6

Microwave Radio Communications and System Gain

INTRODUCTION

Presently, terrestrial (earth) *microwave radio relay systems* provide less than half of the total message circuit mileage in the United States. However, at one time microwave systems carried the bulk of long-distance communications for the public telephone network, military and governmental agencies, and specialized private communications networks. There are many different types of microwave systems that operate over distances varying from 15 to 4000 miles in length. *Intrastate* or *feeder service* systems are generally categorized as *short haul* because they are used for relatively short distances. *Long-haul* radio systems are those used for relatively long distances, such as interstate and backbone route applications. Microwave system capacities range from less than 12 voice band channels to more than 22,000. Early microwave radio systems carried frequency-division-multiplexed voice band circuits and used conventional, noncoherent frequency modulation techniques. More recently developed microwave systems carry pulse-code-modulated time-division-multiplexed voice band circuits and use more modern digital modulation techniques, such as phase shift keying and quadrature amplitude modulation. This chapter deals primarily with conventional FDM/FM microwave systems, and Chapter 7 deals with the more modern PCM/PSK techniques.

FREQUENCY VERSUS AMPLITUDE MODULATION

Frequency modulation (FM) is used in microwave radio systems rather than amplitude modulation (AM) because amplitude-modulated signals are more sensitive to amplitude nonlinearities inherent in *wideband microwave amplifiers.* Frequency-modulated signals are relatively insensitive to this type of nonlinear distortion and can be transmitted through amplifiers that have compression or amplitude nonlinearity with little penalty. In addition, FM signals are less sensitive to random noise and can be propagated with lower transmit powers.

Intermodulation noise is a major factor when designing FM radio systems. In AM systems, intermodulation noise is caused by repeater amplitude nonlinearity. In FM systems, intermodulation noise is caused primarily by transmission gain and delay distortion. Consequently, in AM systems, intermodulation noise is a function of signal amplitude, but in FM systems it is a function of signal amplitude and the magnitude of the frequency deviation. Thus the characteristics of frequency-modulated signals are more suitable than amplitude-modulated signals for microwave transmission.

SIMPLIFIED FM MICROWAVE RADIO SYSTEM

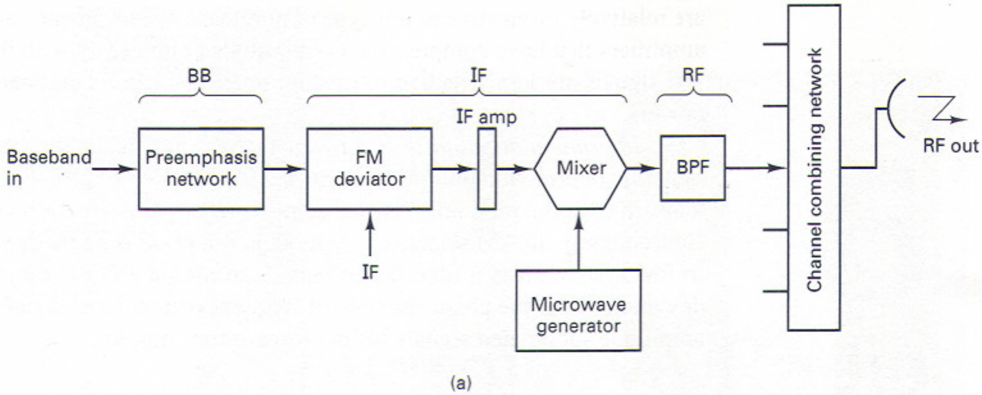
A simplified block diagram of an FM microwave radio system is shown in Figure 6-1. The *baseband* is the composite signal that modulates the FM carrier and may comprise one or more of the following:

1. Frequency-division-multiplexed voice band channels
2. Time-division-multiplexed voice band channels
3. Broadcast-quality composite video or picturephone
4. Wideband data

FM Microwave Radio Transmitter

In the FM *microwave transmitter* shown in Figure 6-1a, a *preemphasis* network precedes the FM deviator. The preemphasis network provides an artificial boost in amplitude to the higher baseband frequencies. This allows the lower baseband frequencies to frequency modulate the IF carrier and the higher baseband frequencies to phase modulate it. This scheme assures a more uniform signal-to-noise ratio throughout the entire baseband spectrum. An FM deviator provides the modulation of the IF carrier which eventually becomes the main microwave carrier. Typically, IF carrier frequencies are between 60 and 80 MHz, with 70 MHz the most common. *Low-index* frequency modulation is used in the FM deviator. Typically, modulation indices are kept between 0.5 and 1. This produces a *narrow-band* FM signal at the output of the deviator. Consequently, the IF bandwidth resembles conventional AM and is approximately equal to twice the highest baseband frequency.

The IF and its associated sidebands are up-converted to the microwave region by the AM mixer, microwave oscillator, and bandpass filter. Mixing, rather than multiplying, is used to translate the IF frequencies to RF frequencies because the modulation index is unchanged by the heterodyning process. Multiplying the IF carrier would also multiply the frequency deviation and the modulation index, thus increasing the bandwidth. Typically, frequencies above 1000 MHz (1 GHz) are considered microwave frequencies. Presently, there are microwave systems operating with carrier frequencies up to approximately 18 GHz. The most common microwave frequencies currently being used are the 2-, 4-, 6-, 12-, and 14-GHz bands. The channel-combining network provides a means of connecting more than one microwave transmitter to a single transmission line feeding the antenna.



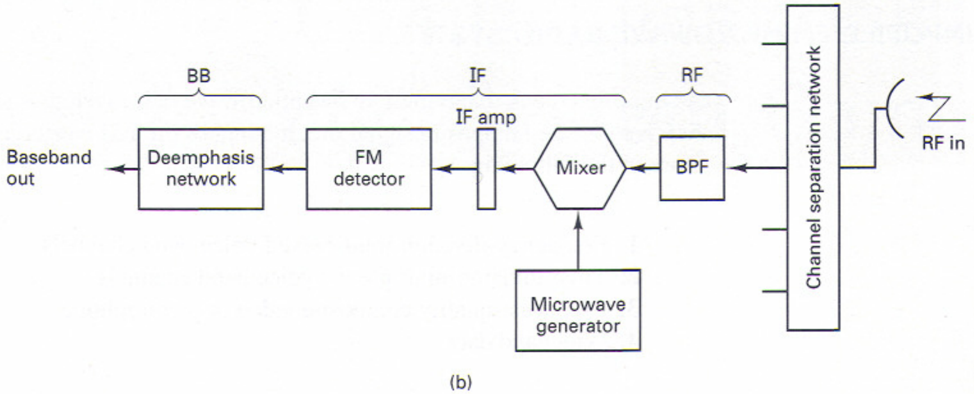


Figure 6-1 Simplified block diagram of an FM microwave radio system: (a) transmitter; (b) receiver.

FM Microwave Radio Receiver

In the FM microwave receiver shown in Figure 6-1b, the channel separation network provides the isolation and filtering necessary to separate individual microwave channels and direct them to their respective receivers. The bandpass filter, AM mixer, and microwave oscillator down-convert the RF microwave frequencies to IF frequencies and pass them on to the FM demodulator. The FM demodulator is a conventional, *noncoherent* FM detector (i.e., a discriminator or a PLL demodulator). At the output of the FM detector, a deemphasis network restores the baseband signal to its original amplitude versus frequency characteristics.

FM MICROWAVE RADIO REPEATERS

The permissible distance between an FM microwave transmitter and its associated microwave receiver depends on several system variables, such as transmitter output power, receiver noise threshold, terrain, atmospheric conditions, system capacity, reliability objectives, and performance expectations. Typically, this distance is between 15 and 40 miles. Longhaul microwave systems span distances considerably longer than this. Consequently, a single-hop microwave system, such as the one shown in Figure 6-1, is inadequate for most practical system applications. With systems that are longer than 40 miles or

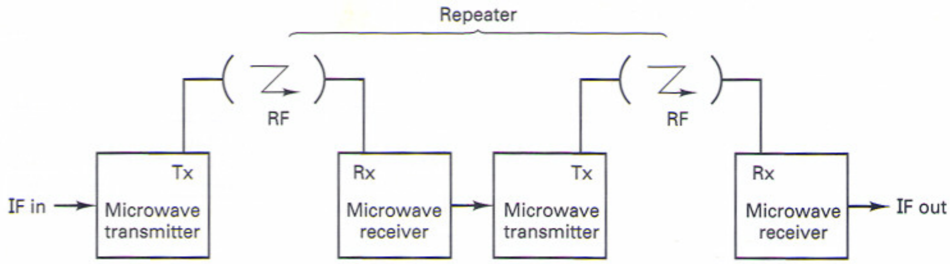


Figure 6-2 Microwave repeater.

when geographical obstructions, such as a mountain, block the transmission path, *repeaters* are needed. A microwave repeater is a receiver and a transmitter placed back to back or in tandem with the system. A block diagram of a microwave repeater is shown in Figure 6-2. The repeater station receives a signal, amplifies and reshapes it, then retransmits the signal to the next repeater or terminal station downline from it.

Basically, there are two types of microwave repeaters: *baseband* and *IF* (Figure 6-3). IF repeaters are also called *heterodyne* repeaters. With an IF repeater (Figure 6-3a), the received RF carrier is down-converted to an IF frequency, amplified, reshaped, up-converted to an RF frequency, and then retransmitted. The signal is never demodulated below IF. Consequently, the baseband intelligence is unmodified by the repeater. With a baseband repeater (Figure 6-3b), the received RF carrier is down-converted to an IF frequency, amplified, filtered, and then further demodulated to baseband. The baseband signal, which is typically frequency-division-multiplexed voice band channels, is further demodulated to a mastergroup, supergroup, group, or even channel level. This allows the baseband signal to be reconfigured to meet the routing needs of the overall communications network. Once the baseband signal has been reconfigured, it FM modulates an IF carrier which is up-converted to an RF carrier and then retransmitted.

Figure 6-3c shows another baseband repeater configuration. The repeater demodulates the RF to baseband, amplifies and reshapes it, then modulates the FM carrier. With this technique, the baseband is not reconfigured. Essentially, this configuration accomplishes the same thing that an IF repeater accomplishes. The difference is that in a baseband configuration, the amplifier and equalizer act on baseband frequencies rather than IF frequencies. The baseband frequencies are generally less than 9 MHz, whereas the IF frequencies are in the range 60 to 80 MHz. Consequently, the filters and amplifiers necessary for baseband repeaters are simpler to design and less expensive than the ones required for IF repeaters. The disadvantage of a baseband configuration is the addition of the FM terminal equipment.

