long-haul radio systems are operated with separate antennas for transmitting and receiving on each path. Short-haul radio systems have generally used only one antenna on each path for both transmitting and receiving. With single antenna systems, there is a risk that the higher power transmitters used in recent short-haul systems may produce intolerable modulation products in the waveguide system. Thus one-antenna operation cannot be used on systems where more than four of the available eight channels will be required. An expanded discussion of the intermodulation problem can be found in Section 940-384-100 (11 GHz).

Intermodulation

2.15 Figure 4 shows the potential 2A-B products. (The figure shows channels 21 through 28 transmitting and channels 11 through 18 receiving. Adjacent repeater stations interchange transmitters and receivers.) The diagram at the upper left is a portion of the frequency plan with the channel center frequencies identified by counting up from the lowest frequency channel. This notation is used in the rest of the figure to calculate the location of the 2A-B modulation products. The midpoint of the 2A-B product spectrum is located at 8.5—(n_2—$2n_1$) channels above f_0. In the example, this quantity is equal to 2.5. This is one-half the channel spacing above the center of CH12. The 2A-B spectrum extends for 1.5 channel spacings at each side of its center, or from the center of CH11 to the center of CH14, i.e., 2.5 ± 1.5 = 4 and 1. The broad digital spectrum extending almost to the edge of its assigned channel accounts for the wide spread.* Figure 4 shows that 2A-B products are avoided by using any four consecutively numbered channels; e.g., transmit CH 22, 23, 24, 25 or CH 12, 13, 14, 15, or CH 25 through 28 or 15 through 18. The choice of CH 21 through 24/11 through 14 followed by CH 25 through 28/15 through 18 on the second antenna provides for easy growth to full route capacity. Beginning with 25 through 28 offers the same advantage.

*Not shown in the figure is the equation for transmitters in the lower band.

$$\text{Product center} = f_0 + 8.5\Delta f + [(2n_2 - n_1) - 8.5]\Delta f$$

The bracketed coefficient of Δf identifies the receiving channel number in the upper band.

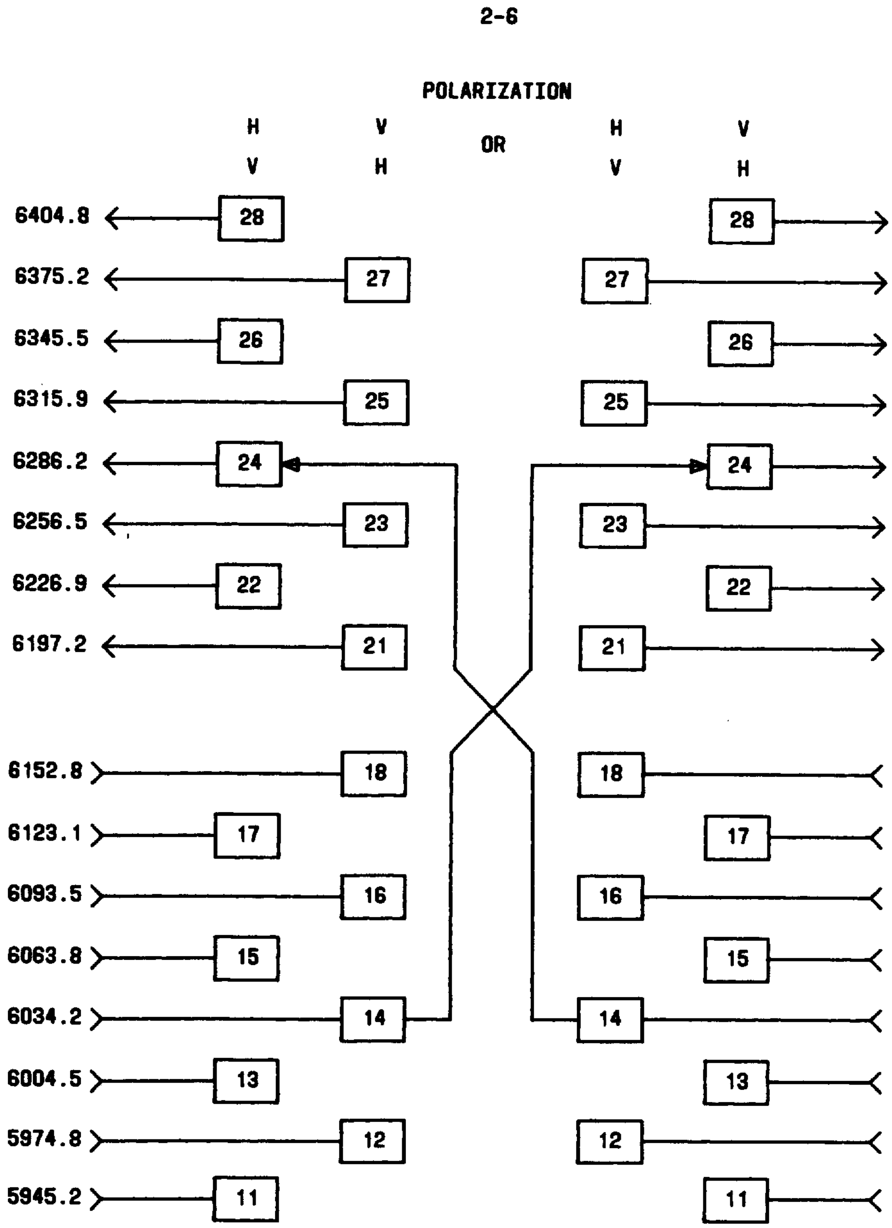
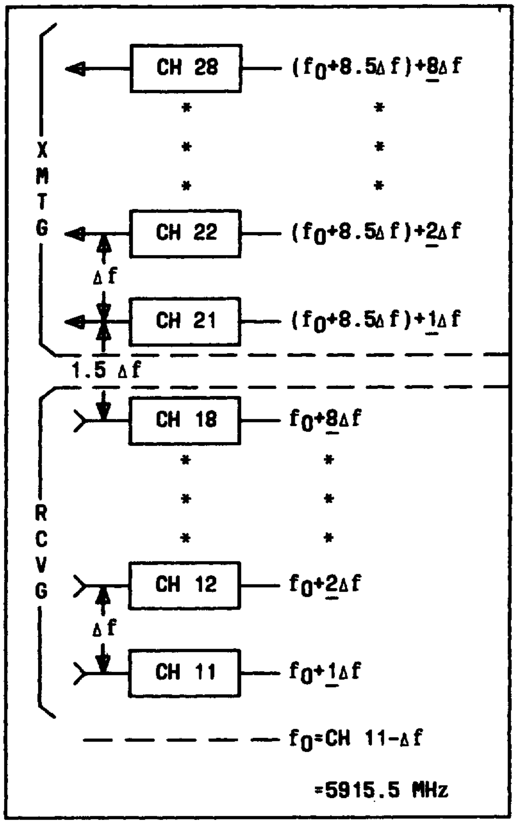


Fig. 3—Frequency Plan

2.16 Using the five highest channels and the five lowest channels will permit up to five channels on one antenna without 2A-B product exposure.

Analog and Digital Systems on the Same Route

2.17 The spectrum of a digital radio system is relatively uniform across the channel, resulting in a typical energy spread (spillover) beyond the channel edge which is higher than that of FM signals of comparable capacity. This results in more adjacent channel interference into analog channels. The spectrum of a digital channel is a function of the modulation or baud rate and, as discussed in Part 8 (interference), the available cross-polarization discrimination (XPD) will not always be sufficient (at 30-MHz channel separation) to provide



2A-B PRODUCTS

$A=(f_0+8.5\Delta f)+n_1\Delta f$

$B=(f_0+8.5\Delta f)+n_2\Delta f$

WHERE $n_2>n_1$

f_0=CH 11-Δf=5915.5 MHz

Δf=29.6 MHz

THEREFORE

$2A-B=(f_0+8.5\Delta f)-(n_2-2n_1)\Delta f$

EXAMPLE: $n_1=1$(CH 21)

$n_2=8$(CH 28)

PRODUCT CENTER AT:

$f_0+8.5\Delta f-(8-2)\Delta f$

$= f_0+2.5\Delta f$ = 5989.5 MHz

MIDWAY CH 12 AND CH 13

SPECTRUM SPREAD

FROM: $f_0+1.0\Delta f$(CH 11)

TO: $f_0+4.0\Delta f$(CH 14)

TWO WORKABLE PLANS

FOR SINGLE ANTENNA OPERATION (NOTE 1)

USE CH 1-4	USE CH 5-8
XMT CH 21-24 REC CH 11-14	XMT CH 25-28 REC CH 15-18
2A-B WITH $n_1=1$(CH 21)$n_2=4$(CH 24)	2A-B WITH $n_1=5$(CH 25)$n_2=8$(CH 28)
$2A-B=f_0+8.5\Delta f-(4-2)\Delta F$	$2A-B=f_0+8.5\Delta f-(8-10)\Delta F$
$=f_0+6.5\Delta f$	$=f_0+10.5\Delta f$
SPREAD: $f_0+8\Delta f$ CH 18	SPREAD: $f_0+9\Delta f$ (ALL IN XMTG BAND)
$f_0+5\Delta f$ CH 15	$f_0+12\Delta f$

(NOTE 1)
ANY OTHER 4 CONSECUTIVE CHANNELS ARE ALSO POSSIBLE, I.E., CH 2-5, CH 3-6, CH 4-7. IF A SECOND ANTENNA AND FULL SYSTEM GROWTH IS DESIRED, THE PLANS SHOWN PERMIT GROWTH WITHOUT REARRANGEMENTS.

Fig. 4—2A-B Products (6 GHz)

the required discrimination. In such cases, an unoccupied channel must be interposed between otherwise adjacent digital and analog channels operating on the same route.

2.18 The transmitted spectrum of the digital radio must permit operation, on the same hop, of an analog FM radio channel with a center frequency separation of 59.3 MHz and like polarization. The digital radio spectral requirement that must be met for a transmitter with a nominal output power of P dBm is stated in paragraph 2.19.

2.19 The power density in a 4-kHz band at a frequency of (50.776−S) MHz from the center of the digital radio channel shall be at least (75+P) dB below the measured transmitter power in dBm. S is the sum of the maximum frequency tolerances (in MHz) of the two transmitters. This requirement will limit the adjacent channel interference noise into the highest frequency baseband circuit of the analog radio to 4 dBrnc0 or less. That circuit is nominally located 50.776 MHz from the center of the digital channel.

2.20 The digital radio should permit operation of an analog FM radio with a center frequency separation of 44.5 MHz (split frequency plan) or 29.65 MHz. In this case, the frequency cited in paragraph 2.19 would be decreased by 14.8 MHz or 29.65 MHz, respectively. The attenuation limit(s) would be unchanged. For adjacent channel separation, a nominal 30 dB of cross-polarization isolation is to be assumed.

3. SYSTEM CHARACTERISTICS AND OVERVIEW

A. General

3.01 This part discusses items and characteristics of particular significance to digital systems. Topics include:

(a) Fade margin

(b) Interference

(c) Bit error rate

(d) Modulation types

(e) Repeater types

(f) Alarming and maintenance

(g) Upfades.

A knowledge of the system fade margin is needed to calculate and predict outage. The theoretical fade margin based on thermal noise criteria will be combined with the deleterious impact of multipath phenomena and interference (rain fading is insignificant at 6 GHz) to arrive at practical values for estimating system outage. The initial determination of the fade margin considers system gain and section loss and is supported by Fig. 5.

B. Theoretical Fade Margin

3.02 The theoretical fade margin (F) is found from the relationship SG = SL + F where:

SG = System Gain

SL = Section Loss

F = Fade Margin.

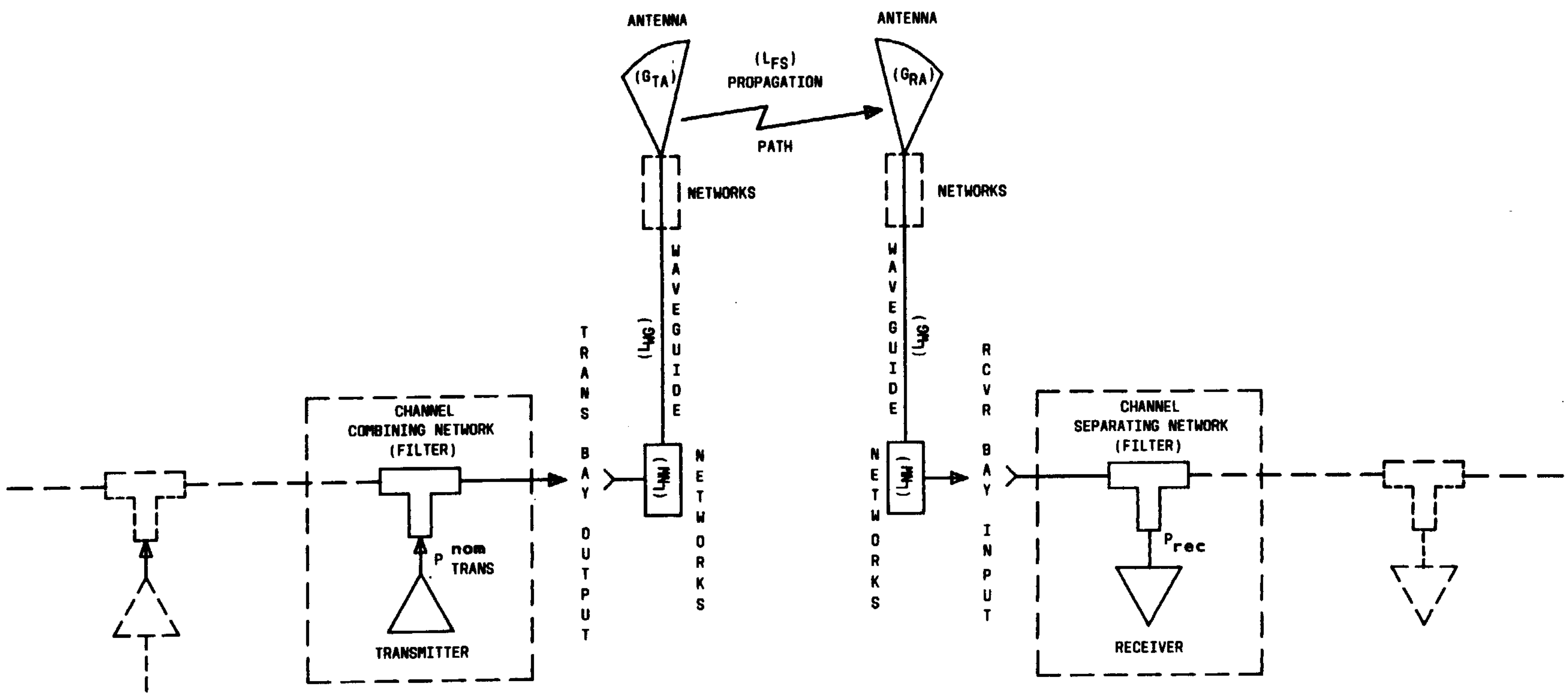


Fig. 5—Radio System Schematic

System gain is determined by equipment design characteristics and is therefore controlled by the manufacturer, while section loss is controlled by the route designer.

System Gain (SG)

3.03 System gain gives the thermal noise performance measure of the radio equipment alone. System gain is defined as the difference between the nominal power (in dBm) measured at the transmitter bay output (see location on Fig. 5) and the minimum power (in dBm) at the receiver bay input for acceptable radio system performance. (Note that the stipulation of acceptable performance includes the receiver as necessary to this evaluation—a point which might be overlooked with strict reference to the specified measurement locations in Fig. 5.) Typical acceptable performance is defined as minimum receiver input power such that the following criteria are met:

Analog Systems: Maximum noise level (worst message channel) = 55 dBrnc0

Digital Systems: Maximum bit error rate (BER) = 10^{-3}.

3.04 It should be recognized that this definition of system gain gives a performance measure of the radio equipment alone. System gain will go up with such factors as higher transmitter power and lower receiver noise figure. System gain does not depend on antenna sizes, waveguide, or path lengths, nor does it include the effect of any interferences. For a higher system fade margin (F), the section loss must be reduced to maintain the minimum power at the receiver. This minimum power for acceptable performance depends on the internal thermal noise and the losses within the radio bay, i.e., filters and other networks. It should also be noted from Fig. 5 that the system gain (SG), as defined by (SG = SL + F), will be smaller than the quantity $[P_{nom\ trans} - P_{rec\ min}]$ (the difference of transmitter power and minimum received signal as measured at the respective bay output and input) by the amount of the channel combining and separating filter insertion losses. For multichannel systems, the losses of several tandem filters are incurred. A high value of system gain alone does not guarantee good performance.

Section Loss (SL)

3.05 Section loss is defined as the total power loss between a transmitter bay output and the succeeding receiver bay input during normal propagation conditions. It is completely controlled by the route design independent of the chosen radio equipment. It is the sum of the losses over one hop due to all station and outdoor waveguide runs and network losses plus the nominal free space path loss minus the gains of the antennas. An expression for SL can be written in terms of these component losses as:

$$SL = L_{FS} + L_{WG_{TOT}} + L_{NW_{TOT}} - G_{TA} - G_{RA}$$

where

L_{FS} = Free-space path loss

$L_{WG_{TOT}}$ = Total waveguide losses (transmitting and receiving)

$L_{NW_{TOT}}$ = Total network losses (transmitting and receiving)

G_{TA} = Gain of transmitting antenna

G_{RA} = Gain of receiving antenna.

A distinction should be made between microwave facilities which handle only 6-GHz radio traffic and those which handle a mixture of 11-, 6-, and 4-GHz traffic over shared waveguide and antenna components. These latter systems are termed "combined systems" and incorporate additional microwave networks whose losses must be included in L_{NWTOT}. Additional specifics related to network, waveguide, and antenna combinations and choices are provided in Part 9.

Waveguide Loss

3.06 All waveguide in the path from a transmitter bay up to the antenna port and from the receiving antenna to the receiver bay input must be included in the calculation. Waveguide losses range from 2 dB to about 10 dB depending on length, size of the guide, and its geometry—rectangular, elliptical, or circular. The choices are closely coupled with the choice of antennas.

Network Losses

3.07 A dual-polarized 6-GHz-only radio system which uses a single vertical waveguide run requires polarization combining networks and, if transitions to other waveguide geometries or sizes occur, transition networks and mode suppressors. In combined systems (4/6/11 GHz) using a common vertical antenna feed-run and antenna, combining networks are required to couple the frequency bands into the waveguide. In some cases, mode suppressor networks may also be required. Each such network contributes to the total section loss through reflection and ohmic losses. Since these networks are usually short, the ohmic loss contributions are very small, and with correct design, reflection losses can also be minimized. Typically, each such network will introduce 0.2- or 0.3-dB loss.

Free-Space Path Loss

3.08 The geometric spreading of energy radiated from the transmitter location to the receiver locations results in the free-space path loss, L_{FS} (see Section 940-310-101 for detailed discussion). This contribution to the overall section loss (in dB) at the midband frequency of 6.2 GHz is given by:

$$L_{FS} = 112.5 + 20 \log D \text{ (miles)}$$

$$= 108.3 + 20 \log D \text{ (kilometers)}$$

where:

D is the path length in miles or kilometers.

Thermal Noise Fade Margin (F)

3.09 The theoretical or thermal noise fade margin (F) of a hop is the difference between the system gain and the section loss as discussed above, and is expressed as:

$$F = SG - SL.$$

C. Fade Margin Reductions Caused by Interference and Dispersive Fading

3.10 For many analog systems of the past, F was the margin that was available to cover propagation disturbances (fades). Higher system gains or lower section losses would lead directly to better performance. One limitation that has always been present is interference (both from within a system and from external sources). Since the definition of system gain excluded all interference effects, F is the thermal noise margin for flat fading in the absence of interference.

3.11 For 6-GHz digital radio systems, an even greater fade margin limitation is imposed by distortion (dispersion) resulting from multipath fading. Dispersion can occur even during relatively shallow fades. Distortion introduced by multipath can cause high bit error rates (BER) well before fade levels reach the thermal noise margin. When either interference or multipath distortion effects are controlling, the well-known means to increase F—such as added transmitter power, larger antennas, or lower noise figures and waveguide losses—are not very effective in reducing outages.

3.12 For these reasons, the unqualified term "fade margin" will seldom be used. Instead, the more specific term "thermal noise margin" (F) and a new term "dispersive fade level" for use in calculating multipath outages will be employed. Dispersive fade level relates the total outage time (high BER periods) observed in digital system experiments to the single frequency multipath fading time observed on the same path. The fade depth for which the measured time below level is the same as the observed high BER time is taken as the dispersive fade level. Part 6 provides methods for combining the thermal noise margin and the effects of interference and dispersion to obtain a composite fade margin.

