Section 4

Digital Radio Relay System Design
The block diagram of a one-way digital radio path is shown in Fig. 7.1. It consists of a transmitter, a receiver and one or more repeaters.

![Image of block diagram](image_url)

**Figure 7.1**

The system consists of $N$ repeaters and hence, the length of the transmission path is divided into $N-1$ hops. Each repeater is a regenerative repeater, i.e. it demodulates the received signal and regenerates the transmitted individual PCM pulses, and then remodulates them before re-transmission to the next repeater.

The block diagrams of typical digital radio transmitter and receiver are shown in Fig. 7.2.
7.1 System parameters-Definitions

In this chapter, we describe the system parameters which are necessary for a system engineer to evaluate the expected performance of a microwave link. There are as follows:

7.1.1 C/N Requirement

The carrier-to-noise power ratio (C/N) required at the input to the receiver to achieve a specific bit error rate (minimum quality objective) e.g. for speech transmission $P_e = 10^{-6}$.

7.1.2 Receiver Input Noise Power

The total noise power at the input of a receiver is given by:

$$N = KT_s B_n$$  \hspace{1cm} (7.1)
Where
\[ T_s = T_{ae} + (LF-1) T_0 \] (7.2)

and where

\( T_s, T_{ae}, B_n, F \) and \( L \) are system temperature, equivalent antenna temperature, noise bandwidth, receiver noise figure and loss representing losses between antenna and receiver.

For terrestrial microwave receiving antennas having the background noise temperature of earth, we may assume \( T_{ae} = T_0 \). Hence, the total noise power at the input to the receiver becomes:

\[ N = KT_0 B_n LF \] (7.3)

Or

\[ N(dBm) = -114 dBm/MHz + 10 \log B_n (MHz) + 10 \log LF \] (7.4)

Since

\[ KT_0 = -114 dBm/MHz \]

Note that dBw refers to dB relative to 1 Watt and dBm refers to dB relative to 1 milliwatt (e.g. \( 1W = 0 dBw = 30 dBm \)).

### 7.1.4 Antenna Gain

Terrestrial and satellite microwave radio systems employ parabolic (dish) antennas for transmitting and receiving signals. A useful, although approximate gain expression for parabolic antennas is given by:

\[ G = \eta \left( \frac{\pi D}{\lambda} \right)^2 \] (7.5)

where

\( \eta = \) antenna efficiency (typically 60 per cent)
\( D = \) antenna diameter
\( \lambda = \) wavelength = \( c/f \)
\( c = \) velocity of light = \( 3 \times 10^8 \) m/s
\( f = \) RF frequency
Equation (7.5) may be written in decibels as:

$$G(dB) = 20.4 + 20 \log f(\text{GHz}) + 20 \log D(m) + 10 \log \eta$$  \hspace{1cm} (7.6)

### 7.1.5 Free-Space Path Loss (Spreading Loss)

The loss of power of a radio wave is given by:

$$L_p = \left( \frac{4\pi d}{\lambda} \right)^2 = \left( \frac{4\pi f d}{c} \right)^2$$  \hspace{1cm} (7.7)

Where

- $f$ = frequency of the radio wave
- $\lambda = \text{wavelength} = \frac{c}{f}$
- $d = \text{distance travelled in space (path length)}$.

Equation (7.7) may be written in decibels as:

$$L_p = (dB) = 92.4 + 20 \log d (km) + 20 \log f (GHz)$$  \hspace{1cm} (7.8)

### 7.1.6 System Availability Objectives

“System unavailability” (usually referred to “system outage”) is defined the percentage, $1-p$, of the total service time in a given period and over a given link length during which the system BER drops below its minimum quality objective due to all causes (hardware failure and propagation). The “system availability” objective is defined as the percentage, $p$, of the total service time in a given period and over a given link length during which the system BER is equal or better than its minimum quality objective.

The “system unavailability” objective of American Telephone Companies of microwave terrestrial radio systems is set to 0.01 percent annually over a 400 Km route due to propagation effects only. This makes their “system availability” objective set to 99.99% annually.