DIVERSITY

Microwave systems use *line-of-sight* transmission. There must be a direct, line-of-sight signal path between the transmit and the receive antennas. Consequently, if that signal path undergoes a severe degradation, a service interruption will occur. *Diversity* suggests that there is more than one transmission path or method of transmission available between a transmitter and a receiver. In a microwave system, the purpose of using diversity is to increase the reliability of the system by increasing its availability. When there is more than one transmission path or method of transmission available, the system can select the path or method that produces the highest-quality received signal. Generally, the highest quality is determined by evaluating the carrier-to-noise (C/N) ratio at the receiver input or by

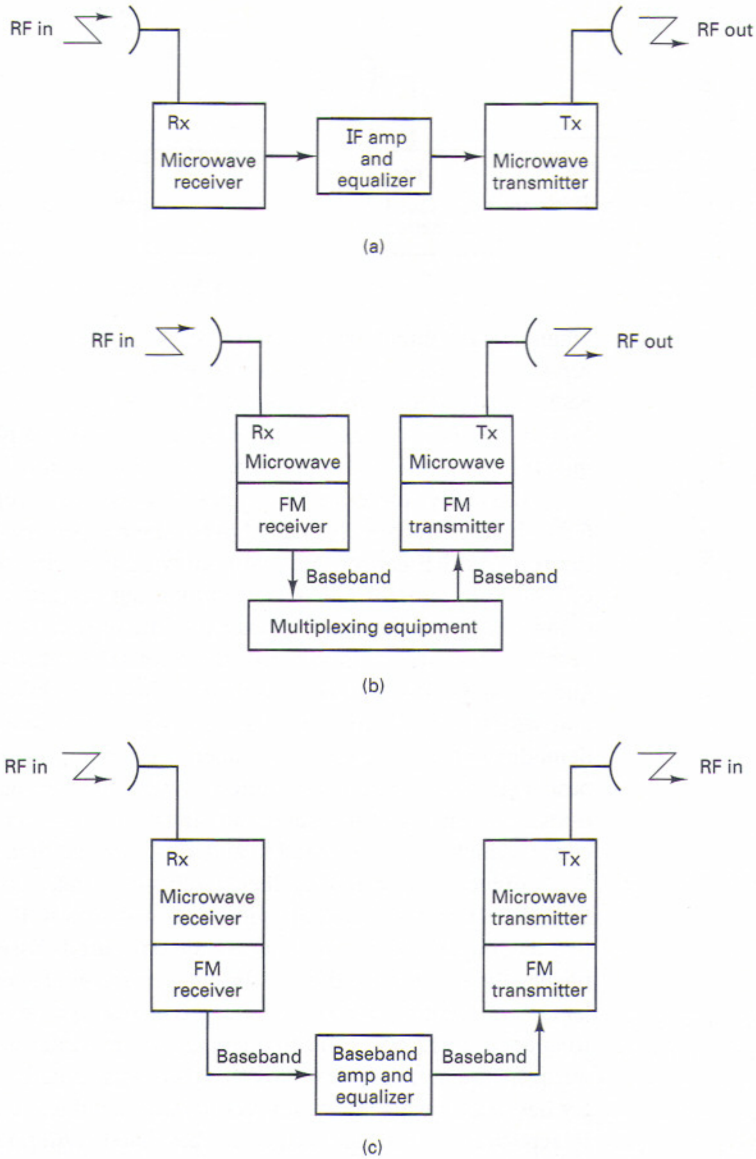


Figure 6-3 Microwave repeaters: (a) IF; (b) and (c) baseband.

simply measuring the received carrier power. Although there are many ways of achieving diversity, the most common methods used are *frequency, space,* and *polarization.*

Frequency Diversity

Frequency diversity is simply modulating two different RF carrier frequencies with the same IF intelligence, then transmitting both RF signals to a given destination. At the destination, both carriers are demodulated, and the one that yields the better-quality IF signal is selected. Figure 6-4 shows a single-channel frequency-diversity microwave system.

In Figure 6-4a, the IF input signal is fed to a power splitter, which directs it to microwave transmitters A and B. The RF outputs from the two transmitters are combined

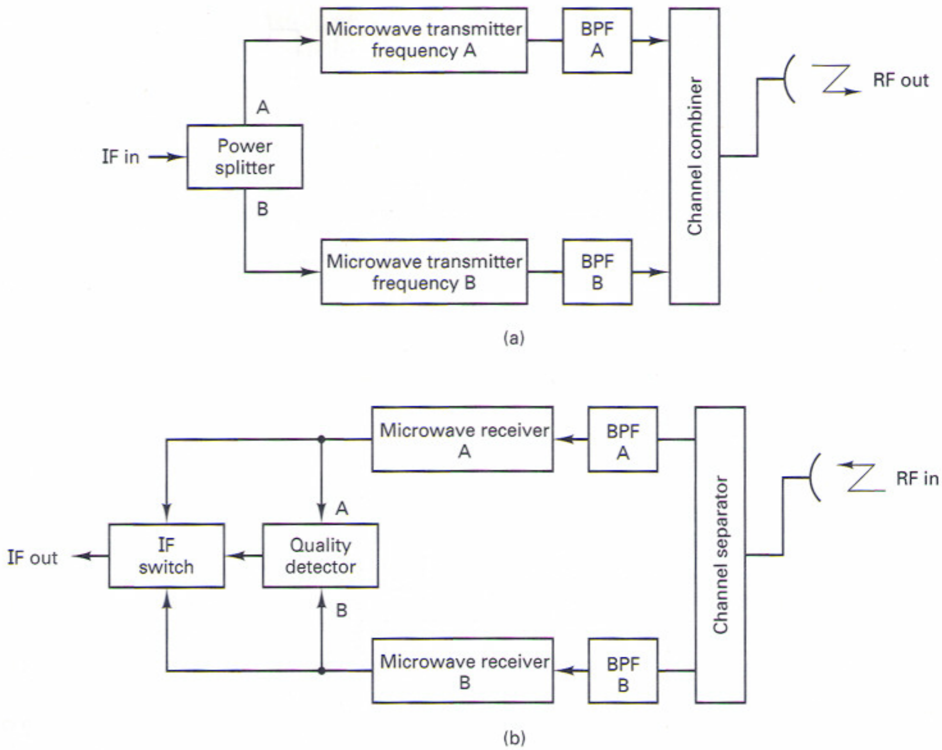


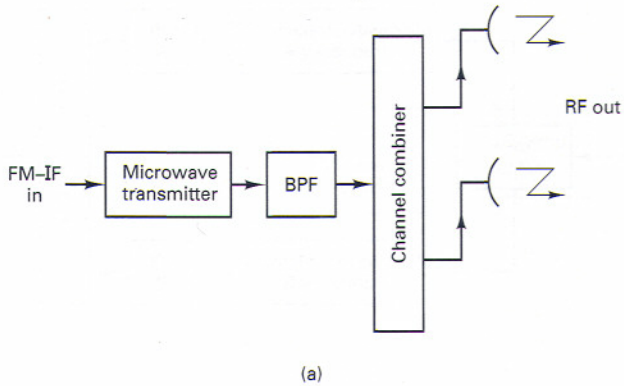
Figure 6-4 Frequency diversity microwave system: (a) transmitter; (b) receiver.

in the channel-combining network and fed to the transmit antenna. At the receive end (Figure 6-4b), the channel separator directs the A and B RF carriers to their respective microwave receivers, where they are down-converted to IF. The quality detector circuit determines which channel, A or B, is the higher quality and directs that channel through the IF switch to be further demodulated to baseband. Many of the temporary, adverse atmospheric conditions that degrade an RF signal are frequency selective; they may degrade one frequency more than another. Therefore, over a given period of time, the IF switch may switch back and forth from receiver A to receiver B, and vice versa many times.

Space Diversity

With space diversity, the output of a transmitter is fed to two or more antennas that are physically separated by an appreciable number of wavelengths. Similarly, at the receiving end, there may be more than one antenna providing the input signal to the receiver. If multiple receiving antennas are used, they must also be separated by an appreciable number of wavelengths. Figure 6-5 shows a single-channel space-diversity microwave system.

When space diversity is used, it is important that the electrical distance from a transmitter to each of its antennas and to a receiver from each of its antennas is an equal multiple of wavelengths long. This is to ensure that when two or more signals of the same frequency arrive at the input to a receiver, they are in phase and additive. If received out of phase, they will cancel and, consequently, result in less received signal power than if simply one antenna system were used. Adverse atmospheric conditions are often isolated to a very small geographical area. With space diversity, there is more than one transmission



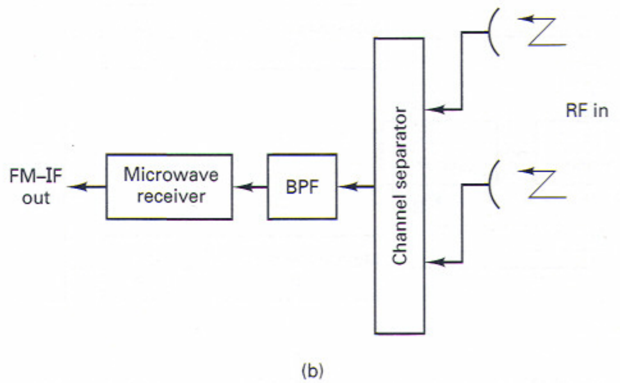


Figure 6-5 Space-diversity microwave system: (a) transmitter; (b) receiver.

path between a transmitter and a receiver. When adverse atmospheric conditions exist in one of the paths, it is unlikely that the alternate path is experiencing the same degradation. Consequently, the probability of receiving an acceptable signal is higher when space diversity is used than when no diversity is used. An alternate method of space diversity uses a single transmitting antenna and two receiving antennas separated vertically. Depending on the atmospheric conditions at a particular time, one of the receiving antennas should be receiving an adequate signal. Again, there are two transmission paths that are unlikely to be affected simultaneously by fading.