D. Interference

Cochannel

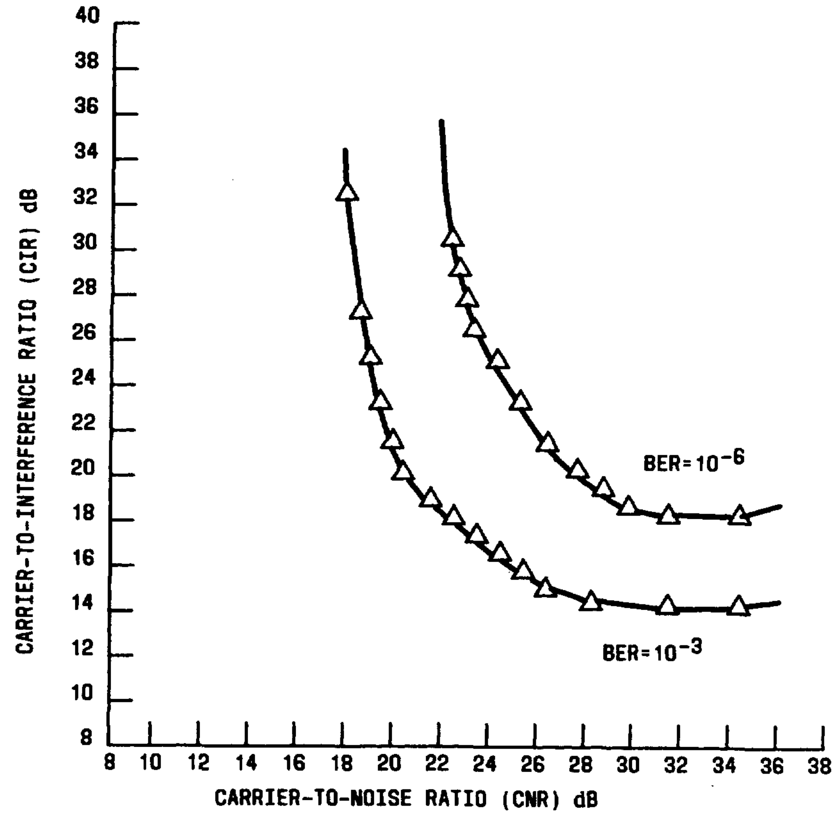
3.13 In digital transmission, the transmitted power is uniformly distributed across much of the radio channel; there is no strong carrier, such as in low index FM. The interference conditions over a narrow bandwidth (such as 4 kHz) do not affect a particular VF circuit carried by the digital signal. The interference tolerance in digital transmission depends upon the total interference power accepted by the receiver; the interference affects all voice circuits in the digital signal equally. The tolerance to interference can be characterized by its impact on the system gain: a C/I of X dB will degrade the system gain by 1 dB. The C/I for cochannel interference resulting in a 1-dB degradation will range from a theoretical minimum of 24 dB to perhaps as high as 30 dB in practical systems. Figure 6 presents an example, based on measured data, of the relationship of BER, C/I, and C/N (thermal noise). Note that the channel bandwidth in this example is 40 rather than 30 MHz (the only data available at the time of writing) and therefore is included for illustrative purposes only.

Adjacent Channel

3.14 With high-capacity digital transmission, some signal energy will necessarily spill over into the adjacent channel even when the transmitted spectrum satisfies the FCC Rules on emission limitations. Further, due to necessary compromises in the receiver filtering, there will be receiver sensitivity to signals in the adjacent channel. Thus adjacent channels have a degrading effect on the system gain of a digital radio. At 6 GHz, the frequency plan calls for adjacent channels to be on orthogonal polarizations. This aids in the discrimination between adjacent channels. A typical statement of a radio system's sensitivity to adjacent channel interference might be: a C/I of Y dB for each of the ***two*** adjacent channel interferences will degrade the system gain by 1 dB. This will provide an indication of the value of cross-polarization discrimination that must be maintained (including fading periods) for a tolerably small influence of the fade margin. The amount of adjacent channel discrimination achieved by transmitter and receiver filtering is a function of adjacent channel spacing. The normal channel spacing, center to center, is 29.65 MHz for the frequency plan. To fully develop a route, the radio system should be designed to operate at this channel spacing. The topic of digital-into-analog interference is discussed in Part 8.

E. Bit Error Rate (BER)

3.15 Bit error rate (BER) is the fraction of bits received incorrectly relative to the total number transmitted. Usually this quantity is measured under some steady state condition so that the bit error rate is the ratio of the number of errors per second to the bit rate in bits per second. The BER may be measured at the DS3 rate (44 Mb/s), the DS1 rate (1.5 Mb/s), or at any multiple or submultiple of these rates. Since at low bit error rates



NOTE: INFORMATION FOR A 30 MHz BANDWIDTH AND ADJACENT CHANNEL INTERFERENCE WAS NOT AVAILABLE AT THE TIME OF PREPARATION

Fig. 6—Example of Relationship of Error Rate, Cochannel Interference, and Thermal Noise for 90-Mb/s (8-Level PSK) Transmission in a 40-MHz Bandwidth

several seconds may pass without an error, it is necessary to observe transmission for an interval which is several times the mean time between errors in order to achieve statistical significance to the error rate measurement. This error counting should be done at the output of the system, after all decoding and descrambling. For each bit error occurring in the radio equipment, typically several errors will be generated in the digital terminal processing. During periods of normal propagation, the radio equipment should, in theory, contribute zero errors. Actual performance of radio systems is such that a typical per-radio hop error rate is 10^{-10} or lower. At such a low error rate, the mean time to an error is about 1 minute at the 90-Mb/s rate. To be 90 percent confident that the true error rate does not exceed twice the measured error rate, one must observe errors for at least 5 minutes.

3.16 A standard DS3 signal has parity bits built into the bit stream by the multiplex; parity violations can be used for error detection. When errors occur in groups, some encoding and scrambling schemes will not necessarily experience parity violations. A consideration in a radio system, especially in instances where switching sections may be connected in tandem, is the restoration of DS3 parity on a per-switching-section basis so that faults can be localized. To further aid in localizing trouble conditions, systems should provide for the substitution of a "blue signal" if the error rate exceeds a threshold, usually about 10^{-3}. This specialized signal contains all of the valid high-level housekeeping bits with a pseudorandom pattern in place of the information bits. The blue signal keeps any following high-level multiplex or transmission equipment from alarming, or initiating protection switching, and thus aids in the fault location process, since only the section failed is alarmed. The blue signal can be considered analogous to the carrier resupply function in conventional analog radio.

3.17 During fading periods, degraded error rate performance may occur. Error rates better than 10^{-6} are of little consequence in the digital transmission of voice since the noise is controlled by the PCM channel banks. At a line error rate greater than about 10^{-3}, voice transmission becomes degraded and the receiving PCM channel banks cannot reliably stay in synchronization. Repeated misframe conditions degrade transmission until the carrier group alarms (CGA) at the receiving channel banks operate, taking the banks out of service and disconnecting all calls in progress. At an error rate of 10^{-3}, one can consider the transmission to be unacceptable and, if the duration exceeds the CGA operation time, an outage results. [The CGA operates when the out-of-frame time exceeds a value specified for a particular channel bank: 300 milliseconds for D1 (except D1D), D2, and early D3, and approximately 2 seconds for D1D, later D3, and D4 channel banks as well as most digital switch terminations.]

3.18 Since an error rate of 10^{-6} is unusual for properly functioning equipment, it is appropriate to request a protection switch at an average error rate of around 10^{-6}. Some hysteresis should be built into the protection switching system so that an excessive number of switching events will not occur. Comparison of switching activity of the radio channels in the system is desirable. A departure of one channel from the average can be an indication of performance deterioration in that channel. From this discussion, one can see the importance of two error rate values: 10^{-6} corresponding to a switch request and 10^{-3} corresponding to an outage. System gains corresponding to these error rates are of interest to the system engineer.

F. Modulation Types

3.19 At the time of writing, most 6-GHz digital systems meeting the FCC 1152-voice-circuit-per-channel requirement are 8 PSK (8-phase, phase shift keyed) with coherent detection or 16 QAM (quadrature amplitude modulation—16 states). Both techniques permit capacities as high as two DS3s (approximately 90 Mb/s) to be achieved in a 6-GHz, 30-MHz channel. The linearity requirements to transmit the 16-QAM signal are more severe than those of a typical 8-phase system, due to the multiple amplitude levels. However, the low baud rate of 22.63 Mbaud for the 90.524-Mb/s capacity reduces adjacent channel interference problems (see Table J) when transmitting in a 30-MHz channel. Both the low baud rate and linearity requirements yield a transmitter spectrum which is narrower than achievable from a 30-Mbaud system. The reduced adjacent channel interference eases full route (eight RF channels) operation with adjacent digital and analog channels.

G. Repeater Types

3.20 One of the most significant characteristics of a digital signal is the ability to reshape and retime, as well as retransmit, the signal at each repeater. As previously noted, such regeneration offsets the cumulative effects of distortion, noise, and interference. When a repeater amplifies and retransmits the received signal without reshaping and retiming, it is said to be a nonregenerative repeater. Since circuitry is eliminated by not regenerating, a cost reduction is effected. For example, if the interconnection is made at IF, then carrier recovery, timing recovery, demodulator, regenerator, and modulator circuits are not needed. However, the distortions and interferences of each span add to one another, lessening the margin for error with each nonregenerative repetition. Some of the disadvantages of a nonregenerative repeater are the lack of access to the baseband signal for maintenance purposes, the possible loss of some fault location capability, possible difficulties associated with auxiliary channel transmission, and the cumulative effects of interference and distortion.

H. Auxiliary Channels

3.21 Auxiliary channel signals can be carried by digital radio either by multiplexing them into the main bit stream or by separate low-level amplitude or phase modulation. Separate modulation techniques always cause some degradation to the payload, but they are relatively simple to implement. The modulation can provide digital or analog channels. Multiplexing additional bits into the payload bit stream slightly increases the bit rate to be transmitted and requires multiplexing equipment at each location where auxiliary channel access is required. On the other hand, this scheme incurs little, if any, degradation to the payload.

I. Maintenance Considerations

General

3.22 The following discussion is intended to enhance awareness of the hardware features and maintenance procedures needed for efficient operation of digital radio systems. In addition to maintenance information of a fairly general nature (for example, FCC-required measurements), the relative merits of various types of maintenance-oriented hardware will also be discussed. Familiarity with the capabilities and limitations of these maintenance aids will help in assessing the suitability of radio and test equipment for a particular application. The importance of maintenance considerations for digital radio systems should not be underestimated. Digital systems are inherently more sensitive to hard-to-find transient problems than analog systems, and maintenance can become a nearly insurmountable task, even on relatively small systems, if the means provided for detecting and troubleshooting problems are not thorough and efficient.

3.23 Early experience with high-speed digital radio has shown some marked contrasts with analog radio which will affect monitoring and maintenance practices and which could have a bearing on various performance indices. Unlike analog radio transmission practices where noise and noise loading measurements are made infrequently, and occasional bursts of noise are usually ignored, digital transmission may be monitored continuously by means of parity bits and/or test patterns embedded directly in the bit stream. Test equipment is becoming available to generate and monitor these test patterns at hierarchical access points within the digital network and to aid in locating defective units of the system. Continuous monitoring can be used to considerable advantage from the early stages of installation onward to check for compatibility of subsystems such as multiplexers, cross-connect fields, and protection switching systems.

3.24 The error performance as monitored should be characterized by long error-free periods, occasional isolated errors caused by marginal transmission on one or more radio hops during fading, short bursts of many errors during multiplex reframing as a result of transients, switching operations, intermittent contacts or other short interruptions, and total outages which may be due to any cause. The need for engineering attention to the causes of the various error conditions cannot be overemphasized. Maintenance activity as herein discussed falls into three categories:

(a) FCC-required measurements and adjustments

(b) Other routine maintenance activities aimed at optimizing adjustments and detecting "silent failures" before they become service-affecting

(c) Fault location and general troubleshooting.

FCC Compliance

3.25 FCC compliance is relatively straightforward, as manufacturers are required to specify all periodic measurements needed to ensure that radio transmitters continue to operate within the rules. At specified intervals, tests must be performed and results recorded in the station log. These tests and all other transmitter maintenance work which may affect the emitted signal must be done by, or under the immediate supervision of, a person holding a general radio telephone operator's license. The measurements (and possible adjustments) specified for meeting FCC requirements encompass two categories of tests:

(a) Determination that frequency sources which may affect the transmitted carrier frequency are within proper limits

(b) Checks on modulation characteristics related to keeping the radiated signal within the proper limits.

3.26 The oscillator frequency test must be made annually if the oscillator units are crystal-controlled or regulated by temperature-controlled or temperature-compensated cavities. If they are not so regulated, oscillator frequencies must be checked monthly. Modulation characteristics must be checked annually. The bit rate can usually be checked by measuring the frequency of an associated clock signal in the transmitting digital terminal. Unlike the tests for verifying the correct carrier frequency which must be done for every hop, the test to determine the bit rate need be done only at the first transmitting digital terminal. All other bit-rate clocks on the same channel will be locked to this one, and should any one of them malfunction, the system will fail immediately. (Blue signal generators are an exception, in that each must be checked separately.) Routine transmitter power measurements, although not required by the FCC, may be done as often as specified by the manufacturer. Power measurements must, of course, be done at every hop.

3.27 Since fulfilling FCC maintenance requirements consists of performing a limited number of very specific tests, and since failure of any test is almost always remedied by readjustment or direct replacement of the unit under test, there is no anticipated difficulty in meeting FCC obligations. Careful planning can significantly reduce the difficulties encountered in making measurements and adjustments of critical circuits. Most measurements and adjustments required by the FCC can be done "in-service."

Other Routine Maintenance

General

3.28 While fairly definite statements could be made about the type of measurements required by the FCC Rules, there is much less certainty about other routine maintenance. Differences in equipment design, and even differences in maintenance philosophy, can lead to wide variations in the type and amount of routine maintenance recommended. Nonetheless, some general remarks can be made to help the user assess the recommended maintenance program. The user is responsible for taking adequate safeguards to prevent loss of service.

Routine Adjustments

3.29 There are usually very few adjustments on modern radio systems which need to be made on a routine basis (excluding FCC-required adjustments). Those which remain usually represent a compromise in favor of manual maintenance in place of increased system cost and electronic complexity, or they provide a fine-grained adjustment of some parameter which adds enough margin to warrant access. The types of routine adjustments which might be recommended could include setting a critical power supply voltage, adjusting the phase of a signal, "tuning-up" a power amplifier, etc. As a guide, one or perhaps two routine adjustments per one-way radio channel per hop would not be excessive. Much more than this could mean excessive maintenance costs which could easily offset any initial savings over buying a system equipped to take care of such things automatically. It may be possible or desirable to simply abstain from all routine adjustments (except those required by FCC Rules) in favor of demand maintenance. This reduces costs and lowers opportunities for operator errors which statistically are bound to occur. However, there is a trade-off to be dealt with which will be discussed below.

Routine Tests to Detect Silent Failures

3.30 A second form of routine maintenance is the discovery and repair of "silent failures," i.e., those due to components or subsystems which when they fail do not immediately affect the performance of the radio equipment. Instead, these failures simply exist with no observable consequences until some new set of circumstances makes them obvious. As a partial list of examples, consider the consequences of loss of AGC range in an amplifier, poor receiver noise figure, or loss of fade range due to erroneous slicing levels in a digital receiver. In unfaded conditions, none of these matter. When fading does occur, any of them can cause premature failure of the channel. Without some form of routine maintenance program to detect them, equipment problems may be diagnosed as statistically excessive fading. This same sort of undiscovered "loss-of-margin" difficulty can be experienced as a result of demand (rather than routine) adjustment of critical system parameters.

3.31 The previous examples of silent failures were all of a kind such that, if fading did occur and the channel did fail prematurely, the protection switching system would take over and prevent a loss of service. This would remain true up to a point, but unbalanced or excessive demands on the protection channel would eventually lead to an overall reduction in reliability. Another type of silent failure is one which eventually leads to loss of service. For example, the performance monitor which must initiate a protection switch may be quietly failed. The actual switch, the protection switch signaling, coding, and decoding apparatus are all similarly vulnerable. (Failures of this type are further considered under equipment outage, Part 7.) These are all subsystems which may fail to do their jobs and may thus cause an unnecessary service failure if routine maintenance checks do not assure that they are operational. In short, use of equipment which automatically exercises all off-line functions and all features which are not used or tested on a regular basis is recommended.

Fault Sectionalization and Localization

General

3.32 The most difficult aspect of maintenance is troubleshooting. In this respect, digital systems are harder to maintain because they are more complex than analog systems; i.e., while radio equipment can be similar, terminal equipment is more complicated. Whereas an FM receiver contains tuned circuits, a rectifier, and linear amplification, a digital terminal receiver may include multiple phase-locked loops, multiple demodulators, combinational logic circuitry, and numerous timing and framing signals and associated hardware. In most analog systems, repeater stations have only microwave radio equipment and no terminal equipment. Digital systems often employ regenerators at intermediate stations, making these stations nearly as complex electronically as terminal stations. In addition, the ability of digital systems to regenerate and eliminate cumulative distortions on multihop systems also means that simple analog test signals can no longer be routinely sent from one end of a system to the other as a means of providing a quick, overall check of performance. An analog test signal would be blocked upon encountering the first regenerator. Finally, digital systems, despite their inherently rugged nature, are much more sensitive to transient problems than analog systems. Submillisecond transient phenomena which were not considered significant to analog communications now show up as thousands of bit errors and sometimes as losses of frame throughout the digital hierarchy being served by the radio system. These problems can sometimes be ignored without penalty if the payload is entirely digitally encoded voice, but if data is to be carried, such transient problems should be substantially eliminated. As a practical matter, the ability to determine that bit errors are occurring will mean that maintenance crews will be called upon to eliminate them regardless of the nature of the payload. This may not be lost effort since transients often foretell more serious problems ahead, but it does present a significant maintenance challenge.

Troubleshooting and Protection Switching

3.33 Troubleshooting techniques are partially determined by the type of protection switching used. Hot-standby protection (with or without space diversity) restricts testing to equipment tests at individual repeaters; out-of-service testing of a channel over tandem hops is not generally possible. Frequency diversity allows out-of-service testing on a switching section basis. Figure 7 is a block diagram showing the major components of a digital radio protection switching section for a single one-way channel. A switching section can be several hops long, and will probably have regenerators at most intermediate stations, although there is the possibility that some radio systems will be configured in such a way that a straight-through connection from the radio receiver to the radio transmitter will be allowed at some intermediate stations. (Such stations would then be termed repeater stations rather than regenerator stations.) The digital terminal transmitter at the head end of the system processes the high-speed digital signal before it is transmitted over the radio, and the digital terminal receiver at the receiver end of the switching section takes the signal out of the format required for radio transmission and puts it back into the format required for transmission to the receiving multiplex. Regenerators are normally composed of some fraction of the circuitry required for a digital terminal receiver and a digital terminal transmitter.

3.34 Each end of the system is equipped with a radio protection switch. Signaling may be required between the ends to coordinate switching actions. Some type of performance monitor at the receive end of the system monitors the received signal and is responsible for initiating and releasing protection switches. Drop and add repeaters (Fig. 8) or junction or spur routes (Fig. 9) may be included within a switching section in some systems. Overall economy may result from these arrangements even though more complex command and control logic is needed than would be necessary with simple section switching.

Failure Sectionalization

3.35 One immediately apparent maintenance consideration concerns failure sectionalization between the radio system, the multiplex, and the channel banks. Some radio/multiplex systems may employ a system of blue signals which can be automatically switched onto the line to prevent alarming of downstream equipment due to the failure. Alternatively, the alarm system may be set up in such a way that multiplex and channel bank personnel have easy access to radio performance information. In this way, alarming in multiplex and channel bank units can be ignored when it is clear that the radio system is at fault.

In-Service Performance Monitoring Options

3.36 Performance monitoring is paramount to digital system maintenance. It is difficult, if not impossible, to troubleshoot a digital system efficiently if the performance monitor cannot detect varied types of failures in radio, regenerator, or digital terminal equipment. (This is especially true in systems consisting of multiple switching sections.) Not only is the job of troubleshooting made much more difficult in such a situation, but the transmission availability of the system will be in serious question. The performance monitor is responsible for issuing protection switch requests. It cannot perform this function adequately if it cannot detect all types of failures. Two general types of in-service performance monitors will be discussed. They are:

(a) Those which rely primarily on "eye-opening" measurements, supplemented by numerous activity detectors and other alarms

(b) Those which rely primarily on the measurement of parity violations, sometimes supplemented by activity detectors and alarms.