### 7.1.7 System Gain and Fade Margin

System gain is a useful measure of performance because it incorporates many parameters of interest to the designer of microwave systems. In its simplest form, applying only to the equipment, it is the difference between the transmitted output power and the receiver threshold sensitivity for a given bit error rate. Its value must be greater or
at least equal to the sum of the gains and losses which are external to the equipment. Mathematically, it is:

\[ G_s = P_t - C_{\text{min}} \geq FM + L_P + L_f + L_b - G_t - G_r \]  \hspace{1cm} (7.9)

where

\[ G_s = \text{system gain (dB)} \]
\[ P_t = \text{transmitter output power (dBm), excluding antenna branching network} \]
\[ C_{\text{min}} = \text{received carrier power (dBm) for a minimum quality objective.} \]
\[ C_{\text{min}} \text{ in } \text{dBm} \text{ is usually specified for a desired bit error rate of } P_e = 10^{-6}. \text{ This is also called the receiver threshold.} \]
\[ L_P = \text{free space loss (it is explained in Section 7.1.5)} \]
\[ L_f = \text{feeder loss (loss factors for commonly used feeders)} \]
\[ L_b = \text{branching loss, that is, the total filter and circulator loss when transmitters and receivers are coupled to a single unit.} \]
\[ G_t, G_r = \text{gain of transmitter and receiver antennas given by Eqn. (7.1.4), although antenna gains are frequency-dependent, for sake of simplicity, boresight gains are considered.} \]
\[ FM = \text{hop fade margin (dB) of a non-diversity-unprotected system required to meet the availability objective. To estimate the required fade margin of a link is not an easy task. The fade margin depends on propagation characteristics of the radio channel which change randomly with time and location. There are many equations derived from extensive power measurements for particular links. Here we use a simple equation derived in U.S.A and is referred to the Barnet-Vigant availability equations. It is given by:} \]

\[ FM = 30 \log d + 10 \log (6 ABf) - 10 \log (1 - p) - 70 \]  \hspace{1cm} (7.10)

where

\[ p = \text{system availability objective (one-way) for a 400 km route (} p \text{ is the system availability and } 1-p \text{ is the system outage)} \]
\[ A = \text{roughness factor} \]
\[ = 4 \text{ for very smooth terrain, including over water} \]
= 1 for average terrain with some roughness
= ¼ for mountainous, very rough terrain

\[ B = \text{factor to convert worst-month probability to annual probability} \]
= ¼ for Great Lakes or similar hot, humid area
= ½ for average inland area
= ⅛ for mountainous or very dry areas

This fade margin is for availabilities on an annual basis. It may be used on a worst-month basis by setting \( B=1 \). (Note that if it is not mentioned that the availability objective \( p \) is annually then we may assume that it is worst month and set \( B=1 \)). In this case, \( p \) is the availability objective, per hop for the worst month.

Using Eqns. (7.9) and (7.10), one may easily obtain the system gain requirements for arbitrary path length, antenna gain, and reliability objectives or obtain the maximum hop length of a microwave link for a given system gain and for a given availability objective.

### 7.2 Radio System Performance Design Guidelines

In this section, as an illustrative design procedure, the link budget of a typical 64-QAM radio system is derived. The method used in the following example to derive the key system performance parameters is general and can readily be adapted for other radio frequencies, bit rates, or modulation techniques.

**Example:**

A microwave link, having a length of 400 km for transmission of 1920 digitized telephony channels is required (140 Mb/s). It is expected that a commercially available 64-QAM radio, operating in the 6 GHz band, will be purchased. The transmitted spectrum has to be confined to 30 MHz bandwidth. The system is required to meet a system availability objective of 99.99% annually. Determine the required system parameters.
**Solution:**

The following is an outline of a recommended procedure for obtaining the required system parameters.

**Step 1: C/N requirement**

Assume that the system is considered out-of-service when the system bit error rate, $P_e$ exceeds $10^{-6}$.

