5. MICROWAVE SYSTEMS

5.1 INTRODUCTION

Microwave systems are broadband terrestrial line-of-sight radio systems. They are commonly used by telcos to provide wideband fixed point-to-point radio communication links for distances up to about 50 km, which offer major trunk channels for long distance communication to carry voice, data and video traffic. They operate in the frequency range from 1 GHz to about 30 GHz. Though their bandwidth is less compared to that of optical fiber, microwave systems have major advantages over cabling systems. These advantages include, inter alia:

- Freedom from land acquisition rights; that is, acquisition of rights to lay cabling or repair cabling, and have permanent access to repeater. The use of radio links, that require only the acquisition of the transmitter/receiver station, removes this requirement. It also simplifies the maintenance and repair of the link.
- Ease of communication over difficult terrain. Some terrains make cable laying extremely difficult and expensive, even if the land acquisition cost is negligible.
- Wider bandwidths, which are required for broadband signals like television signals and for provision of large number of telephone channels.

A basic microwave link consists of a transmitting station, Tx, one or more relay stations (or repeaters), RPT, and a receiving station, Rx, as shown in Figure 5.1.

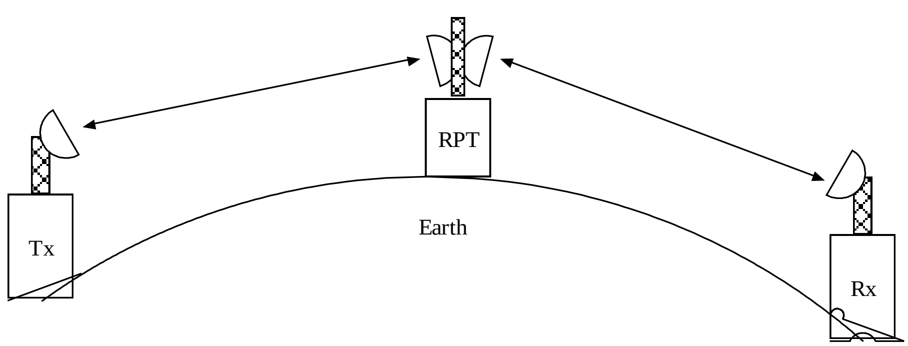


Figure 5.1 Microwave radio relay link

At the transmitting station the signal to be transmitted (i.e. baseband signal) is first processed (i.e. encoded) before it is used to modulate an intermediate carrier of 70 MHz (or 140 MHz). The modulated signal is then up-converted to the allocated microwave frequency and amplified before being fed to the antenna for radiation.

The repeater or relay station is added at the obstacle point or other suitable place to provide LoS or at 50 km intervals to boost the power of the signal so that it can go a longer distance. There are two types of repeater: passive and active repeater. Passive is like a beam diverter to make the beam surpass obstacle using back-to-back parabolic antennas connected by a section of a waveguide, and they do not have any amplifying device. Active repeater includes an amplifier to boost the signal strength and others also have frequency translation circuits to change the frequency of the signal before retransmitting it. The former active repeater, which does not have frequency translation circuit, is referred to as *RF direct relay station*, while the latter is called a *regenerative relay station*.

At the receiving station the signal is down-converted to 70 MHz (or 140 MHz) before it is demodulated to recover the baseband signal.

To radiate or receive the radio waves, the microwave system use directional high gain parabolic dish antennas.

The old microwave systems were analogue: using analogue modulation and FDM; however, nowadays microwave systems are digital. These digital microwave systems use digital modulation and TDM.

Digital modulation schemes used are M-ary modulation schemes, such as QPSK, 16-QAM or higher-QAM. They offer capacities from low (8Mbps), medium (34Mbps) to High (≥ 140Mbps). They use time division based multiplexing techniques, such as PDH and SDH and the commonly used capacity configurations are as follows

- 4 x 2 Mbps (4 x E1)
- 8 x 2 Mbps (8 x E1)
- 16 x 2 Mbps (16 x E1)
- 155 Mbps (STM1)

5.2DIGITAL MICROWAVE EQUIPMENT

Digital microwave equipment can be classified based on multiplexing method used (i.e. PDH or SDH), capacity, or structure. However, the most commonly used method to classify microwave equipment is based on the structure as follows:

- All-indoor microwave
- All-outdoor microwave
- Split microwave

5.2.1 All-indoor Microwave

The all-indoor microwave, also called big microwave, has all its units; that is, RF unit (RFU), Signal Processing Unit (SPU), and Multiplexer residing indoor, and its only the antenna that is outdoor. Compared to other types, it is having a high transmission capacity, though that comes at a price of high costs. It is suitable for backbone line transmission or backhaul.

5.2.2 All-outdoor microwave

The all-outdoor microwave has all its units residing outdoor. It is easy to install, saves equipment room space; however, it can be easily damaged.

5.2.3 Split microwave

Consists of both indoor unit (IDI) and outdoor unit (ODU), which are connected using IF cable. The cable carries IF service signals, communication control signals and power to the ODU. Though it is easy to install, split microwave has a low capacity.