3.37 So called "eye" diagrams are an oscilloscope figure formed by superimposing all possible pulse sequences over a duration of two signaling intervals. The measurement of eye-opening is basically a measure of margin against error made on the analog signal delivered to the digital terminal receiver by the radio, and is made after demodulation but before the signal is regenerated. Eye-opening measurements can detect failures due to intersymbol interference, excessive radio thermal noise, and interference along the radio path. Thus, most microwave radio problems can be detected in this way. However, eye-opening measurements are almost totally ineffective against digital problems which may occur in regenerators and terminals. For this reason, they should be supplemented by activity or "energy" detectors which monitor various critical points in an effort to detect catastrophic failures which result in loss of signal within the digital terminal. A shortcoming to activity detectors is that they leave undetected a significant class of failures: those failures of combinational logic circuitry and other subsystems which do not result in loss of activity. The outputs of logic gates and flip-flops do not necessarily freeze when marginal conditions exist or failures occur. Data can continue to flow, but it will contain errors, many times to the extent that the system becomes totally unusable. Digital terminals and regenerators can contain scramblers, coders, countdown circuits, and numerous other circuits which are digital in nature and which may fail in this manner. For these reasons, the detection of parity violations is a powerful monitor of performance. Parity monitors examine the received signal after it has passed through all of the circuitry mentioned above. The framing pattern of the signal is detected and the monitor locks into the parity bit which was inserted by the multiplex at the head end. By comparing the parity bits to groups of received data,

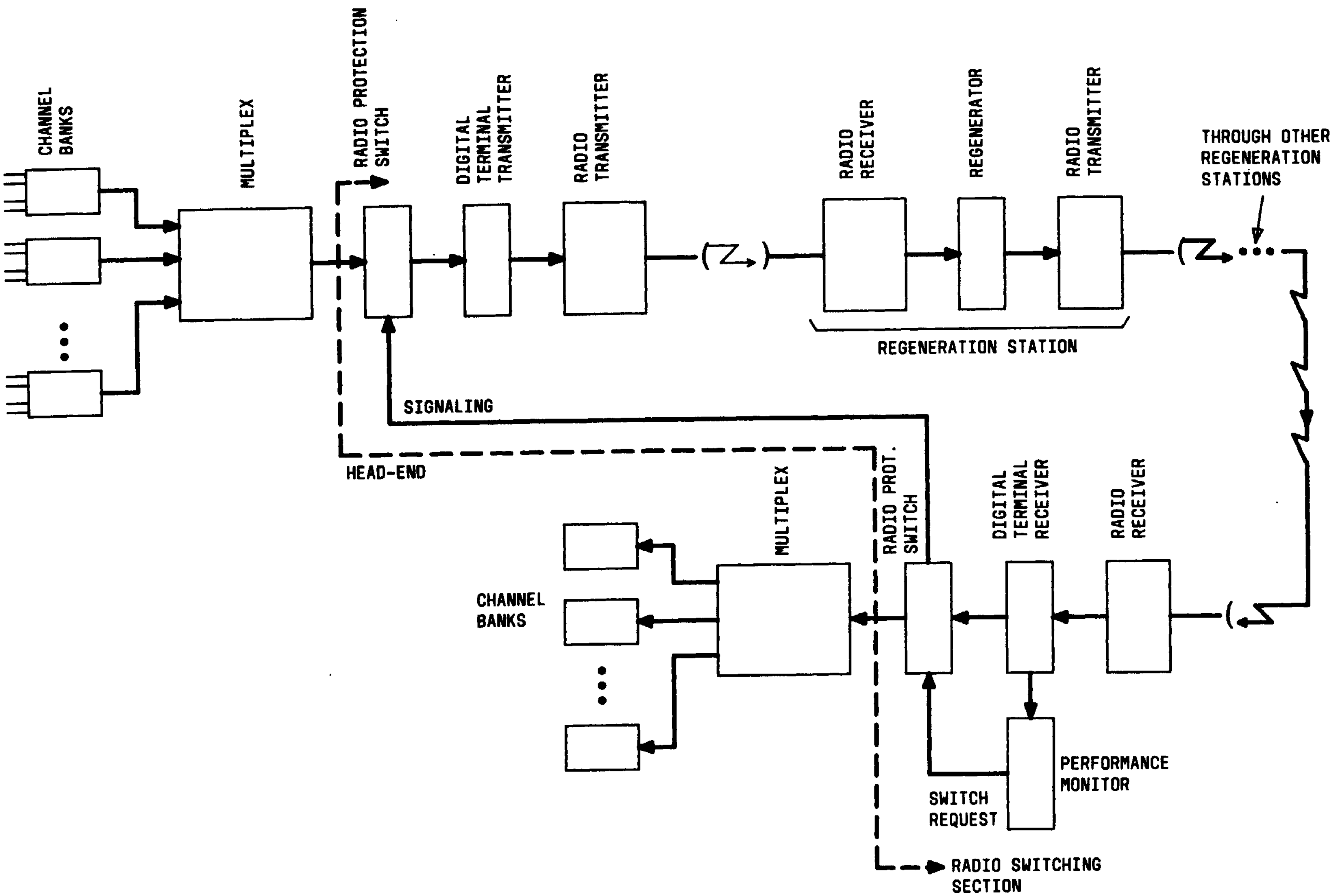


Fig. 7—Radio Switching Section—Block Diagram

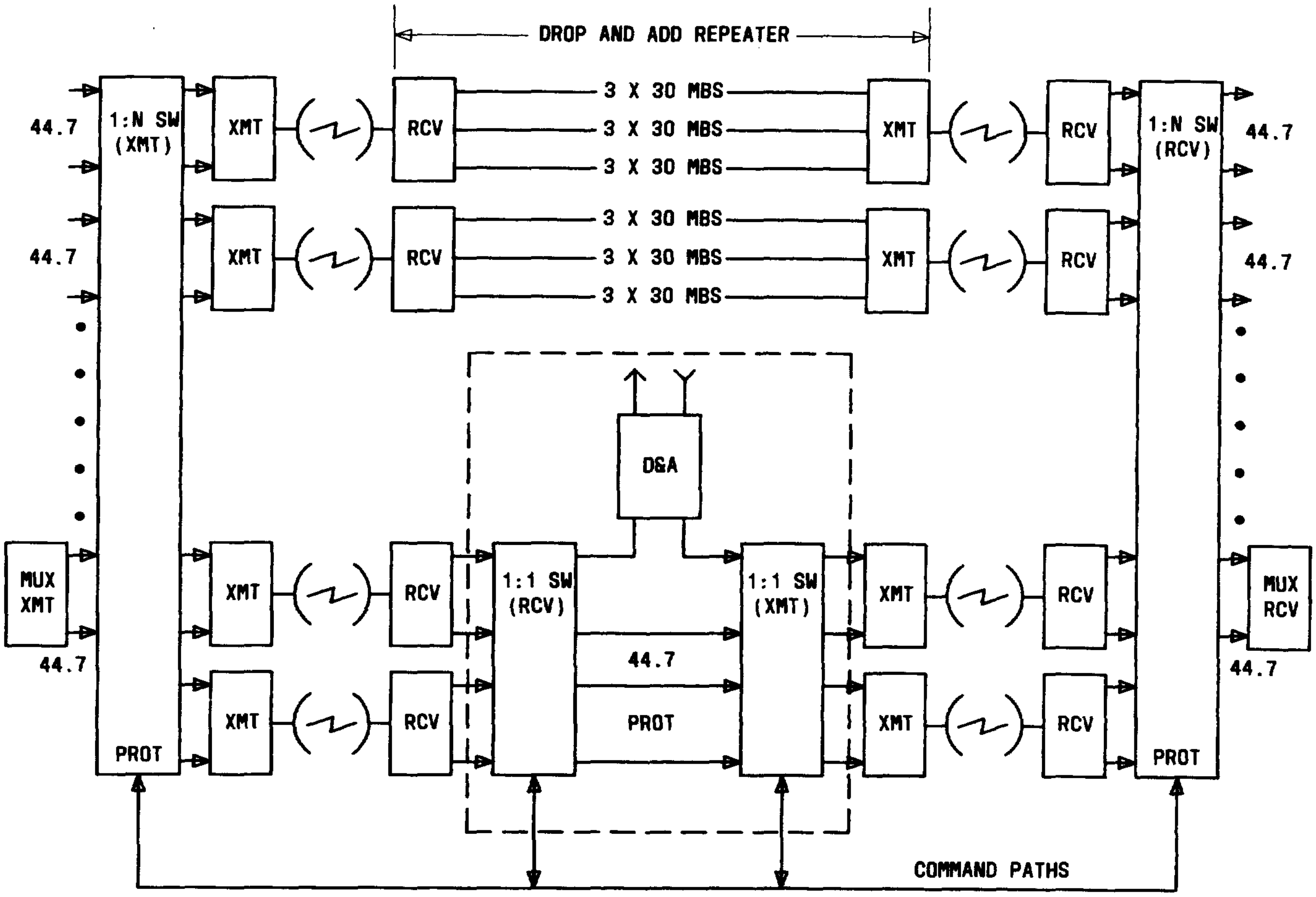


Fig. 8—1:N With Drop and Add Repeater (90-Mb System Shown)

the performance monitor can detect digital errors regardless of their source. Obviously, to be totally effective, the performance monitor must examine the data stream at the very end of the system. For various reasons, this is not possible. Some small amount of circuitry may follow the performance monitor, in which case activity detectors should be used on this circuitry to supplement the process of monitoring parity violations. Examination and comparison of the time history of performance monitor records can point to radio channels that have subnormal performance. Finally, it should be added that monitoring bipolar violations is generally an unsuitable way to determine the performance of the digital radio system. The digital signal is normally stripped of all bipolar characteristics early in the process of preparing the signal for radio transmission. The bipolar format is usually reinstated at the very output of the radio digital terminal receiver. Thus, failures of the digital and/or microwave radio equipment have no connection to the bipolar format.

3.38 The sources of background errors on a multihop digital radio route are not easy to troubleshoot because:

(a) Most of available digital radios lack a per-hop indication of background errors

(b) Most background errors do not affect message telephone service (MTS) and do not initiate remote alarms or carrier group alarms

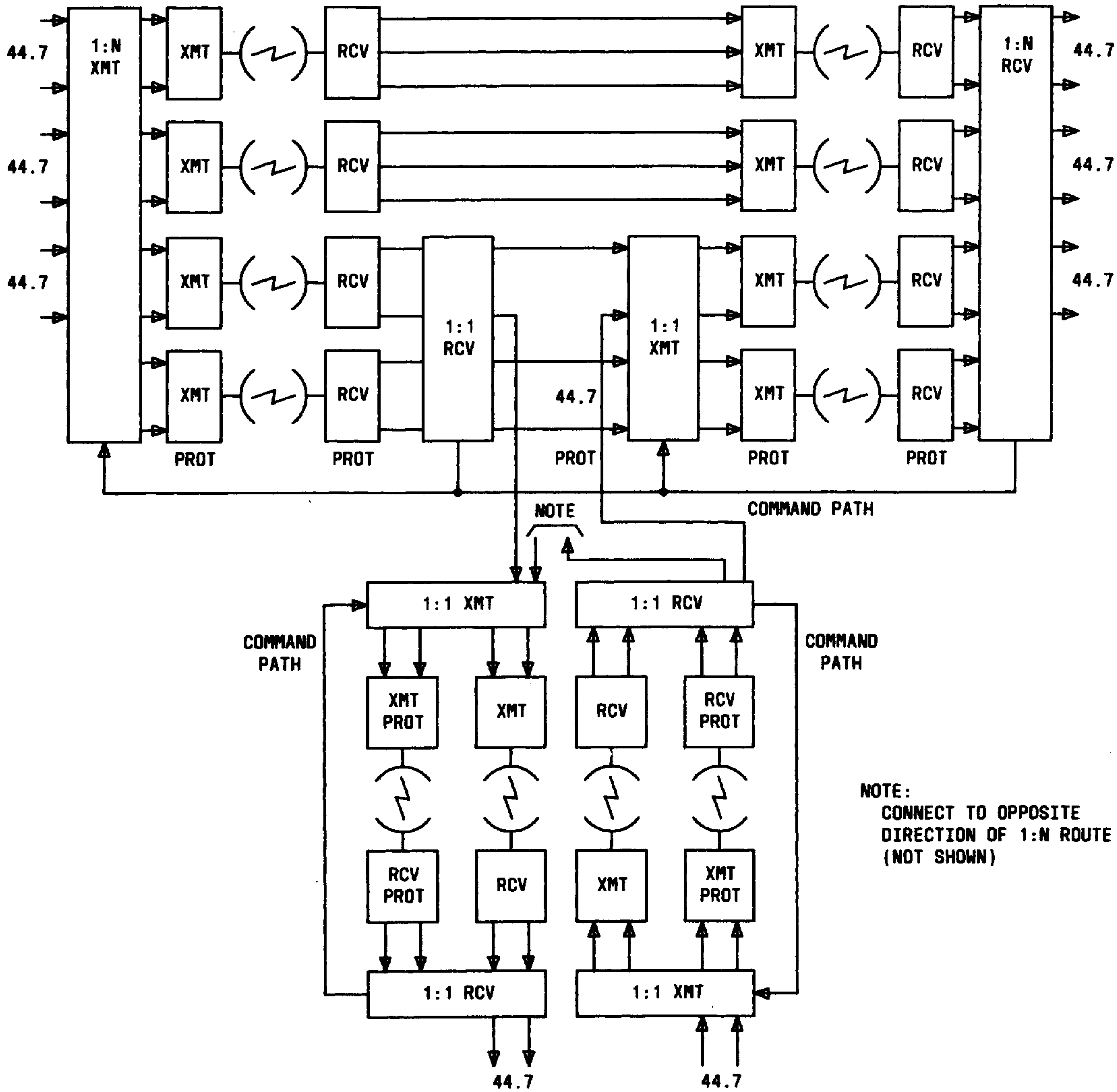


Fig. 9—1:N With Junction

(c) Some background errors initiate short intermittent local alarms. However, radio fading can also cause short intermittent alarms. The fading-caused alarms are confusing to a craftperson attempting to locate equipment problems.

3.39 The existing maintenance procedure requires tedious and time-consuming out-of-service tests to locate the trouble source. Based upon these experiences, the following additional features are desirable for future digital radio to carry the more demanding digital services such as PICTUREPHONE® Meeting Service (PMS), DDS, etc.

(a) Detection of background errored second on a per-hop basis using some coding schemes such as parity check and parity restoration on every hop

(b) Separate fading-caused error seconds from equipment generated background error seconds (e.g., use AGC voltage for fading indication)

(c) Count errored seconds per day per hop excluding fading-caused errors

(d) If the number of errored seconds per hop exceeds the objective in a 24-hour period, initiate local and remote alarms so that the alarm center can immediately dispatch a craftperson to the trouble station for correction.

Alarming and In-Service Fault Locating

3.40 Regardless of the method used for performance monitoring leading to switch initiation, it is beneficial to have alarms in strategic locations forming an in-service fault-locating network. Such a system would not be totally effective since most types of alarms have the same shortcomings with respect to detecting digital failures as mentioned above for activity detectors. One very thorough method of alarming is to use a parity monitor and its associated circuitry at every regenerator. By reporting the parity monitor output back through the alarm system, sources of trouble can always be pinpointed to within one station of the actual location. Early experience on digital radio systems indicates that it is desirable that these in-service monitors have the capability of detecting and reporting very low error rates, perhaps even single errors. This capability adds significantly to the ability to locate intermittent problems and to detect the onset of degraded performance, thus reducing the possibility of silent failures.

3.41 A major factor affecting the value of alarms is the type of human interface provided. Knowing that a whole group of alarms were activated in the last half hour is often insufficient information. The order in which the alarms occurred is very valuable knowledge. The alarm system should be automatically scanned, the results printed out, and the alarm system cleared in preparation for new incoming alarms. Of course, the output should be in a form which can be used with minimal decoding.

3.42 Except for alarms generated by very fast circuitry, such as parity monitors or eye-opening detectors, most very short transient problems cannot be detected in service. These troubles must often be located by special test equipment on an out-of-service basis. However, alarms are often useful in detecting longer transient problems. Aside from its function as a method of reporting alarms to a central location, the alarm system acts as a memory for alarm information. The fact that an alarm was activated should be stored in the alarm system even after the alarm itself has cleared. However, this memory, though useful, is often inadequate for making the best use of alarms during troubleshooting. Many times the alarm reported to the alarm system is actually the result of combining a number of separate alarms. For example, several points within a digital terminal may be separately alarmed, but only one alarm for the overall terminal may be reported. The alarm system is then capable of storing within its memory the fact that a digital terminal alarm occurred, but information as to exactly which alarm within the digital terminal was activated is unavailable. Memory or stretching must be provided for short duration events (<15 seconds) where it is determined that knowledge of such events, e.g., error bursts, protection switching, etc., will be needed to properly maintain the digital radio system. As used here, memory refers to holding an indication in a telemetry remote until it is scanned. Stretching refers to a feature of the monitoring equipment in which an indication once set will remain set for a predetermined time to ensure that the point will be scanned and the indication reported even if the monitored point quickly returns to normal status. Latched alarms which hold an indication indefinitely until released by external commands should be avoided. Additional information on alarms is contained in ATT PUB 43803, "Facility Maintenance Features Required for Interoffice Digital Transmission Equipment."

Out-of-Service Fault Locating

3.43 As a last resort for finding a trouble within a radio channel, equipment can be taken out of service and various tests performed in order to locate the source of the trouble. For troubles which appear as a constant poor bit error rate, one method of troubleshooting often used is a trial-and-error replacement of various circuit boards or plug-in modules until the trouble disappears. This method relies on the alarm system to provide information about the general location of the defective circuitry and is useful only on those pieces of equipment where trial-and-error replacement of circuits is not too time-consuming.

3.44 For troubles which are not amenable to the trial-and-error method (such as transients with substantial times between occurrences) or for troubles occurring in equipment without any easily changed modules, different techniques of fault location are necessary. With frequency-diversity protection, some systems may permit digital test signals with known patterns to be inserted at the head end while all regenerators and the digital terminal receiver are monitored to determine the location at which errors first occur. If the information derived from these tests is automatically relayed back to the service center, the source of trouble can always be determined to within one hop of the actual location before dispatching maintenance personnel. A less efficient but sometimes necessary method of fault location requires that the system be energized with a digital test signal from the head end and the source of trouble sought by transporting a digital test set receiver to successive locations until the trouble is found.

Test Equipment

3.45 Test equipment which often proves useful in troubleshooting a system or performing routine maintenance includes the following:

(a) Digital test set transmitter and digital test set receiver. The transmitter should be capable of generating a known digital test pattern, and the receiver must be able to detect and display errors in this pattern due to radio system problems.

(b) A portable test terminal made up of combinations of circuitry which allows it to simulate a digital terminal transmitter, a digital terminal receiver, or a regenerator.

3.46 In addition to these pieces of test equipment which are peculiar to digital radio systems, more traditional types of test equipment associated with analog radio systems may sometimes be needed to complete the task of fault location. Regardless of whether digital modulation takes place at IF or RF, the microwave radio equipment, as distinguished from the digital terminal equipment, is a collection of analog amplifiers, filters, and mixers. It is subject to interference from all of the same sources which affect traditional analog radio systems. Thus there will be times, though hopefully rare, when spectrum analyzers, transmission measuring sets capable of displaying EDD and amplitude versus frequency, and equipment capable of searching for spurious tones must be employed.

4. RELIABILITY

A. General

4.01 This part introduces discussions of outage objective determination and the contributions of multipath fading, equipment failure, and interference to this outage.

B. Digital Objective

4.02 Outages in digital radio transmission will be perceived by customers as disconnected calls, since all calls in progress are disconnected when the error rate at a digital channel bank persistently exceeds a threshold and causes a carrier group alarm. This differs from FM radio where customers make their own decisions on when to terminate a temporarily noisy connection. The outage objective for both analog and digital systems is usually stated as a percentage outage time averaged over long time periods (and over all channels in a route).

C. Causes of Outage

4.03 There are seven mechanisms that cause transmission errors on digital radio. Rain outage, however, becomes significant only at frequencies of 11 GHz or higher. The remaining six mechanisms of concern to 6-GHz digital systems are as follows:

1. ***Multipath Fading:*** A statistical multipath fading model exists to allow an estimate of the time when the signal power will fade below any level for a given radio route. General information on multipath fading can be found in Section 940-310-102.

2. ***Obstruction Fading:*** Obstruction fading (i.e., earth bulge) is caused by unusually strong vertical gradients in air temperature and humidity. Severe obstruction fading causes transmission outage. An engineering model and a computer program, OBSFAD, provide the method for determining antenna tower heights of the radio paths to meet the allocated outage objective which is 25 percent of the total outage objective.

