Chapter 2
Basic Principles in Radiowave Propagation

2.1 Introduction

This chapter is dedicated to basic principles commonly used in radiowave propagation and will be frequently referred to in succeeding chapters. Due to the variety of topics to be discussed, only brief and general descriptions and formulas are given. The details can be found in more specialized references.

Among various subjects, radiowave equations and polarization, transmission media characteristics and its phenomena, K-factor and Earth equivalent radius, and free-space and basic transmission losses are included. To understand these topics, good knowledge of fields and waves theory, electromagnetic engineering, antenna theory, statistics, and applied mathematics is required. Also to get more familiar with the basic principles of radiowave propagation, some examples are presented.

To facilitate the design of radio links, supplementary issues related to the radio networks such as the following items should be considered:

- List of technical calculations
- Hypothetical reference networks
- Design criteria including availability/unavailability, reliability, quality, and performance objectives
- Unavailability budget
- Fading occurrence and fade margin
- Concept of the worst month
- Improvement and reception diversity techniques
- Radio noise

More details are outlined in a separate chapter for radio experts and designers.

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2.2 Transmission Media

As shown in Fig. 2.1, transmission media of radiowaves include all routes between radio transmitter and receiver consisting of one or more of the following main paths:

- Free space
- Earth atmosphere
- Ground surface and surrounding medium
- Ocean and seawater
- Inside Earth

Among the above-stated media, the first three are more important on which a lot of efforts have been spent during the recent decades at national and international levels.

2.2.1 Media Characteristics

Radiowave propagation in free space or air occurs with acceptable loss while they are attenuated rapidly in seawater or inside lands, increasing with frequency. Every medium is characterized by three parameters as mentioned below:

- Permittivity denoted by ϵ in Farad per meter (F/m)
- Permeability denoted by μ in Henry per meter (H/m)
- Conductivity denoted by σ in Siemens per meter (S/m)

Fig. 2.1 Radiowave transmission media

In free space, values of the above parameters are:

$$\sigma = 0, \quad \epsilon_0 = 8.85 \times 10^{-12} (\mathrm{F/m}), \mu_0 = 4\pi \times 10^{-7}\,(\mathrm{H/m}) \tag{2.1}$$

Conductivity of the transmission medium can be evaluated. Good conductivity is equivalent to $\frac{\sigma}{\omega\epsilon} \gg 1$, while poor conductivity is equivalent to $\frac{\sigma}{\omega\epsilon} \ll 1$.

Example 2.1. Calculate the conductivity of a piece of land specified by $\sigma = 5\,\mathrm{mS/m}$, $\mu_r = 1$ and $\epsilon_r = 12$ for radiowaves of $f_1 = 10\,\mathrm{kHz}$ and $f_2 = 10\,\mathrm{GHz}$.

Solution. For $f_1 = 10\,\mathrm{kHz}$

$$\frac{\sigma}{\omega\epsilon_r\epsilon_0} = \frac{0.005}{2\pi \times 10^4 \times 8.85 \times 10^{-12} \times 12}$$
$$= 749.3 \gg 1$$

Thus the land is of good conductivity at f_1, and for $f_2 = 10\,\mathrm{GHz}$. The conductivity index is:

$$\frac{\sigma}{\omega\epsilon_r\epsilon_0} = 7.5 \times 10^{-4} \ll 1$$

Therefore the land is a good dielectric at f_2. ■

2.2.2 Radiowave Velocity

Velocity of radiowaves is related to the medium parameters by the following formula:

$$V = \frac{1}{\sqrt{\epsilon\mu}} = \frac{1}{\sqrt{\epsilon_r\mu_r \cdot \epsilon_0 \cdot \mu_0}} \tag{2.2}$$

In the above formula, each component is defined as follows:

- V is velocity of radiowave in m/s.
- ϵ and μ are media permittivity and permeability in F/m and H/m, respectively.
- ϵ_0 and μ_0 are free-space permittivity and permeability, respectively.
- ϵ_r and μ_r are relative permittivity and permeability constants.

In free space, the velocity of radiowave is:

$$V = \frac{1}{\sqrt{\epsilon_0\mu_0}} = 2.998 \times \mathrm{km/s} = 2.998 \times 10^8\ \mathrm{m/s} \tag{2.3}$$

This value is the same as the light velocity in free space.

We know that in linear media, the frequency does not change when the radiowave goes from one medium to another. Hence by considering the relationship among frequency, wavelength and wave velocity, i.e., $\lambda = \frac{V}{f}$, it is clear that wavelength is directly proportional to the velocity.

Example 2.2. Calculate the velocity of a radiowave propagating at 100 MHz in the following media:

1. Seawater, $\mu_r = 1$ and $\epsilon_r = 81$
2. Air with $\epsilon_r = \mu_r = 1$

Specify λ and V for $f_2 = 1$ GHz

Solution. 1.

$$V_1 = \frac{1}{\sqrt{\mu\epsilon}} = \frac{C}{9} = 3.33 \times 10^7\,\mathrm{m/s}$$

2.

$$V_2 = \frac{1}{\sqrt{\mu_0\epsilon_0}} = C = 3 \times 10^8\,\mathrm{m/s}$$

Since we have assumed the medium specification to be constant with frequency, propagation velocity does not depend on frequency; thus, for both frequencies ($f_1 = 100$ MHz and $f_2 = 1$ GHz), the velocity is the same.

$$f_1 = 100\,\mathrm{MHz} \quad \Rightarrow \quad \lambda_1 = \frac{v_1}{f_1} = 0.333\,\mathrm{m}$$

$$\lambda_2 = \frac{v_2}{f_1} = 3\,\mathrm{m}$$

$$f_2 = 1\,\mathrm{GHz} \quad \Rightarrow \quad \lambda_1' = \frac{v_1}{f_2} = 0.33\,\mathrm{cm}$$

$$\lambda_2' = \frac{v_2}{f_2} = 30\,\mathrm{cm}$$

2.2.3 Depth of Radiowave Penetration

Radiowaves passing through a lossy medium will be attenuated, and in case of significant values of attenuation rate (e^{α}), the waves will be damped rapidly. Depth of penetration is defined as a distance in the medium (like Earth) at which the wave amplitude of a radiowave incident at surface falls to 1/e (0.368) of its initial value.

In a conductor or medium with good conductivity, depth of penetration denoted by δ could be expressed by the following formula:

$$\delta = 1/\alpha = \frac{1}{\sqrt{\pi f \mu \sigma}} = \sqrt{\frac{2}{\omega \mu \sigma}} \tag{2.4}$$

In the above equation δ, f, μ, and σ represent depth of radiowave penetration, frequency, medium permeability, and medium conductivity, respectively, and all are in metric system of units.

Since δ is inversely proportional to the square root of the frequency, hence, it reduces by increasing the frequency. Evidently because of high value of δ, propagation of radiowaves is limited and rather difficult in seawater.

By simple calculations, it may be verified that for frequencies of more than 100 kHz, propagation of radiowaves in Earth land and seawater is very lossy. Even for LF and VLF bands, the wave amplitude remarkably decays along propagation, and for long distances, these waves are not of much interest.

Example 2.3. For a surface radiowave with $\bar{H} = \hat{\alpha_y} \cos(10^7 t)$, H/m propagating over land characterized by $\epsilon_r = 15$, $\mu_r = 14$ and $\sigma = 0.08$ S/m, calculate:

1. Attenuation, phase, and propagation constants
2. Depth of the land where radiowave power is reduced to half of its initial value when the wave propagates perpendicular to the land surface.