Polarization Diversity

With polarization diversity, a single RF carrier is propagated with two different electromagnetic polarizations (vertical and horizontal). Electromagnetic waves of different polarizations do not necessarily experience the same transmission impairments. Polarization diversity is generally used in conjunction with space diversity. One transmit/receive antenna pair is vertically polarized and the other is horizontally polarized. It is also possible to use frequency, space, and polarization diversity simultaneously.

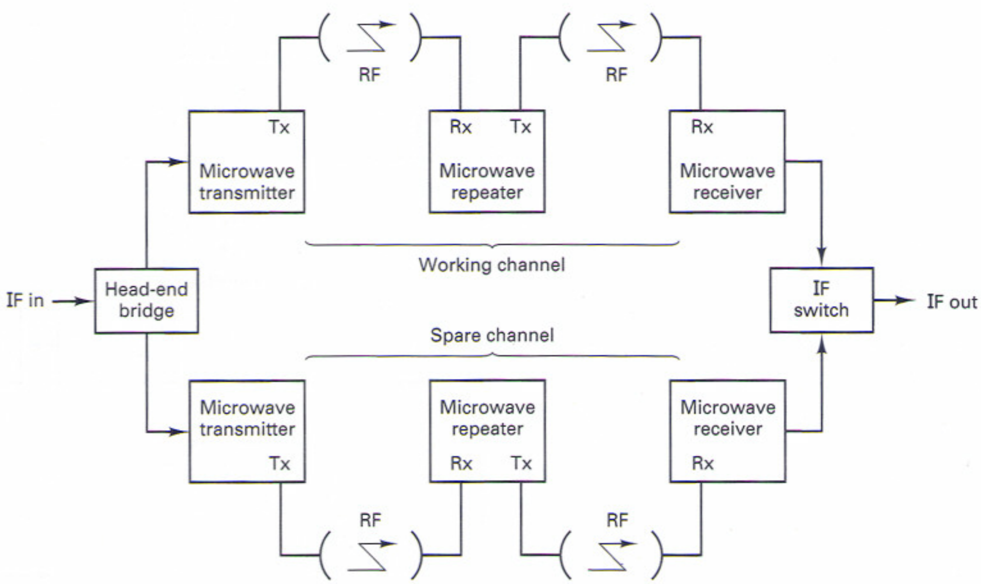
PROTECTION SWITCHING

Radio path losses vary with atmospheric conditions. Over a period of time, the atmospheric conditions between transmitting and receiving antenna can vary significantly, causing a corresponding reduction in the received signal strength of 20, 30, 40, or more dB.

This reduction in signal strength is referred to as a *radio fade. Automatic gain control circuits,* built into radio receivers, can compensate for fades of 25 to 40 dB, depending on the system design. However, fades in excess of 40 dB cause a total loss of the received signal. When this happens, service continuity is lost. To avoid a service interruption during periods of deep fades or equipment failures, alternate facilities are temporarily made available in what is called a *protection switching* arrangement. Essentially, there are two types of protection switching arrangements: *hot standby* and *diversity.* With hot standby protection, each working radio channel has a dedicated backup or spare channel. With diversity protection, a single backup channel is made available to as many as 11 working channels. Hot standby systems offer 100% protection for each working radio channel. A diversity system offers 100% protection only to the first working channel that fails. If two radio channels fail at the same time, a service interruption will occur.

Hot Standby

Figure 6-6a shows a single-channel hot standby protection switching arrangement. At the transmitting end, the IF goes into a *head-end bridge,* which splits the signal power and directs it to the working and the spare (standby) microwave channels simultaneously. Consequently, both the working and standby channels are carrying the same baseband information. At the receiving end, the IF switch passes the IF signal from the working channel to the FM terminal equipment. The IF switch continuously monitors the received signal power on the working channel and if it fails, switches to the standby channel. When the IF signal on the working channel is restored, the IF switch resumes its normal position.



(a)

Figure 6-6 Microwave protection switching arrangements: (a) hot standby;
(Continued on next page.)

Diversity

Figure 6-6b shows a diversity protection switching arrangement. This system has two working channels (channel 1 and channel 2), one spare channel, and an *auxiliary* channel. The IF switch at the receive end continuously monitors the receive signal strength of both working channels. If either one should fail, the IF switch detects a loss of carrier and sends back to the transmitting station IF switch a VF (*voice frequency*) tone-encoded signal that directs it to switch the IF signal from the failed channel onto the spare microwave channel. When the failed channel is restored, the IF switches resume their normal positions. The auxiliary channel simply provides a transmission path between the two IF switches. Typically, the auxiliary channel is a low-capacity low-power microwave radio that is designed to be used for a maintenance channel only.

Reliability

The number of repeater stations between protection switches depends on the *reliability objectives* of the system. Typically, there are between two and six repeaters between switching stations.

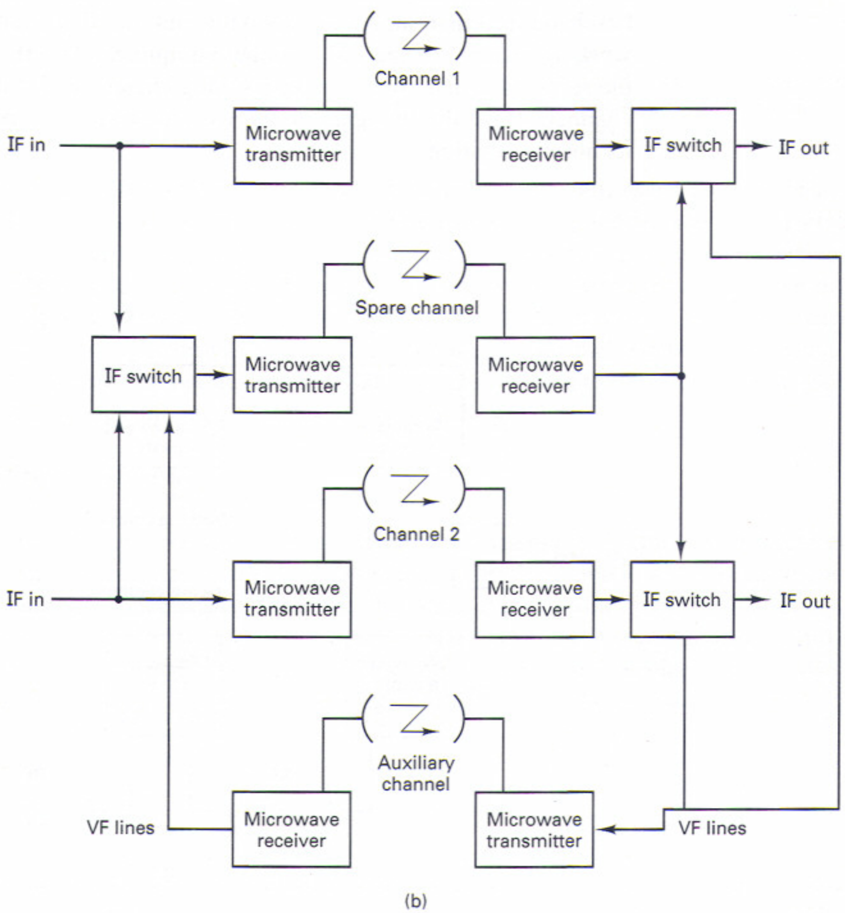


Figure 6-6 ***(continued)*** (b) diversity.

As you can see, diversity systems and protection switching arrangements are quite similar. The primary difference between the two is that diversity systems are permanent arrangements and are intended only to compensate for temporary, abnormal atmospheric conditions between only two selected stations in a system. Protection switching arrangements, on the other hand, compensate for both radio fades and equipment failures and may include from six to eight repeater stations between switches. Protection channels may also be used as temporary communication facilities, while routine maintenance is performed on a regular working channel. With a protection switching arrangement, all signal paths and radio equipment are protected. Diversity is used selectively, that is, only between stations that historically experience severe fading a high percentage of the time.

A statistical study of outage time (i.e., service interruptions) caused by radio fades, equipment failures, and maintenance is important in the design of a microwave radio system. From such a study, engineering decisions can be made on which type of diversity system and protection switching arrangement is best suited for a particular application.

FM MICROWAVE RADIO STATIONS

Basically, there are two types of FM microwave stations: terminals and repeaters. *Terminal stations* are points in the system where baseband signals either originate or terminate. *Repeater stations* are points in a system where baseband signals may be reconfigured or where RF carriers are simply "repeated" or amplified.

Terminal Station

Essentially, a terminal station consists of four major sections: the baseband, wire line entrance link (WLEL), FM-IF, and RF sections. Figure 6-7 shows the block diagram of the baseband, WLEL, and FM-IF sections. As mentioned previously, the baseband may be one of several different types of signals. For our example, frequency-division-multiplexed voice band channels are used.

Wire line entrance link (WLEL). Very often in large communications networks such as the American Telephone and Telegraph Company (AT&T), the building that houses the radio station is quite large. Consequently, it is desirable that similar equipment be physically placed at a common location (i.e., all FDM equipment in the same room). This simplifies alarm systems, providing dc power to the equipment, maintenance, and other general cabling requirements. Dissimilar equipment may be separated by a considerable distance. For example, the distance between the FDM multiplexing equipment and the FM-IF section is typically several hundred feet and in some cases several miles. For this reason a WLEL is required. A WLEL serves as the interface between the multiplex terminal equipment and the FM-IF equipment. A WLEL generally consists of an amplifier and an equalizer (which together compensate for cable transmission losses) and level-shaping devices commonly called pre- and deemphasis networks.