3. ***Equipment Failure and Human Error:*** For route design purposes, outage in this class should be controlled to be less than 25 percent of the total outage. EL-4687 and EL-6120 as well as Part 7 of this section provide methods to estimate the equipment failure time.

4. ***Background Errors:*** Transmission errors on digital radio have been observed with no apparent cause (none of the above). They usually occur at a very low bit error rate. The background errored seconds should, at most, cause temporary blemish or temporary interruption. They dominate the errored-second performance. The cause of background errors has not been fully understood yet. However, it has been demonstrated that, when a digital radio is correctly adjusted initially and properly maintained, the background error rate can be kept to a low and acceptable level; e.g., 5 errored-seconds per day per 10-mile hop per 1-way transmission measured at DS1 level.

5. ***Interference:*** As previously discussed in paragraphs 1.06, 3.13, and 3.14, interference is also treated distinctly from analog methodology and is covered in Part 8.

6. ***Upfades:*** Atmospheric variations somewhat similar to those that cause multipath or obstruction fading can lead to periods when the path loss temporarily drops to values less than normal. If the upfade is large enough, the higher than nominal signals may overload the radio receiver and lead to high error rates. Methods for computing the time that a given path may have an upfade exceeding a stated amount are given in EL 7622 (IL 82-06-207).

D. Diversity Protection

4.04 Space-diversity and, in the case of multichannel routes, frequency-diversity protection reduce the effects of multipath propagation. Frequency-diversity protection becomes less effective as the number of working channels increases, and the improvement factor or I_0 obtained with both space and frequency diversity degrades with reduced fade margins. Furthermore, frequency diversity might not be permitted on routes with few channels. Route engineering tools such as the computer program FMDIV can calculate the outage reduction due to frequency diversity (FD). Available experimental data indicate that the calculations are somewhat conservative, i.e., the actual outage with FD is less than the computed outage. Equipment protection will be provided by hot standby or frequency diversity which, when available, can facilitate off-line maintenance on otherwise working channels through transfer of the message load.

4.05 The normal configuration for space-diversity protection is one transmitting antenna and two vertically separated receiving antennas. Various means for processing the two received signals are possible, such as blind switching, continuous phase-aligned combining at RF or IF, or switching between time-aligned data streams at baseband. The expected improvement due to space diversity can be calculated as a function of the vertical separation of the receiving antennas, path length, frequency, and fade level. Application of this improvement to predicted fading for a path provides an estimate of the residual multipath outage time for the path in question.

4.06 Space-diversity antennas can frequently be placed below main antennas (see heading F). This minimizes the cost of tower strengthening. Placement of diversity antennas above main antennas may increase costs, since tower strengthening requirements increase with height; the separation in such cases should be no larger than that required to meet outage objectives.

E. Paths With Ground Reflections

4.07 Paths with ground reflections are undesirable, but if unavoidable ground reflections exist, then space diversity can be used to reduce their effect. Ground reflections put constraints on antenna placement, since the received signal has maxima and minima along the height of the tower depending on the relative phase of the directly-received and ground-reflected energies. Examples of terrain generating ground reflections are lakes, sandy areas without vegetative cover, or flat farmed areas when these are not shielded by ridges or forests. Path test results showing received signal ripple larger than ±2 dB as antenna heights are varied indicate the presence of significant ground reflections. Section 940-330-160 includes a method for locating reflecting points.

4.08 Main antennas should be placed to provide as near a maximum signal as possible when the atmosphere is normal. One antenna in a space-diversity pair should be at or near a maximum when the other is at a minimum; placement such that both antennas are at minima should not be permitted to occur under any expected atmospheric conditions. With antennas properly placed to accommodate ground reflections, calculation of outage due to multipath fading proceeds as before, but antenna separation must now satisfy both outage requirements and reflection constraints.

4.09 Space-diversity design for reflective paths is complicated by the fact that the locations and spacings of maxima and minima on a radio tower are functions of atmospheric gradients, i.e., functions of K. Analytical design procedures are available for overland paths with fixed reflection points (isolated reflecting areas). Graphical procedures based on computer-generated drawings of path profiles and Fresnel zone boundaries (Sections 940-310-105 and 940-310-104) are suitable when reflection points have not been determined by path testing, or when the reflecting area is large (many miles), permitting a shift of reflection point as K varies. Considerable engineering judgment is required in placing antennas on reflective paths; personnel specializing in route engineering and path testing should be consulted when reflection designs are needed. Section 940-310-115 contains a discussion of space diversity on reflective paths.

F. Terrain Clearance

General

4.10 Minimum tower heights needed to prevent the terrain from blocking transmission are specified by clearance rules, which take into account the deviation of the transmitted radio beam caused by changes in refractive bending introduced by anomalous atmospheric conditions. Clearance is the vertical distance from the terrain to the ray path that describes propagation from the transmitting to the receiving antenna. The clearance is termed grazing when the ray path is tangent to the controlling obstruction; it is negative when the ray path is blocked. Obstruction fading is more pronounced at night when atmospheric stratification and consequent beam bending can create temporary blockage on microwave paths which are otherwise clear in a "standard" daytime atmosphere. Refractive bending is characterized by a number denoted by K, which is the ratio of the radii of an equivalent earth used in drawing path profiles and the actual earth.

4.11 Recent advances in meteorology and statistical estimation of annual obstruction fading make it possible to determine required antenna heights from transmission performance objectives. This method, embodied in a computer program (OBSFAD), is discussed in Section 940-310-103.

The OBSFAD Program

4.12 Obstruction fading is estimated individually for each path (hop). The variables determining the amount of obstruction fading are the centerline heights of the antennas, path geometry, radio frequency, fade margin, and a set of parameters that provide a geophysical and meteorological description of the path. These parameters are the means and the standard deviations of the probability distributions of positive refractivity gradients.

4.13 The procedures for estimating obstruction fading are in the OBSFAD program. Users of the program can determine the refractivity means and standard deviations for their paths from United States contour maps prepared for this purpose. These maps are included with instructions on the use of the program which is distributed to operating company frequency coordination representatives. The program is available in the MRSELS CMS time-sharing system.

4.14 Engineering judgment is presumed in applying the results obtained from the method outlined in this section. In the case of economic or technical constraints, the quantitative methodology for obstruction fading design permits parametric and tradeoff studies to determine the best course of action.

Short-Haul Objectives and Options

4.15 Microwave radio transmission performance objectives for a hop in long-haul service differ from those for the same hop in short-haul service. Corresponding differences in antenna heights are possible in some cases, as specified by allocations of objectives, since the method relates antenna heights to performance objectives. This is a change from previous practice, where one set of clearance rules applied to both long-haul and short-haul service.

4.16 For short-haul service, the annual all-cause 2-way transmission unavailability objective of 0.02 percent applies to a 250-mile route (630 seconds per year prorated to a 25-mile hop). Two options are available for allocating a part of this objective to obstruction fading. The choice of option, based on technical and economic factors, is a prerogative of the route planner and the route designer.

4.17 One option is to use the long-haul obstruction fading allocation of 10 seconds per year prorated to a 25-mile hop. The resulting antenna centerline heights can be used for any radio system in a given frequency band, and long-haul traffic can share the antennas. The antenna heights reduce obstruction fading to negligible proportions (10 seconds or less out of 630 seconds). Because of this, previous design practices regarding multipath fading, rain, and equipment can remain unchanged.

4.18 A second short-haul option is a prorated obstruction fading allocation of 160 seconds per year for a 25-mile hop. This retains the standard 1-to-16 ratio of per-mile performance between long-haul and short-haul service for an impairment that affects all radio systems. The resulting centerline heights of the antennas are smaller than those obtained from the 10-second allocation. This option can be used ***only*** when the characteristics of the communications traffic and the radio system are sufficiently firm and permanent to be incorporated into antenna height requirements. In cases where the estimated obstruction fading is less than the allocation, the unused portion of the allocation can be applied to other categories of impairments.

4.19 When used as design criteria, the short-haul obstruction fading allocations are prorated to the length of the switching section or route segment between terminals or drop and add points.

4.20 Table A illustrates OBSFAD calculated antenna heights and outage time between two stations (H and J) in northern Florida. The value of outage time is estimated for a number of antenna pairs. To relate these results to operational experience and to permit introduction of engineering judgment, the centerline pairs are associated with grazing values of K, defined as the value of K at which the ray path between the antennas is tangent to the controlling obstruction. The centerline pair of 220 feet at Station J and 270 feet at Station H has a grazing K that is slightly less than 1/2, but this combination does not meet the design objective of 9.7 seconds per year for this 24.3-mile path, based on the 10-second allocation. The objective is met for centerlines of 350 and 325 feet, for a grazing K that is close to 1/3. A suitable height for a diversity antenna at Station J is 300 feet, which provides a 50-foot vertical separation of the antennas. Requirements and objectives applicable to diversity antennas are elaborated in Section 940-310-103.

TABLE A

STATION J—STATION H OBSTRUCTION FADING

PATH LENGTH = 24.3 MILES FREQUENCY = 6.0 GHz FADE LEVEL = −35.0 dB			
ANTENNA CENTERLINES, FEET ABOVE GROUND		OBSTRUCTION FADE TIME, SEC/YEAR	GRAZING K
J	H		
220	270	1351	0.4759
270	270	389	0.4236
300	270	175	0.3974
300	300	79	0.3751
300	325	39	0.3584
325	325	19	0.3425
350	325	8	0.3279

5. OUTAGE OBJECTIVES

A. General

5.01 This part reviews the historical outage objectives and then applies these objectives to long- and short-haul facilities. Guidelines are given for limiting the maximum length of short-haul facilities to conform with objectives set by the model, and a procedure is suggested for meeting the objectives when route lengths exceed the limitations.

B. Historical Objective

5.02 The outage objectives for radio systems are stated as an accumulated annual outage time (0.02 percent 2-way per year) occurring on a system no longer than 4000 miles for long-haul systems and 250 miles for short-haul systems. Shorter systems are allocated a porportional share of the objective based on their length. These objectives were designed:

(a) To ensure enough available trunks so that the microwave system would not contribute significantly to overall network blocking

(b) To limit the actual outage time to about the same duration that maximum tolerable noise was permitted.

For analog radio systems, most failure modes lead to high noise conditions. Customers with calls in progress at the time of failure usually can make their own decision on when to terminate a connection. In sharp contrast, with trunks operating over digital channel banks equipped with carrier group alarms (CGA), the customer has no option; all calls will be disconnected when error conditions exceed the CGA threshold. For digital systems, the outage definition is based on the CGA threshold and current CGA timing. A line ***BER*** $> 10^{-3}$ lasting for two or more seconds has a high probability of triggering a CGA and disconnecting all message trunks and many private line channels. A proposed International Telegraph and Telephone Consultative Committee (CCITT) definition extends the timing interval to 10 seconds.

5.03 The historical allocation of total outage time to the several outage mechanisms has been:

(a) 50 percent to propagation (multipath, rain, and upfades)

(b) 25 percent to obstruction fades

(c) 25 percent to equipment failures/man-made failures.

These allocations are to be interpreted as guidelines in the absence of specific route information. In engineering specific routes, obstruction fading time (see paragraph 4.10) is computed and tower heights are adjusted until the time is equal to or less than the 25-percent allocation. If the computed obstruction time is less than 25 percent of the total objective, the unused allocation can be added to the allowable multipath propagation outage. In a similar way, the equipment outage is limited to a maximum of 25 percent and when the computed outage is less than 25 percent, the difference can be added to the multipath allocation.

C. Long-Haul Versus Short-Haul Systems

5.04 The distinction between long-haul and short-haul systems made above requires clarification. In the past, certain carrier and radio systems were usually engineered to be long-haul systems. They were designed to meet both noise and outage performance objectives suitable for use on circuits several thousand miles long. Other systems were considered short haul; their design allowed higher noise and more outage time than a similar length long-haul system. The length of such short-haul facilities typically did not exceed 250 miles. With the new digital systems available today, the noise performance is not determined by length. Indeed, when digital facilities are switched by No. 4 ESS machines, the noise on the overall connection is normally completely independent of both distance and the number of intermediate switches. Only the outage objective remains as a significant difference between long- and short-haul facilities.

5.05 Short-haul facilities can be defined as those designed to meet the short-haul outage objective of 0.02-percent outage time at 250 miles (400 km), while long-haul facilities are those whose outage objective is 0.02-percent outage time at 4000 miles (6400 km).

D. Maximum Length of Short-Haul Radio Systems

5.06 Previous discussions presented the outage objectives for trunks on both short- and long-haul facilities. This discussion recommends maximum lengths for short-haul radio facilities. Longer trunks are assumed to be routed over facilities meeting long-haul outage objectives. The length restriction is needed both to maintain the average short-haul trunk length to approximately the value assumed in setting the objective and to limit worst cases to an acceptable outage.

5.07 The general recommendation is that no more than 250 miles of short-haul facilities should be connected together in any call. To meet this recommendation, short-haul facilities into a high-ranking toll switch are nominally limited to 125 miles from the most distant toll center homing on that switch. This ensures a maximum of 250 miles when either two such trunks are switched together or a long-haul trunk from a distant area is switched to a short-haul trunk at each end. (In Part 11, the specific guidelines allow exceptions to the above generalized 250-mile limit of up to 300 miles. Additionally, the nominal 125-mile distance specified above serves as a simple example which, in Part 11, takes into account the rank of the offices and their homing pattern to derive the maximum length short-haul radio system allowed between specific offices.) These maximum length recommendations are more restrictive than those previously used. These restrictions are necessary because of the trunking patterns of the digital radio systems currently foreseen and the need to control the worst case outage to a reasonable level.

5.08 The trunking patterns currently foreseen are a result of the deployment of No. 4 ESS digital toll switching equipment. These switching machines have, in many cases, been the controlling element in the decision to implement digital microwave systems as opposed to other types of facilities. The character of the placement of the No. 4 ESS equipment is typically leading to a small number of machines to provide toll switching for a comparatively large geographic area. This will require longer trunks and tend to increase the average trunk length unless the maximum length is restricted. The overall objective is to keep the average short-haul trunk length to the 62.5 miles used in setting the objective, thereby ensuring that on the average the objective is met.

5.09 It is also necessary to consider worst-case conditions which could be encountered and to restrict these to reasonable levels. Also important is the fact that the aforementioned trunking pattern also tends to reduce the number of possible connections from a given office to the switched network which leads to an increased probability that the longer trunks will be encountered. This unfortunately ensures that customers who happen to encounter the worse-than-average performance due to the system design will do so consistently.

E. Route Design to Standards Tighter Than Short Haul

5.10 The application rules thus far discussed are intended to limit the length of short-haul facilities in any connection to a nominal maximum of 250 miles with a worst case of 300 miles. Applications not falling within those guidelines should be routed on long-haul facilities. It is feasible to design segments of the short-haul network to standards tighter than short-haul (but more lenient than long-haul) objectives, thereby establishing a short-haul system which has an outage performance equivalent to that of a short-haul system of less length. This "equivalent short-haul length" would then be used in all calculations of allowable short-haul system length.

5.11 An example might be a proposed short-haul route from a class 4 office to its home chain class 3 which is 180 miles away. This length exceeds the 125-mile maximum length by 55 miles. The new route must be designed to have an equivalent short-haul length of 125 miles or less.

5.12 The necessary improvement can sometimes be obtained by adding a more advanced adaptive equalizer, by adding one repeater to a planned route, or by providing space diversity on one or more hops over that required by short-haul objectives. Part 11 gives a worked-out example for a portion of an intrastate network using both the application guidelines and the concept of equivalent short-haul length.

6. DISPERSION OUTAGE

A. General

6.01 As noted in the introduction to this section, the propagation dynamic of dispersion acting on digital signals constitutes a critical factor which exceeds the deleterious influence of multipath fading, per se, in thermal noise limited systems such as conventional FM. During multipath fading, distortion (dispersion) of received signals is critically important to determining outage in a digital radio system. The recommendations in this part are based on results from field investigations of available digital radio equipment.

B. Dispersion

6.02 At any instant, the vector sum of the interfering and direct rays is a continuous function of frequency, often varying significantly over a frequency band corresponding to a channel assignment. Multipath fading therefore distorts the amplitude and phase (and envelope delay) of the signals carried over the channel. This distortion is called dispersion. The error rate in digital transmission is extremely sensitive to dispersion, which therefore complicates the estimation of outage, since the degree of dispersion obtained at a particular (nominal) fade level can vary widely from fade to fade. On the average, however, dispersion increases as fades become deeper. The amplitude (and phase) variations over the band occupied by a radio channel can be partially compensated for by including an adaptive equalizer in the radio receiver. A simple slope equalizer will make the transmission equal at the upper and lower band edges of the channel. More complicated equalizers are available to provide additional control of the amplitude shape of the channel. Such equalizers significantly reduce the outage time due to multipath fading, with the improvement going up as the equalizer becomes more complex.

C. Estimation of Outage

Outage Equivalence

6.03 The annual outage time of a digital radio facility is the sum of the time intervals during which the bit error rate is excessive; a bit error rate of 10^{-3} or more on the radio line is normally considered too high. The estimation of error-caused outage time requires an "equivalency bridge" to the available multipath occurrence statistics such as those in Sections 940-310-115 (Space Diversity Engineering) and 940-310-102 (Selective Fading). The bridge is required since these errors are caused primarily by dispersion, while the multipath occurrence expressions predict the occurrence of fade depth levels of an RF tone (FM carrier) rather than the occurrence of dispersion. Since the available occurrence statistics consider both frequency of occurrence together with fade duration at specific fade depths to yield a net "time below level" over an extended time period (a month or year, for example), it follows that any correlation which can serve to equate dispersion outage with an equivalent fade depth can provide predicted outage time when referred to the conventional expressions. This "bridge" is provided by finding the fade depth on the experimental path which would be exceeded for the same ***time*** as the digital radio experienced high BERs due to dispersion. This fade depth is called the dispersive fade level, DM. It has been found to be independent of path length and is a characteristic of the particular radio equipment. Radio systems without any form of adaptive equalization have DM values of 30 dB or less.

6.04 The dispersive fade level is a function of the modulation technique (8-phase PSK, 16 QAM, etc.) and the complexity of the adaptive equalizer offered by various manufacturers. Table B shows typical DM values for several commonly available configurations. Differences between equipment from different manufacturers have been found, but are usually relatively small. When specific dispersive fade levels are known for a specific manufacturer's equipment, they may be used instead of the Table B values.

6.05 To estimate the outage on a radio path, the effects of dispersion, DM, interference (see Part 8), and the thermal noise margin (F) must be combined. The composite fade margin (CFM) is given by a power sum of DM, F, and IM, the non-faded CIR - CIR at 10^{-3} BER.

$$CFM = -10 \log [10^{-F/10} + 10^{-DM/10} + 10^{-IM/10}].$$

The CFM is then used in the standard multipath outage calculations in place of the simple fade margin of FM radios. Wherever paths do not have the same CFMs in both directions (or where other factors exist, e.g., different space diversity configurations), the two directions must be computed separately and the results added.

TABLE B

TYPICAL DISPERSIVE FADE LEVELS

MODULATION	EQUALIZER	W/O SD dB	W/SD dB
8 PSK	SLOPE	33.0	33.0
16 QAM	SLOPE	33.5	33.5
16 QAM	TRANSVERSAL AND SLOPE	38.0*	38.0*

*Future improvements are possible

D. Outage Calculation

6.06 Given the foregoing assumptions, an estimate of the annual 2-way outage time (O_{MP}) caused by multipath propagation on a 6-GHz radio hop, in minutes, is:

$$O_{MP} = c(6.25)\ (t/50)\ (D/25)^3(10^{-CFM/10}) * 10^{-4} \mathit{min/yr}$$

The hop length D is expressed in miles, t describes the average annual temperature in °F as obtained from Fig. 10, and the quantity c depends on climate and terrain. The average values of c are:

c = 4 over water and Gulf coast,

= 1 for average terrain and climate,

= 1/4 for mountains and dry climate.

Outage calculations are typically done using the computer programs FMDIV or TDDIV. These programs also calculate the outage reductions due to both frequency and space diversity. If path profile data are available, the terrain roughness, w, can be calculated to obtain a more precise value of c:

$c = 2(w/50)^{-1.3}$, coastal areas,

$= (w/50)^{-1.3}$, average climate,

$= 0.5\ (w/50)^{-1.3}$, dry climate.

The calculation of the terrain roughness factor, w, is covered in Part 13 of this section, and the use of actual path profile data is recommended when possible.