Solution. $\omega = 10^7$ rad/m

1. To qualify the land for radiowave:

$$\frac{\sigma}{\omega \epsilon} = \frac{0.08}{10^7 \times 8.85 \times 10^{-12}} = 60 \gg 1$$

The land can be assumed to be of good conductivity so the required constants are calculated as follows:

$$\alpha = \sqrt{\pi f \mu \sigma} = 0.71\,\mathrm{Np/m}$$

$$\beta \approx \alpha \quad \Rightarrow \quad \beta = \sqrt{\pi f \mu \sigma} = 0.71\,\mathrm{rad/m}$$

$$\gamma = \alpha + j\beta \quad \Rightarrow \quad \gamma = 0.71 + 0.71\,j 1/\mathrm{m}$$

2. Amplitude and power of the radiowave will decrease with rates $e^{-\alpha}$ and $e^{-2\alpha}$, respectively; thus:

$$e^{-2\alpha z} = 0.5 \quad \Rightarrow \quad z = 0.49\,\mathrm{m}$$

■

2.3 Electromagnetic Waves

2.3.1 Maxwell Equations

Governing formulas for EM fields are based on Maxwell's equations with the following differential forms:

$$\bar{\nabla} \times \bar{E} = -\frac{\partial \bar{B}}{\partial t} \tag{2.5}$$

$$\bar{\nabla} \times \bar{H} = \bar{J} + \frac{\partial \bar{D}}{\partial t} \tag{2.6}$$

$$\bar{\nabla} \cdot \bar{E} = \frac{\rho}{\epsilon} \tag{2.7}$$

$$\bar{\nabla} \cdot \bar{B} = 0 \tag{2.8}$$

Integral forms of the above equations over closed curve/surface are as follow:

$$\oint_c \bar{E} \cdot \bar{dl} = -\frac{d\varphi}{dt} \tag{2.9}$$

$$\oint_c \bar{H} \cdot \bar{dl} = I + \frac{\partial}{\delta t} \iint_s \bar{D} \cdot \bar{ds} \tag{2.10}$$

$$\oiint_c \bar{E} \cdot \bar{ds} = +\frac{Q}{\epsilon} \tag{2.11}$$

$$\oiint_c \bar{B} \cdot \bar{ds} = 0 \tag{2.12}$$

Also the following relations are between the main parameters:

$$\bar{B} = \mu \bar{H}, \bar{D} = \epsilon \bar{E} \tag{2.13}$$

In the above formulas, each notation stands for:

$\bar{E}$: Electric field intensity
$\bar{B}$: Magnetic flux density
$\bar{D}$: Electric flux density
$\bar{H}$: Magnetic field intensity
μ: Medium permittivity
ϵ: Medium permeability
I: Electric current intensity
Q: Electric charge

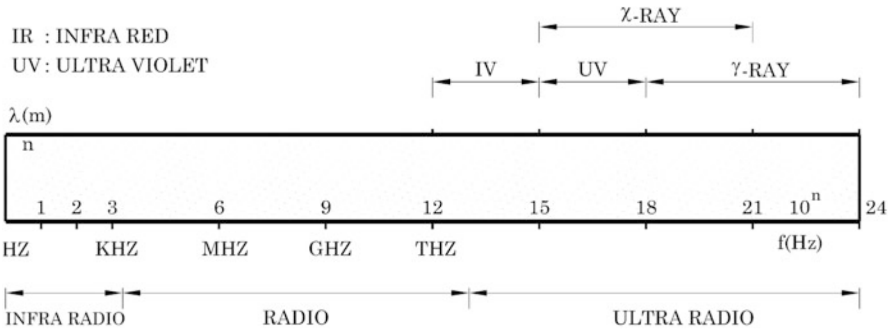

Fig. 2.2 Electromagnetic wave spectrum

2.3.2 *Electromagnetic Wave Spectrum*

J.C. Maxwell using mathematical relations proved that EM waves consist of time-varying electric and magnetic fields propagating in the media. In their simple form, radiowaves are time-harmonic fields in sinusoidal form with frequency f. When the medium is not dispersive, its velocity is not dependent on the frequency but is only related to the medium parameters.

EM waves spectrum includes a wide range of frequencies and as shown on Fig. 2.2 covers all infra-radio, ultra-radio, infrared, laser, visible light, ultraviolet, X-ray, and γ-ray bands.

2.4 Wave Equations and Spectrum

2.4.1 *Plane Waves*

Wave equations in general form, i.e., three-dimensional and in lossy media including electric and magnetic sources, are as follow:

$$\nabla^2\bar{H} - \mu\sigma\frac{\partial\bar{H}}{\partial t} - \mu\epsilon\frac{\partial^2\bar{H}}{\partial t^2} = -\bar{\nabla}\times\bar{J} \tag{2.14}$$

$$\nabla^2\bar{E} - \mu\sigma\frac{\partial\bar{E}}{\partial t} - \mu\epsilon\frac{\partial^2\bar{E}}{\partial t^2} = -\bar{\nabla}\times\bar{M} \tag{2.15}$$

In the simplest form, i.e., one-dimensional and in lossless media without any source and in time-harmonic condition, the wave equations reduce to:

$$\nabla^2 H + \omega^2\mu\epsilon H = 0 \tag{2.16}$$

$$\nabla^2 E + \omega^2\mu\epsilon E = 0 \tag{2.17}$$

The last two formulas are algebraic equations known as Helmholtz's equations consisting of three scalar equations for each field component (one per each direction). Uniform plane wave is a particular response of wave equations having similar direction, magnitude, and phase of $\bar{E}$ or $\bar{H}$ fields in planes perpendicular to the direction of wave propagation.

Phase velocity indicating radiowave velocity is:

$$V_p = \frac{dZ}{dt} = \frac{1}{\sqrt{\mu\epsilon}} \tag{2.18}$$

In free space with μ_0 and ϵ_0, radiowave velocity is equal to light velocity approximately equal to 300,000 km/s and in other media is less than 300,000 km/s due to greater values of μ_r and ϵ_r.

2.4.2 Radiowave Spectrum

Radiowave frequency bands in accordance with Article 5 of the Radio Regulations ranges from 9 kHz to 275 GHz. Also, it should be noted that in the recent years resorting to higher frequency bands has been taken into account by ITU-R through a number of study groups leading to the recommendations below:

- ITU-R, Rec. P-1621 and P-1622, using frequency band between 20 and 375 THz for the design of Earth-space systems
- ITU-R, Rec. P.1814 and P.1817, using lower portion of the optical spectrum for the design of terrestrial free-space links.

EM waves with frequencies less than 9 kHz are not employed due to the following reasons:

- Limited bandwidth resulting in low traffic capacity
- Very large antennas because of long wavelengths

Also frequency bands higher than 100 GHz are not usually employed for the time being due to the following reasons:

- High free-space loss
- High atmospheric attenuation
- Limitations in RF component manufacturing

Optical communications are available by using low visible electromagnetic waves in 850, 1310, and 1550 nm windows over fiber optic cable networks.

2.5 Media Effects on Radiowaves

Radiowaves are affected during propagation by some media phenomena which are summarized below:

- Reflection and multipath radio links
- Atmospheric refraction
- Curvature of radio path and K-factor
- Earth-based and elevated radio ducts
- Diffraction and obstruction loss
- Free-space loss
- Atmospheric attenuation due to absorptions
- Scattering of radiowaves
- Depolarization of radiowaves
- Sunspot effects
- Magnetic storms

The above phenomena are related to the troposphere layer or ionosphere layer or both. In the succeeding chapters, the mentioned effects are explained in more details.

2.6 Propagation Parameters

Main propagation parameters related to medium are:

- Characteristic impedance, η in ohm
- Attenuation constant, α in Neper/m
- Phase constant, β in rad/m
- Wave number, k in rad/m
- Propagation constant, γ in m^{-1}
- Refraction index, n

η and k normally are complex values but α and β are real quantities related to the propagation constant by $\gamma = \alpha + j\beta$. Characteristic impedance of free space is a real value:

$$\eta_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = 120\pi = 377\,\Omega \tag{2.19}$$

Also wave number, k, for free space is a real value as follows:

$$K_0 = \omega\sqrt{\mu_0\epsilon_0} = \frac{\epsilon}{C} = \frac{2\pi}{\lambda} \tag{2.20}$$

$$\text{Light velocity} = C = 3 \times 10^8\ \text{m/s} \tag{2.21}$$

For more details of the abovementioned parameters and related formulas, reference is made to *Electromagnetic Fields and Waves* books addressed in the attachment.

2.7 Radiowave Polarization

2.7.1 Definition of Polarization

Polarization is characteristic of radiowaves which describes time-dependent variations of electric field vector $\bar{E}$ at a point in the space. To specify the polarization of a radiowave, it is not necessary to define the magnetic field vector $\bar{H}$ separately because for a plane wave in homogeneous isotropic medium $\bar{E}$ and $\bar{H}$ are perpendicular to each other and the ratio of their magnitudes is equal to intrinsic impedance of the medium. Main types of radiowaves polarization are:

1. If $\bar{E}$ is continually horizontal, its polarization is called horizontal.
2. If $\bar{E}$ is continually perpendicular to the horizontal plane, its polarization is called vertical.
3. If the projection of the head of $\bar{E}$ on a plane perpendicular to radiowave propagation direction at any point in the space follows a circle, its polarization is circular. In the case of rotation by time (for an observer looking in the direction of propagation) in clockwise (CW) direction, it is known as right-hand circular polarization, RHCP. Also, if the specified rotation is counter clockwise (CCW), it is known as left-hand circular polarization (LHCP).
4. If the projection of the head of $\bar{E}$ on a plane perpendicular to radiowave propagation direction at any point in the space follows an ellipse, its polarization is called elliptical. In the case of rotation by time (for an observer looking in the direction of propagation) in clockwise (CW) direction, it is known as right-hand elliptical polarization, RHEP. Also, if the specified rotation is CCW, it is known as left-hand elliptical polarization, LHEP.

