2. THE CONCEPTS OF SYSTEM LOSS, TRANSMISSION LOSS, PATH ANTENNA GAIN, AND PATH ANTENNA POWER GAIN

Definitions have been given in CCIR Recommendation 341 for system loss, L_s, transmission loss, L, propagation loss, L_p, basic transmission loss, L_b, path antenna gain, G_p, and path antenna power gain G_{pp}. This section restates some of the definitions, introduces a definition of "path loss", L_o, illustrates the use of these terms and concepts, and describes methods of measurement [Norton, 1953, 1959, Wait 1959]. The notation used here differs slightly from that used in Recommendation 341 and in Report 112 [CCIR 1963a, b]. For the frequency range considered in this report system loss, transmission loss, and propagation loss can be considered equal with negligible error in almost all cases, because antenna gains and antenna circuit resistances are essentially those encountered in free space.

2.1 System Loss and Transmission Loss

The system loss of a radio circuit consisting of a transmitting antenna, receiving antenna, and the intervening propagation medium is defined as the dimensionless ratio, w'_t/w'_a, where w'_t is the radio frequency power input to the terminals of the transmitting antenna and w'_a is the resultant radio frequency signal power available at the terminals of the receiving antenna. The system loss is usually expressed in decibels:

$$L_s = 10 \log (w'_t/w'_a) = W'_t - W'_a \quad \text{db} \tag{2.1}$$

Throughout this report logarithms are to the base 10 unless otherwise stated.

The inclusion of ground and dielectric losses and antenna circuit losses in L_s provides a quantity which can be directly and accurately measured. In propagation studies, however, it is convenient to deal with related quantities such as transmission loss and basic transmission loss which can be derived only from theoretical estimates of radiated power and available power for various hypothetical situations.

In this report, capital letters are often used to denote the ratios, expressed in db, dbu, or dbw, of the corresponding quantities designated with lower-case type. For instance, in (2.1), $W'_t = 10 \log w'_t$ in dbw corresponds to w'_t in watts.

Transmission loss is defined as the dimensionless ratio w_t/w_a, where w_t is the total power radiated from the transmitting antenna in a given band of radio frequencies, and w_a is the resultant radio frequency signal power which would be available from an equivalent loss-free antenna. The transmission loss is usually expressed in decibels:

$$L = 10 \log (w_t/w_a) = W_t - W_a = L_s - L_{et} - L_{er} \quad \text{db} \tag{2.2}$$

$$L_{et} = 10 \log \ell_{et}, \quad L_{er} = 10 \log \ell_{er} \tag{2.3}$$

where $1/\ell_{et}$ and $1/\ell_{er}$ as defined in annex II are power radiation and reception efficiencies for the transmitting and receiving antennas, respectively. With the frequencies and antenna heights usually considered for tropospheric communication circuits, these efficiencies are nearly unity and the difference between L_s and L is negligible. With antennas a fraction of a wavelength above ground, as they usually are at lower frequencies, and especially when horizontal polarization is used, L_{et} and L_{er} are not negligible, but are influenced substantially by the presence of the ground and other nearby portions of the antenna environment.

From transmitter output to receiver input, the following symbols are used:

Transmitter Output Power		Power Input to Antenna		Total Radiated Power		Available Power at Loss-Free Receiving Antenna		Available Power at Actual Receiving Antenna		Available Power at Receiver Input
$W_{\ell t}$	→	W'_t	→	W_t	→	W_a	→	W'_a	→	$W_{\ell r}$
	$L_{\ell t}$		L_{et}		L		L_{er}		$L_{\ell r}$	

L_s (spanning L_{et}, L, L_{er}, from W'_t to W'_a)

It should be noted that $L_{\ell t}$ and $L_{\ell r}$ are conceptually different. Since $W_{\ell t}$ and W'_t represent the power observed at the transmitter and at the transmitting antenna, respectively, $L_{\ell t}$ includes both transmission line and mismatch losses. Since W'_a and $W_{\ell r}$ represent available power at the receiving antenna and at the receiver, mismatch losses must be accounted for separately, since $L_{\ell r}$ includes only the transmission line loss between the antenna and the receiver. Available power and effective loss factors are discussed in annex II.

2.2 Antenna Directive Gain and Power Gain

A transmitting antenna has a directive gain $g_t(\hat{r})$ in the direction of a unit vector $\hat{r}$ if:

(1) it radiates a total of w_t watts through the surface of any large sphere with the antenna at its center, and

(2) it radiates $g_t w_t/(4\pi)$ watts per steradian in the direction $\hat{r}$.