5.3 PROPAGATION

Microwave energy does not follow the earth's curvature or diffract easily, hence their propagation is restricted to line-of-sight (LoS). To help providing the required line-of-sight microwave antennas need to be located on high ground (i.e. top of the hill or building) to avoid obstacles.
Microwave signals are high frequency signals with shorter wavelength and they are easily degraded by rain, clouds and other atmospheric effects. That is, they are susceptible to absorption by gases in the atmosphere, especially water vapor around *22 GHz* and oxygen around *57 GHz*, and attenuation by rain, fog and clouds. Microwave frequencies are also susceptible to scintillation and refraction by the ionosphere.

Atmospheric absorption, clouds, fog, precipitation, and scintillation cause power losses in the propagated signal. At lower frequencies these power losses are negligible small, and only free space loss is considered. However, as the frequency increases, these losses become significant, especially in frequencies from the SHF band upwards. This dominance of these atmospheric losses requires them to be taken into consideration when determining path loss. Thus, path loss, L_p, at higher frequencies becomes the sum of free space loss, L_S, and atmospheric loss, L_a; that is,

$$L_P = L_a + L_S \quad (5.1)$$

Terrain conditions over which the wave propagate also affects the microwave signals. Major terrain influences on the signal include reflection, diffraction and ground scattering.

According to ITU-R Rec. P.530, the overall loss that is incurred by the radio signal during terrestrial LoS propagation relative to free space loss is the sum of different contributions, such as attenuation due to atmospheric gases, attenuation due to precipitation, diffraction fading due to full or partial obstruction of the path, and fading due to multipath. Each of these contributions has its own characteristic as a function of frequency, path length, and geographical location.

Comment [s1]:

5.3.1 Atmospheric Absorption

The atmosphere introduces other losses in addition to free space losses. These losses are mainly due to molecular absorption by electrons, uncondensed water vapor, and molecules of various gases present in the atmosphere. Free electrons cause increasing loss at low frequencies, water vapors cause increasing loss which peaks around *22 GHz*, and oxygen causes sharp peak absorption around *57HGz* as shown in Figure 5.2. The oxygen volume ratio in the gases is quite stable, while the water vapor density varies a lot, with strong regional and seasonal dependence. Specific gaseous attenuation due to oxygen and water vapour is given by

$$\gamma = \gamma_w + \gamma_o \tag{5.2}$$

Where γ_w is the specific attenuation due to water vapour in the horizontal dependence, which is given by

$$\gamma_W = \left[0.067 + \frac{3}{(f-2.23)^2 + 7.3} + \frac{9}{(f-183.3)^2 + 6} + \frac{4.3}{(f-323.8)^2 + 10}\right] f^2 \rho 10^{-4}\, dB/km \tag{5.3}$$

where f is frequency in *GHz* and ρ is the water vapor density in g/m^3.
γ_o is the specific attenuation due to oxygen in the horizontal dependence, which is given by

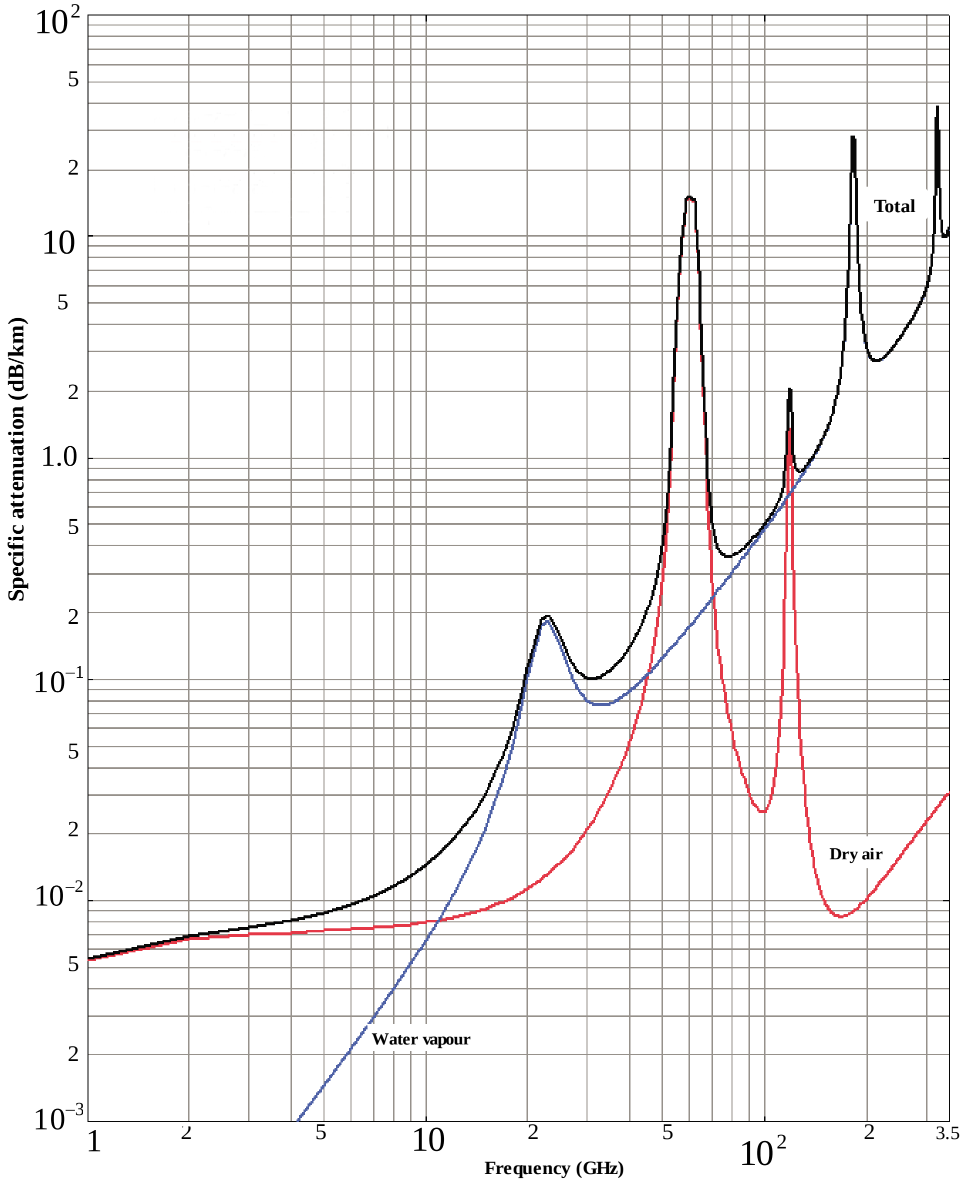
$$\gamma_o = \left[7.19\times10^{-3} + \frac{6.09}{f^2 + 0.227} + \frac{4.81}{(f-57)^2 + 1.50}\right] f^2 \times 10^{-3}\, dB/km \tag{5.4}$$