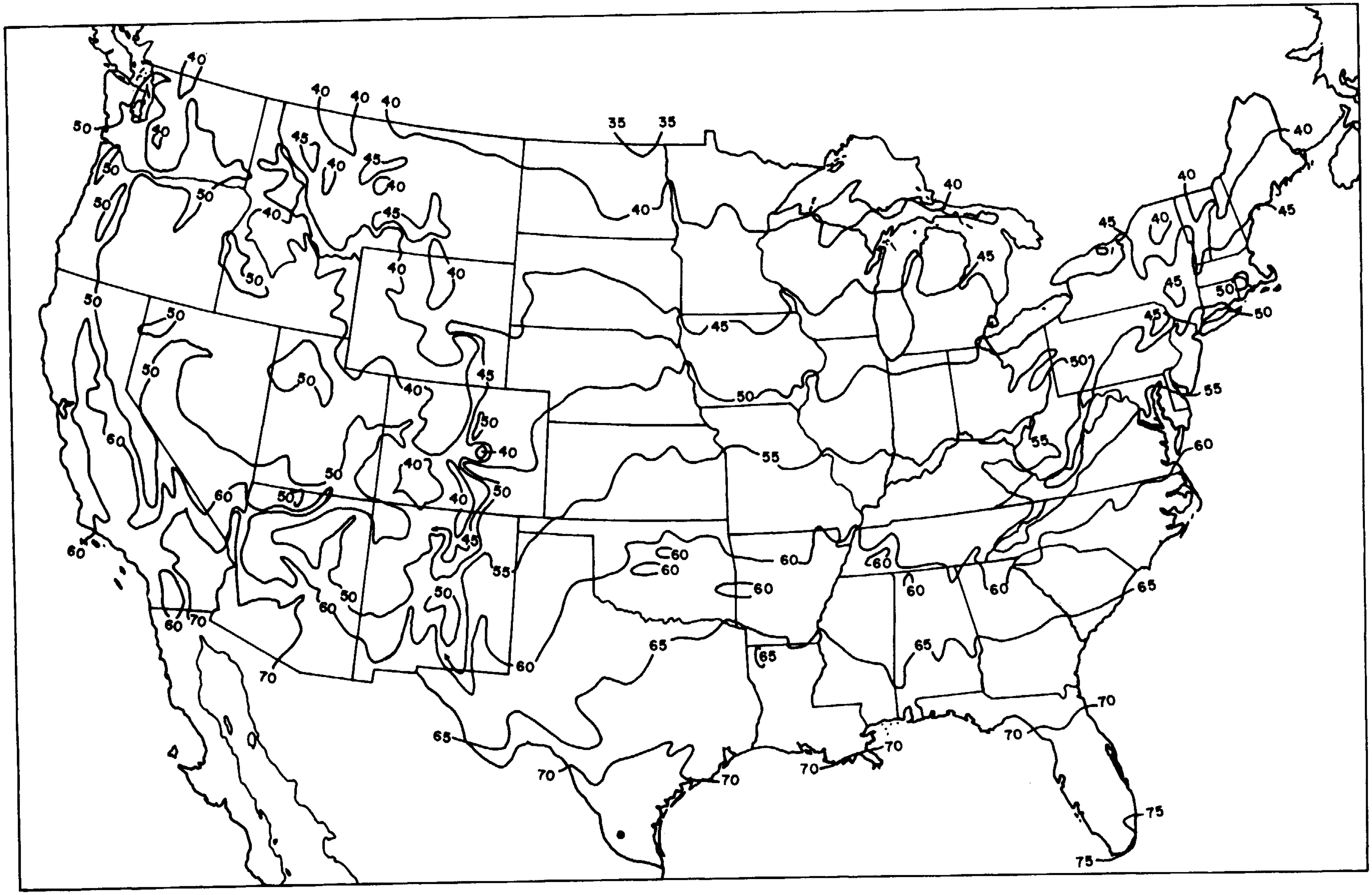


Fig. 10—Average Annual Temperature in °F

E. Space-Diversity Improvement

General

6.07 The presence or absence of diversity protection is described by an improvement factor, I_0, where I_0 is the combined improvement factor for both directions of transmission. The value of I_0 is unity for an unprotected radio channel.

Space Diversity

6.08 Space-diversity reception can be used to reduce digital radio outage caused by dispersion. Experiments have shown (assuming phase-aligned combining) that the reduction (improvement) in error-caused outage can be estimated from previously developed RF single-tone improvement expressions (Section 940-310-115) at the space-diversity composite fade margin. The expected improvement for receiving antennas of equal size and spacing at both ends of the section is:

$$I_0 = 42(S_0/50)^2 * 25/D * 10^{+CFM/10} * 10^{-3}$$

where S_0 is the vertical separation of the receiving antennas in feet center to center and D is the path length in miles. I_0 is assigned a value of 200 when the right side of the equation has a value larger than 200; similarly, I_0 is assigned a value of unity when the right side of the equation has a value less than unity.

6.09 Different antenna separations at the two ends of a radio hop can lead to an improvement of I_1 in one direction of transmission and I_2 in the other. In such a case:

$$I_1 = 42(S_1/50)^2 * 25/D * 10^{+CFM/10} * 10^{-3}$$

and

$$I_2 = 42(S_2/50)^2 * 25/D * 10^{+CFM/10} * 10^{-3}$$

and the combined improvement is:

$$I_0 = 2\,I_1I_2/(I_1 + I_2).$$

F. Summary Examples

6.10 Table C presents two examples of calculated multipath outage (O_{MP}). The values are chosen for variety and are not intended to imply specific design rules.

7. OUTAGE DUE TO EQUIPMENT FAILURE

A. General

7.01 Assuming some form of protection switching, modern solid-state microwave equipment should have failure rates which make outage times due to equipment failure small compared to propagation outages at 6 GHz. This part will first discuss outages due to simultaneous failures of two or more transmitter-receiver (TR) panels. Then methods will be presented for estimating and minimizing outages due to the silent failures of the protection system noted in Part 3.

TABLE C

EXAMPLE OF MULTIPATH FADING CALCULATION

ITEM	PATH A-B	PATH B-C
Climate	Average	Average
Average Temperature, °F	63	63
Path Length, Miles	29	16
Roughness, Feet	50	38.6
Value of C	1.0	1.4
CMF	32.7	32.9
O_{MP} Outage, min/yr (unprotected)	66.0	14.8
Antenna Separation (Feet)	50 at A 75 at B	25 at B 25 at C
Improvement		
I_1	67	32
I_2	152	32
I_0	93	32
O_{MP}, min/yr (with space diversity)	0.7	0.5

B. Outages Due to Double Equipment Failures

7.02 The expected value of 2-way outage time per channel (T_E), in minutes, for a protected system of R hops can be approximated by:

$$T_E = \frac{2(N+1)}{2}\left| MTTR_E \left[\frac{1}{MTBF_T} + \frac{(R-1)}{MTBF_E}\right]\right|^2 \frac{60}{8760} \text{ min/yr} \quad 1\times N \text{ FD}$$

or

$$T_E = 2\left|\frac{A^2+1}{(A+1)^2}\right| \left\{\left|\frac{MTTR_E}{MTBF_T}\right|^2 + (R-1)\left|\frac{MTTR_E}{MTBF_E}\right|^2\right\} \frac{60}{8760} \text{ min/yr} \quad 1\times 1 \text{ HS}$$

where:

$MTTR_E$ = Mean time to repair a failure (hours)

$MTBF_T$ = Mean time between failures (years) of a one-way both-end terminal repeater

$MTBF_E$ = Mean time between failures (years) of a single TR unit

$$A = \frac{\text{MTBF — Receiver unit}}{\text{MTBF — Transmitter unit}},\ A \geq 1.$$

Table C was calculated assuming A = 1.

The quantity $MTTR_E$ includes all the sectionalization and fault location time discussed in Part 3, plus travel time to the failure site and time on-site to diagnose, obtain spares if necessary, and/or repair. With reliable solid-state equipment, T_E should range from a small fraction of a minute to a few minutes per year. Double equipment failures will seldom use the full allocation of 25 percent of the total outage time objective. (See Table D.)

C. Outages Due to Joint Equipment and Protection Switching System Failure

7.03 The previous discussion calculated the outage time per working channel due to equipment failures assuming a perfectly operating protection switching system. This section will consider system outages caused by a single equipment failure and a simultaneous failure of the protection switching system. A simultaneous failure does not mean a failure of the protection channel TR equipment, the possibility described in the foregoing discussion, but instead refers to logic or control failures which prevent switching to a good and available protection channel when needed. Also, protection system components that are continuously monitored and alarmed will not be considered here, as the concern is directed to those "silent" failures which, as described in

TABLE D

DOUBLE EQUIPMENT FAILURES
(TIME — PROTECTED 2-WAY CHANNEL)

NO. OF HOPS	1×N FREQ. DIV.			HOT STANDBY
	N = 1 MIN.	N = 3 MIN.	N = 7 MIN.	1×1 MIN.
$MTBF_E$ = 4 yrs, $MTBF_T$ = 3 yrs, MTTR = 4 hrs				
1	0.02	0.05	0.10	0.01
2	0.07	0.15	0.30	0.02
5	0.39	0.78	1.56	0.04
$MTBF_E$ = 2 yrs, $MTBF_T$ = 1 yr, MTTR = 5 hrs				
1	0.34	0.68	1.37	0.17
2	0.77	1.54	3.08	0.21
5	3.08	6.16	12.33	0.34

Part 3, manifest themselves only when protection switching is called upon. Examples of troubles not considered here are:

(a) False indications of protection or regular channel failure

(b) Lack of continuity or high noise on a signaling channel.

It is assumed in both cases that the alarms will trigger prompt repair. Thus, the joint failures of such events and a regular channel equipment failure is quite low.

7.04 The model used to calculate the effects of such joint failures assumes that silent failures occur at relatively long intervals with many single equipment failures occurring between each silent failure. Exact and rigorous results for all possible combinations of silent failures, routine manual switch operations and routine testing of the protection system do not appear to be needed. A simplified approach will be used which first assumes there are no protection system tests and no routine manual switch operations. This assumption results in every silent failure being followed at some later time (determined by the MTBF of the TR equipment) by a service failure. A second approach will include the effect of periodic routine testing (or periodic manual switch operations). Such testing or exercising of the system will result in the discovery (and prompt repair) of any silent failures which have occurred since the last switch operation. When the interval between tests is equal to the interval between the failure of any panel in the working channels, the average number of outages will be reduced by one-half. Decreasing the maintenance interval will give a further improvement proportional to the ratio of the panel failure interval to the exercise interval.

7.05 The outage time w/o exercising, T_{P+e}, is given by:

$$T_{p+e} = 4(R) \left| \frac{MTTR_E}{MTBF_P} \right| (60) \text{ min/yr HS}$$

$$= 2 \left[\frac{1}{N} \right] \left| \frac{MTTR_E}{MTBF_P} \right| (60) \text{ min/yr } 1{\times}N \text{ FD}$$

The reduction with exercising, I, is given by:

$$I = 2 \left| \frac{F}{E} \right|$$

Where E = exercise interval in years; i.e., 1/12 for monthly, 7/365 for weekly

$$F = \frac{1}{N} \left| \frac{1}{\frac{1}{MTBF_T} + \frac{(R-1)}{MTBF_E}} \right| = \text{failure interval in years}$$

Time with exercising = T_{p+e}/I

7.06 The duration of silent failure service outages will vary significantly with the type of protection switching and the sophistication of the fault sectionalizing and location aids available. Hot-standby (1×1) will usually have silent failure outage durations almost equal to the $MTTR_E$ for any equipment failure. More complex 1×N frequency-diversity systems equipped with remote surveillance and control features may locate and clear many protection system faults quickly.

7.07 Table E provides some numerical examples which can be compared with double equipment failure results for similar systems in Table D. In this table, the results do not depend on the equipment failure rate since all silent failures are assumed to result in an eventual service failure. Multihop 1×1 hot-standby systems degrade as the number of hops is increased because there are four protection systems involved in each 2-way hop.

7.08 Table F shows the improvements when a 1×N frequency-diversity system is exercised at periodic intervals. With relatively reliable equipment, the protection system should be exercised weekly to make the silent failures small compared to double equipment failures. Without exercising, silent-failure-related outages would be several times more frequent than double equipment failures. With less reliable equipment, only weekly exercising can significantly reduce the number of silent failure outages. The double equipment failures will always occur more often than the silent failures in this particular case. Table G shows the situation with hot-standby protection systems. Because of the large number of protection systems, the equipment outage is completely dominated by the protection system failures.

TABLE E

JOINT EQUIPMENT AND PROTECTION SWITCHING SYSTEM FAILURE (WITHOUT EXERCISING)

FOR 1×N FREQ. DIV. — ANY NO. OF HOPS $MTBF_{PROT}$ = 10 yrs (one-way), $MTTR_P$ = 4 hrs					
MTBF AVG. CHANNEL			OUTAGE TIME/YEAR		
N = 1 YRS	N = 3 YRS	N = 7 YRS	N = 1 MIN	N = 3 MIN	N = 7 MIN
5	15	35	48	16	6.9

FOR 1×1 HOT STANDBY $MTBF_P$ = 60 yrs, $MTTR_P$ = 4 hrs		
NO. OF HOPS	MTBF AVG. CHANNEL YRS	ANNUAL OUTAGE TIME MIN
1	15	16
3	5	48
5	3	80

8. INTERFERENCE CONSIDERATIONS

A. Overview

8.01 This part will discuss the sources of interference, present an interference budget for 6-GHz digital radio systems, and show how interference can degrade the outage performance of such systems. The interference budget will combine interference from within the same radio system (overreach or adjacent section) with outside (foreign system or satellite) interference sources.

8.02 The treatment of interference in analog and digital microwave systems is significantly different. For analog systems, attention is centered on the nonfaded time periods. The noise from all interference sources is required to be a small fraction of the total system noise during nonfaded periods. This ensures that, during deep fades, the system fade margin is essentially not affected by the interference. For digital systems, attention is centered on the effect of interference on outage. For many digital radio paths, the nonfaded carrier-to-interference ratio (C/I) is about equal to or even less than the nonfaded carrier-to-noise ratio (C/N). System outage due to interference will occur at a fade depth which is less than the thermal noise margin, F, discussed in Part 3. This increase in system outage is limited to acceptable values by means of the interference budget.

B. Interference Source Indentification

8.03 A pictorial representation and tabulation of interference sources is shown in Fig. 11. Most of the sources shown in Fig. 11 are paths which will fade independently of the desired signal; i.e., arrive on paths not coinciding with the desired signal. Thus in the interference budget, the C/I due to such sources will be assumed to degrade dB for dB with the fade of the wanted signal. Adjacent channel interference, on the other hand, is

TABLE F

JOINT EQUIPMENT AND PROTECTION SWITCHING SYSTEM FAILURE (WITH PERIODIC EXERCISING)

1×N FREQ. DIV. — 2-WAY

	NO. OF HOPS	TIME DOUBLE EQPT	TIME P&E W/EXERCISE INTERVAL OF				COMB TIME 1 MO	COMB TIME WKLY
			NONE	1 MO	WKLY	DAILY		
$MTBF_p$ = 10 yrs, $MTBF_E$ = 4 yrs, $MTTR_E$ = $MTTR_p$ = 4 hrs, $MTBF_T$ = 3 yrs								
1×3	1	0.05	16	0.67	0.16	0.02	0.72	0.20
	2	0.15	16	1.17	0.27	0.04	1.32	0.42
	3	0.30	16	1.67	0.39	0.05	1.97	0.69
	5	0.78	16	2.67	0.62	0.09	3.45	1.40
1×7	1	0.10	6.9	0.67	0.16	0.02	0.76	0.25
	2	0.30	6.9	1.17	0.27	0.04	1.46	0.57
	3	0.61	6.9	1.67	0.39	0.05	2.28	1.00
	5	1.56	6.9	2.67	0.62	0.09	4.23	2.18
$MTBF_E$ = 2 yrs, $MTBF_T$ = 1 yr, $MTTR_E$ = $MTTR_p$ = 5 hrs								
1×3	1	0.68	20	2.50	0.58	0.08	3.18	1.27
	2	1.54	20	3.75	0.88	0.12	5.29	2.42
	3	2.74	20	5.00	1.17	0.16	7.74	3.91
	5	6.16	20	7.50	1.75	0.25	13.7	7.91
1×7	1	1.37	8.6	2.50	0.58	0.08	3.87	1.45
	2	3.08	8.6	3.75	0.88	0.12	6.83	3.21
	3	5.48	8.6	4.90	1.17	0.16	10.38	5.64
	5	12.33	8.6	6.12	1.75	0.25	18.45	12.58

clearly partially correlated with fades of the desired signal. For this budget, same section interference is assumed to be completely correlated with the desired signal.

C. Interference Budget

8.04 Table H presents a recommended interference budget. It is representative of the interference environment in and around many existing 6-GHz stations. The total or net C/Is are the power sum of the specific listed categories. The adjacent channel interference listed at the bottom of Table H is discussed in paragraphs 8.06 and 8.07.

TABLE G

JOINT EQUIPMENT AND PROTECTION SWITCHING SYSTEM FAILURE (WITH PERIODIC EXERCISING)

1×1 HOT STANDBY — 2-WAY

$MTBF_p$ = 60 yrs		$MTTR_p$ = 4 hrs				
	NO. OF HOPS	TIME DOUBLE EQPT MIN	TIME P&E		COMBINED TIME	
			YRLY MIN	6 MOS MIN	YRLY MIN	6 MOS MIN
A	1	0.01	1.33	0.67	1.35	0.68
	5	0.04	5.33	2.67	5.37	2.71
B	1	0.17	4.00	2.00	4.17	2.17
	5	0.34	12.00	6.00	12.34	6.34

A Equipment: $MTBF_E$ = 4 years; $MTBF_T$ = 3 years; $MTTR_E$ = 4 hours

B Equipment: $MTBF_E$ = 2 years; $MTBF_T$ = 1 year; $MTTR_E$ = 5 hours

D. Variations in the Interference Budget

8.05 The interference budget in Table H is representative of conditions at many 6-GHz radio stations. From site to site the contributions of different sources may differ from the budget in either direction. Variations in interference are accounted for in the calculation of the CFM (paragraph 6.05).

E. Adjacent Channel Interference

8.06 Adjacent channels in the normal frequency plan are always on opposite polarizations. When fading is not occurring, all channels are at equal levels. Adjacent channel interference has a nonfaded C/I which is the sum of the normal XPD and the net filter discrimination of the receiver in the wanted channel which may either enhance or attenuate the integrated power from the adjacent channel signal.

8.07 During deep fades on the wanted channel, there will be correlation with fading on the adjacent channels. The higher the correlation, the less the C/I degrades due to signal level differences, but the more the XPD of the adjacent channel will tend to degrade. The net effect will always be a significant reduction in C/I. The experimental data in Fig. 12 shows that a C/I of 26 dB in the absence of fading decreases to an rms value of 17 dB at the 30-dB fade level. At shallower fade depths in the adjacent channel, the XPD will be higher, but the difference in received signals will make the adjacent channel C/I degrade further. Only when the net filter discrimination provided in the radio equipment gives significant attenuation, on the order of 10 dB, can adjacent channels be used on most paths. When growth to adjacent channel operation is anticipated, the manufacturer's specifications should be consulted to determine the margin available.