For M-QAM systems, the system bit error probability is given by:

$$P_e = \frac{2(\sqrt{M-1})}{\sqrt{M \log_2 M}} \text{erfc} \left( \frac{3}{2(M-1)} \left( \frac{C}{N} \right) \right)$$

Thus, for a 64-QAM, we have

$$P_e = \frac{7}{24} \text{erfc} \left( \frac{1}{42} \left( \frac{C}{N} \right) \right)$$

$$\frac{7}{24} \text{erfc} \left( \frac{1}{42} \frac{C}{N} \right) = 10^{-6}$$

$$1 - \text{erf} \left( \frac{1}{42} \frac{C}{N} \right) = \frac{24}{7} \times 10^{-6}$$

$$\text{erf} \left( \frac{1}{42} \frac{C}{N} \right) = 1 - \frac{24}{7} \times 10 = 0.9999965$$

$$\sqrt{\frac{C}{42 N}} = 3.28$$

$$\left( \frac{C}{N} \right)_{db} = 26.5 \text{ dB}$$

In a practical system, a higher C/N ratio is required because of various degradations. In this example, we assume that the total degradation caused by the back-to-back modem and RF channel imperfections is 2.5 dB. This degradation, when added to the theoretical 26.5 dB requirement, increases the practical required C/N to 29 dB.
Step 2: Receiver noise figure and noise power

The overall noise figure of a typical receiver for the 6 GHz band is 4 dB (including the losses between the antenna and receiver. The total noise power $N$ at the receiver input is given by Eq. (7.3) as:

$$N = -114 + 10\log B_n (MHz) + 10\log L.F$$

For 64-QAM systems, the minimum bandwidth is $f_s = \frac{f_b}{6}$ where $f_b$ is the bit rate, hence

$$B_n = \frac{140 \text{ Mb/s}}{6} = 23.3 \text{ MHz}$$

and therefore

$$N = -114 + 10\log 23.3(MHz) + 4 = -96.3 dBm$$

Step 3: Required received carrier power

The required received carrier power for a minimum objective (receiver threshold) is given by:

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

In this example, the receiver threshold at $P_e = 10^{-6}$ is

$$C_{\text{min}} = -96.3 dBm + 29 dB = -67.3 dBm$$

Step 4: Transmit power ($P_t$)

We assume that the 64-QAM system employs a power amplifier with an output power of $P_t = 1W = 30 dBm$.

Step 5: System gain ($G_s$)

The system gain is obtained by:

$$G_s = P_t - C_{\text{min}} = 30 dBm - (-67.3 dBm) = 97.3 dB$$
Step 6: Repeater spacing

From the calculated system gain, the chosen transmit and receive antenna gain, the system availability objectives (e.g. system outage to be limited to 0.01% annually), and by the aid of Eqns. (7.9) and (7.10), the system designer is able to calculate the required repeater spacing.

(As an exercise do the last step yourself).

7.3 Attenuation Due to Rain in a Microwave Radio Link

CCIR (now renamed as ITU-R) proposes a method for determining the value of attenuation due to rain. It follows in several steps:

Step 1. Determine the rain fall rate, \( R \) (mm/h) exceeded during 0.01 percentage of time annually, i.e. \( R_{0.01} \) (mm/h) for the area under study. This can be obtained from CCIR Rep 563 for various geographical regions. An example is given in Fig. 7.3.

Step 2. Calculate specific attenuation \( \gamma_R \) (dB/Km) from CCIR Rep. 721 formula given by:

\[
\gamma_R = K R_{0.01}^\alpha
\]

where \( K \) and \( \alpha \) are regression coefficients to be found from CCIR Rep. 721 or use the nomogram shown in Fig. 7.2.

Step 3. Calculate effective path length

\[
d_{\text{eff}} = \frac{1}{1 + \frac{d}{d_0}}
\]

where \( d \) is the actual path length and

\[
d_0 = 35 e^{-0.015 R_{0.01}}
\]
Step 4. The rain attenuation exceeded for 0.01 percentage of an average time is then obtained from:

\[ A_{0.01} = \gamma_a \text{deff} \]

Step 5. Attenuation exceeded for other percentage times \( P \) in the range of 0.01% to 1% is deduced from the following equation.

\[ A_p = A_{0.01} \times 0.12 \times P \times P^{-(0.546 + 0.0431 \log_{10} P)} \]
Contours of rainfall rate, \( R_{0.01} \) (mm/h) exceeded for 0.01% if an average year.
Specific attenuation due to rain

(H): horizontal polarization
(V): vertical polarization

Note - Above about 40 GHz the values of k and σ on which this nomogram is based may be underestimated and overestimated, respectively.