IF section. The FM terminal equipment shown in Figure 6-7 generates a frequency-modulated IF carrier. This is accomplished by mixing the outputs of two deviated oscillators that differ in frequency by the desired IF carrier. The oscillators are deviated in phase opposition, which reduces the magnitude of phase deviation required of a single deviator by a factor of 2. This technique also reduces the deviation linearity requirements

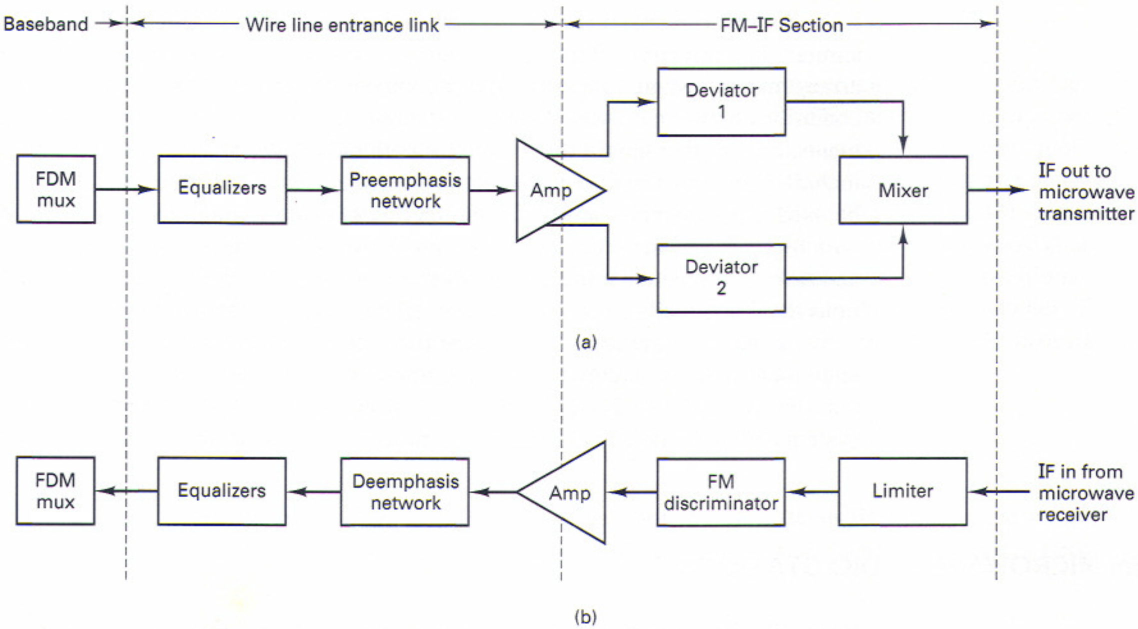


Figure 6-7 Microwave terminal station, baseband, wire line entrance link, and FM-IF: (a) transmitter; (b) receiver.

for the oscillators and provides for the partial cancellation of unwanted modulation products. Again, the receiver is a conventional noncoherent FM detector.

RF section. A block diagram of the RF section of a microwave terminal station is shown in Figure 6-8. The IF signal enters the transmitter (Figure 6-8a) through a protection switch. The IF and compression amplifiers help keep the IF signal power constant and at approximately the required input level to the transmit modulator (*transmod*). A transmod is a balanced modulator that when used in conjunction with a microwave generator, power amplifier, and bandpass filter, up-converts the IF carrier to an RF carrier and amplifies the RF to the desired output power. Power amplifiers for microwave radios must be capable of amplifying very high frequencies and passing very wide bandwidth signals. *Klystron tubes, traveling-wave tubes* (TWTs), and *IMPATT* (*impact/avalanche and Transit Time*) diodes are several of the devices currently being used in microwave power amplifiers. Because high-gain antennas are used and the distance between microwave stations is relatively short, it is not necessary to develop a high output power from the transmitter output amplifiers. Typical gains for microwave antennas range from 10 to 40 dB, and typical transmitter output powers are between 0.5 and 10 W.

A *microwave generator* provides the RF carrier input to the up-converter. It is called a microwave generator rather than an oscillator because it is difficult to construct a stable circuit that will oscillate in the gigahertz range. Instead, a crystal-controlled oscillator operating in the range 5 to 25 MHz is used to provide a base frequency that is multiplied up to the desired RF carrier frequency.

An *isolator* is a unidirectional device often made from a ferrite material. The isolator is used in conjunction with a channel-combining network to prevent the output of one transmitter from interfering with the output of another transmitter.

The RF receiver (Figure 6-8b) is essentially the same as the transmitter except that it works in the opposite direction. However, one difference is the presence of an IF amplifier

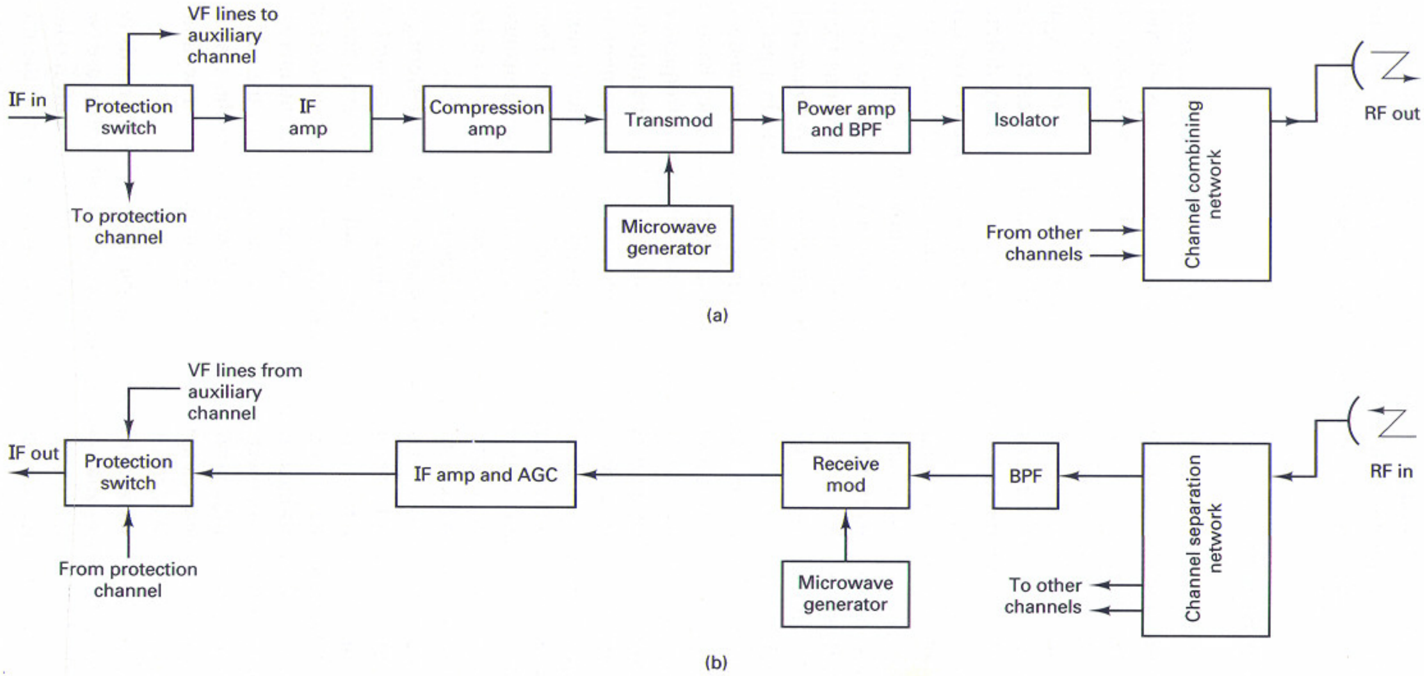


Figure 6-8 Microwave terminal station: (a) transmitter; (b) receiver.

in the receiver. This IF amplifier has an *automatic gain control* (AGC) circuit. Also, very often, there are no RF amplifiers in the receiver. Typically, a very sensitive, low-noise-balanced demodulator is used for the receive demodulator (receive mod). This eliminates the need for an RF amplifier and improves the overall signal-to-noise ratio. When RF amplifiers are required, high-quality, *low-noise amplifiers* (LNAs) are used. Examples of commonly used LNAs are tunnel diodes and parametric amplifiers.

Repeater Station

Figure 6-9 shows the block diagram of a microwave IF repeater station. The received RF signal enters the receiver through the channel separation network and bandpass filter. The receive mod down-converts the RF carrier to IF. The IF AMP/AGC and equalizer circuits amplify and reshape the IF. The equalizer compensates for *gain versus frequency nonlinearities* and *envelope delay distortion* introduced in the system. Again, the transmod up-converts the IF to RF for retransmission. However, in a repeater station, the method used to generate the RF microwave carrier frequencies is slightly different from the method used in a terminal station. In the IF repeater, only one microwave generator is required to supply both the transmod and the receive mod with an RF carrier signal. The microwave generator, shift oscillator, and shift modulator allow the repeater to receive one RF carrier frequency, down-convert it to IF, and then up-convert the IF to a different RF carrier frequency. It is possible for station C to receive the transmissions from both station A and station B simultaneously (this is called *multihop interference* and is shown in Figure 6-10a). This can occur only when three stations are placed in a geographical straight line in the system. To prevent this from occurring, the allocated bandwidth for the system is divided in half, creating a low-frequency and a high-frequency band. Each station, in turn, alternates from a low-band to a high-band transmit carrier frequency (Figure 6-10b). If a transmission from station A is received by station C, it will be rejected in the channel separation network and cause no interference. This arrangement is called a high/low microwave repeater system. The rules are simple: If a repeater station receives a low-band RF carrier, it retransmits a high-band RF carrier, and vice versa. The only time that multiple carriers of the same frequency can be received is when a transmission from one station is received from another station that is three hops away. This is unlikely to happen.

Another reason for using a high/low-frequency scheme is to prevent the power that "leaks" out the back and sides of a transmit antenna from interfering with the signal entering the input of a nearby receive antenna. This is called *ringaround.* All antennas, no matter how high their gain or how directive their radiation pattern, radiate a small percentage of their power out the back and sides; giving a finite *front-to-back* ratio for the antenna. Although the front-to-back ratio of a typical microwave antenna is quite high, the relatively small amount of power that is radiated out the back of the antenna may be quite substantial compared to the normal received carrier power in the system. If the transmit and receive carrier frequencies are different, filters in the receiver separation network will prevent ringaround from occurring.