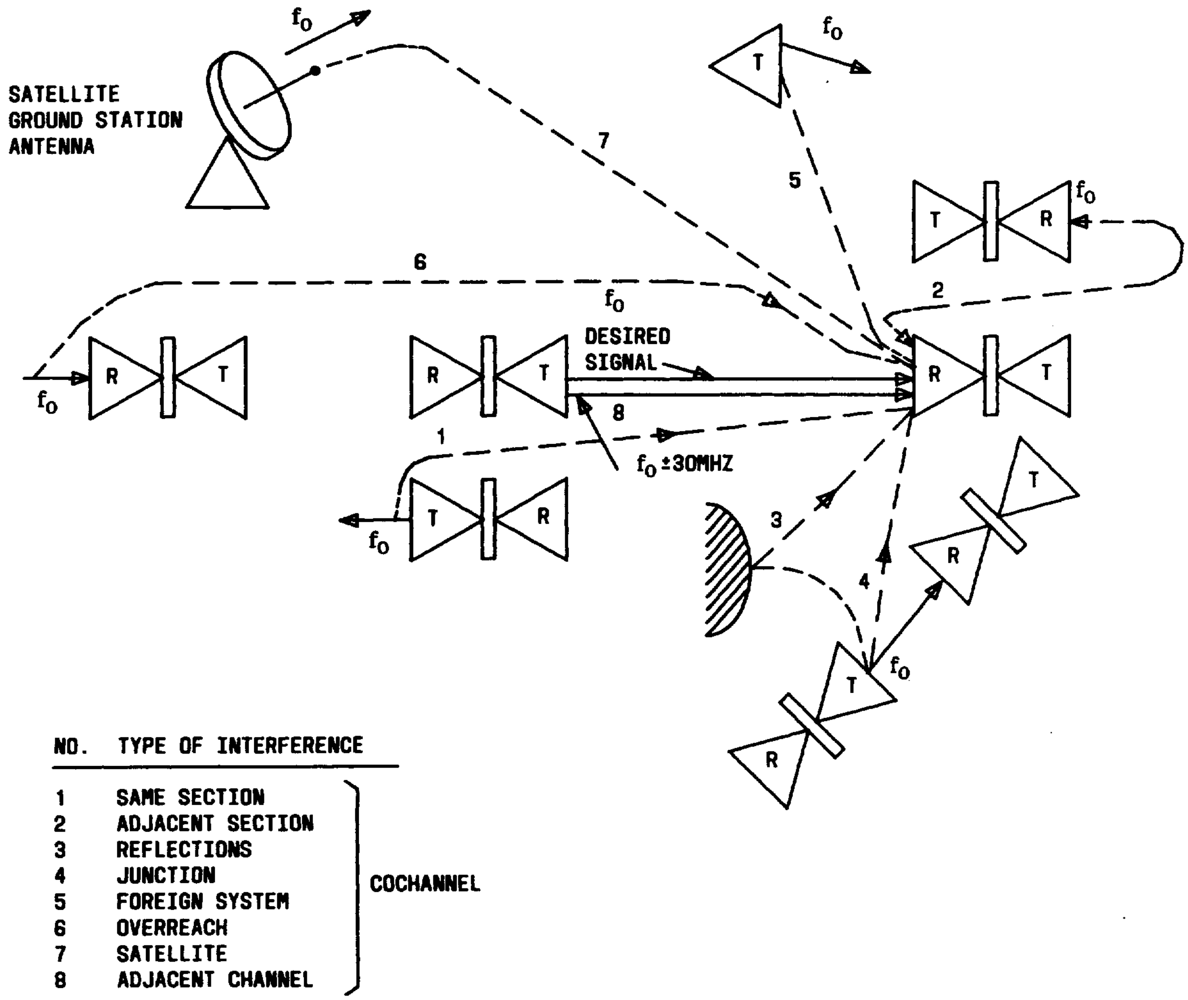


Fig. 11—Sources of Interference (6 GHz)

F. Digital-Into-Analog Interference

8.08 The spectrum of a digital radio signal is relatively uniform within the channel; typically the spectral energy beyond the nominal channel edges is more intense than in FM signals of similar capacity. This results in an increase in adjacent channel interference into analog channels. The adjacent channel discrimination ratios required for limiting interference into several different analog systems are shown in Table I. See Section 940-330-130 for a complete listing of 6-GHz C/I objectives. Table I shows that adjacent channel operation of analog and digital systems on the same route is not generally possible with 8-PSK, 90-Mb/s digital radio.

8.09 Values of XPD will be approximately 30 dB for normal installations in the absence of fading. During multipath fading, this will often degrade. A guard space of one unoccupied 30-MHz channel between analog and digital systems therefore appears to be required for same route operation.

8.10 The susceptibility of the AR 6A Single-Sideband Microwave System to cochannel digital interference is about the same as that of FDM-FM systems when the usual transmitter power disparities are taken into

TABLE H

INTERFERENCE BUDGET
8-PHASE CPSK

TYPE OF COCHANNEL INTERFERENCE	NO. OF INTERFERERS PER PATH	NONFADED C/I dB	35-dB FADE C/I dB
Same Section	1	67	67
Adjacent Section	1	67	32
Reflections	1	67	32
Junction	3	53	18
		60	25
		60	25
Foreign Systems	1	65	30
Overreach	1	67	32
Satellite	1	60	25
	Total (Net C/I)	50	15
Adjacent Channel	2		

account. The AR 6A system is, however, more susceptible to adjacent channel interferences than FDM-FM systems because its baseband extends to the outer edges of its channel.

9. ANTENNA AND WAVEGUIDE SYSTEMS

A. Antennas

Basic Types

9.01 Two basic types of antennas are suitable for high-performance telecommunications: horn-reflectors and parabolic dishes. Horn-reflector antennas consist of a tapered electromagnetic horn capped by a sector of an offset paraboloid. The axis of the electromagnetic horn is vertical, and the horn apex is both the point of attachment for the feeding waveguide and the focal point of the paraboloid. Because the horn section defines the sides of the antenna, excellent electromagnetic shielding of the feed is achieved and the antennas are characterized by excellent sidelobe suppression. The two general types of horn-reflectors, the pyramidal and conical, get their names from the shape of the feeding electromagnetic horn. Pyramidal horn-reflectors obviously use a pyramidal horn; conical horn reflectors use a conical horn.

9.02 While horn-reflectors use only a sector of paraboloid, dishes use the full, symmetrical surface. These antennas are also fed from the prime focal position, though now the feed must reach out to that point. This is accomplished by either bringing the feed around the reflector rim from behind—the "button-hook"—or through the reflector along the axis of revolution. Because the feed is fully exposed, to achieve satisfactory sidelobe suppression typically requires shrouding the antenna with an absorber-lined metallic cylinder, thereby

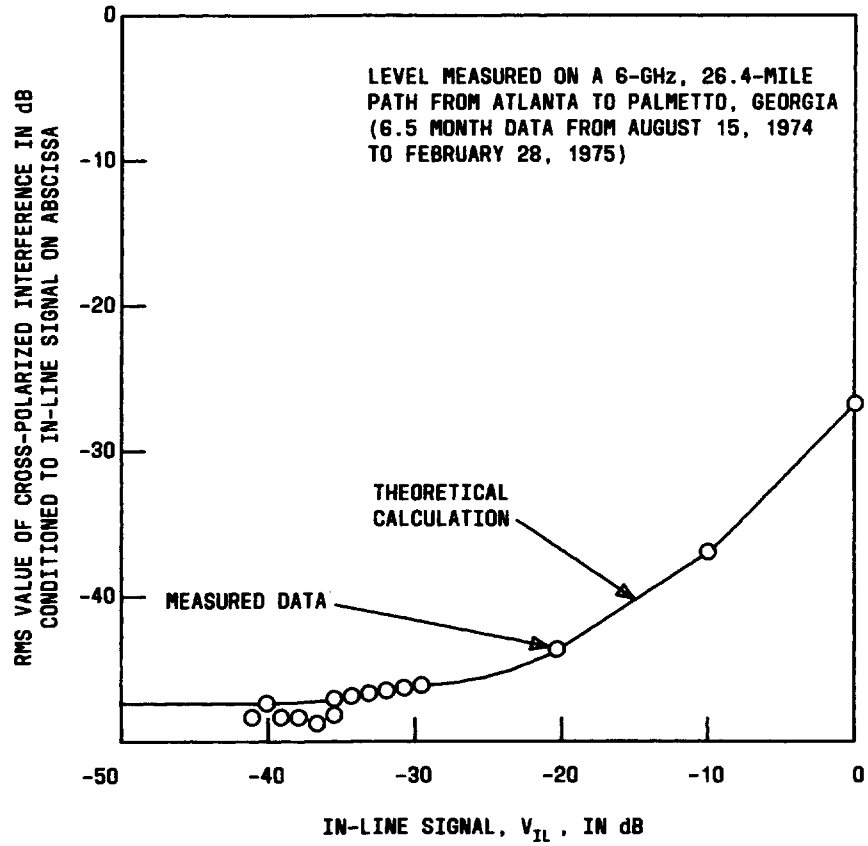


Fig. 12—Dependence of RMS Value of Cochannel Cross-Polarization Interference on In-Line Signal Level

hiding the feed from view. Comparable radiation patterns for a pyramidal horn-reflector, a conical horn-reflector, and a parabolic dish of roughly comparable gain and the FCC radiation standard "A" are depicted in Fig. 13. All three antennas are well within standard "A."

9.03 The foregoing antennas have high gain because of the sharp focusing of radiated energy. This gain reduces the section loss of the microwave path by the sum of the on-axis gains (in decibels) of the two antennas. The on-axis power gains for some antennas which might typically be used with a 6-GHz radio system are given in Table J, together with other antenna parameters of interest.

Return Loss

9.04 Analog radio systems have fairly tight specifications on the dominant-mode return losses at both the top of the waveguide run (the antenna return loss) and at the bottom of the waveguide run (the return loss of the radio equipment). Multiple reflections in a long waveguide run can lead to envelope delay distortion (EDD) and contribute to system noise during normal propagation conditions. The antenna return losses indicated in Table J are more than adequate for current digital systems. The related topic of multimoding is discussed under Waveguide Systems, paragraphs 9.18 through 9.24.

TABLE I

TOTAL SIGNAL TO INTERFERENCE OBJECTIVES (dB) — DIGITAL INTO ANALOG MESSAGE SYSTEMS

SYSTEM FREQ. SEPARATION	BIT RATE	TM-1 600CH	TM-1 1200CH	TM-2 1200CH	TH-1 1860CH	TH-3 1800CH	AR 6A SSB-AM
Cochannel	90	54/54	63/63	73/73	80/81	79/79	63/64
	78/45	54	62	72	80	79	64
7.5 MHz	90	54/54	62/62	72/72	78/79	77/77	63/64
	78/45	54	62	72	79	77	63
15 MHz	90	49/50	59/60	69/70	78/78	76/76	63/64
	78/45	50	59	69	77	76	64
22.5 MHz	90	32/23	47/38	55/46	69/60	67/60	63/64
	78/45	24	45	48	70	69	64
30 MHz	90	20/20	28/25	35/33	50/45	49/44	51/38
	78/45	20	20	32	43	42	47

Note: Objective for TM-1 is 14 dBrnc0/hop. When two objectives appear (AA/BB), AA is for 8 PSK and BB is 16 QAM. Objective for all others is 4 dBrnc0/hop.

Cross-Polarization Discrimination

9.05 Several effects can occur within an antenna, its associated waveguide, and other antenna system components, all of which may give rise to coupling of cross-polarized energy into a radio channel. In this discussion, antenna cross-polarization discrimination is examined. The discussion under Waveguide Systems covers waveguide and networks and their influence on a net cross-polarization discrimination.

9.06 The antenna itself responds to a cross-polarization signal with a sensitivity which depends on the vertical and azimuthal arrival angle of the incoming wave. The cross-polarized antenna response pattern is the measure of this sensitivity.

9.07 Horn-reflector antennas (both the pyramidal and conical variety) have a deep null in the cross-polarized antenna response pattern at the center of the main beam of the normal (copolarized) antenna pattern. This null exists for all angles of arrival in the vertical plane containing the main beam axis, though the null depth may decrease somewhat with increasing departure from the zero degree elevation angle. The antenna cross-polarized response initially increases rapidly as the azimuthal arrival angle departs from the main-beam axis. The full width of the azimuthal null as a function of cross-polarization level is tabulated in Table K for two horn-reflector antennas operating in the 6-GHz band. The appropriate manufacturer's specifications should be consulted for other antennas.

9.08 Because their design is inherently different from that of horn-reflector antennas, parabolic dish antennas have polarization discrimination that is not characterized by an on-axis null. In general, one should expect a cross-polarized response that looks more like a suppressed main beam. A review of technical literature

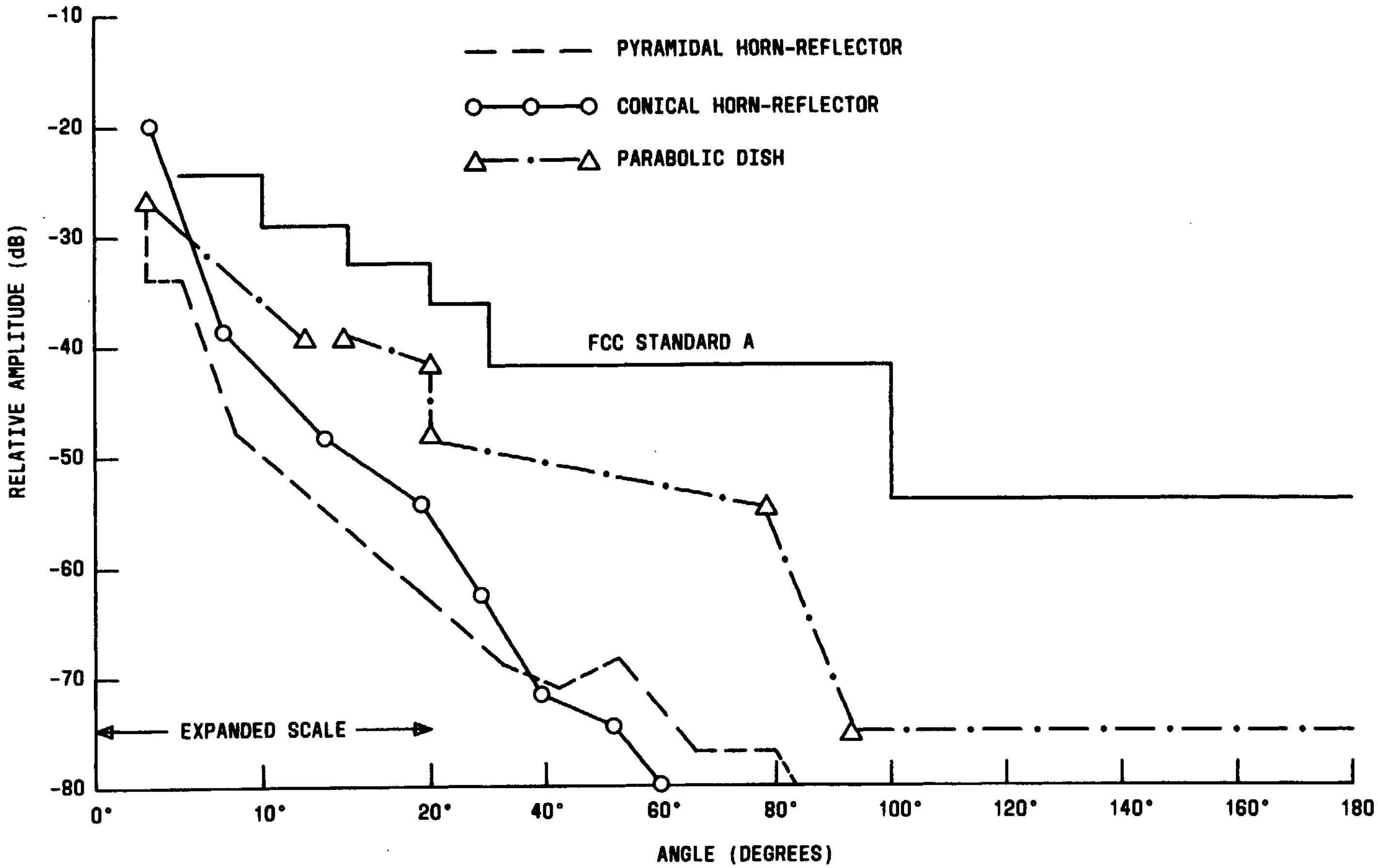


Fig. 13—Antenna Radiation Patterns (Horizontal Polarization, 6 GHz)

TABLE J

ANTENNA RADIATION PARAMETERS AT 6 GHz

ANTENNA TYPE	GAIN (dB)	BEAMWIDTH (DEGREES)	FRONT-TO-BACK COUPLING (dB)	RETURN LOSS AT ANTENNA FEED (dB)
K-15676 Horn-Reflector (10-foot Pyramidal)	43.2(V Pol) 43.0(H Pol)	1.26 0.99	≥ 81 ≥ 80	> 40 > 40
KS-21972 (10-foot Conical)	43.4(V Pol) 43.1(H Pol)	1.40 1.30	≥ 83 ≥ 86	> 40 > 40
Gabriel Maxihorn Horn-Reflector UHR-10 (10-foot Conical)	44.4(V Pol) 44.4(H Pol)	1.25 1.00	≥ 80 ≥ 80	> 40 > 40
Parabolic Dishes (10 feet)	41.3(V Pol) 41.3(H Pol)	1.4 (Max)	≥ 75	31 to 34
Parabolic Dishes (12 feet)	43.2(V Pol) 43.2(H Pol)	1.1 (Max)	≥ 75	31 to 34

Note 1: The entries for the KS-15676 and KS-21972 antennas are based upon BTL measurements.

Note 2: These front-to-back values are determined from range-measured radiation patterns and do not include environmental effects.

Note 3: For parabolic dishes, the performance varies with manufacturer, the values shown being representative for shrouded dishes.

TABLE K

WIDTH OF AZIMUTHAL PLANE CROSS-POLARIZATION RESPONSE, HORN-REFLECTOR ANTENNAS AT 6 GHz

		APPROXIMATE NULL WIDTH (DEGREES)	
ANTENNA TYPE	CROSS-POLARIZATION LEVEL (dB)	VERTICAL RESPONSE TO HORIZONTAL INCIDENT FIELD	HORIZONTAL RESPONSE TO VERTICAL INCIDENT FIELD
KS-15676 Horn-Reflector Antenna	−27 −30 −35	0.58 0.37 0.17	0.30 0.24 0.17
KS-21972 Horn-Reflector Antenna	−27 −30 −35	1.07 0.63 0.32	0.53 0.38 0.21

from parabolic dish manufacturers shows that the antenna is capable of 29- to 38-dB cross-polarization discrimination. The extent to which ancillary equipment, such as waveguide and polarization networks, influences system polarization discrimination is discussed in conjunction with the topic of waveguide which follows.

B. Waveguide Systems

Categories and Applications

9.09 Waveguide runs required at a radio station can be grouped into two categories:

1. Predominantly short, horizontal runs from the transmitter-receiver bay to the antenna-tower base.

2. Long vertical runs which feed tower-mounted antennas.

For category 1, dominant mode, single-polarization waveguide is typically used. This may include rectangular waveguide WR-159 or WR-137 or elliptical waveguide EW-52. This type of guide does not create objectionable loss since short sections are typically used. These waveguides are commonly used because of their convenience in handling, bending, etc. However, elliptical waveguide frequently requires factory or field tuning of the waveguide flanges to achieve high return loss.

9.10 Since tower-mounted antennas usually require long runs of vertical waveguide, loss and cost are significant factors in selecting a suitable waveguide for category 2. Circular waveguide has a substantial advantage over other guide geometries by providing low loss and dual polarization operation via a single guide run. The type of antenna used will also influence the selection of waveguide type since interfacing of the guide and antenna may require transition networks in some cases. Such transitions increase cost and introduce additional loss. Waveguides typically used on long vertical runs to horn-reflector antennas are WC-281, WC-205, WC-166, and WC-150. Typically with parabolic dish antennas, long runs of rectangular waveguide are used to carry a single polarization. Elliptical waveguide can also be run between the antenna and the building.

9.11 The types of waveguide listed in Table L are frequently used for 6-GHz radio systems. Special note should be made that WC-281 and, to a lesser extent, WC-205 can support modes higher than the TM_{01} "aiming" mode used with horn-reflector antennas. Care should be exercised in using these waveguides so that multimoding does not become a problem (see paragraphs 9.18 through 9.24).

TABLE L

6-GHz WAVEGUIDE

WAVEGUIDE DESIGNATION	CROSS SECTIONAL GEOMETRY	ATTENUATION/100 FT. AT 6 GHz (dB)
WR-159	Rectangular	1.4
WR-137	Rectangular	2.0
EWP-52	Elliptical	1.15
WC-281	Circular	0.28
WC-205	Circular	0.52
WC-166	Circular	0.90
WC-150	Circular	1.3

9.12 The options in selecting a waveguide for a vertical run will also depend on whether the station is to handle only 6-GHz traffic or combined 4-GHz/6-GHz signals. Simultaneous use of lower frequency signals together with 6 GHz requires the use of the larger size guide, which is oversize for the 6-GHz signal. Additionally, the use of multiband signals probably necessitates the use of a horn-reflector antenna.

9.13 Circular waveguide is commonly used with horn-reflectors because of its low loss and the capability to carry orthogonal polarizations simultaneously. It may also be used with parabolic dishes. With dishes, single-band operation is recommended because of bandwidth limitations inherent in higher-order mode suppressors used in such paraboloidal system configurations.

Configurations

9.14 A dual-polarization 6-GHz-only radio system may be configured in two ways. Either two individual retangular or elliptical waveguide runs are used in conjunction with a parabolic dish, or a single circular waveguide run is used with either a dish or a horn-reflector.

9.15 The use of a single circular waveguide run necessitates the use of polarization splitting/combining networks and, if transitions of other waveguide geometries or sizes occur, transition networks and mode suppressors. If a parabolic dish is used, the polarizer appears at both the top and the bottom of the run (at the top because the feed input for parabolic dishes is customarily rectangular, a necessity precipitated by the lack of broadband 90° circular waveguide bends); if a horn-reflector is used (with circular waveguide), a single network is situated at the bottom of the run. The polarization splitting/combining networks for 6-GHz-only systems are available.