2.8 Main Types of Radiowave Polarization

In an overall classification, radiowave polarizations are divided into linear and nonlinear types. As shown in Fig. 2.3, linear types include the following three groups:

- Horizontal
- Vertical
- Inclined

Also, nonlinear polarizations mainly consist of the following groups:

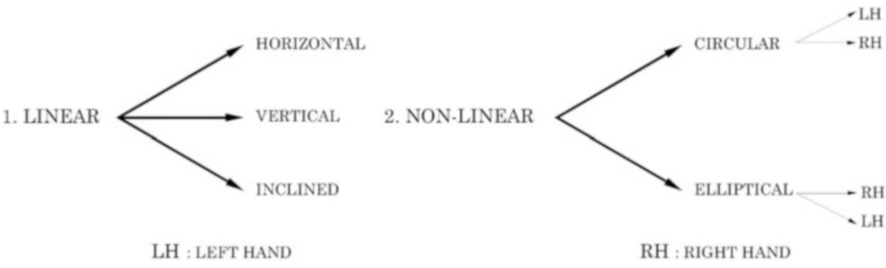

Fig. 2.3 Basic types of polarization

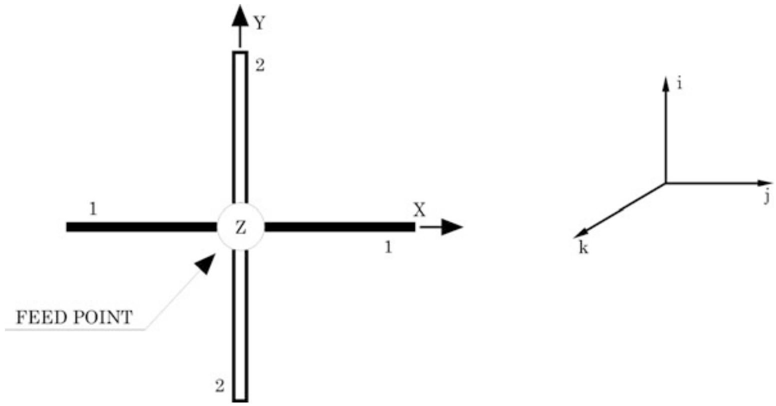

Fig. 2.4 Concept of generating polarized waves

- Right-hand circular polarization, RHCP
- Left-hand circular polarization, LHCP
- Right-hand elliptical polarization, RHEP
- Left-hand elliptical polarization, LHEP

2.8.1 Basic Polarized Radiowaves

To produce basic polarized radiowaves, a simple practical way is to employ two orthogonal dipole antennas. As shown in Fig. 2.4, antenna 1 is horizontal dipole and antenna 2 is a vertical dipole.

By proper feeding of the antennas, the following radiowaves will be generated:

$$\bar{E}_1 = E_x \times \hat{\alpha}_x = E_A \sin(\omega t - \beta z) \cdot \hat{\alpha}_x \tag{2.22}$$

$$\bar{E}_2 = E_y \times \hat{\alpha}_y = E_B \sin(\omega t - \beta z + \bar{\varphi}) \cdot \hat{\alpha}_y \tag{2.23}$$

In the plane $Z = 0$, the above relations result in:

$$Z = 0 \Rightarrow \left| \begin{array}{l} \bar{E}_1 = E_A \ \sin(\omega t) \cdot \hat{\alpha_x} \\ \bar{E}_2 = E_B \ \sin(\omega t + \phi) \cdot \hat{\alpha_y} \end{array} \right. \Rightarrow \left| \begin{array}{l} \bar{E_X} = E_A \ \sin(\omega t) \\ \bar{E_Y} = E_B \ \sin(\omega t + \phi) \end{array} \right. \tag{2.24}$$

$$\Rightarrow \ \sin \omega t = \frac{E_X}{E_A}, \quad \cos \omega t = \sqrt{1 - \left(\frac{E_X}{E_A}\right)^2} \tag{2.25}$$

$$E_Y = E_B \sin \omega t \ \cos \phi + E_B \cos \omega t \ \sin \phi \tag{2.26}$$

$$\frac{E_Y}{E_B} = \frac{E_X}{E_A} \cos \phi + \sqrt{1 - \left(\frac{E_X}{E_A}\right)^2} \cdot \sin \phi \tag{2.27}$$

By squaring the relation (2.27) and simple manipulations, we have:

$$\tfrac{E_Y^2}{E_B^2} + \tfrac{E_X^2}{E_A^2} - 2\tfrac{E_X}{E_A} \times \tfrac{E_Y}{E_B} \cos \phi = \sin^2 \phi, \text{or} \tag{2.28}$$

$$E_Y^2 \left(\tfrac{1}{E_B^2 \sin^2 \phi}\right) + E_X^2 \left(\tfrac{1}{E_A^2 \sin^2 \phi}\right) - 2E_X E_Y \tfrac{\cos \phi}{E_A \cdot E_B \sin^2 \phi} = 1 \tag{2.29}$$

The last expression is in the general form of $aE_X^2 + bE_Y^2 - cE_X E_Y = 1$ from which for various values of a, b, and c, basic polarized radiowaves may be generated as follows:

1. For horizontal polarization, only dipole 1 shall be fed, i.e., $E_A \neq 0, E_B = 0$.
2. For vertical polarization, only dipole 2 shall be fed, i.e., $E_A = 0, E_B \neq 0$.
3. For inclined linear polarization, both dipoles shall be fed in-phase with a fixed amplitude ratio, i.e., $\Phi = 0$ and $\frac{E_A}{E_B} = cte$.
4. For circular polarization, both dipoles shall be fed by equal amplitudes and ±90° phase difference.
5. If none of the above conditions are met, the polarization would be elliptical.

Example 2.4. Find polarization of a uniform plane radiowave with magnetic field: $\bar{H} = 10^{-6}(\hat{\alpha_Y} + j\hat{\alpha_Z}) \cos \beta X$ A/m

Solution. Propagation of the specified radiowave is in the x-axis direction, and due to its nature, only E_y and E_z components exist. To determine the type of polarization, E-field variations versus time should be studied in a plane perpendicular to the propagation direction, say $x = 0$:

$$\bar{E} = -\eta \hat{\alpha_x} \times \bar{H} = 10^{-6} \times 120\pi [\hat{\alpha_z} - j\hat{\alpha_y}] \cos \beta x \, \text{V/m}$$

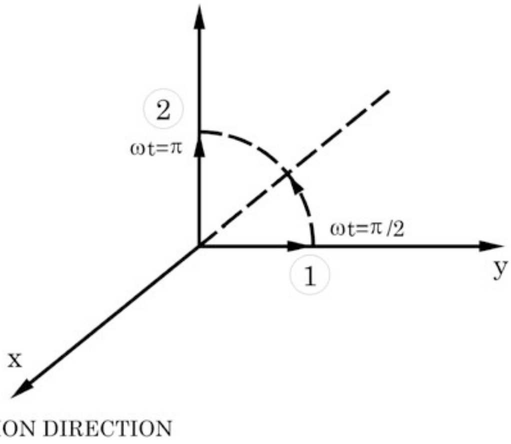

Fig. 2.5 Rotation of $\bar{E}$ with time ($\omega t = \pi/2$ *and* $\omega t = \pi$)

$\bar{E}(x, t)$ is:

$$\bar{E}(x, t) = -10^{-6} \times 120\pi [\hat{\alpha}_z \cos(\omega t - \beta x) - \hat{\alpha}_y \sin(\omega t - \beta x)]$$

$$\text{At plane } x = 0 \Rightarrow \left| \begin{array}{l} E_Z = -10^{-6} \times 120\pi \cos \omega t \\ E_Y = 10^{-6} \times 120\pi \sin \omega t \end{array} \right.$$

$$\Rightarrow (E_Y)^2 + (E_Z)^2 = (10^{-6} \times 120\pi)^2 = R^2$$

It is clear that the polarization is circular. To fix rotation of $\bar{E}$ with time, its position shall be investigated by a reference observer. By using Fig. 2.5 and fixing the $\bar{E}$ positions at say $\omega t = \pi/2$ and $\omega t = \pi$, respectively, direction of radiowave rotation can be determined.