The same antenna has a power gain $g_t'(\hat{r})$ in the direction $\hat{r}$ if:

(1) the power input to the antenna terminals is $w_t' = \ell_{et} w_t$, and

(2) it radiates $g_t' w_t'/(4\pi)$ watts per steradian in the direction $\hat{r}$.

The antenna power gain g_t' is smaller than the directive gain g_t simply as a result of the loss factor ℓ_{et}. It follows that

$$G_t(\hat{r}) = G_t'(\hat{r}) + L_{et} \tag{2.4a}$$

expressed in decibels above the gain of an isotropic radiator. Note that the antenna power gain $G_t'(\hat{r})$ is less than the antenna directive gain $G_t(\hat{r})$ by the amount L_{et} dB, where the power radiation efficiency $1/\ell_{et}$ is independent of the direction $\hat{r}$.

The gain of an antenna is the same whether it is used for transmitting or receiving. For a receiving antenna, the directive gain $G_r(\hat{r})$ and power gain $G_r'(\hat{r})$ are related by

$$G_r(\hat{r}) = G_r'(\hat{r}) + L_{er}. \tag{2.4b}$$

The remainder of this report will deal with directive gains, since the power gains may be determined simply by subtracting L_{et} or L_{er}. The maximum value of a directive gain $G(\hat{r})$ is designated simply as G. As noted in Annex II, it is sometimes useful to divide the directive gain into principal and cross-polarization components.

An idealized antenna in free space with a half-power semi-beamwidth δ expressed in radians, and with a circular beam cross-section, may be assumed to radiate x percent of its power isotropically through an area equal to $\pi\delta^2$ on the surface of a large sphere of unit radius, and to radiate (100-x) percent of its power isotropically through the remainder of the sphere. In this case the power radiated in the direction of the main beam is equal to $xw_t/(100\pi\delta^2)$ watts per steradian and the maximum gain g is, by definition, equal to $4\pi x/(100\pi\delta^2)$. One may assume a beam solid angle efficiency $x = 56$ percent for parabolic reflectors with 10 db tapered illumination, and obtain $g = 2.24/\delta^2$. The maximum free space gain G in decibels relative to an isotropic radiator is then

$$G = 10 \log g = 3.50 - 20 \log \delta \text{ db}. \tag{2.5}$$

If azimuthal and vertical beamwidths $2\delta_w$ and $2\delta_z$ are different:

$$\delta = \sqrt{\delta_w \delta_z} . \tag{2.6}$$

The above analysis is useful in connection with measured antenna radiation patterns.

For antennas such as horns or parabolic reflectors which have a clearly definable physical aperture, the concept of antenna aperture efficiency is useful. For example, the free space maximum gain of a parabolic dish with a 56 percent aperture efficiency and a diameter D is the ratio of 56 percent of its area to the effective absorbing area of an isotropic radiator:

$$G = 10 \log \left[\frac{0.56\pi D^2/4}{\lambda^2/4\pi}\right] = 20 \log D + 20 \log f - 42.10 \quad \text{db} \tag{2.7}$$

where D and λ are in meters and f is the radio frequency in megahertz, MHz. Equations (2.5) and (2.7) are useful for determining the gains of actual antennas only when their beam solid angle efficiencies or aperture efficiencies are known, and these can be determined accurately only by measurement.

With a dipole feed, for instance, and $10 < D/\lambda < 25$, experiments have shown the following empirical formula to be superior to (2.7):

$$G = 23.3 \log D + 23.3 \log f - 55.1 \quad \text{db} \tag{2.8}$$

where D is expressed in meters and f in MHz.

Cozzens [1962] has published a nomograph for determining paraboloidal maximum gain as a function of feed pattern and angular aperture. Discussions of a variety of commonly-used antennas are given in recent books [Jasik, 1961; Thourel, 1960].

Much more is known about the amplitude, phase, and polarization response of available antennas in the directions of maximum radiation or reception than in other directions. Most of the theoretical and developmental work has concentrated on minimizing the transmission loss between antennas and on studies of the response of an arbitrary antenna to a standard plane wave. An increasing amount of attention, however, is being devoted to maximizing the transmission loss between antennas in order to reject unwanted signals. For this purpose it is important to be able to specify, sometimes in statistical terms, the directivity, phase, and polarization response of an antenna in every direction from which multipath components of each unwanted signal may be expected. A large part of annex II is devoted to this subject.

For the frequencies of interest in this report, antenna radiation resistances r_ν at any radio frequency ν hertz are usually assumed independent of their environment, or else the immediate environment is considered part of the antenna, as in the case of an antenna mounted on an airplane or space vehicle.