9.16 Suitable splitting/combining networks are available for multiband operation with horn-reflector antennas. The specific network to be used depends upon a number of factors as specified in SD-59852-02 (Horn Reflector Antenna and Outdoor Waveguide Circuit). Worthy of special mention, however, are the 6-GHz system combining networks (the 1428A and 1428B networks). When both 6-GHz and 11-GHz are used, and good cross-polarization discrimination is required at 11-GHz, one 1428A and one 1428B network should be installed as a pair even though only single polarization operation at 6-GHz is anticipated.

9.17 In addition to these networks, the designer may also find it necessary to use waveguide transitions and mode suppressors; the choice of these is strongly influenced by the waveguide size and supplier. All networks and transducers introduced in the transmission path can be expected to: (a) introduce additional loss (typically a few tenths of a dB at 6 GHz), (b) degrade return-loss performance, and (c) enhance the possibility of multimoding. In addition to SD-59852-02, Section 804-331-158 and technical literature provided by equipment suppliers are valuable sources of information.

Multimoding

9.18 As indicated in the preceding discussion, the circular waveguides typically used at 6 GHz (WC-281, -205, -166, and/or -150) are all capable of supporting, in addition to the desired dominant mode, one or more higher-order modes. The dominant mode is the field distribution or mode that can exist at the lowest frequency for the applicable circular geometry. This is the desired transmission mode; if it were the only one that could exist in the waveguide system, multimoding would not be possible. However, these circular waveguides are large enough to reduce waveguide loss, with the result that higher-order modes will also propagate.

9.19 In these antenna-waveguide systems, higher-order modes may be generated and then reconverted into the dominant mode. This results in a received signal consisting of two components. One is a direct component resulting from the signal which was transmitted only by the dominant mode. The other is a delayed component resulting from the signal transmitted by the higher-order modes. The delay results from the slower velocities of the higher-order modes as well as the fact that they may have traversed a longer path than the dominant mode due to a round trip in the waveguide system. The delayed component can degrade transmission quality. The delays encountered may be very long (up to 60 nsecs) depending on the lengths of the waveguide runs used and the location of the higher-order mode generation and reconversion mechanisms. Sources of this higher-order mode coupling are misaligned waveguide flanges, damaged waveguides, networks, transitions, and the antennas.

9.20 Horn-reflector antennas will generate higher-order modes even though they may be in perfect condition and precisely aligned. In this case, the higher-order modes at 6 GHz are taper-induced. Hence, only the other sources of coupling can be controlled in order to keep the delayed signal amplitude at a minimal level. More detailed information on this subject may be found in EL-536.

9.21 During multipath propagation, the multimoding situation may be accentuated. The multipath phenomenon results in off-axis signals impinging on the receiving antennas in addition to signals from the original propagation path. These multiple signals may interfere destructively with each other and cause severe fading in the signal level of the direct component. Simultaneously, the off-axis signals will generate higher-order modes. Recall, for example, the TM_{01} mode used for precision alignment for horn-reflector antennas. This mode has a radiation pattern which has a null on axis and, for vertically polarized signals, increases in level for angles slightly off boresight in the elevation plane. Clearly, an off-axis, vertically polarized signal will generate this mode in the antenna system. If there is a mechanism for reconverting the higher-order mode to dominant mode, the result during a fade is a much reduced direct signal and a delayed signal whose amplitude may actually increase.

9.22 The antenna system for high-speed digital service should have a delayed signal component objective per hop of at least 60 dB below the direct. It is important to realize that the relative delayed signal amplitude during fading can increase. In addition, it is practical to establish the level only during unfaded conditions. Therefore, optimization during unfaded conditions should at least ensure that the delayed signal level will be minimized during fading.

9.23 The multimoding effect can be removed completely with horn-reflector antenna systems by using a dominant mode waveguide run, for example, WR-137. Using this waveguide will cause increased waveguide loss. The loss of WR-137 is approximately 2.0 dB/100 feet; this may be compared to the loss of other waveguides cited earlier. However, this increased waveguide loss may be tolerable on some short hops.

9.24 The input ports to parabolic dish antennas are dominant mode rectangular waveguide. The higher-order modes generated by this antenna are, therefore, rejected by the feed system. The long vertical waveguide runs may, however, be circular waveguides with polarizers at both the top and bottom. Such circular waveguide runs usually incorporate higher-order mode filters to attenuate any multimoding that may be generated. When a parabolic dish antenna system is carefully designed, installed, and maintained, multimoding should not be a problem.

10. EXAMPLE OF 6-GHz DIGITAL DESIGN

A. Introduction

10.01 The design of a digital radio route requires traffic and growth estimates, route engineering (site selection, path profiles, tower heights, and perhaps path testing), frequency coordination, interference calculations, equipment specifications, propagation calculations, and outage estimation to determine that outage objectives are met. These items interact, and the manner of the interaction can be expected to vary from route to route. For a given route, a number of design strategies will probably be explored, and the design may be an iterative process. The example in this part consolidates calculations outlined in the previous parts for the case of given route and equipment specifications. The parameters used in the calculations were defined in Part 3.

B. Parameters and Objectives

10.02 A 45-mile digital radio route is proposed from A to C. The intermediate repeater at B is an existing site, 29 miles from A and 16 miles from C. The proposed equipment is a 16 QAM digital radio with a stated system gain (at 10^{-3} BER) of 102 dB. A tentative layout suggests waveguide runs, networks, and antennas as provided below. Other path information is shown in Table C of Part 6. The section loss for hops A-B and B-C is based on the following values. The G_{TA} and G_{RA} parameters for hop A-B are taken from the KS-15676 horn antenna (vertical polarization) data of Table J, while those of hop B-C represent 10-foot parabolic dish antennas.

HOP A-B	HOP B-C
$L_{NW_{TOT}} = 1.0$ dB	$L_{NW_{TOT}} = 0.5$ dB
$L_{WG_{TOT}} = 2.1$ dB	$L_{WG_{TOT}} = 3.9$ dB
$L_{FS} = 141.7$ dB	$L_{FS} = 136.6$ dB
$G_{TA} = 43.2$ dB	$G_{TA} = 41.3$ dB
$G_{RA} = 43.2$ dB	$G_{RA} = 41.3$ dB

$$SL_{A\text{-}B} = 141.7 + 1.0 + 2.1 - 86.4 = 58.4 \text{ dB}$$

$$SL_{B\text{-}C} = 136.6 + 3.9 + 0.5 - 82.6 = 58.4 \text{ dB}$$

The thermal noise margins of the two hops are:

$$F_{A\text{-}B} = 102 - 58.4 = 43.6 \text{ dB}$$

$$F_{B\text{-}C} = 102 - 58.4 = 43.6 \text{ dB}$$

The manufacturer states that a CIR of 18.5 dB gives a 10^{-3} BER and that the upfade margin at this received signal level = 16.0 dB. The interference situations on the four paths are as follows:

At A and at B from A: nonfaded CIR = 62 dB

IM = 62 −18.5 = 43.5 dB

At B from C: nonfaded CIR = 65 dB

The interference IM = 65 − 18.5 = 46.5 dB

10.03 To compute outage, we first calculate the CFM for the two paths. The DM for a 16 QAM system is given in Table B as 33.5 dB. Combined with the IMs and a thermal fade margin of 43.6 dBm, this yields a CFM of 32.7 dB on A-B and 32.9 dB on B-C. Using the outage equation of paragraph 6.06 yields an outage time of 66.0 min/yr on path A-B and 14.8 min/yr on path B-C for a total of 80.8 min/yr. The overall objective is 105 (45/250) = 18.9 min/yr. Some improvement will be needed to meet short-haul objectives. Frequency diversity is ignored here since the calculated improvement is small ($< 2{:}1$) on the long A-B hop.

10.04 Other outage causes must be considered. The methods of EL-7622 for computing upfade outage time yield 0.1 min/yr as the 2-way outage A to C. We shall assume that the tower heights will be adjusted using the OBSFAD program to meet the long-haul objective of 10 seconds per 25 miles per year. This yields an obstruction fading time of 0.3 min/yr. The equipment outage time for a 2-hop 1×3 system is found in the example of Table E in Part 7 as 1.3 min/yr. Both components are well below their maximum allocations of 25 percent of the objective. The multipath allocation thus becomes 18.9 − 1.3 − 0.1 − 0.3 = 17.2 min/yr. The outage of 80.8 min/yr must be reduced to ≤ 17.2 min/yr.

C. Space-Diversity Improvement

10.05 Using vertical antenna separations (in feet, center to center) of 75 at A and 50 at B on hop A-B and 25 at both B and C on hop B-C, the multipath outage would become 0.7 + 0.5 = 1.2 minutes (from Table C) if space diversity were used on both hops. Use of space diversity on hop A-B alone, which is the recommended design for the route in this example, produces an estimated outage of 0.7 + 14.8 = 15.5 minutes, which is comfortably less than the 17.2-minute multipath objective.

D. Equivalent Short-Haul Length

10.06 The "equivalent short-haul" length of this route would be 45 (15.5 + 1.3 + 0.3 + 0.1)/18.9 = 41.0 miles. This means that the calculated outages on this route are the same as those on a 41.0-mile route which just met the objectives. If needed, the "equivalent short-haul" length could be substantially reduced to 45(1.2 + 1.3 + 0.3 + 0.1)/18.9 = 6.9 miles by the addition of space diversity on hop B-C.

11. SHORT-HAUL APPLICATION GUIDELINES

A. Definitions and Constraints

11.01 This part covers guidelines for short-haul radio networks. The guidelines are intended to ensure that:

(a) The maximum length of short-haul facilities interconnecting toll centers will exceed 250 miles only rarely

(b) Short-haul facilities used in a connection within a sectional or regional center area will never exceed 275 miles

(c) Connections between widely separated areas (i.e., linked by long-haul facilities) will never employ more than 300 miles of short-haul facilities—150 miles maximum at both ends.

This objective can be attained by a series of constraints on the maximum lengths of short-haul facilities between toll switching offices; the constraints depend upon the rank of the offices in the toll switching hierarchy and the home chain relationships of the switching machines.

11.02 Short-haul facilities connecting toll centers (class 4) to their home class 1, 2, or 3 office (which connects to distant points via the long-haul network) should rarely exceed 125 miles. A worst case of up to 150 miles is tolerable. Thus, a call involving short-haul facilities at each end with one or more long-haul trunks in between will normally be limited to a total of 250 miles of short-haul facilities. Within the compact geographical area of single regional, sectional, or primary center areas (or between toll centers in adjacent areas), the maximum length of short-haul facilities would be 275 miles. The toll machine hierarchy and symbology appears in Fig. 14.

11.03 For the purpose of these guidelines, it does not matter whether a call actually switches at a given office or is simply routed on transmission facilities which pass through that office. For example, in Fig. 15 traffic from TC-A to TC-B may be carried on two trunks switched together at PC-4 (the final route) or on a high-usage trunk TC-A to TC-B carried on the same facilities. In either case, the short-haul mileage is 25 + 75 = 100 miles.

B. Summary of Constraints

11.04 The following five categories summarize short-haul application constraints. Examples refer to Fig. 16.

1. L_{MAX} is the length of short-haul facilities from a control switching point (CSP) to the most distant toll center (TC) whose final route is via that CSP.

RANK OF TOLL MACHINE	CLASS	ABBREVIATION	SYMBOL
REGIONAL CENTER	1	RC	□
SECTIONAL CENTER	2	SC	△
PRIMARY CENTER	3	PC	○
TOLL CENTER/TOLL POINT	4	TC	⊖
END OFFICE	5	EO	●

CLASS 1, 2, OR 3 OFFICES ARE
CONTROL SWITCH POINTS (CSP'S)

Fig. 14—Toll Machine Hierarchy

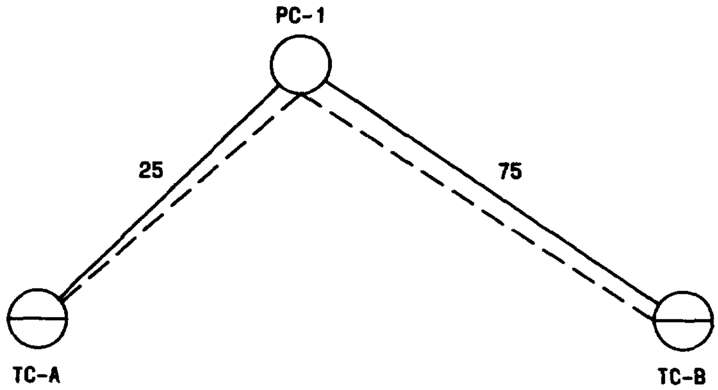


Fig. 15—Trunking Mileage

A. Class 3: $L_{MAX} \leq 125$ miles

B. Class 1 or 2:

(1) $L_{MAX} \leq 150$ miles, and

(2) If L_{MAX} is >125 miles, the length of short-haul facilities to any other TC homing on the class 1 or 2 whose final route to the L_{MAX} TC switches at the class 1 or 2 must be $\leq 275 - L_{MAX}$.

Examples:

L_{MAX} at SC-1 = 145 = 80 + 65 (To TC-D of PC1-3)

Second longest to ***any*** TC = 140 = 80 + 60 (To TC-E of PC1-3)

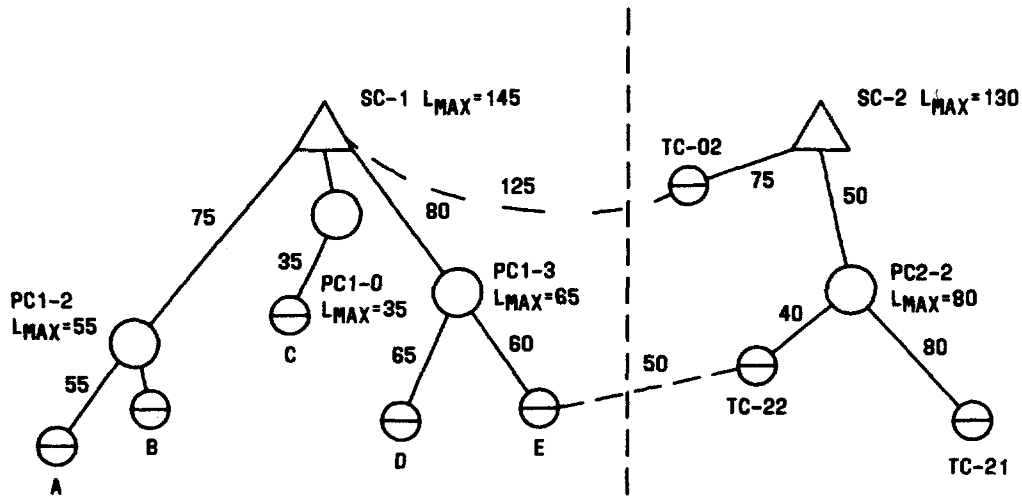


Fig. 16—Constraint Examples

But TC-D to TC-E does ***not*** route through SC-1; therefore the next longest TC homing on SC-1 is TC-A and,

Second longest L_{MAX} = 130 = 75 + 55 (To TC-A)

130 + 145 = 275 just at maximum [constraint 1B-(2)]

TC-22 which homes on SC-2 is ***not*** considered in determining L_{MAX} at SC-1.

2. CSP to CSP

A. If one CSP homes on the other, the maximum length CSP-CSP is determined by L_{MAX} at the higher ranking CSP. (See 1 above.)

B. If CSPs are in different final chains

Maximum length = 275 − L_{MAX} of CSP #1 − L_{MAX} of CSP #2.

Examples:

SC-1 to SC-2

275 − 145 − 130 = 0 — Long haul ***must*** be used to interconnect SC-1 to SC-2

PC1-2 to PC2-2

275 − 55 − 80 = 140 — 140 miles of short haul can be in the path PC1-2 to PC2-2

PC1-3 to PC2-2

275 − 65 − 80 = 130 — 130 miles of short haul can be in the path PC1-3 to PC2-2

For example:

50 miles short haul from TC-E to TC-22 gives route from PC1-3 to PC2-2 = 150 miles. 150 miles > 130 miles. Long-haul or short-haul equivalent to 130 miles must be used.

3. Class 4 to CSP

A. If class 4 homes on the CSP (either directly or via another CSP), L_{MAX} at the CSP controls. (See 1 above.)

B. If class 4 to nonhome CSP,

Max length = 275 − L_{MAX} of CSP

Example:

TC-02 to SC-1
275 − 145 = 130 — 130 > 125; therefore, short-haul connection could be made.

4. Class 4 to Class 4

Max length = 275 miles — same regional center area

= 300 miles — different regional center area

(Longer length allows for L_{MAX} = 150 in both regional center areas; final route might be 300 miles.)

5. Class 5 to Class 4 (Toll-Connecting Trunks)

Toll-connecting trunks, except as indicated in constraint 2(a) below, are not counted in determining L_{MAX} or the maximum short-haul length of trunks from that class 4. This is because toll-connecting trunks have a separate allocation based on the use of T1 for most toll-connecting trunks. This permits, except for one special case (see constraint 2 below), short-haul radio trunks to be engineered the same whether they are used in the toll-connecting or the intertoll network.

Specifically, constraints on toll-connecting trunks are:

1. Toll-connecting trunks for short-haul radio should be limited to a maximum length of ≤150 miles.

2. Toll-connecting trunks on short-haul radio which are longer than 150 miles should meet the following requirements:

(a) The trunks should be designed for a short-haul equivalent of ≤150 miles, or

(b) Excess length over 125 miles should be assigned to the intertoll trunk network which may reduce permissible lengths in that network, or

(c) In the special case when a toll center is detolled and its end offices are recentered to the previous primary center (PC), the length of the toll-connecting trunk may be increased to 250 miles.

12. EXAMPLE OF SHORT-HAUL APPLICATION GUIDELINES

A. Objectives and Premises

12.01 The following example illustrates the use of both the application guidelines and the concept of equivalent short-haul mileage. A sectional center area will be analyzed for two conditions:

(a) A short-haul digital radio network is to be used to bring outlying toll centers into their home primary centers and to provide trunking between nearby toll centers. The primary centers are linked to each other and to their sectional center by long-haul facilities.

(b) Expansion of the scope of the first network to eliminate the use of long-haul facilities ***within*** the sectional center area.

Figure 17 shows the basic network to be studied. Three primary centers and a sectional center are shown with all the significant toll centers within the area. The mileages between toll centers are shown on the figure.

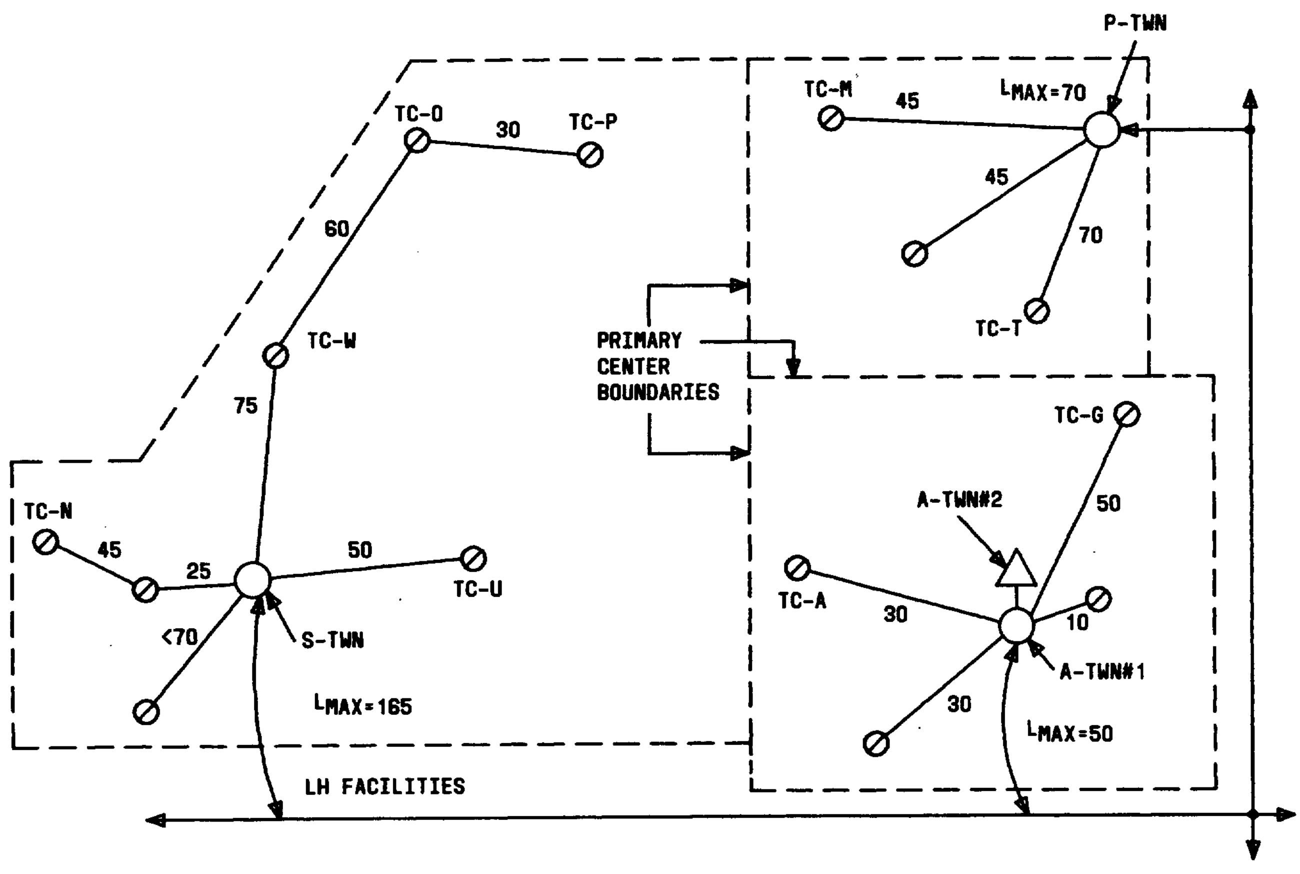


Fig. 17—Basic Network

12.02 In subsequent figures and in the text below, some of these mileages will be shown as 30/50 or 15/45, etc., where the first number is the equivalent short-haul mileage and the second is the actual route mileage. Thus 15/45 designates a 45-mile section designed to the outage requirements of a 15-mile short-haul section.