For $\omega t = \pi/2$, $\bar{E}$ position is shown by **1** and for $\omega t = \pi$ by **2**, thus the rotation of $\bar{E}$ for reference observer is clockwise and it is concluded that the radiowave polarization is RHCP. ■

Example 2.5. Determine polarization of a radiowave expressed by $\bar{E} = (A\hat{\alpha}_X + jB\hat{\alpha}_Y)e^{-j\beta Z}$

Solution. Propagation is in Z-axis direction and at plane $Z = 0$; thus, $\bar{E}$ field components are:

$$\left| \begin{array}{l} E_X = A \cos \omega t \\ E_Y = B \sin \omega t \end{array} \right. \Rightarrow \left(\frac{E_X}{A}\right)^2 + \left(\frac{E_Y}{B}\right)^2 = 1$$

Polarization of the radiowave will change based on A and B conditions as follow:

$A = 0, B \neq 0$ Vertical (linear)
$A \neq 0, B = 0$ Horizontal (linear)
$A = B \neq 0$ Circular
$A \neq B \neq 0$ Elliptical

To determine the rotation of $\bar{E}$, its position should be studied at two different times, say $t = 0$ and $t = \pi/2$:

$$\left| \begin{array}{lll} \omega t = 0 & \Rightarrow & E_X = A, \quad E_Y = 0 \\ \omega t = \pi/2 & \Rightarrow & E_X = 0, \quad E_Y = B \end{array} \right.$$

$$\begin{array}{lll} a > 0, \quad b > 0 & \Rightarrow & \text{CW, right hand} \\ a > 0, \quad b < 0 & \Rightarrow & \text{CCW, left hand} \\ a < 0, \quad b > 0 & \Rightarrow & \text{CCW, left hand} \\ a < 0, \quad b < 0 & \Rightarrow & \text{CW, right hand} \end{array}$$

■

2.9 Radio Links

Different types of radio links may be propagating between transmitter and receiver radio units. As shown in Fig. 2.6, the main types of radio links are:

1. Ground waves commonly used for AM broadcasting, radio navigational aids, and shortwave radio systems
2. Reflective waves producing multipath links along with the main route which are common in UHF and microwave radio links including FM broadcasting in TV networks as well
3. Line-of-sight (LOS) links used in terrestrial microwave, UHF, and radar networks
4. Tropospheric links for point-to-point telecommunications by refracting/reflecting waves through troposphere layer and using over-horizon troposcatters
5. Ionospheric links employed for long-distance telecommunications using reflection from ionosphere D, E, and F layers in MF, HF, and public audio broadcasting networks
6. Satellite links for communications between satellites and ground stations with a distance ranging from several hundred up to around 40,000 km
7. Radio links for space telecommunications between ground and spacecraft stations

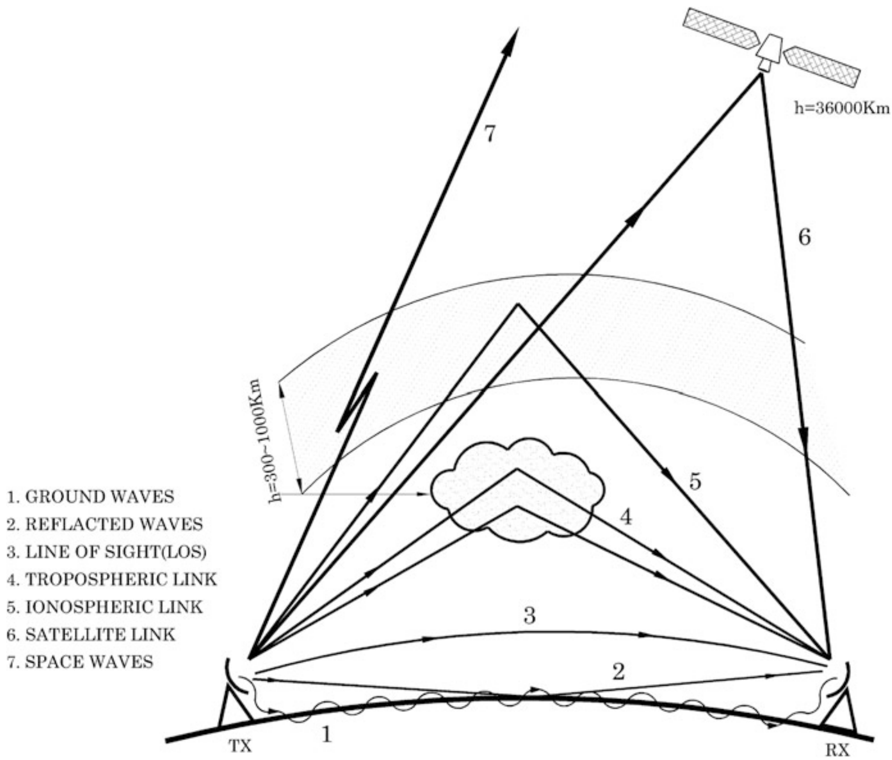

Fig. 2.6 Types of main radio links

2.10 Free-Space Loss

Free space is an ideal condition without any energy absorption or adverse propagation effects. When radiowaves are radiated in the space by an isotropic antenna, they will propagate identically in all directions.

2.10.1 Power Flux Density

Instantaneous power flux density W_i of a plane wave at any location in the space based on electromagnetic theory is:

$$W_i = |\bar{E} \times \bar{H}| = c\epsilon_0 |\bar{E}|^2 = c\mu_0 |\bar{H}|^2 \tag{2.30}$$

E and H denote electric and magnetic fields in V/m and A/m, respectively; W_i is maximum power flux density in W/m^2. Applying relevant equation yields:

$$\frac{1}{c\epsilon_0} = c\mu_0 = \eta_0 = 120\pi\,\Omega \tag{2.31}$$

Mean value of W_i based on sinusoidal nature of radiowaves, denoted by W, is expressed by:

$$W = \frac{1}{2}W_i = \frac{1}{2\eta_0}|E|^2 = \frac{\eta_0}{2}|H|^2 \tag{2.32}$$

Example 2.6. At a given location, the mean value of power flux density is $100\,\text{pW/m}^2$, calculate effective values of E and H.

Solution.

$$W = 100\,\text{pW/m}^2 \quad \Rightarrow \quad E_m = \sqrt{2\eta_0 \cdot W}$$

$$E_m = 275\,\mu\text{V/m} \quad \Rightarrow \quad E_e = \frac{E_m}{\sqrt{2}} = 196\,\mu\text{V/m}$$

$$H_m = \sqrt{\frac{2 \times 10^{-10}}{120\pi}} = 0.728\,\mu\text{A/m} \;\Rightarrow\; H_e = 0.52\,\mu\text{A/m}$$

■

2.10.2 Free-Space Loss

Radiation of radio power P_t by an isotropic antenna in free space results in power flux density P_0 at a distance d:

$$P_0 = \frac{P_t}{4\pi d^2} = \frac{E_0^2}{2\eta_0} \tag{2.33}$$

In the above formula, P_t is the transmitter power in Watts, d is the distance from antenna in m, E_0 is electric field magnitude in V/m, and η_0 is free-space intrinsic impedance equal to $120\pi\,\Omega$. Applying G_t as TX antenna gain, power flux density P will be:

$$P = \frac{P_t \cdot G_t}{4\pi d^2} \tag{2.34}$$

Using a receiving antenna with effective aperture area A_e, received signal power would be:

$$P_r = P \cdot A_e \tag{2.35}$$

A_e according to the EM waves theory is:

$$A_e = \frac{G_r \cdot \lambda^2}{4\pi} \tag{2.36}$$

By manipulating the last three relations, the following formula is derived:

$$P_r = \frac{P_t \cdot G_t}{4\pi d^2} \times \frac{G_r \cdot \lambda^2}{4\pi} = \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi d)^2} \tag{2.37}$$

To calculate free-space loss by using the above relation and assuming $G_t = G_r = 1$:

$$L_{fb} = \mathrm{FSL} = 10 \ \log \frac{P_t}{P_r} = -10 \ \log \frac{\lambda^2}{(4\pi d)^2} \tag{2.38}$$

$$\Rightarrow \quad \mathrm{FSL} = 20 \ \log \frac{4\pi d}{\lambda} \tag{2.39}$$

Considering $\lambda = c/f$, we have:

$$\mathrm{FSL} = 20 \ \log \frac{4\pi f \cdot d}{c} \tag{2.40}$$

The above formula is generic form of FSL in metric system of units. Since in actual links the frequency is in MHz or GHz and distance in km, by putting $c = 3 \times 10^8$ m/s, then FSL is specified by one of the following formulas:

$$\mathrm{FSL[dB]} = 32.4 + 20 \ \log f[\mathrm{MHz}] + 20 \ \log d[\mathrm{km}] \tag{2.41}$$

$$\mathrm{FSL[dB]} = 92.4 + 20 \ \log f[\mathrm{GHz}] + 20 \ \log d[\mathrm{km}] \tag{2.42}$$

Example 2.7. In a radio link of 40 km length and working at 7.5 GHz, 60 % of free-space loss is compensated by using high-gain TX and RX antennas.