For terrestrial, or slightly inclined paths close to ground, the path attenuation, *A*, may be written as

$$A = \gamma d \tag{5.5}$$

where *d* is the path length in km.

Atmospheric gas absorption occurs mainly at low altitudes



Surface pressure: 1 013 hPa
Surface temperature: $15^0 C$
Surface water vapour density: $7.5\,g/m^3$

Figure 5.2 Specific attenuation due to atmospheric gases (Adapted from ITU-R P.676-9)

5.3.2 Attenuation by Rainfall and Hydrometeors

Rain and hydrometeors, such as hail, ice, and snow, can cause severe attenuation for higher frequency signals. Water drops will absorb energy from incident waves. If the size of the water drops or droplets approaches a quarter wavelength of the transmitted frequency, then that drops or droplets will become highly reflective to the signal being transmitted. Many drops or droplets will become like multiple reflectors or deflectors resulting in the energy from the incident wave being scattered in many directions. This absorption and scattering causes the attenuation to increase exponentially as the frequency increases. The severity of radio signal loss through the rain is strongly dependent on the local rainfall rates, rain cloud heights, and signal frequencies. ITU rain attenuation model specifies attenuation rate, γ_R, which is a function of rain fall rate, *R, as*

$$\gamma_R = kR^{\alpha} \tag{5.6}$$

where two coefficients α and *k* are functions of signal's frequency and elevation angle given in ITU-R, Rec. 838.

Clouds and fog or mist can be described as collections of smaller rain droplets or moisture clusters. However, droplet size in fog and clouds is smaller than the wavelength at 3–30 GHz, hence the interactions with fog and clouds is different from that from rain. Moisture clusters are non-homogenous materials that can absorb, reflect, scatter and refract the waves. Attenuation is dependent on frequency, temperature (refractive index), and elevation angle, and it can be expressed in terms of the total water content per unit volume based on Rayleigh approximation:

$$\gamma_c = K_1 M \tag{5.7}$$

where γ_c = specific attenuation *(dB/km)* within the cloud*;* K_l = specific attenuation coefficient $[(dB/km)/(g/m^3)]$ and *M* is liquid water density in the cloud or fog (g/m^3). However, attenuation due to clouds or fog is not as severe as rain attenuation.

5.3.3 Attenuation due to Scintillation

Scintillation can be described as a rapid random fluctuation of a radio signal about a mean level, which is either constant or changing much slowly than scintillation itself. These fluctuations can either be phase or amplitude fluctuations. One of the causes of scintillation is turbulent air with variations in the refractive index. Attenuation due to scintillations rapidly increases with increasing frequency and decreasing elevation angle.

The losses due to scintillation are strongly dependent on time percentage, elevation angle, and antenna size.

In trans-ionospheric radio propagation, such as satellite communication, the ionosphere is the primary cause.

5.3.4 Refraction in the atmosphere

Radio waves travel in a straight line unless something reflects, refracts or diffracts them. When the radio waves leave the source they seldom follow a straight line between transmitter and receiver. They spread out as they get farther from the source, and the area that the signal spreads out into is called the *Fresnel zone*. The thickness of the Fresnel zone is inversely proportional to the frequency of the signal being radiated. If there is an obstruction in the Fresnel zone, part of the signal will be diffracted or be bent away from the straight line path.

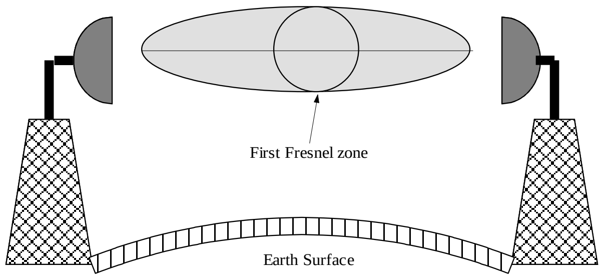


Figure 5.3 Fresnel zones

Additional to diffraction or reflection the direction of the radiated wave can also be altered due to refraction in the atmosphere. The condition of the atmosphere is a temperature and pressure gradient with which is associated a gradient of refraction index. As the atmospheric condition [temperature or moisture] changes, the gradient of the index of refraction also changes, resulting in the propagated wave bending. Depending on the atmospheric conditions it can either be bent towards the earth or away from the earth. When the meteorological conditions have resulted in a steeper gradient such that rays are bent towards the earth strongly, the atmosphere forms a duct or a waveguide, which restricts the wave propagation over the surface of the earth. Variability in the atmosphere is modeled using earth curvature (*K*) factor.