2.3 Polarization Coupling Loss and Multipath Coupling Loss

It is sometimes necessary to minimize the response of a receiving antenna to unwanted signals from a single source by way of different paths. This requires attention to the amplitudes, polarizations, and relative phases of a number of waves arriving from different directions. In any theoretical model, the phases of principal and cross-polarization components of each wave, as well as the relative phase response of the receiving antenna to each component, must be considered. Complex voltages are added at the antenna terminals to make proper allowance for this amplitude and phase information.

In annex II it is shown how complex vectors $\underline{\vec{e}}$ and $\underline{\vec{e}}_r$ may be used to represent transmitting and receiving antenna radiation and reception patterns which will contain amplitude, polarization, and phase information [Kales, 1951] for a given free-space wavelength, λ. A bar is used under the symbol for a complex vector $\underline{\vec{e}} = \vec{e}_p + i\,\vec{e}_c$, where $i = \sqrt{-1}$ and $\vec{e}_p$, $\vec{e}_c$ are real vectors which may be associated with principal and cross-polarized components of a uniform elliptically polarized plane wave.

Calculating the power transfer between two antennas in free space, complex polarization vectors $\underline{\hat{p}}(\hat{r})$ and $\underline{\hat{p}}_r(-\hat{r})$ are determined for each antenna as if it were the transmitter and the other were the receiver. Each antenna must be in the far field or radiation field of the other. The sense of polarization of the field $\underline{\vec{e}}$ is right-handed or left-handed depending on whether the axial ratio of the polarization ellipse, a_x, is positive or negative:

$$a_x = e_c / e_p \, . \tag{2.9}$$

The polarization is circular if $|e_p| = |e_c|$ and linear if $e_c = 0$, where $\vec{e}_p = \vec{e}_p \hat{e}_p$ is in the principal polarization direction defined by the unit vector $\hat{e}_p$. The polarization coupling loss in free space is

$$L_{cp} = -10 \log |\underline{\vec{p}} \cdot \underline{\vec{p}}_r|^2 \quad \text{db}, \tag{2.10}$$

In terms of the axial ratios a_x and a_{xr} defined by (II.48) and (II.50) and the acute angle ψ_p between principal polarization vectors $\vec{e}_p$ and $\vec{e}_{pr}$, the corresponding polarization efficiency may be written as

$$|\underline{\hat{p}} \cdot \underline{\hat{p}}_r|^2 = \frac{\cos^2 \psi_p (a_x a_{xr} + 1)^2 + \sin^2 \psi_p (a_x + a_{xr})^2}{(a_x^2 + 1)(a_{xr}^2 + 1)} \, . \tag{2.11}$$

This is the same as (II.62). Annex II explains how these definitions and relationships are extended to the general case where antennas are not in free space.

There is a maximum transfer of power between two antennas if the polarization ellipse of the receiving antenna has the same sense, eccentricity, and principal polarization direction as the polarization ellipse of the incident radio wave. The receiving antenna is completely "blind" to the incident wave if the sense of polarization is opposite, the eccentricity is the same, and the principal polarization direction is orthogonal to that of the incident wave. In theory this situation would result in the complete rejection of an unwanted signal propagating in a direction $-\hat{r}$. Small values of $g_r(-\hat{r})$ could at the same time discriminate against unwanted signals coming from other directions.

When more than one plane wave is incident upon a receiving antenna from a single source, there may be a "multipath coupling loss" which includes beam orientation, polarization coupling, and phase mismatch losses. A statistical average of phase incoherence effects, such as that described in subsection 9.4, is called "antenna-to-medium coupling loss." Multipath coupling loss is the same as the "loss in path antenna gain," L_{gp}, defined in the next subsection. Precise expressions for L_{gp} may also be derived from the relationships in annex II.

2.4 Path Loss, Basic Transmission Loss, Path Antenna Gain, and Attenuation Relative to Free Space

Recorded values of transmission loss are often normalized to "path loss" by adding the sum of the maximum free space gains of the antennas, $G_t + G_r$, to the transmission loss, L. Path loss is defined as

$$L_o = L + G_t + G_r \quad \text{db}. \tag{2.12}$$

Basic transmission loss, L_b, is the system loss for a situation where the actual antennas are replaced at the same locations by hypothetical antennas which are:

(1) Isotropic, so that $G_t(\hat{r}) = 0$ db and $G_r(-\hat{r}) = 0$ db for all important propagation directions, $\hat{r}$.

(2) Loss-free, so that $L_{et} = 0$ db and $L_{er} = 0$ db.