A high/low microwave repeater station (Figure 6-10b) needs two microwave carrier supplies for the down- and up-converting process. Rather than use two microwave generators, a single generator together with a shift oscillator, a shift modulator, and a bandpass filter can generate the two required signals. One output from the microwave generator is fed directly into the transmod and another output (from the same microwave generator) is mixed with the shift oscillator signal in the shift modulator to produce a second microwave carrier frequency. The second microwave carrier frequency is offset from the

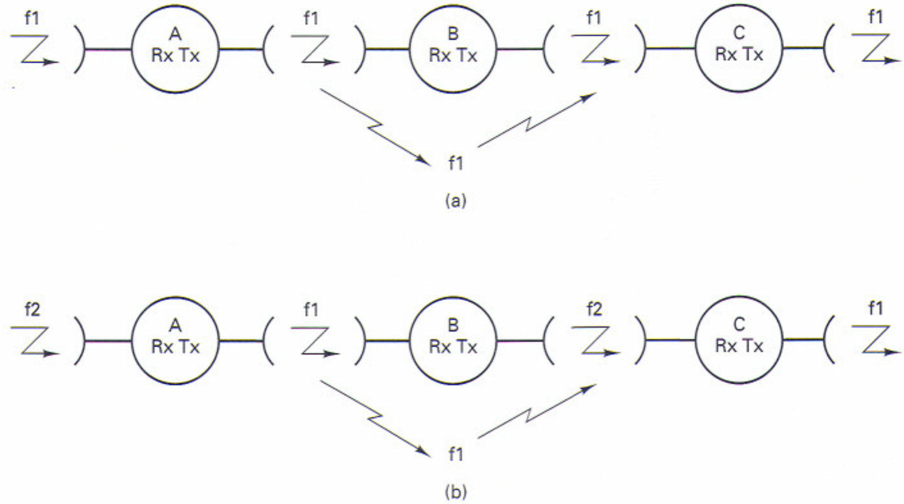


Figure 6-10 (a) Multihop interference and (b) high/low microwave system.

first by the shift oscillator frequency. The second microwave carrier frequency is fed into the receive modulator.

EXAMPLE 6-1

In Figure 6-9 the received RF carrier frequency is 6180 MHz, and the transmitted RF carrier frequency is 6000 MHz. With a 70-MHz IF frequency, a 5930-MHz microwave generator frequency, and a 180-MHz shift oscillator frequency, the output filter of the shift mod must be tuned to 6110 MHz. This is the sum of the microwave generator and the shift oscillator frequencies (5930 MHz + 180 MHz = 6110 MHz).

This process does not reduce the number of oscillators required, but it is simpler and cheaper to build one microwave generator and one relatively low-frequency shift oscillator than to build two microwave generators. This arrangement also provides a certain degree of synchronization between repeaters. The obvious disadvantage of the high/low scheme is that the number of channels available in a given bandwidth is cut in half.

Figure 6-11 shows a high/low-frequency plan with eight channels (four high-band and four low-band). Each channel occupies a 29.7-MHz bandwidth. The west terminal transmits the low-band frequencies and receives the high-band frequencies. Channel 1 and 3 (Figure 6-11a) are designated as *V channels.* This means that they are propagated with vertical polarization. Channels 2 and 4 are designated as H or horizontally polarized channels. This is not a polarization diversity system. Channels 1 through 4 are totally independent of each other; they carry different baseband information. The transmission of *orthogonally* polarized carriers (90° out of phase) further enhances the isolation between the transmit and receive signals. In the west-to-east direction, the repeater receives the low-band and transmits the high-band frequencies. After channel 1 is received and down-converted to IF, it is up-converted to a different RF frequency and a different polarization for retransmission. The low-band channel 1 corresponds to the high-band channel 11, channel 2 to channel 12, and so on. The east-to-west direction (Figure 6-11b) propagates the high- and low-band carriers in the sequence opposite to the west-to-east system. The polarizations are also reversed. If some of the power from channel 1 of the west terminal were to propagate directly to the east terminal receiver, it has a different frequency and polarization than channel 11's transmissions. Consequently, it would not interfere with the

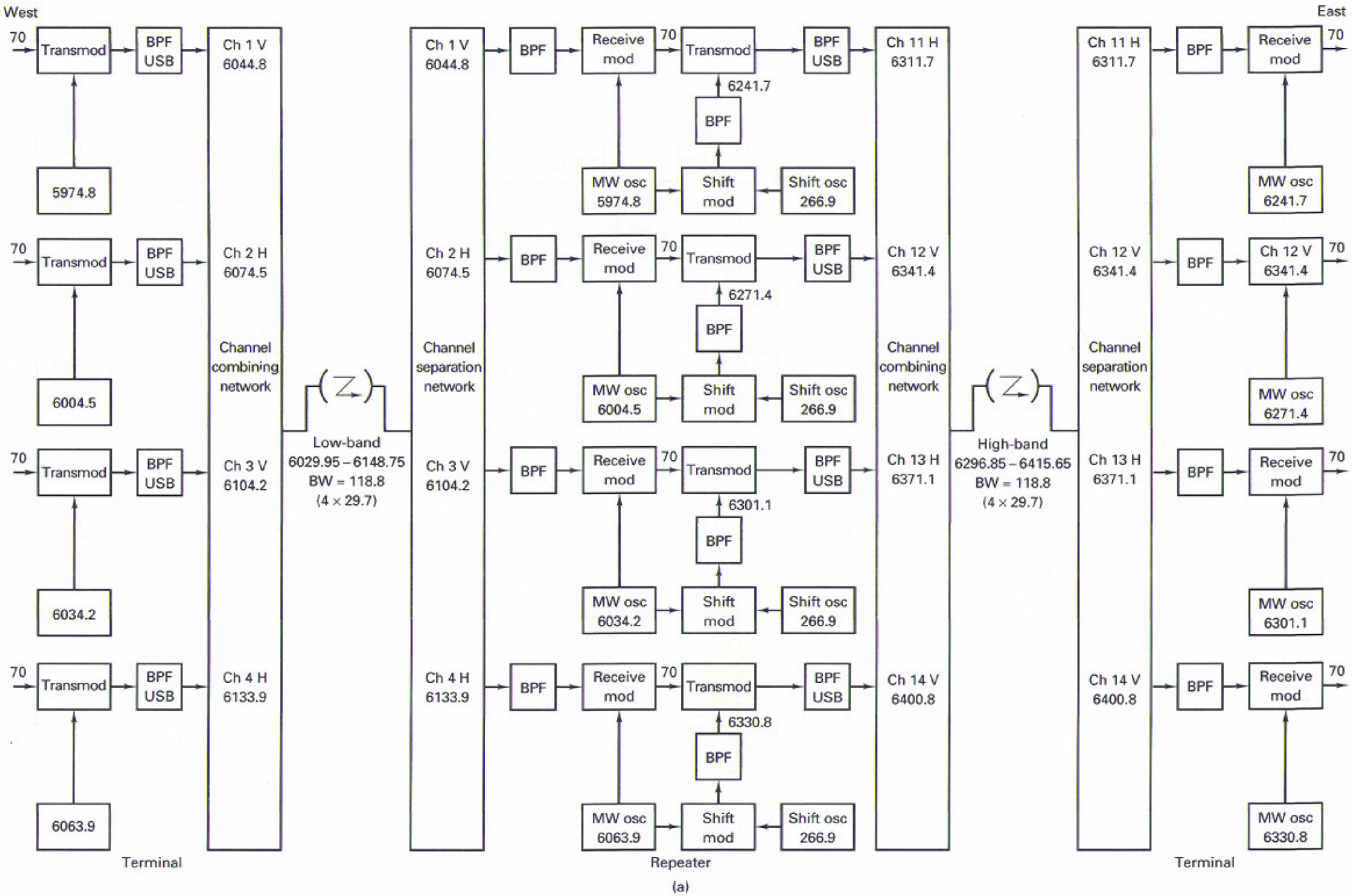


Figure 6-11 Eight-channel high/low frequency plan: (a) west to east; *(Continued next page.)*

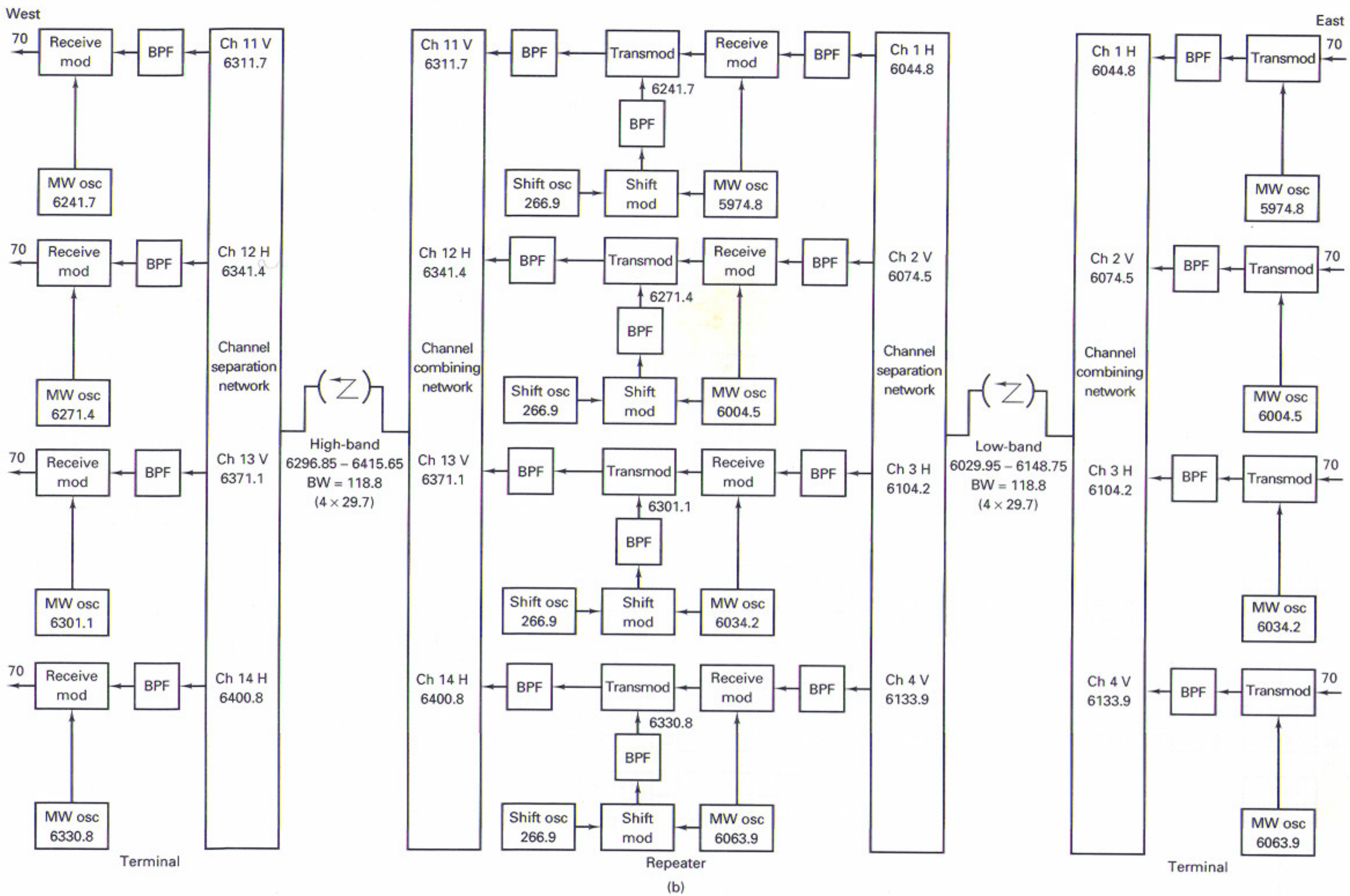


Figure 6-11 ***(continued)*** (b) east to west. All frequencies in megahertz.

reception of channel 11 (no multihop interference). Also, note that none of the transmit or receive channels at the repeater station has both the same frequency and polarization. Consequently, the interference from the transmitters to the receivers due to ringaround is insignificant.