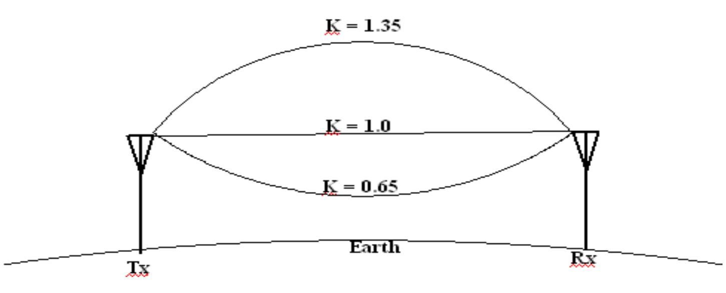


Figure 5.4 Propagated ray trajectories for different values of K

5.3.5 Fading

Scattering, reflections and other effects will result in multipath transmissions. Due to multipath transmissions, waves that have travelled different path will interact at the receiver causing power to increase if the phase is the same or to decrease if the phase is not the same.

Another type of fading occurs when the wave is trapped in the formed atmospheric duct or waveguide. The wave propagating in this duct or atmospheric waveguide can propagate for longer distances beyond the LoS.

If the atmospheric conditions are such that the resultant K factor is very low, the ray path will be bent in such a way that the earth surface obstructs the path of the signal from transmitter to the receiver giving rise to the type of fading called *diffraction fading*. The diffraction loss depends on terrain and vegetation and is given by

$$G_d = -20\frac{h}{r_{1e}} + 10 \qquad (5.8)$$

where h is the height difference in meters between the most significant path blockage and the path trajectory, and r_{1e} is the radius of the first Fresnel zone ellipsoid (Afullo and Odedina, 2006).

The effects of fading can be mitigated to a certain extent by the use of *fade margin* and/or *diversity*. Fade margin involves the adding of extra power or excess gain to the transmitting end of the link to overcome potential fading. The value of the excess gain depends on the required percentage of availability time as shown in Table 5.1

Table 5.1 Required fade margins for percentage of availability times

Time Availability (%)	Required Fade Margin (dB)
90	8
99	18
99.9	28
99.99	38
99.999	48

Diversity involves the use of more than one transmitting and receiving system coupled to a common network, which selects at all times the strongest signal available or combines all the signals into one. The rationale behind diversity is the fact that although fading may be severe at some instant in time, some frequency, some point on earth or some polarization, it is extremely unlikely that the signals at different points, different frequencies or different polarization will fade simultaneously.

5.4 MICROWAVE LINK DESIGN

The design of a terrestrial LoS microwave link involves four steps: defining of system performance requirements, doing radio path profiling, determining the antenna heights, and link budgeting.

5.4.1 Defining of system performance requirements

Defining or setting system performance requirements involves defining the type of circuit or circuits that are going to be provided; that is, what type of traffic is to be transmitted. Remember each type of traffic has its bandwidth and BER requirements to be considered. Additional to bandwidth and signal impairment (BER) limit, other performance requirements that need to be considered during microwave link design include the following:

- Period for which the link is going to be used; that is, is it going to be used for a short period to provide a temporary link or is it going to be used for a longer period.
- The possibility of growth: are there any plans to upgrade the system to a higher capacity or not.
- Percentage of availability so that a suitable value can be chosen during link budgeting. Redundancy to provide an alternative path or backup during partial or complete link failure, and diversity to counter the effects of fading.

5.4.2 Radio Path Profile

The rationale behind radio path profiling is to collect the information about the site and the path that is going to be used for the microwave link. Path profiling involves site selection where the equipment will be installed; surveying the site and the path from transmitter to the receiver in order to get terrain profile and terrain cover. Path profiling helps to identify the obstacle along the route that can be an infringement to LoS, such as buildings, vegetation, earth bulge, hills or mountains.

Site selection and path profiling usually involves using [hard or soft copies] of topographical maps of the area. First you identify the two sites, and you then draw a straight line from the transmitting site to the receiving site. After that you read from the map the heights of the two sites and the heights and the distances of any potential obstructions along the path, once this has been completed the path profile can be plotted either manually or using computer program such as Path Loss. Then you add an allowance of about 3 m for vegetation and if the obstruction is a tree, a clearance value of 12 m must be added to the 3 m allowance. The height of each obstacle must include earth curvature or earth bulge, where the amount of the earth bulge, h_{EB}, is given by

$$h_{EB} = h_B + h_{TR} \tag{5.9}$$

Where $$h_B = \frac{d_1 d_2}{2a} \tag{5.10}$$

And $$h_{TR} = h_B\left(\frac{1}{K} - 1\right) \tag{5.11}$$

Substituting for h_B and h_{TR} in Equation 5.9 we get

$$\begin{aligned} h_{EB} &= \frac{d_1 d_2}{2a} + \frac{d_1 d_2}{2a}\left(\frac{1}{K} - 1\right) \\ &= \frac{d_1 d_2}{2a} + \frac{d_1 d_2}{2aK} - \frac{d_1 d_2}{2a} \\ &= \frac{d_1 d_2}{2aK} \end{aligned}$$