1. How much is the received signal level (RSL) at the output of RX antenna with one watt TX output power and considering 15 dB additional losses?
2. Find fade margin of the link if RX threshold is to be $P_{\mathrm{th}} = -78\,\mathrm{dB}_m$.

Solution. 1.

$$\mathrm{FSL} = 92.4 + 20 \ \log f \cdot d = 141\,\mathrm{dB}$$

$$P_t = 1\,\mathrm{W} \quad \Rightarrow \quad P_t[\mathrm{dB}_m] = 30\,\mathrm{dB}_m$$

$$P_r = \mathrm{RSL} = P_t[\mathrm{dB}_m] - 0.4\,\mathrm{FSL} - L_a$$

$$= 30 - 56.8 - 15 = -41.4\,\mathrm{dB}_m$$

2.

$$\text{FM} = P_r[\text{dB}_m] - P_{\text{th}}[db_m] = -41.4 + 78 = 36.6\,\text{dB}$$

■

2.10.3 ITU-R Formulas

Considering that free-space propagation is a fundamental reference for engineering of radio links, ITU-R assembly recommends Rec. P.525 that the following methods be used for the calculation of attenuation in free space.

2.10.3.1 Point-to-Area Links

If there is a transmitter serving several randomly distributed receivers (broadcasting, mobile service), the field strength is calculated at a point located at some appropriate distance from the transmitter by the expression:

$$e = \frac{\sqrt{30p}}{d} \tag{2.43}$$

where:

e: r.m.s. field strength (V/m)
p: Equivalent isotropically radiated power (e.i.r.p.) of the transmitter in the direction of the point in question
d: Distance from the transmitter to the point in question (m)

Equation (2.43) is often replaced by Eq. (2.44) which uses practical units:

$$e_m[\text{V/m}] = 173\frac{\sqrt{p\ [\text{kW}]}}{d\ [\text{km}]} \tag{2.44}$$

For antennas operating in free-space conditions, the cymomotive force as defined by ITU-R may be obtained by multiplying together e and d in Eq. (2.43). Its dimension is volts and to apply the above formulas, the following points shall be taken into account:

- If the wave is elliptically polarized and not linear, and if the electric field components along two orthogonal axes are expressed by e_x and e_y, the left-hand term of Eq. (2.43) should be replaced by $\sqrt{e_x^2 + e_y^2}$ or it may be simplified only if the axial ratio is known. The term e should be replaced by $e\sqrt{2}$ in the case of circular polarization.

- In the case of antennas located at ground level and operating on relatively low frequencies with vertical polarization, radiation is generally considered only in the upper half-space. This should be taken into account in determining the e.i.r.p. (see Recommendation ITU-R PN.368).

2.10.3.2 Point-to-Point Links

With a point-to-point link, it is preferable to calculate the free-space attenuation between isotropic antennas, also known as the free-space basic transmission loss (symbols: L_{bf} or A_0), as follows:

$$L_{bf} = 20 \log \left(\frac{4\pi}{\lambda} \right) \tag{2.45}$$

where:

L_{bf}: Free-space basic transmission loss (dB)
d: Distance
λ: Wavelength, and

d and λ are expressed in the same unit.

Equation (2.45) can also be written using the frequency instead of the wavelength:

$$L_{bf} = 32.4 + 20 \log f + 20 \log d \tag{2.46}$$

where:

f: Frequency (MHz)
d: Distance (km)

2.10.3.3 Radar Links

Radar systems represent a special case because the signal is subjected to a loss while propagating both from the transmitter to the target and from the target to the receiver. For radars using a common antenna for both transmitter and receiver, a radar free-space basic transmission loss, L_{br}, can be written as follows:

$$L_{br}[\mathrm{dB}] = 103.4 + 20 \log f + 40 \log d - 10 \log \sigma \tag{2.47}$$

where:

σ: Radar target cross-section (m^2)
d: Distance from the radar to the target (km)
f: Frequency of the system (MHz)

The radar target cross-section of an object is the ratio of the total isotropically equivalent scattered power to the incident power density.

2.10.3.4 Power Flux Density

There are also relations between the characteristics of a plane wave (or a wave which can be treated as a plane wave) at a point:

$$S = \frac{e^2}{120\,\pi} = \frac{4\pi p_r}{\lambda^2} \tag{2.48}$$

where:

S: Power flux density (W/m^2)
e: r.m.s. field strength (V/m)
p_r: Power (W) available from an isotropic antenna located at this point
λ: Wavelength (m)

2.10.3.5 Conversion Relations

On the basis of free-space propagation, the following conversion formulas may be used. Field strength for a given isotropically transmitted power:

$$E = P_t - 20\log\ d + 74.8 \tag{2.49}$$

Isotropically received power for a given field strength:

$$P_r = E - 20\log f - 167.2 \tag{2.50}$$

Free-space basic transmission loss for a given isotropically transmitted power and field strength:

$$L_{bf} = P_t - E + 20\log f + 167.2 \tag{2.51}$$

Power flux density for a given field strength:

$$S = E - 145.8 \tag{2.52}$$

where:

P_t: Isotropically transmitted power (dB(W))
P_r: Isotropically received power (dB(W))
E: Electric field strength (dB(μV/m))
f: Frequency (GHz)

d: Radio path length (km)
L_{bf}: Free-space basic transmission loss (dB)
S: Power flux density (dB(W/m^2))

Note that Eqs. (2.49) and (2.51) can be used to derive Eq. (2.46).

2.11 Equivalent Radiated Power

2.11.1 Antenna Gain

Antenna gain is defined as "the ratio of the power required at the input of a loss-free reference antenna to the power supplied to the input of the given antenna to produce the same field strength or the same power flux density at the same distance and in the desired direction."

Usually, antenna gain is expressed in decibels and refers to the direction of maximum radiation. The amount of gain is proportional to its dimension compared to the RF wavelength (λ) and design efficiency. In general, antennas being used in higher frequency bands such as SHF and EHF are high gain, while antennas in LF/MF/HF frequency bands are normally medium/low gain types.

A variety of antennas are employed in radio networks among which the following types are more common:

- T-type, inverted-L, conical, biconical, rhombic, and log-periodic used in LF, MF, and HF radiocommunications and AM broadcasting.
- Whip, collinear, Yagi, and corner reflector used in VHF/UHF radio systems and FM and TV broadcasting
- Horn and panel antennas in UHF/SHF frequency bands used in line-of-sight radio links.
- Directional antennas of high gain such as parabolic or Cassegrain used in microwave and satellite telecommunications.
- Special antennas for specific applications such as radio navigations, GPS, etc.

Antenna gain, depending on the selected reference antenna, may be expressed in different ways as follows:

1. When reference antenna is an isotropic antenna isolated in free space, then gain is denoted by G_i and known as isotropic or absolute gain.
2. When reference antenna is a half wave dipole isolated in free space whose equatorial plane contains the given direction then the gain is denoted by G_d and known as dipole-related gain. Between dipole and isotropic gains for a given antenna, the following relation exists:

$$G[\mathrm{dB}_i] = G[\mathrm{dB}_d] + 2.15 \tag{2.53}$$

3. When the reference antenna is a Hertzian dipole or short vertical conductor (monopole) much shorter than one-quarter of the RF wavelength, and normal to the surface of perfectly conducting plane containing the given direction, then the gain is denoted by G_v and known as short vertical/Hertzian dipole-related gain. Between Hertzian dipole-related and isotropic gains of a given antenna, the following relation exists:

$$G[\mathrm{dB}_i] = G[\mathrm{dB}_v] + 4.8 \tag{2.54}$$

Usual applications of the mentioned gains are:

1. G_i at UHF, SHF, and EHF bands
2. G_d at VHF and UHF bands
3. G_v at LF and MF bands

2.11.2 ERP and EIRP

Equivalent radiated power, ERP, includes all gain and loss factors on the transmitting side and usually expressed in dB_m or dB_w. In fact, ERP is the product of TX output power and antenna gain in the desired direction by taking into account all losses regarding to RF feeder, connectors, etc., simply expressed by:

$$\mathrm{ERP} = \frac{G_t \cdot P_t}{L_t} \tag{2.55}$$

Reference antenna in the above expression is half wave dipole and its logarithmic form is:

$$\mathrm{ERP}[\mathrm{dB}_m] = P_t[\mathrm{dB}_m] + G_t[\mathrm{dB}_d] - L_t[\mathrm{dB}] \tag{2.56}$$

In the case of selecting isotropic antenna as reference, then it is called equivalent isotropic radiated power denoted by EIRP and expressed by:

$$\mathrm{EIRP}[\mathrm{dB}_m] = P_t[\mathrm{dB}_m] + G_t[\mathrm{dB}_i] - L_t[\mathrm{dB}], \quad \text{or} \tag{2.57}$$

$$\mathrm{EIRP}[\mathrm{dB}_w] = P_t[\mathrm{dB}_w] + G_t[\mathrm{dB}_d] - L_t[\mathrm{dB}] \tag{2.58}$$

2.11.3 Electric Field Intensity

Electric field intensity can be expressed versus EIRP. To find its relation first it should be noted that:

$$W = R_e\left\{\bar{E} \times \bar{H}\right\} = \frac{|E_d^2|}{\eta_0} \tag{2.59}$$

In line-of-sight radio propagation in free space, the power flux density at a distance d is:

$$W = \frac{P_t \cdot G_t}{L_t \cdot 4\pi d^2} = \frac{\text{EIRP}}{4\pi d^2} \tag{2.60}$$

Considering $\eta_0 = 120\pi$ in free space and using the last two formulas:

$$\frac{|E_d|^2}{\eta_0} = \frac{P_t \cdot G_t}{L_t \cdot 4\pi d^2} = \frac{\text{EIRP}}{4\pi d^2} \tag{2.61}$$

$$\Rightarrow \quad |E_d| = \frac{\sqrt{30\ \text{EIRP}}}{d} \tag{2.62}$$

It is noted that in (2.62) numerical (not logarithmic) value of EIRP shall be employed in proper system of units.

Example 2.8. Radiowaves are radiated by a 10 W transmitter connected to a 5 dB_i antenna:

1. Find EIRP if feeder loss is 2 dB
2. Find $|E_d|$ and W at a location of 8 km from TX

Solution. 1.

$$\text{EIRP}[\text{dB}_w] = P_t[\text{dB}_w] + G_t[\text{dB}_i] - L_t[\text{dB}] = 13\,\text{dB}_w$$
$$\Rightarrow \quad \text{EIRP} = \text{Antilog}13 = 20\,\text{W}$$

2. Applying (2.62) and $\eta_0 = 377\,\Omega$:

$$|E_d| = \frac{\sqrt{30 \times 20}}{8000} = 3.06 \times 10^{-3}\,\text{V/m} = 3.06\,\text{mV/m}$$
$$W = \frac{1}{2\eta_0}|E_d|^2 \quad \Rightarrow \quad W = 12.4\,\text{nW/m}^2$$

■

2.12 Transmission Loss

2.12.1 Loss Terms in Radio Links

Radiowaves propagating between transmitting and receiving antennas, in addition to free-space loss, are subject to excess attenuations including, but not limited to, the following items:

- RF feeder loss
- Antenna gain/loss
- Propagation mechanism losses
- Depolarization loss

For actual calculations and radio design, all factors shall be taken into account. To describe and standardize the terminology and notations employed to characterize transmission loss and its component, ITU-R under Recommendation No. P.341 has defined the concept of transmission loss for radio links.

As shown on Fig. 2.7, the following types of losses are indicated:

- Free-space loss, FSL of L_{bf}
- Basic transmission loss, L_b
- Transmission loss, L
- System loss, L_s
- Total loss, L_t

Full definitions are given in ITU-R, P.341 for each of the above terms.

2.12.2 Basic Transmission Loss

Free-space loss as permanent radiowave loss is calculated by formulas stated in (2.40)–(2.42). In actual transmission condition, some other attenuation factors are imposed on radiowaves due to medium effects. Sum of FSL and medium loss L_m is defined as basic transmission loss L_b:

$$L_b = \mathrm{FSL} \times L_m \tag{2.63}$$

The above formula in logarithmic form is:

$$L_b[\mathrm{dB}] = \mathrm{FSL}[\mathrm{dB}] + L_m[\mathrm{dB}] \tag{2.64}$$

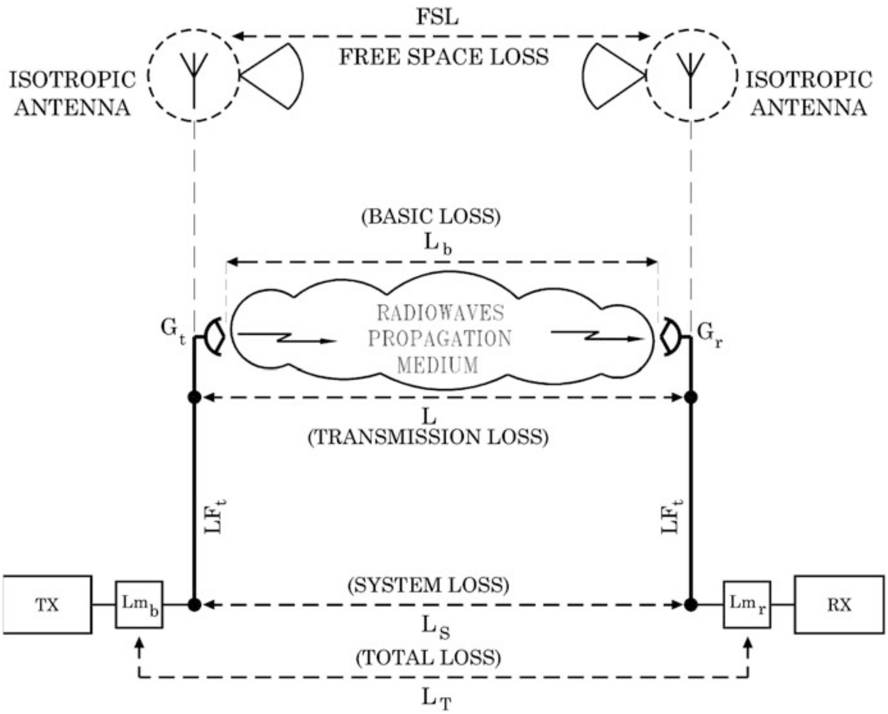

Fig. 2.7 ITU-based concept of transmission loss

A number of medium losses are:

- Atmospheric absorption loss due to gases, vapor, and aerosols
- Reflection loss, including focusing or defocusing due to curvature of reflecting layer
- Scattering of radiowaves due to irregularities in the atmospheric refractive index or by hydrometeors
- Diffraction loss due to obstructions
- Radio precipitation due to rain and snow
- Temporal climatic effects such as fog and cloud
- Antenna to medium coupling loss
- Polarization coupling loss
- Multipath adverse effects

By considering TX and RX antennas, then transmission loss L is calculated:

$$L[\mathrm{dB}] = L_b[\mathrm{dB}] - G_t[\mathrm{dB}_i] - G_r[\mathrm{dB}_i] \tag{2.65}$$

2.12.3 System and Total Losses

In accordance with ITU transmission loss concept, system loss L_s is defined as the following ratio:

$$L_s[\text{dB}] = 10\ \log\left(\frac{P_t}{P_a}\right), \tag{2.66}$$

where

P_t: Transmitter power delivered to the input of TX antenna
P_a: Received signal level (RSL) at the output of RX antenna

Combining the mentioned relation yields:

$$L_s[\text{dB}] = L[\text{dB}] + L_{tc}[\text{dB}] + L_{rc}[d] = P_t[\text{dB}_m] - P_a[\text{dB}_m] \tag{2.67}$$

Total loss L_t is defined as ratio of signal levels at selected points within transmitter and receiver systems. Exact points shall be indicated to avoid misunderstanding.

Example 2.9. A radio link is characterized by:

$$\text{FSL} = 128\,\text{dB},\ \ L_b = 135\,\text{dB},\ \ L_c = L_{tc} + L_{rc} = 5\,\text{dB},\ \ G_t = G_r = 30\,\text{dB}_i$$

1. Find medium loss
2. Find P_t for received signal level of $-60\,\text{dB}_m$

Solution. 1.

$$L_m[\text{dB}] = L_b - \text{FSL} = 7\,\text{dB}$$
$$L_m = \text{Antilog } 7 = 5$$

Thus medium attenuates radiowave five times more.