(3) Free of polarization and multipath coupling loss, so that $L_{cp} = 0$ db.

If the maximum antenna gains are realized, $L_o = L_b$.

Corresponding to this same situation, the path antenna gain, G_p, is defined as the change in the transmission loss if hypothetical loss-free isotropic antennas with no multipath coupling loss were used at the same locations as the actual antennas. Assumptions used in estimating G_p should always be carefully stated.

Replace both antennas by loss-free isotropic antennas at the same locations, with no coupling loss between them and having the same radiation resistances as the actual antennas, and let W_{ab} represent the resulting available power at the terminals of the hypothetical isotropic receiving antenna. Then the basic transmission loss L_b, the path antenna gain G_p, and the path antenna power gain G_{pp}, are given by

$$L_b = W_t - W_{ab} = L + G_p \quad \text{db} \tag{2.13}$$

$$G_p = W_a - W_{ab} = L_b - L \quad \text{db} \tag{2.14a}$$

$$G_{pp} = W'_a - W_{ab} = L_b - L_s \quad \text{db} \tag{2.14b}$$

where W_t, W_a, W'_a and L_s are defined in section 2.1.

In free space, for instance:

$$W_a = W_t + G_t(\hat{r}) + G_r(-\hat{r}) - L_{cp} + 20 \log\left(\frac{\lambda}{4\pi r}\right) \quad \text{dbw} \tag{2.15a}$$

$$W_{ab} = W_t + 20 \log\left(\frac{\lambda}{4\pi r}\right) \quad \text{dbw}. \tag{2.15b}$$

A special symbol, L_{bf}, is used to denote the corresponding basic transmission loss in free space:

$$L_{bf} = 20 \log\left(\frac{4\pi r}{\lambda}\right) = 32.45 + 20 \log f + 20 \log r \quad \text{db} \tag{2.16}$$

where the antenna separation r is expressed in kilometers and the free space wavelength λ equals $0.2997925/f$ kilometers for a radio frequency f in megaherts.

When low gain antennas are used, as on aircraft, the frequency dependence in (2.16) indicates that the service range for UHF equipment can be made equal to that in the VHF band only by using additional power in direct proportion to the square of the frequency. Fixed point-to-point communications links usually employ high-gain antennas at each terminal, and for a given antenna size more gain is realized at UHF that at VHF, thus more than compensating for the additional free space loss at UHF indicated in (2.16).

Comparing (2.13), (2.14), and (2.15), it is seen that the path antenna gain in free space, G_{pf}, is

$$G_{pf} = G_t(\hat{r}) + G_r(-\hat{r}) - L_{cp} \quad \text{db.} \tag{2.17}$$

For most wanted propagation paths, this is well approximated by $G_t + G_r$, the sum of the maximum antenna gains. For unwanted propagation paths it is often desirable to minimize G_{pf}. This can be achieved not only by making $G_t(\hat{r})$ and $G_r(-\hat{r})$ small, but also by using different polarizations for receiving and transmitting antennas so as to maximize L_{cp}.

In free space the transmission loss is

$$L = L_{bf} - G_{pf} \quad \text{db.} \tag{2.18}$$

The concepts of basic transmission loss and path antenna gain are also useful for normalizing the results of propagation studies for paths which are not in free space. Defining an "equivalent free-space transmission loss", L_f, as

$$L_f = L_{bf} - G_p, \tag{2.19}$$

note that G_p in (2.19) is not equal to $G_t + G_r$ unless this is true for the actual propagation path. It is often convenient to investigate the "attenuation relative to free space", A, or the basic transmission loss relative to that in free space, defined here as

$$A = L_b - L_{bf} = L - L_f \quad \text{db.} \tag{2.20}$$

This definition, with (2.19), makes A independent of the path antenna gain, G_p. Where terrain has little effect on line-of-sight propagation, it is sometimes desirable to study A rather than the transmission loss, L.

Although G_p varies with time, it is customary to suppress this variation [Hartman, 1963] and to estimate G_p as the difference between long-term median values of L_b and L.

Multipath coupling loss, or the "loss in path antenna gain", L_{gp}, is defined as the difference between path loss L_o and basic transmission loss L_b:

$$L_{gp} = L_o - L_b = G_t + G_r - G_p \quad db. \tag{2.21}$$

The loss in path antenna gain will therefore, in general, include components of beam orientation loss and polarization coupling loss as well as any aperture-to-medium coupling loss that may result from scattering by the troposphere, by rough or irregular terrain, or by terrain clutter such as vegetation, buildings, bridges, or power lines.

The relationships between transmission loss, propagation loss and field strength are discussed in annex II.