Substituting for *a = 6371 km*, which is the earth radius, we get

$$h_{EB} = \frac{d_1 d_2}{2 \times 6371 \times K}$$

$$\therefore h_{EB} = \frac{0.078 d_1 d_2}{K} \tag{5.12}$$

Where h is in meters, d_1 is the distance, in kilometers, from the near end of the hop to the obstacle in question and d_2 is the distance, in kilometers, from the obstacle to the far end of the hop. Since it has been mentioned in Section 5.3.4 that the rays will be bent due to atmospheric refraction, K is included as a modifying factor to accommodate the bending effects, and if there was no bending the rays will travel in a straight line and the value of K will be unity, thus Equation 5.12 would be

$$h_{EB} = 0.078 d_1 d_2 \tag{5.13}$$

5.4.3 Antenna Heights

Once the sites and the route have been carefully selected, the next step is to determine the antenna heights that will be high enough for radio beam to surmount obstacles in the path. That is, antenna heights required to overcome any infringements to LoS that are caused by the terrain.

In order to guarantee path clearance between the transmitter and receiver, we need to add Fresnel zone clearance that is given by

$$h_{FZC} = 17.3\sqrt{\frac{d_{1(km)}d_{2(km)}}{f_{GHz}d_{km}}} \quad (5.14)$$

Where h_{FZC} is the first Fresnel zone clearance in meters, d is the total length of the link in kilometers and f is the frequency in Gigahertz.

Therefore the total antenna height would be the sum of the earth bulge and the first Fresnel zone clearance; that is,

$$h_T = h_{EB} + h_{FZC} \quad (5.15)$$

5.4.4 Link Budget

In Chapter 2, Section 2.8 link budget was introduced as a communication balance sheet of power and losses that outlines the detailed apportionment of both transmission and reception resources, noise sources, signal attenuators, and effects of processes throughout the entire link. Mathematically, Equation 2.20 expressed link budget as

$$S_r(dBm) = P_t(dBm) + \sum Gains(dB) - \sum Losses(dB) - M\arg in$$

For radio Equation 2.20 was expanded to Equation 2.33, which is given by

$$\begin{aligned} S_r(dBm) = {} & P_t(dBm) - L_{Bt}(dB) - L_{ft}(dB) + G_{At}(dB) - L_S(dB) - FM(dB) \\ & - L_{Br}(dB) - L_{fr}(dB) + G_{Ar}(dB) \end{aligned}$$

If from the above equation we can replace free space loss with path loss from Equation 5.1, and lump all the loss between the transmitter and the antenna as *transmit chain losses*, L_{TX}, and those between the receiving antenna and the receiver as *receive chain losses*, L_{RX}, then Equation 2.33 above can be rewritten as

$$\begin{aligned} S_r(dBm) = {} & P_t(dBm) - L_{TX}(dB) + G_{At}(dB) - L_p(dB) - FM(dB) \\ & - L_{RX}(dB) + G_{Ar}(dB) \end{aligned} \quad (5.16)$$

Where the gain of a parabolic antenna is given by

$$D = \left(\frac{\pi D_r}{\lambda}\right)^2 I(\theta) \quad (5.17)$$

Where D_r is the diameter of the parabolic dish and $I(\theta)$ is the illumination efficiency.

5.4.5 Receiver Noise, E_b/N_0 and Bit Error Probability

Any device generates thermal noise when its absolute temperature is above zero. The thermal noise generated is a function of the receiver bandwidth and noise figure and temperature. For digital systems, the noise level of interest is in only 1 Hz of the bandwidth. For a perfect receiver (i.e. a receiver that has a noise figure of zero) the thermal noise power at absolute zero is

$$P_n = 10\log\left(\frac{1.38\times10^{-23}}{1W}\right) = -228.6 dBW/Hz \tag{5.18a}$$

Or

$$P_n = 10\log\left(\frac{1.38\times10^{-23}}{1mW}\right) = -198.6 dBm/Hz \tag{5.18b}$$

And the thermal noise at temperatures above the absolute zero will be

$$P_n = -228.6 dBW/Hz + 10\log Temp_{(Kelvin)} \tag{5.19a}$$

Or

$$P_n = -198.6 dBm/Hz + 10\log Temp_{(Kelvin)} \tag{5.19b}$$

Where $Temp_{(Kelvin)}$ is the temperature in Kelvin, which is given by

$$Temp_{(Kelvin)} = (T_{(^0C)} + 273)K \tag{5.20}$$

The available margin for E_b/N_0 and modulation is given by

$$S_r - P_n \tag{5.21}$$

Taking the noise figure of the system into consideration Equation 5.19 can be rewritten as

$$N_0 = -228.6 dBW/Hz + 10\log Temp_{(Kelvin)} + NF_{dB} \tag{5.22a}$$

Or

$$N_0 = -198.6 dBm/Hz + 10\log Temp_{(Kelvin)} + NF_{dB} \tag{5.22b}$$

The energy per bit is the function of the received power and the bit rate; that is,

$$E_b = RSL - 10\log(bit\ rate) \tag{5.23}$$

Once N_0 and E_b have been determined, the E_b/N_0 ratio can also be determined using the following equation

$$E_b/N_o = E_b - N_o = RSL - 10\log(bit\,rate) - \left(-228.6dBW/Hz + 10\log Temp_{(Kelvin)} + NF_{dB}\right)$$

E_b **N_o**

$$\therefore E_b/N_o = RSL - 10\log(bit\,rate) + 228.6dBW/Hz - 10\log Temp_{(Kelvin)} - NF_{dB}$$

and thereafter a corresponding bit error probability (BER) can be obtained using the bit error probability versus E_b/N_0 performance curve of that particular modulation scheme. For example, if QPSK is used and the value of E_b/N_0 is 10, then the bit error probability will be 10^{-5}.