PATH CHARACTERISTICS

The normal *propagation paths* between two radio antennas in a microwave radio system is shown in Figure 6-12. The *free-space path* is the *line-of-sight path* directly between the transmit and receive antennas (this is also called the *direct wave*). The *ground-reflected wave* is the portion of the transmit signal that is reflected off Earth's surface and captured by the receive antenna. The *surface wave* consists of the electric and magnetic fields associated with the currents induced in Earth's surface. The magnitude of the surface wave depends on the characteristics of Earth's surface and the electromagnetic polarization of the wave. The sum of these three paths (taking into account their amplitude and phase) is called the *ground wave*. The *sky wave* is the portion of the transmit signal that is returned (reflected) back to Earth's surface by the ionized layers of Earth's atmosphere.

All of the paths shown in Figure 6-12 exist in any microwave radio system, but some are negligible in certain frequency ranges. At frequencies below 1.5 MHz, the surface wave provides the primary coverage, and the sky wave helps to extend this coverage at night when the absorption of the ionosphere is at a minimum. For frequencies above about 30 to 50 MHz, the free-space and ground-reflected paths are generally the only paths of importance. The surface wave can also be neglected at these frequencies, provided that the antenna heights are not too low. The sky wave is only a source of occasional long-distance interference and not a reliable signal for microwave communications purposes. In this chapter the surface and sky-wave propagations are neglected, and attention is focused on those phenomena that affect the direct and reflected waves.

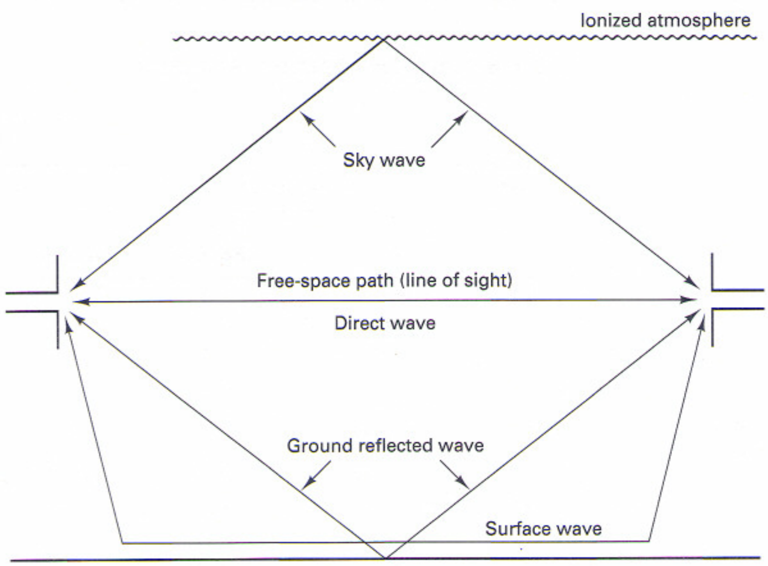


Figure 6-12 Propagation paths.

SYSTEM GAIN

In its simplest form, *system gain* is the difference between the nominal output power of a transmitter and the minimum input power required by a receiver. System gain must be greater than or equal to the sum of all the gains and losses incurred by a signal as it propagates from a transmitter to a receiver. In essence, it represents the net loss of a radio system. System gain is used to predict the reliability of a system for given system parameters. Mathematically, system gain is

$$G_s = P_t - C_{\min}$$

where: G_s = system gain (dB)
P_t = transmitter output power (dBm)
$C_{\min}$ = minimum receiver input power for a given quality objective (dBm)

and where:

$$P_t - C_{\min} \geq \text{losses} - \text{gains}$$

Gains:

A_t = transmit antenna gain (dB) relative to an isotropic radiator
A_r = receive antenna gain (dB) relative to an isotropic radiator

Losses:

L_p = free-space path loss between antennas (dB)
L_f = waveguide feeder loss (dB) between the distribution network (channel combining network or channel separation network) and its respective antenna (see Table 6-1)
L_b = total coupling or branching loss (dB) in the circulators, filters, and distribution network between the output of a transmitter or the input to a receiver and its respective waveguide feed (see Table 6-1)
F_m = fade margin for a given reliability objective

TABLE 6-1 SYSTEM GAIN PARAMETERS

Frequency (GHz)	Feeder loss, L_f		Branching loss (dB) Diversity:		Antenna gain, A_t or A_r	
	Type	Loss (dB/100 m)	Frequency	Space	Size (m)	Gain (dB)
1.8	Air-filled coaxial cable	5.4	5	2	1.2	25.2
					2.4	31.2
					3.0	33.2
					3.7	34.7
7.4	EWP 64 eliptical waveguide	4.7	3	2	1.5	38.8
					2.4	43.1
					3.0	44.8
					3.7	46.5
8.0	EWP 69 eliptical waveguide	6.5	3	2	2.4	43.8
					3.0	45.6
					3.7	47.3
					4.8	49.8

Mathematically, system gain is

$$G_s = P_t - C_{\min} \geq F_m + L_p + L_f + L_b - A_t - A_r \qquad (6\text{-}1)$$

where all values are expressed in dB or dBm. Because system gain is indicative of a net loss, the losses are represented with positive dB values and the gains are represented with negative dB values. Figure 6-13 shows an overall microwave system diagram and indicates where the respective losses and gains are incurred.

Free-Space Path Loss

Free-space path loss is defined as the loss incurred by an electromagnetic wave as it propagates in a straight line through a vacuum with no absorption or reflection of energy from nearby objects. The expression for free-space path loss is given as

$$L_p = \left(\frac{4\pi D}{\lambda}\right)^2 = \left(\frac{4\pi f D}{c}\right)^2$$

where: L_p = free-space path loss
D = distance
f = frequency
λ = wavelength
c = velocity of light in free space (3×10^8 m/s)

Converting to dB yields

$$L_p\,(\text{dB}) = 20 \log \frac{4\pi f D}{c} = 20 \log \frac{4\pi}{c} + 20 \log f + 20 \log D$$

When the frequency is given in MHz and the distance in km,

$$L_p\,(\text{dB}) = 20 \log \frac{4\pi(10)^6\,(10)^3}{3 \times 10^8} + 20 \log f\,(\text{MHz}) + 20 \log D\,(\text{km}) \qquad (6\text{-}2)$$

$$= 32.4 + 20 \log f\,(\text{MHz}) + 20 \log D\,(\text{km})$$

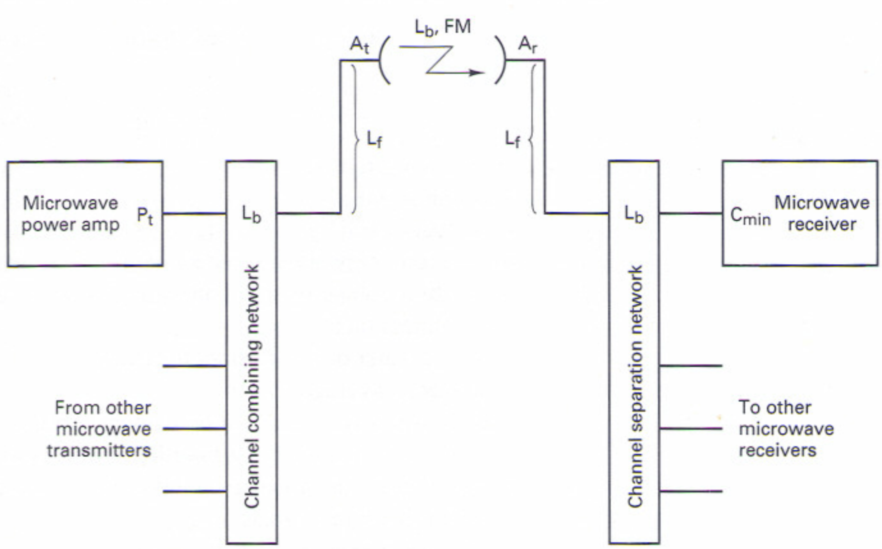


Figure 6-13 System gains and losses.

When the frequency is given in GHz and the distance in km,

$$L_p\,(\text{dB}) = 92.4 + 20\log f\,(\text{GHz}) + 20\log D\,(\text{km}) \tag{6-3}$$

Similar conversions can be made using distance in miles, frequency in kHz, and so on.

EXAMPLE 6-2

For a carrier frequency of 6 GHz and a distance of 50 km, determine the free-space path loss.