12.03 For the first condition, L_{MAX} at S-TWN is determined by TC-P, and only a modification of that leg is required to meet the guidelines for the simple network.

B. First Network Modification

12.04 With the modification shown directly below, this simple short-haul network brings outlying toll centers into their home class 3 and provides for some class 4 trunks (Fig. 18).

TC-0 to TC-P design for 15/30 (15-mile reduction in equivalent length)

TC-W to TC-0 design for 30/60 (30-mile reduction in equivalent length)

Route from S-TWN to TC-P is now

75 + 30 + 15 = 120-mile short-haul equivalent

L_{MAX} @ S-TWN = 120; therefore,

L_{MAX} @ A-TWN #2 = 120

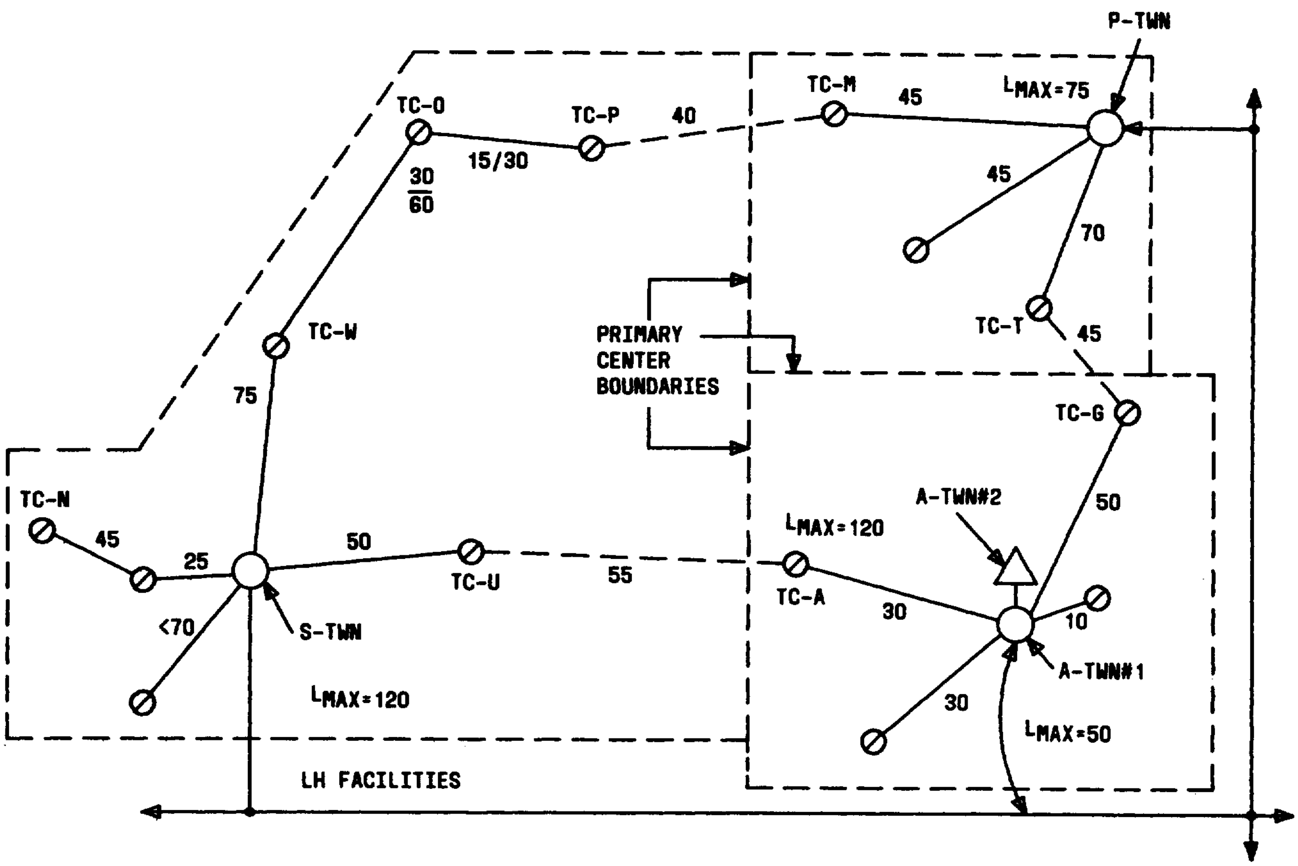


Fig. 18—First Network Modification

12.05 The modified network is shown in Fig. 18. Adding the dotted sections to connect different primary center area networks will not permit PC-PC trunks on short-haul facilities for the distances shown; i.e., long-haul facilities are required S-TWN to A-TWN, A-TWN to P-TWN, and S-TWN to P-TWN.

P-TWN to A-TWN #1 — class 3 to class 3

Route = 70 + 45 + 50	=	165 miles	
L_{MAX} P-TWN	=	70	
L_{MAX} A-TWN #1	=	50	
		285 miles	(285>275)

S-TWN to P-TWN via northern route

Route = 75 + 30 + 15 + 40 + 45	=	205 miles	
L_{MAX} P-TWN	=	70	
L_{MAX} S-TWN	=	120	
		395 miles	(395>275)

A-TWN #1 to S-TWN

Route = 30 + 55 + 50	=	135 miles	
L_{MAX} S-TWN	=	120	
L_{MAX} A-TWN #1	=	50	
		305 miles	(305>275)

Some high-usage trunks are possible:

TC-U to A-TWN #1 and #2

Route = 55 + 30	=	85 miles (85 miles<150 @A-TWN #2)	
L_{MAX} A-TWN #1	=	50	
		135 miles	(135<275)

TC-W to P-TWN

Route = 30 + 15 + 40 + 45	=	130 miles	
L_{MAX} P-TWN	=	70	
		200 miles	(200<275)

TC-W to A-TWN #1 via S-TWN

Route = 75 + 50 + 55 + 30	=	210 miles	
L_{MAX} A-TWN #1	=	50	
		260 miles	(260<275)

C. Second Network Modification

12.06 To get more use from the short-haul network, some sections can be designed to tighter than short-haul objectives. Reducing a segment that is both part of a PC-PC route and part of the limiting path in determining L_{MAX} for one of the PCs is a good initial attempt since such reductions have a double effect.

1. Reduce TC-T to P-TWN from 70- to 45-mile short-haul equivalent (45/70), a reduction of 25 miles in both the route and in the L_{MAX} at P-TWN.

2. Reduce TC-G to A-TWN from 50- to 30-mile short-haul equivalent (30/50). This results in:

Route = 30 + 45 + 45	=	120	
L_{MAX} @P-TWN	=	45	
		165	
L_{MAX} @A-TWN #1	=	30	
		195	(195<275)

Thus P-TWN to A-TWN #1 can be short haul. However, P-TWN to A-TWN #2 = 120 + 45 = 165.

L_{MAX} @A-TWN #2	=	165	165>150.

3. To allow P-TWN to A-TWN #2, we must do more:

TC-T to TC-G must be reduced from 45- to 15-mile short-haul equivalent.

(Strictly speaking, a reduction of 45 to 30 would just meet the 150-mile objective at A-TWN #2. We choose to go lower to permit other routes into A-TWN #2 to exceed 125 miles.)

Now	Route = 30 + 15 + 45	=	90	
	L_{MAX} @P-TWN	=	45	
	L_{MAX} @A-TWN #2	=	135	(135<150)

With this modification, long-haul facilities are no longer required from P-TWN to A-TWN (Fig. 19).

However S-TWN to A-TWN #1

Route = 50 + 55 + 30	=	135
L_{MAX} @S-TWN	=	120
L_{MAX} @A-TWN #1	=	30
		285 still exceeds 275

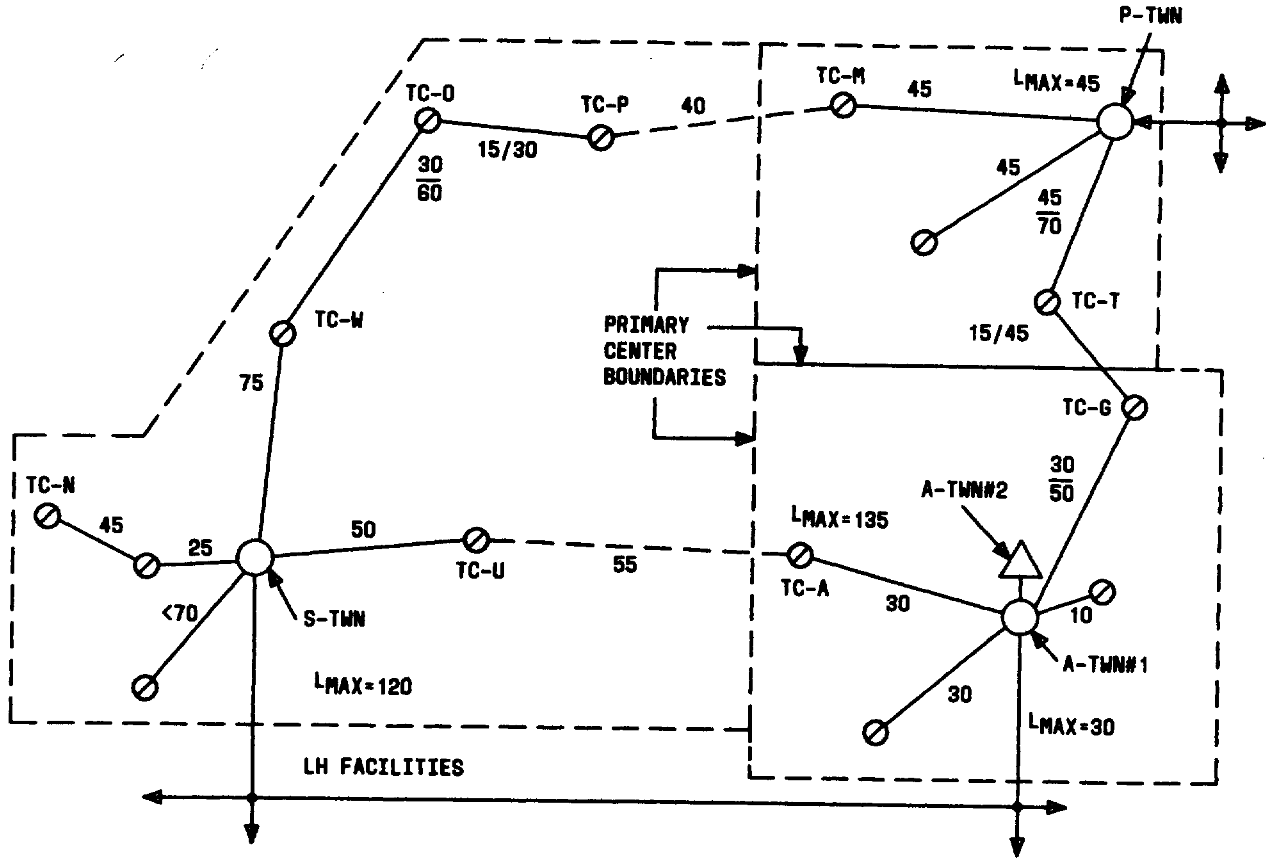


Fig. 19—Second Network Modification

D. Third Network Modification

12.07 To add S-TWN to A-TWN #1 and #2, we must reduce both the S-TWN to A-TWN route and reduce L_{MAX} at S-TWN.

1. Reduce TC-W to S-TWN from 75 to 35/75 (40-mile reduction in equiv. length)

   TC-W to TC-0 from 30/60 to 20/60 (10-mile reduction in equiv. length)

   This makes L_{MAX} @S-TWN = 70 miles

   (on the routes to both TC-N and TC-P)

   L_{MAX} @A-TWN #2 from S-TWN

   Route = 50 + 55 + 30 = 135

   L_{MAX} @S-TWN = 70

   205 (205>150)

   Route must be reduced by at least 55 miles. We choose to leave the TC-A to A-TWN span at 30 miles.

2. Reduce TC-A to TC-U from 55 to 15/55 (40-mile reduction in equiv. length)

3. Reduce TC-U to S-TWN from 50 to 25/50 (25-mile reduction in equiv. length)

   65-mile total reduction

Now L_{MAX} @A-TWN from S-TWN

Route = 25 + 15 + 30	=	70	
L_{MAX} @S-TWN	=	70	
		140	(140<150)
With L_{MAX} from P-TWN	=	135	
L_{MAX} from S-TWN	=	140	
		275 miles max. from any TC in S-TWN PC area to any TC in P-TWN PC area via A-TWN #2.	

Check of northern route — P-TWN to S-TWN via TC-W, etc.

Route = 35 + 20 + 15 + 40 + 45	=	155	
L_{MAX} @S-TWN	=	70	
L_{MAX} @P-TWN	=	45	
		270	(270<275)

The resulting network is shown in Fig. 20. All toll centers in the area can be interconnected freely on short-haul facilities:

direct HUs

via PC-PC HUs

via PC-SC-PC finals.

Long-haul facilities are no longer needed ***within*** the area shown. Long haul would be used for traffic to distant points ***outside*** the A-TWN #2 sectional center area. Long haul would be used for traffic going to the regional center for this area (approximately 140 miles from A-TWN). With L_{MAX} at the PCs relatively short, extension of some legs into adjacent SC and PC areas is feasible.

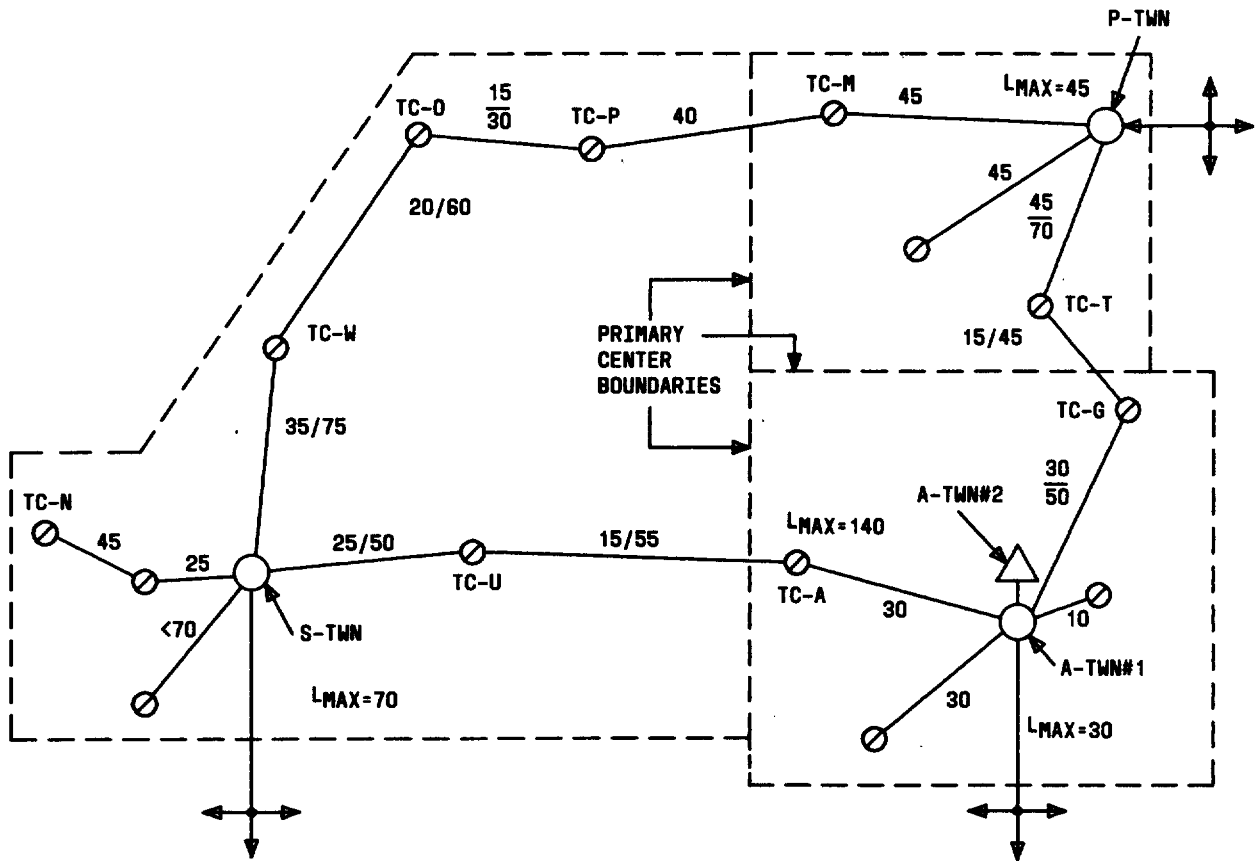


Fig. 20—Third Network Modification

13. COMPUTATION OF TERRAIN ROUGHNESS

A. Definition and Methodology

13.01 Terrain roughness is calculated from terrain heights above a reference level (sea level, for example) obtained from the path profile at one-mile intervals, with the ends of the path excluded. The standard deviation of the resulting set of numbers is the terrain roughness, denoted by "w". Expressed mathematically:

$$w = \left| \frac{\Sigma(x-M)^2}{n} \right|^{1/2}$$

where "x" is the vertical height in feet of the path profile as measured from some horizontal reference at one-mile intervals, excluding the station locations; "n" is the number of such measurements; and "M" is the arithmetic mean, or average, of the measurements.

13.02 Applicable values of "w" range from 20 feet (considered as smooth) to 140 feet (rough). These values of 20 and 140 should be used when calculated values of "w" are less than 20 or larger than 140. A value of 50 has been defined as normal.

B. Simplification and Calculation

13.03 The above equation for "w" may be altered so that the number of subtractions will be greatly reduced but at the expense of acquiring larger squared terms:

$$w = \left| \frac{\Sigma (x^2)}{n} - M^2 \right|^{1/2}$$

It should be noted that $\Sigma(x^2) \neq (\Sigma x)^2$.

13.04 An interval less than one mile (perhaps one kilometer or one-half mile) should be used on short paths to provide at least 15 to 20 values of terrain height.

13.05 Thus, for a hypothetical hop of 19 miles, "w" is computed as shown in Table M. Preparation of such a table helps keep computations under control. Measurements at $n = 0$ and $n = 19$ are omitted.

TABLE M

HYPOTHETICAL CALCULATION DATA

NUMBER OF MEASUREMENT	HEIGHT MEASUREMENT	SQUARE OF HEIGHT MEASUREMENT
	(x) feet	(x^2) feet^2
1	600	360,000
2	625	390,625
3	515	265,225
4	440	193,600
5	480	230,400
6	450	202,500
7	400	160,000
8	420	176,400
9	460	211,600
10	420	176,400
11	450	202,500
12	480	230,400
13	450	202,500
14	420	176,400
15	390	152,100
16	480	230,400
17	520	270,400
18	550	302,500
n = 18	$\Sigma x = 8{,}550$	$\Sigma(x^2) = 4{,}133{,}950$

$$M = \frac{\Sigma x}{n} = \frac{8550}{18} = 475 \text{ ft} \qquad w = \left| \frac{4{,}133{,}950}{18} - (475)^2 \right|^{1/2} = 63.5$$