2.

$$P_t[\text{dB}_m] - P_r[\text{dB}_m] = L_c[\text{dB}] + L_b[\text{dB}] - G_t[\text{dB}_i] - G_r[\text{dB}_i]$$
$$P_t + 60 = 5 + 135 - 30 - 30 \quad \Rightarrow \quad P_t[\text{dB}_m] = 20\,\text{dB}_m$$
$$P_t = \text{Antilog } 20 \quad \Rightarrow \quad P_t = 100\,\text{mW}$$

■

2.13 Radio Ray Path and K-Factor

2.13.1 Curvature of Ray Path

Radiowaves passing through the Earth atmosphere are continually refracted by it and related aerosols. By increasing the height, air density gradually decrease resulting in variations of the refraction index. As indicated in Fig. 2.8, due to the refraction effects, the ray path will deviate from geometric straight line and will follow a curved path.

Instead of actual Earth radius, R_e, by assuming an equivalent value denoted by R'_e, the relative ray path will be a straight line. To calculate curvature of the ray path, as shown on Fig. 2.9, air is divided into a lot of thin layers with roughly constant value of refraction index.

Ray path in the atmosphere satisfies the following relation:

$$n\,R_e \sin\varphi = cte \tag{2.68}$$

Referring to Fig. 2.9, and the given notations, simple calculations result in:

$$AB = R(d\varphi) = \frac{dh}{\cos(\varphi_i + d\varphi)} \tag{2.69}$$

$$R = \frac{dh}{\cos\varphi_i \cdot d\varphi} \tag{2.70}$$

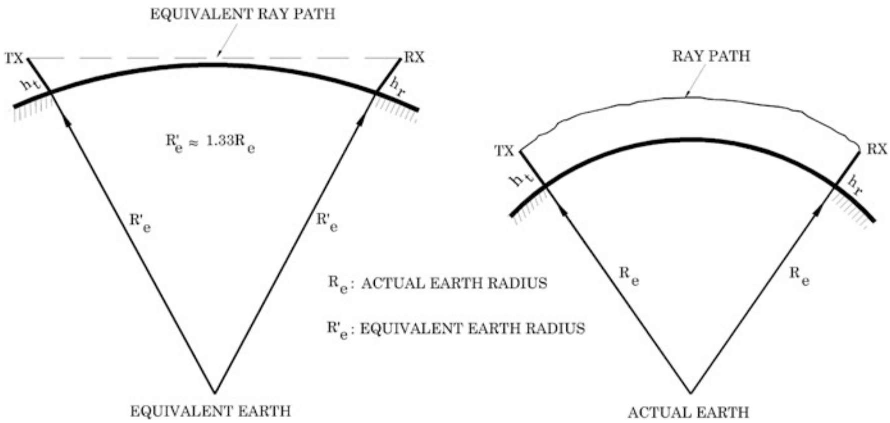

Fig. 2.8 Actual and equivalent ray path

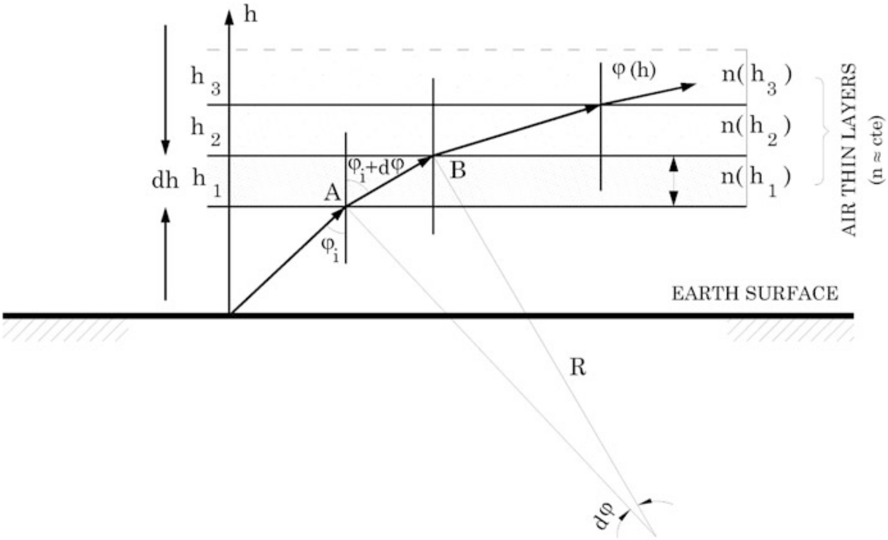

Fig. 2.9 Curvature of ray path

Applying condition set by (2.68):

$$
\begin{aligned}
n\sin\varphi_i &= (n+dn)\sin(\varphi_i + d\varphi) \\
&= n\sin\varphi_i\cos d\varphi + n\cos\varphi_i\sin d\varphi + dn\sin\varphi_i\cos d\varphi + dn\cos\varphi_i\sin d\varphi
\end{aligned} \tag{2.71}
$$

Assuming that $\cos(d\varphi) = 1, \sin(d\varphi) = d\varphi$, then (2.71) yields:

$$n\cos\varphi_i \cdot d\varphi = -dn\sin\varphi_i \tag{2.72}$$

$$\Rightarrow \quad \cos\varphi_i \cdot d\varphi = -\frac{dn}{n}\sin\varphi_i \tag{2.73}$$

Relations (2.70) and (2.73) result in:

$$R = dh/\left(-\frac{dn}{n}\sin\varphi_i\right) = -n/\left(\sin\varphi_i \cdot \frac{dn}{dh}\right) \tag{2.74}$$

$$\frac{dn}{dh} < 0 \quad \Rightarrow \quad R = n/\left|\frac{dn}{dh}\right| \cdot \sin\varphi_i \tag{2.75}$$

In line-of-sight radio links in troposphere such as microwave links, usually $\varphi_i \approx \pi/2$ and $\sin\varphi_i \approx 1$; thus:

$$R = n/\left|\frac{dn}{dh}\right| \tag{2.76}$$

For standard troposphere and based on normal variation of n, ray path curvature radius R is approximately 25,000 km.

Example 2.10. How much is the radiowave curvature radius if refraction indices are 1.00025 and 1.00023 at the heights of 1 km and 1.5 km, respectively.

Solution.

$$\Delta n = 1.00025 - 1.00023 = 2 \times 10^{-5}$$

$$\Delta h = 1.5 - 1 = 0.5\,\text{km} = 500\,\text{m}$$

$$\frac{dn}{dh} = \frac{\Delta n}{\Delta h} = 4 \times 10^{-8}$$

$$R = n/\left|\frac{dn}{dh}\right| \quad \Rightarrow \quad R = \frac{1.00026}{4 \times 10^{-8}} = 25{,}006\,\text{km}$$

■

2.13.2 K-Factor

In line-of-sight radio link design, the preference is to have straight line for ray path. This virtual assumption is possible by considering an equivalent Earth radius R'_e. Referring to Fig. 2.10, there are two alternatives to meet this requirement.

In order to have similar conclusion, relative curvature is required to be equal. Due to inverse dependence between curvature of each curve with its radius, we have:

$$\frac{1}{R_e} - \frac{1}{R} = \frac{1}{R'_e} - \frac{1}{R'} \tag{2.77}$$

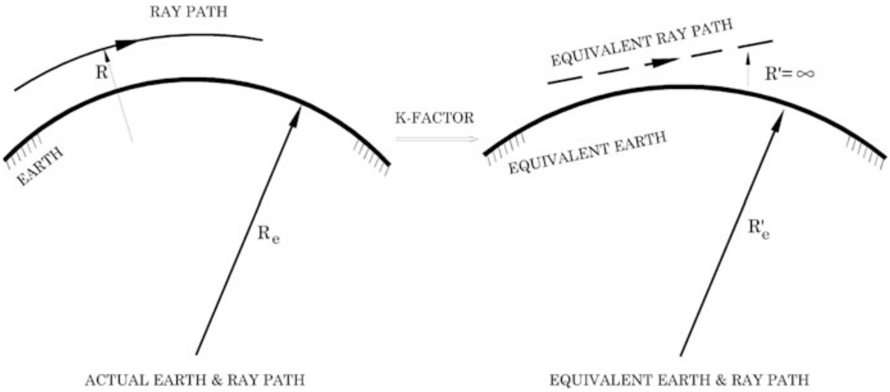

Fig. 2.10 Actual and equivalent earth and ray path

In this last expression, R_e and R'_e are actual and equivalent radii of Earth, while R and R' are actual and equivalent radii of the path, respectively. It is required that $R' = \infty$, thus:

$$R' = \infty \quad \Rightarrow \quad R'_e = \frac{R \cdot R_e}{R - R_e} \tag{2.78}$$

K-factor is defined as the ratio of equivalent radius of Earth to its actual value R_e:

$$K = \frac{R'_e}{R_e} = \frac{R}{R - R_e} \tag{2.79}$$

Based on standard values for $R = 25{,}000\,\text{km}$ and $R_e = 6370\,\text{km}$, the standard value of K-factor is 4/3 = 1.33. Also, the relation of K-factor with vertical gradient of air refraction index may be derived as follows:

$$K = \left(1 + R_e \frac{dn}{dh}\right)^{-1} \tag{2.80}$$

Example 2.11. Calculate $K,\ R'_e$, and R' for $R = 25{,}000\,\text{km}$ and $R_e = 6370\,\text{km}$.