Solution

$$\begin{aligned} L_p\,(\text{dB}) &= 32.4 + 20\log 6000 + 20\log 50 \\ &= 32.4 + 75.6 + 34 \\ &= 142\text{ dB} \end{aligned}$$

or

$$\begin{aligned} L_p\,(\text{dB}) &= 92.4 + 20\log 6 + 20\log 50 \\ &= 92.4 + 15.6 + 34 \\ &= 142\text{ dB} \end{aligned}$$

Fade Margin

Essentially, *fade margin* is a "fudge factor" included in the system gain equation that considers the nonideal and less predictable characteristics of radio-wave propagation, such as *multipath propagation* (*multipath loss*) and *terrain sensitivity*. These characteristics cause temporary, abnormal atmospheric conditions that alter the free-space path loss and are usually detrimental to the overall system performance. Fade margin also considers system reliability objectives. Thus fade margin is included in the system gain equation as a loss.

Solving the Barnett–Vignant reliability equations for a specified annual system availability for an unprotected, nondiversity system yields the following expression:

$$F_m = \underbrace{30\log D}_{\substack{\text{multipath}\\ \text{effect}}} + \underbrace{10\log(6ABf)}_{\substack{\text{terrain}\\ \text{sensitivity}}} - \underbrace{10\log(1-R)}_{\substack{\text{reliability}\\ \text{objectives}}} - \underbrace{70}_{\text{constant}} \tag{6-4}$$

where: F_m = fade margin (dB)
D = distance (km)
f = frequency (GHz)
R = reliability expressed as a decimal (i.e., 99.99% = 0.9999 reliability)
$1 - R$ = reliability objective for a one-way 400-km route
A = roughness factor
= 4 over water or a very smooth terrain
= 1 over an average terrain
= 0.25 over a very rough, mountainous terrain
B = factor to convert a worst-month probability to an annual probability
= 1 to convert an annual availability to a worst-month basis
= 0.5 for hot humid areas
= 0.25 for average inland areas
= 0.125 for very dry or mountainous areas

EXAMPLE 6-3

Consider a space-diversity microwave radio system operating at an RF carrier frequency of 1.8 GHz. Each station has a 2.4-m-diameter parabolic antenna that is fed by 100 m of air-filled coaxial cable. The terrain is smooth and the area has a humid climate. The distance between stations is 40 km. A reliability objective of 99.99% is desired. Determine the system gain.

Solution Substituting into Equation 6-4, we find that the fade margin is

$$\begin{aligned} F_m &= 30 \log 40 + 10 \log (6)(4)(0.5)(1.8) - 10 \log (1 - 0.9999) - 70 \\ &= 48.06 + 13.34 - (-40) - 70 \\ &= 48.06 + 13.34 + 40 - 70 \\ &= 31.4 \text{ dB} \end{aligned}$$

Substituting into Equation 6-3, we obtain path loss

$$\begin{aligned} L_p &= 92.4 + 20 \log 1.8 + 20 \log 40 \\ &= 92.4 + 5.11 + 32.04 \\ &= 129.55 \text{ dB} \end{aligned}$$

From Table 6-1,

$$L_b = 4 \text{ dB } (2 + 2 = 4)$$

$$L_f = 10.8 \text{ dB } (100 \text{ m} + 100 \text{ m} = 200 \text{ m})$$

$$A_t = A_r = 31.2 \text{ dB}$$

Substituting into Equation 6-1 gives us system gain

$$G_s = 31.4 + 129.55 + 10.8 + 4 - 31.2 - 31.2 = 113.35 \text{ dB}$$

The results indicate that for this system to perform at 99.99% reliability with the given terrain, distribution networks, transmission lines, and antennas, the transmitter output power must be at least 113.35 dB more than the minimum receive signal level.

Receiver Threshold

Carrier-to-noise (*C/N*) is probably the most important parameter considered when evaluating the performance of a microwave communications system. The minimum wideband carrier power ($C_{\min}$) at the input to a receiver that will provide a usable baseband output is called the receiver *threshold* or, sometimes, receiver *sensitivity*. The receiver threshold is dependent on the wideband noise power present at the input of a receiver, the noise introduced within the receiver, and the noise sensitivity of the baseband detector. Before $C_{\min}$ can be calculated, the input noise power must be determined. The input noise power is expressed mathematically as

$$N = KTB$$

where: N = noise power (watts)
K = Boltzmann's constant (1.38×10^{-23} J/K)
T = equivalent noise temperature of the receiver (Kelvin) (room temperature = 290 K)
B = noise bandwidth (hertz)

Expressed in dBm,

$$N\,(\text{dBm}) = 10 \log \frac{KTB}{0.001} = 10 \log \frac{KT}{0.001} + 10 \log B$$

For a 1-Hz bandwidth at room temperature,

$$N = 10 \log \frac{(1.38 \times 10^{-23})\,(290)}{0.001} + 10 \log 1$$

$$= -174 \text{ dBm}$$

Thus

$$N\,(\text{dBm}) = -174 \text{ dBm} + 10 \log \text{B} \tag{6-5}$$

EXAMPLE 6-4

For an equivalent noise bandwidth of 10 MHz, determine the noise power.

Solution Substituting into equation 6-5 yields

$$N = -174 \text{ dBm} + 10 \log (10 \times 10^6)$$

$$= -174 \text{ dBm} + 70 \text{ dB} = -104 \text{ dBm}$$

If the minimum *C/N* requirement for a receiver with a 10-MHz noise bandwidth is 24 dB, the minimum receive carrier power is

$$C_{\min} = \frac{C}{N}\,(\text{dB}) + N\,(\text{dB})$$

$$= 24 \text{ dB} + (-104 \text{ dBm}) = -80 \text{ dBm}$$

For a system gain of 113.35 dB, it would require a minimum transmit carrier power (P_t) of

$$P_t = G_s + C_{\min}$$

$$= 113.35 \text{ dB} + (-80 \text{ dBm}) = 33.35 \text{ dBm}$$

This indicates that a minimum transmit power of 33.35 dBm (2.16 W) is required to achieve a carrier-to-noise ratio of 24 dB with a system gain of 113.35 dB and a bandwidth of 10 MHz.

Carrier-to-Noise versus Signal-to-Noise

Carrier-to-noise (*C/N*) is the ratio of the wideband "carrier" (actually, not just the carrier, but rather the carrier and its associated sidebands) to the wideband noise power (the noise bandwidth of the receiver). *C/N* can be determined at an RF or an IF point in the receiver. Essentially, *C/N* is a *predetection* (before the FM demodulator) signal-to-noise ratio. Signal-to-noise (*S/N*) is a *postdetection* (after the FM demodulator) ratio. At a baseband point in the receiver, a single voice band channel can be separated from the rest of the baseband and measured independently. At an RF or IF point in the receiver, it is impossible to separate a single voice band channel from the composite FM signal. For example, a typical bandwidth for a single microwave channel is 30 MHz. The bandwidth of a voice band channel is 4 kHz. *C/N* is the ratio of the power of the composite RF signal to the total noise power in the 30-MHz bandwidth. *S/N* is the ratio of the signal power of a single voice band channel to the noise power in a 4-kHz bandwidth.

Noise Figure

In its simplest form, *noise figure* (NF) is the signal-to-noise ratio of an ideal noiseless device divided by the *S/N* ratio at the output of an amplifier or a receiver. In a more practical sense, noise figure is defined as the ratio of the *S/N* ratio at the input to a device divided by the *S/N* ratio at the output. Mathematically, noise figure is

$$\mathrm{NF(dB)} = 10 \log \frac{(S/N)_{\mathrm{in}}}{(S/N)_{\mathrm{out}}}$$

Thus noise figure is a ratio of ratios. The noise figure of a totally noiseless device is unity or 0 dB. Remember, the noise present at the input to an amplifier is amplified by the same gain as the signal. Consequently, only noise added within the amplifier can decrease the signal-to-noise ratio at the output and increase the noise figure. (Keep in mind, the higher the noise figure, the worse the *S/N* ratio at its output).

Essentially, noise figure indicates the relative increase of the noise power to the increase in signal power. A noise figure of 10 means that the device added sufficient noise to reduce the *S/N* ratio by a factor of 10, or the noise power increased tenfold in respect to the increase in signal power.

When two or more amplifiers or devices are cascaded together (Figure 6-14), the total noise figure ($\mathrm{NF_T}$) is an accumulation of the individual noise figures. Mathematically, the total noise figure is

$$\mathrm{NF_T} = \mathrm{NF_1} + \frac{\mathrm{NF_2} - 1}{A_1} + \frac{\mathrm{NF_3} - 1}{A_1 A_2} + \frac{\mathrm{NF_4} - 1}{A_1 A_2 A_3} \quad \text{etc.} \tag{6-6}$$

where: $\mathrm{NF_T}$ = total noise figure
$\mathrm{NF_1}$ = noise figure of amplifier 1
$\mathrm{NF_2}$ = noise figure of amplifier 2
$\mathrm{NF_3}$ = noise figure of amplifier 3
A_1 = power gain of amplifier 1
A_2 = power gain of amplifier 2

Note: In equation 6-6 noise figures and gains are expressed as absolute values rather than in dB.

It can be seen that the noise figure of the first amplifier ($\mathrm{NF_1}$) contributes the most toward the overall noise figure. The noise introduced in the first stage is amplified by each of the succeeding amplifiers. Therefore, when compared to the noise introduced in the first stage, the noise added by each succeeding amplifier is effectively reduced by a factor equal to the product of the power gains of the preceding amplifiers.

When precise noise calculations (0.1 dB or less) are necessary, it is generally more convenient to express noise figure in terms of noise temperature or equivalent noise temperature rather than as an absolute power (Chapter 7). Because noise power (N) is proportional to temperature, the noise present at the input to a device can be expressed as a function of the device's environmental temperature (T) and its equivalent noise temperature

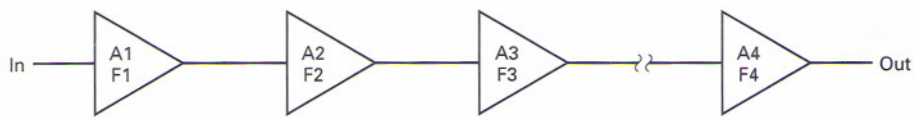


Figure 6-14 Total noise figure.

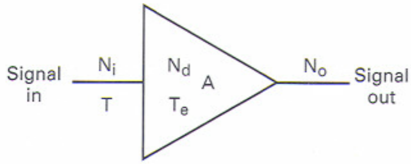


Figure 6-15 Noise figure as a function of temperature.

(T_e). Noise figure can be converted to a term dependent on temperature only as follows (refer to Figure 6-15).