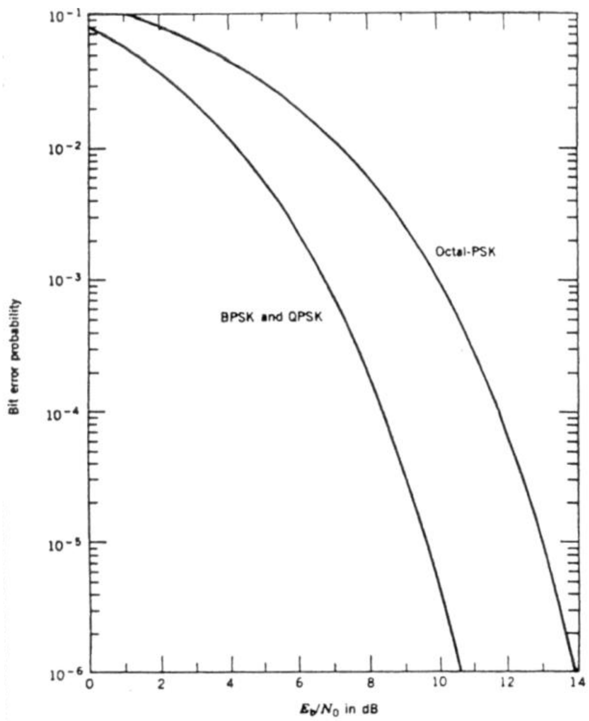


Figure 5.5 BER versus E_b/N_0 performance curve BPSK, QPSK and Octal PSK

NB: THE FOLLOWING SECTIONS THAT ARE HIGHLIGHTED IN RED ARE NOT GOING TO BE EXAMINED

5.5 MICROWAWE TRANSMISSION LINES (NOT FOR TEST/EXAM)

Transmission lines are devices that guide electromagnetic waves from one place to another. For lower frequencies, two wire transmission lines are used. This type of a transmission line is limited to low frequencies due to radiation loss at high frequencies. For frequencies above 200 MHz, coaxial (coax) cable is recommended because it does not suffer from radiation loss due to the inherent shielding provided by the outer conductor that surrounds the center conductor. However, they have a limitation due to dielectric loss and skin effect. Thus, their main drawback is limited power-handling capabilities.
To overcome some of the problems mentioned above, waveguides are used at microwave frequencies because of their all-round characteristics, which are better than most of the transmission lines, especially when it come to power-handling capabilities.
As frequencies are pushed up even higher, especially near millimeter wave bands, the microstrip and stripline have distinct advantages.

5.5.1 Waveguide

A waveguide is a hollow metal tube that is used for propagating electromagnetic waves and unlike a coaxial cable, waveguide utilizes no inner conductor, but relies on the tube to guide the wave from the source to its destination. Waveguides do not support a TEM wave but in waveguides the waves are TE and TM variety.
The common configurations of waveguide are rectangular, rigid rectangular, circular, and elliptical.

The rectangular waveguide is the waveguide with a rectangular cross section and is the most commonly used to couple transmitters and receivers to the antenna.

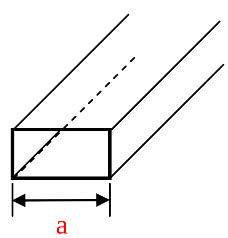


Figure 5.6 Rectangular waveguide

Sometimes a ridge is added to a rectangular waveguide to form a *ridged waveguide* as shown in Figure 5.7.

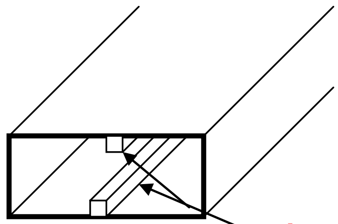


Figure 5.5 Ridge waveguide

The addition of the ridge increases the bandwidth of operation. The cutoff frequency is lowered while the higher-modes have their frequency elevated. This is done at the expense of power-handling capability of the guide. The impedance also changes with the addition of a ridge to a lower value.

The waveguides are made of copper, brass, or aluminum and at extremely high frequencies and for short lengths, the inner walls of the waveguide are coated with silver or gold to reduce losses in the walls of the tube. For high power application the waveguide is filled with an inert gas such as nitrogen and pressurized in order to increase the voltage breakdown rating. Because the cross-sectional area dimensions of the waveguide must be of the same order as those of a wavelength, use of frequencies below about 1 GHz is not normally considered, unless special circumstances warrants it.

Waveguides only propagate frequencies above a given cutoff, which is determined by the width of the waveguide. These limits on wavelength and frequency are given by the following equations, respectively, and are such that a half-wavelength of the propagated signal fits in the wide dimension of the waveguide.

$$\lambda_c = 2a \tag{5.24}$$

$$f_c = \frac{c}{\lambda_c} \tag{5.25}$$

Where λ_c is the cutoff wavelength, f_c is the cutoff frequency, a is the width of the waveguide and c is the speed of light.