Solution.

$$K = \frac{R}{R - R_e} = \frac{25{,}000}{25{,}000 - 6370} = 1.342$$

$$R'_e = KR_e = 1.342 \times 6370 \approx 8548\,\text{km}$$

$$\frac{1}{R'} = \frac{1}{R'_e} - \frac{1}{R_e} + \frac{1}{R} \quad \Rightarrow \quad R' \approx \infty$$

■

2.14 Summary

A number of basic principles including the following issues were dealt within this chapter:

- Transmission media and related characteristics having significant impacts on radiowave propagation
- Maxwell and wave equations in general forms focusing on the simplest form and plane radiowaves
- EM spectrum and the portion of it dedicated to radiowaves
- Media effects on radiowaves listed and parameters related to media such as α, γ, η, k, and refractive index as well as relevant formulas

- Polarization of radiowaves, either linear or nonlinear
- Free-space loss and the related formulas including ITU-R recommended expressions
- Equivalent radiated power in different forms including ERP and EIRP
- Transmission loss of different categories based on ITU definition including free-space, transmission, system, and total losses
- Effects of air refractivity and ray path curvature in line-of-sight radiocommunications
- K-factor and equivalent Earth radius

2.15 Exercises

Question

1. Prepare a list containing parameters related to transmission medium and indicate normal ranges of those parameters for available common media.
2. Specify propagation parameter and its related units.
3. By simple calculations, show that radiowaves for frequencies more than 100 kHz cannot pass through metallic sheets. Verify your response by calculating penetration depth in copper sheet of 2 mm thickness at $f_1 = 100$ kHz and $f_2 = 10$ GHz.
4. Determine main reasons why radiocommunications is not possible in frequencies less than 10 kHz or more than 100 GHz.
5. Define radiowave polarization and indicate its types.
6. Prepare a report on applications of different types of polarization in radio systems.
7. Indicate the portion of the following radiowaves which may be received by a horizontally polarized antenna:
   - Vertical polarized radiowaves
   - Horizontal polarized radiowaves
   - Circular polarized radiowaves

   Prove your response with proper calculations.
8. Repeat question 7 for RHCP antenna receiving LHCP, RHEP, and vertically polarized radio waves.
9. Define peak power flux density and state its formula and relation with the mean value.
10. Referring to the ITU-based concept of transmission loss, determine their normal rough values for LOS microwave links working at 8 GHz and satellite links working in Ku band.
11. Define EIRP by specifying its formula in logarithmic form. Determine maximum value of EIRP in $dB_m$for the following cases:

- $G_a = 52\,\text{dB}_i, \quad P_t = 1.5\,\text{kW}$
- $G_a = 38\,\text{dB}_i, \quad P_t = 500\,\text{mW}$
- $G_a = 10\,\text{dB}_d, \quad P_t = 20\,\text{W}$

12. Define K-factor and study about its application in radiocommunications.
13. Define actual and equivalent Earth radius and find its relations. Indicate ray path in each of them.
14. Applying Maxwell's equations and EM theory, extract the radiowave equations in lossy and lossless media.
15. Describe characteristics of a plane wave propagating in Z-direction.
16. How much is the radiowave velocity in atmosphere? State its relation with media characteristics.

Problems

1. A radiowave characterized by $\bar{E} = \hat{\alpha_y} 80\,\cos(10^6 t)\ \text{V/m}$ is propagating over land with $\epsilon_r = 12,\ \mu_r = 1$ and $\sigma = 0.005\,\text{S/m}$.

- Calculate propagation constants including $\alpha, \beta, \gamma, \eta, \lambda$, and V
- Find penetration depth (δ) and the depth at which the amplitude reduces to its half value.

2. Repeat problem 1 for $\bar{E} = \hat{\alpha_x} 10\sin(10^5 \pi t)\ \text{V/m}$ propagating in seawater $\epsilon_r = 81,\ \mu_r = 1$, and $\sigma = 4\,\text{S/m}$. Also calculate water conductivity for $f_1 = 10\,\text{kHz}$, $f_2 = 10\,\text{MHz}$, and $f_3 = 10\,\text{GHz}$.

3. For radiowaves with frequencies from 150 MHz to 4.2 GHz, determine upper and lower extremes of wavelength in a medium with $\epsilon_r = 72$ and $\mu_r = 1$.

4. Determine the polarization of a plane wave propagating in Z-direction with the following components:

$$E_x = 2\cos\omega t, \quad E_y = 3\sin\omega t$$

5. Find the polarization of radiowave specified by:

$$\bar{E} = \left[(2+3j)\hat{\alpha_x} + (3-2j)\hat{\alpha_y}\right] e^{-j\beta z}$$

6. A radiowave propagating in free space is specified by the following expression:

$$\bar{E} = \frac{1}{2}\left[\left(2\sqrt{3} - j\right)\hat{\alpha_x} + \left(2 - j\sqrt{3}\right)\hat{\alpha_y} + 2j\sqrt{3}\hat{\alpha_z}\right] e^{-j\frac{2\pi}{100}\left(\sqrt{3}+3y+2z\right)}$$

Find free-space loss at a distance $d_1 = 25\,\text{km}$ for $f = 4\,\text{GHz}$.
At a remote location $d_2 = 2\,d_1$, how much FSL will increase?

7. Effective amplitude of electric field at radiation source is 100 V/m and its value at a location 8 km far from the radiating source is $200\,\mu\text{V/m}$. At frequency $f = 300\,\text{MHz}$, find:

- Free-space loss, FSL
- Transmission basic loss
- Transmitting power of the source and receiving power at the distant location.

8. A 400 MHz radiowave with 200 V/m effective amplitude vertically penetrates inside seawater with $\epsilon_r = 81,\ \mu_r = 1$, and $\sigma = 4$ S/m.

- Find velocity and wavelength in the sea
- Calculate penetration depth
- Calculate electric field amplitude at the depth of 1 cm and also at 1 m

9. 500 mW output power of a microwave transmitter is connected to 40 dB_i directional antenna via a feeder with 6 dB loss.

- Find receiving power and electric field amplitude at a distance of 40 km in line-of-sight condition.
- Assuming total path loss equal to 140 dB, is it possible to detect the received signal by a receiver with $-80\,\mathrm{dB}_m$ threshold level connecting to an omnidirectional antenna ($G = 0\,\mathrm{dB}_i$) via RF feeder with 2 dB loss?
- Calculate antenna gain required for receiving a signal with 30 dB more power than threshold level.

10. Calculate free space and basic transmission losses for:

- $d = 25\,\mathrm{km},\quad f = 420\,\mathrm{MHz},\quad L_p = 15\,\mathrm{dB}$
- $d = 30\,\mathrm{km},\quad f = 7.5\,\mathrm{MHz},\quad L_p = 4\,\mathrm{dB}$

11. Find equivalent radiated power for 2 W transmitter connected by an RF feeder with $L_f = 5$ loss to an antenna with $G_i = 1000$. How much are amplitude of E-field at locations of 1 and 5 km away from the transmitter?

12. Solve the example (2.7) for $f = 2.5$ GHz, $P_t = 2$ W, and $P_r = -88\,\mathrm{dB}_m$.

13. Solve the example (2.8) for $P_t = 20$ W and $G_a = 8\,\mathrm{dB}_i$.

14. Solve the example (2.11) for ray path curvature radius $R = 24{,}000$ km.

15. Consider $R = 26{,}333$ km for radius of ray path curvature and calculate:

- K-factor
- Earth equivalent radius
- For K-factor variation in the range of 0.9–1.3 (due to variations of air refractive index), find minimum and maximum value of Earth equivalent radius.

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