Let

N_d = noise power added by a single amplifier, referred to its input

Then

$$N_d = KT_eB$$

where T_e is the equivalent noise temperature. Let

N_o = total output noise power of an amplifier
N_i = total input noise power of an amplifier
A = power gain of an amplifier

Therefore,

N_o may be expressed as

$$N_o = AN_i + AN_d$$

and

$$N_o = AKTB + AKT_eB$$

Simplifying yields

$$N_o = AKB\,(T + T_e)$$

and the overall noise figure (NF_T) equals

$$NF_T = \frac{(S/N)_{in}}{(S/N)_{out}} = \frac{S/N_i}{AS/N_o} = \frac{N_o}{AN_i} = \frac{AKB\,(T + T_e)}{AKTB} \tag{6-7}$$

$$= \frac{T + T_e}{T} = 1 + \frac{T_e}{T}$$

EXAMPLE 6-5

In Figure 6-14, let $NF_1 = NF_2 = NF_3 = 3$ dB and $A_1 = A_2 = A_3 = 10$ dB. Solve for the total noise figure.

Solution Substituting into equation 6-6 (*Note:* All gains and noise figures have been converted to absolute values) yields

$$NF_T = NF_1 + \frac{NF_2 - 1}{A_1} + \frac{NF_3 - 1}{A_1A_2}$$

$$= 2 + \frac{2 - 1}{10} + \frac{2 - 1}{100}$$

$$= 2.11 \text{ or } 10 \log 2.11 = 3.24 \text{ dB}$$

An overall noise figure of 3.24 dB indicates that the *S/N* ratio at the output of A3 is 3.24 dB less than the *S/N* ratio at the input to A1.

The noise figure of a receiver must be considered when determining C_{min}. The noise figure is included in the system gain equation as an equivalent loss. (Essentially, a gain in the total noise power is equivalent to a corresponding loss in the signal power.)

EXAMPLE 6-6

Refer to Figure 6-16. For a system gain of 112 dB, a total noise figure of 6.5 dB, an input noise power of −104 dBm, and a minimum $(S/N)_{\text{out}}$ of the FM demodulator of 32 dB, determine the minimum receive carrier power and the minimum transmit power.

Solution To achieve a S/N ratio of 32 dB out of the FM demodulator, an input C/N of 15 dB is required (17 dB of improvement due to FM quieting). Solving for the receiver input carrier-to-noise ratio gives

$$\frac{C_{\text{min}}}{N} = \frac{C}{N} + \text{NF}_T = 15\text{ dB} + 6.5\text{ dB} = 21.5\text{ dB}$$

Thus

$$C_{\text{min}} = \frac{C_{\text{min}}}{N} + N$$

$$= 21.5\text{ dB} + (-104\text{ dBm}) = -82.5\text{ dBm}$$

$$P_t = G_s + C_{\text{min}}$$

$$= 112\text{ dB} + (-82.5\text{ dBm}) = 29.5\text{ dBm}$$

EXAMPLE 6-7

For the system shown in Figure 6-17, determine the following: G_s, C_{min}/N, C_{min}, N, G_s, and P_t.

Solution The minimum C/N at the input to the FM receiver is 23 dB.

$$\frac{C_{\text{min}}}{N} = \frac{C}{N} + \text{NF}_T$$

$$= 23\text{ dB} + 4.24\text{ dB} = 27.24\text{ dB}$$

Substituting into equation 6-5 yields

$$N = -174\text{ dBm} + 10\log B$$

$$= -174\text{ dBm} + 68\text{ dB} = -106\text{ dBm}$$

$$C_{\text{min}} = \frac{C_{\text{min}}}{N} + N$$

$$= 27.24\text{ dB} + (-106\text{ dBm}) = -78.76\text{ dBm}$$

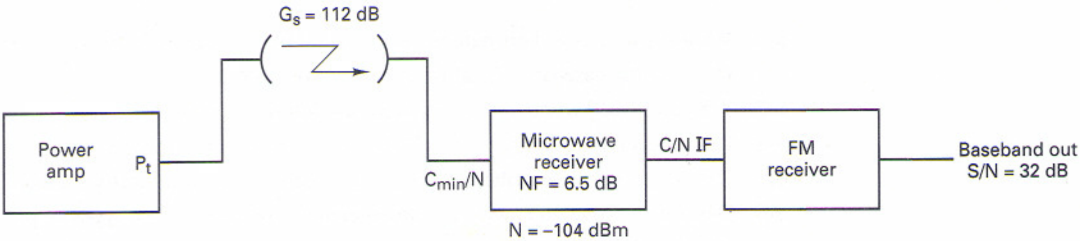


Figure 6-16 System gain example.

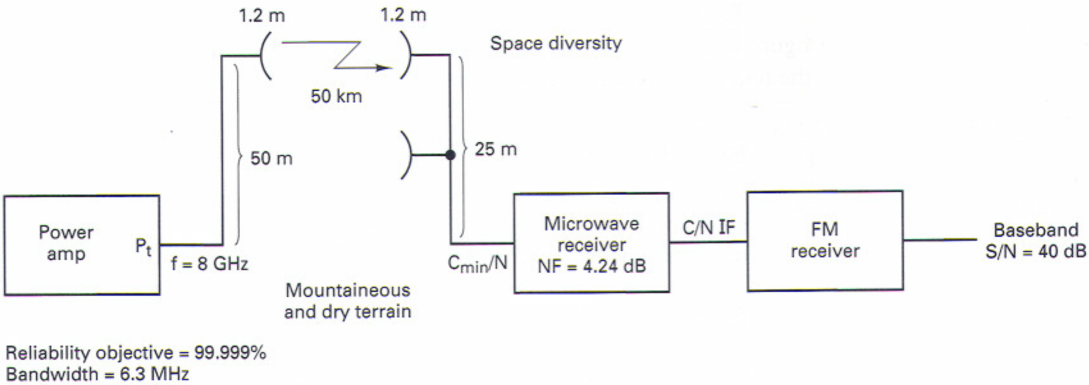


Figure 6-17 System gain example.

Substituting into equation 6-4 gives us

$$F_m = 30 \log 50 + 10 \log [(6)(0.25)(0.125)(8)]$$
$$= -10 \log (1 - 0.99999) - 70$$
$$= 32.76 \text{ dB}$$

Substituting into equation 6-3, we have

$$L_p = 92.4 \text{ dB} + 20 \log 8 + 20 \log 50$$
$$= 92.4 \text{ dB} + 18.06 \text{ dB} + 33.98 \text{ dB} = 144.44 \text{ dB}$$

From Table 6-1,

$$L_b = 4 \text{ dB}$$
$$L_f = 0.75\,(6.5 \text{ dB}) = 4.875 \text{ dB}$$
$$A_t = A_r = 37.8 \text{ dB}$$

Note: The gain of an antenna increases or decreases proportional to the square of its diameter (i.e., if its diameter changes by a factor of 2, its gain changes by a factor of 4 which is 6 dB).

Substituting into equation 6-1 yields

$$G_s = 32.76 + 144.44 + 4.875 + 4 - 37.8 - 37.8 = 110.475 \text{ dB}$$
$$P_t = G_s + C_{\min}$$
$$= 110.475 \text{ dB} + (-78.76 \text{ dBm}) = 31.715 \text{ dBm}$$

QUESTIONS

6-1. What constitutes a short-haul microwave system? A long-haul microwave system?

6-2. Describe the baseband signal for a microwave system.

6-3. Why do FDM/FM microwave systems use low-index FM?

6-4. Describe a microwave repeater. Contrast baseband and IF repeaters.

6-5. Define *diversity*. Describe the three most commonly used diversity schemes.

6-6. Describe a protection switching arrangement. Contrast the two types of protection switching arrangements.

6-7. Briefly describe the four major sections of a microwave terminal station.

6-8. Define *ringaround.*

6-9. Briefly describe a high/low microwave system.

6-10. Define *system gain.*

6-11. Define the following terms: free-space path loss, branching loss, and feeder loss.

6-12. Define *fade margin.* Describe multipath losses, terrain sensitivity, and reliability objectives and how they affect fade margin.

6-13. Define *receiver threshold.*

6-14. Contrast carrier-to-noise ratio and signal-to-noise ratio.

6-15. Define *noise figure.*

PROBLEMS

6-1. Calculate the noise power at the input to a receiver that has a radio carrier frequency of 4 GHz and a bandwidth of 30 MHz (assume room temperature).

6-2. Determine the path loss for a 3.4-GHz signal propagating 20,000 m.

6-3. Determine the fade margin for a 60-km microwave hop. The RF carrier frequency is 6 GHz, the terrain is very smooth and dry, and the reliability objective is 99.95%.

6-4. Determine the noise power for a 20-MHz bandwidth at the input to a receiver with an input noise temperature of 290°C.

6-5. For a system gain of 120 dB, a minimum input C/N of 30 dB, and an input noise power of -115 dBm, determine the minimum transmit power (P_t).

6-6. Determine the amount of loss attributed to a reliability objective of 99.98%.

6-7. Determine the terrain sensitivity loss for a 4-GHz carrier that is propagating over a very dry, mountainous area.

6-8. A frequency-diversity microwave system operates at an RF carrier frequency of 7.4 GHz. The IF is a low-index frequency-modulated subcarrier. The baseband signal is the 1800-channel FDM system described in Chapter 6 (564 to 8284 kHz). The antennas are 4.8-m-diameter parabolic dishes. The feeder lengths are 150 m at one station and 50 m at the other station. The reliability objective is 99.999%. The system propagates over an average terrain that has a very dry climate. The distance between stations is 50 km. The minimum carrier-to-noise ratio at the receiver input is 30 dB. Determine the following: fade margin, antenna gain, free-space path loss, total branching and feeder losses, receiver input noise power, C_{min}, minimum transmit power, and system gain.

6-9. Determine the overall noise figure for a receiver that has two RF amplifiers each with a noise figure of 6 dB and a gain of 10 dB, a mixer down-converter with a noise figure of 10 dB, and a conversion gain of -6 dB, and 40 dB of IF gain with a noise figure of 6 dB.

6-10. A microwave receiver has a total input noise power of -102 dBm and an overall noise figure of 4 dB. For a minimum C/N ratio of 20 dB at the input to the FM detector, determine the minimum receive carrier power.