A circular waveguide is the waveguide with a circular cross section and is the most commonly used in vertical runs between the source and the antenna. The dominant TE mode for circular waveguide is TE_{11}, while the dominant TM mode is TM_{01}.
It has higher-power handling capability than a comparable sized rectangular guide.

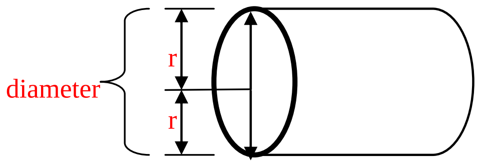


Figure 5.8 Circular waveguide

Circular guides can support both vertical and horizontal polarized signals simultaneously. The main disadvantage of a circular guide is that you need a larger guide than rectangular for the same frequency.

The cutoff frequency for a circular waveguide is

$$\lambda_c = \frac{2\pi r}{B_{(mn)}} \quad (5.26)$$

where r = radius of the guide in meters, and B = Bessel roots for a given mode.

5.5.1.1 Waveguide Coupling

There are four basic methods of launching energy into a waveguide: capacitive coupling, inductive coupling, slot coupling, and horn antenna.

Capacitive coupling is achieved by putting a section of the center conductor of a coax line into one end, usually one-quarter wavelength from the closed end, of a rectangular guide. This method can be used effectively to launch either TE or TM mode of propagation depending on the placement of the center conductor of the coaxial line.
This method can be also used to get power back out of the guide. The are commercial coax-to-waveguide adapters that are available to perform this task.

Inductive coupling is almost the same as capacitive coupling with the exception that the coaxial cable is terminated with a loop. This loop can be either in the end or at the side wall of the waveguide.

Slot coupling make use of slots or holes in the walls of the waveguide to radiate. When a hole is made in the waveguide wall, energy can escape from the waveguide through the slot or possibly enter into the waveguide from outside.

Horn antenna is the fourth method, which can be used to effectively couple energy into or out of the waveguide.

5.5.2 Stripline and Microstrip

Stripline and microstrip can be described as a class of miniature transmission lines. Unlike other transmission lines they can operate at higher frequencies up to millimeter wave bands. Since both stripline and microstrip are two-wire structures, propagation is done via the TEM mode.

5.5.2.1 Microstrip

Microstrip is a transmission line, which consists of a thin metal strip, which is laid on an insulator, or dielectric material. This insulator, or dielectric material, is in turn laid on a flat metal base. The impedance of the microstrip is determined by the strip width, the dielectric constant and the thickness of the dielectric material.

5.5.2.2 Stripline

Stripline consists of a thin metal strip sandwiched between two insulators laid on two metal bases. The stripline has both Q and power handling higher than the microstrip.

5.6 MICROWAVE COMPONENTS

5.6.1 Directional Couplers

A directional coupler is a passive device that allows signal sampling, signal injection, and the measurement of incident and reflected power to determine the voltage standing wave ratio (VSWR). Figure 5.7 shows a two-hole directional coupler.

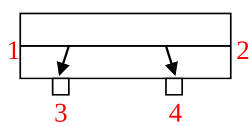


Figure 5.9 Directional coupler

Port 1 is the input, port 2 is the main output, and port 3 and port 4 are sampled output ports. The holes for port 3 and port 4 are placed one-quarter wavelength (90^0) apart, so that a signal travelling in the forward direction is in phase at the coupling holes, but a signal coupling back travels one-half wavelength (180^0) and cancels.

The coupling factor, which is the ratio of the input port power to the sampled port power, is expressed in dB as

$$CF_{dB} = 10\log\frac{P_1}{P_3} \qquad (5.27)$$

The device insertion loss (main line transfer) is

$$IL_{dB} = -10\log\frac{P_2}{P_1} \quad (5.28)$$

The amount of directivity, which is the of the forward power to reverse power in decibels, is

$$D_{dB} = 10\log\frac{Outputpower(forward)}{Outputpower(reverse)} \quad (5.29)$$

5.6.2 Circulators

A circulator is a multiport device in which the adjacent ports are effectively connected in one direction but isolated in the reverse direction. Circulators use ferrites, which allow microwave energy to travel in one direction but absorb energy and attenuate signal that is travelling the opposite direction. Figure 5.10 shows a three-port circulator.

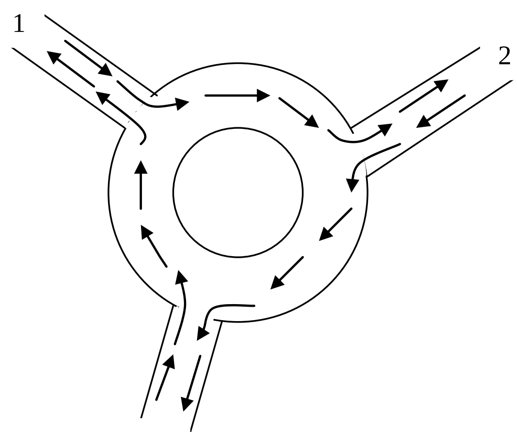


Figure 5.10 Three-port circulator

The three ports are labeled 1, 2, and 3. The signal entering port 1 exits at port 2, the one entering port 2 exits at port 3 and the one entering port 3 will exit at port 1; no signal from port 1 will appear at port 3. Neither signal from port 2 will appear at port 1, nor signal from port 3 will appear at port 3.

One typical application of a circulator is to separate transmitted signal from the received signal at the antenna.

5.6.3 Attenuators

Attenuators are passive components that are used to reduce power. There are two types of attenuators: fixed and variable. The attenuation can be accomplished by either graphitized sand located in end so that the power loss is generated as heat whenever a microwave signal encounters the sand, or by using a resistive rod or vane placed at the center of the electric field so that the microwave energy can induce current into the vane, thus resulting in ohmic power loss. The vane method is useful for variable attenuators, since the vane can rotate or slide between the end and the center of the waveguide.

5.6.4 Isolators

Isolators are passive devices that passe electromagnetic energy in one direction only. Isolators, like circulators, use ferrites, which allow microwave energy to travel in one direction but absorb energy and attenuate signal that is travelling the opposite direction.
One typical application of an isolator is to be used for buffering between the transmitter (or receiver) and the transmission line, so that if there are any impedance mismatch occurring down the line, no reflections can come back to affect the operation of the system.

5.6.5 Cavity resonators

Cavity resonator is a metallic enclosure, like a piece of waveguide closed off at both ends with metallic plates. Cavity resonators operate as tuned circuits (tanks) at microwave frequencies. Like all tuned circuits it has a resonant frequencies, that is, the fundamental frequency and a number of harmonics. The resonant frequencies are obtained when the length of the cavity is an integral multiple of one-half wavelength. At resonance, the cavity has high impedance and zero impedance. If the length of the cavity is increased the cavity exhibits inductive reactance; when it is slightly shortened, it exhibits capacitive reactance.

The cavity resonators are used as tuned LC circuits in oscillators, amplifiers, and filtering. Cavity resonators are also used to measure wavelength (or frequency).

5.6.6 Microwave Electron Tubes

Most of the solid-state devices can not handle the high power that is used by microwave transmitters. However, the vacuum tube device can handle high power. The microwave electron tubes may be divided into two categories: the conventional vacuum tubes and electron beam tubes.
The conventional vacuum tubes, which include planar triode, gyroton, reflex triode, pencil triode, and parametric amplifier, operate by varying the number of electrons passing through the device by varying the voltages applied to the grids.
The electron beam tube, in contrast to the conventional vacuum tubes, operates using a focussed or a directed beam of electrons. The arrangement of conventional vacuum tubes

or electron beam tube can create amplification or oscillation. Thus the tubes in both categories can be used for generation and amplification of microwave signals.
Most of the tubes use velocity modulation to achieve amplification and oscillation.

5.6.6.1 Electron beam tubes

Electron beam tube is a vacuum tube that uses an electronic beam generator rather than a typical cathode. This type of vacuum tubes includes klystron, magnetron, cathode ray, and photomultiplier tubes. The electron beam tubes use magnetic fields to control the electron flow and the grid is replaced with a resonant cavity.

Klystron Tubes are linear beam tubes that incorporate an electronic gun, one or more cavities, and apparatus for modulating the beam produced by the electron gun. Different types of klystron tubes includes **two cavity klystron** for moderate power levels, **multicavity klystron** for high power, and **reflex klystron** for microwave signal generation (oscillator) at low to medium power levels.

Magnetron tubes are used for ultra-high and microwave frequency generation. Most magnetrons contain a central and a surrounding plate. The plate is usually divided into two or more sections by radial barriers called cavities. With cathode connected to the negative terminal of a high voltage source and anode connected to the positive terminal, the electrons flow from the cathode to the anode. These electrons travel in spiral paths due to the magnetic field that is applied in a longitudinal direction and the electrons tend to travel in bunches because of interaction of magnetic and electric fields. This bunching results in oscillation, with frequency being somewhat stabilized by cavities. To reduce harmonics and other unwanted frequency in magnetron oscillators, metal strips are connected between the resonator elements.

5.6.7 Travelling Wave Tube

Travelling wave tubes (TWT) are used as high-powered wide-band amplifiers of microwave signals. There are three general classes of travelling wave tubes: linear-beam forward wave tube or traveling wave amplifier, the crossed-field *backward wave tube*, and the crossed-field *forward wave tube*.

Traveling wave amplifier is an amplifier that uses one or more TWTs to provide a useful amplification at frequencies of the order of several Gigahertz.

Backward wave tube is a TWT in which the electrons travel in the direction opposite to that in which the wave is propagated.

Forward wave is a wave whose group velocity is the same as the electron stream motion in a TWT.

The TWT consists of an electronic gun that produces a beam of electrons, an anode to accelerate the electrons, a long thin glass tube housing a wire helix that forms the input

and output coupling. The helix also serves as a delay line to reduce the RF wave velocity to the electron beam velocity to allow velocity and density modulation of the beam. The RF wave voltage builds up along the length of the line, causing amplification. For higher power at higher frequencies, cavities are used instead of helix. The TWT that uses helix is called a helix TWT and the one using cavities is called coupled-cavity TWT.
TWT also consists of an attenuator to regulate the power, and a collecting electrode that can have its voltage changed to change the average speed of electrons in the beam.

The waveguide can be coupled directly to the tube at high frequencies and at low frequencies, a coaxial cable can be used with the center conductor of the coax connected directly to the helix.

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