Chapter 2

Propagation and Noise

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2.1 Introduction

- Propagation:
  - provides prediction models for estimating the power required to *close a communications links* and provide reliable communications.
  - also provides clues to receive techniques for compensating the impairments introduced through wireless transmission.
- Channel: the propagation effects and other signal impairments are often collected and categorically referred to as the channel.

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2.1 Introduction

- Channel models
  - Physical models: takes into account the exact physics of the propagation environment.
    - Free-space propagation
    - Reflection
    - Diffraction
    - Refraction
  - Statistical models: takes an empirical approach, measuring propagation characteristics in a variety of environments and then developing a model based on the measured statistics for a particular class of environments.
- Noise and interference effects.

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2.2 Free-Space Propagation

- Electric signal represents
  - desired information, propagation of radio waves through space
  - receiver that estimates the transmitted information from the recovered electrical signal.
- Transmission system is
  - characterized antennas that convert between electrical signals and radio waves.
- Assumption:
  - A linear medium in which all distortions can be characterized by attenuation or superposition of different signals.

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2.2.1 Isotropic Radiation

- Isotropic antenna transmits equally in all directions.
- In reality, isotropic antenna does not exist.
- All antennas have some *directivity* associated with them

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2.2.1 Isotropic Radiation

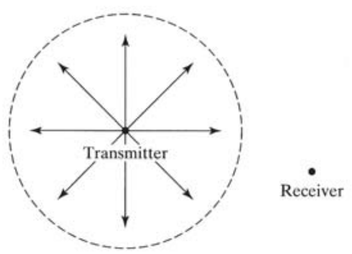

FIGURE 2.2 Illustration of isotropic radiation.

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2.2.1 Isotropic Radiation

- The power per unit area, or power *flux density* on the surface of a sphere of radius *R* centered on the source is given by

$$\Phi_R = \frac{P_T}{4\pi R^2} \qquad (2.1)$$

- The power P_R received by the antenna depends on the size and orientation of the antenna. The power received by an antenna of *effective area* or *absorption cross section* A_e is given by

$$P_R = \Phi_R A_e = \frac{P_T}{4\pi R^2} A_e \qquad (2.2)$$

2.2.1 Isotropic Radiation

- An antenna's Physical area A and its effective area A_e are related by the *antenna efficiency*

$$\eta = \frac{A_e}{A} \qquad (2.3)$$

- From electromagne ic theory, effective area of an isotropic antenna in any direction is given by

$$A_{ISO} = \frac{\lambda^2}{4\pi} \qquad (2.4)$$

2.2.1 Isotropic Radiation

- Relationship between transmitted and received power for isotropic antennas:

$$P_R = \frac{P_T}{(4\pi R/\lambda)^2} = \frac{P_T}{L_P} \qquad (2.5)$$

- Path loss L_P is the *free-space path loss* between two isotropic antennas, which defined as

$$L_P = \left(\frac{4\pi R}{\lambda}\right)^2 \qquad (2.6)$$

EXAMPLE 2.1 Receiver Sensitivity

Sensitivity is a receiver parameter that indicates the minimum signal level required at the antenna terminals in order to provide reliable communications. The factors it depends on include the receiver design, modulation format, and transmission rate. Receiver sensitivity is often expressed in dBm—that is, the power in milliwatts, expressed in decibels. For example, a commercial mobile receiver for data transmission may be specified with a sensitivity of –90 dBm. Assuming a 100-milliwatt transmitter and free-space path loss between the transmitting and receiving isotropic antennas, what is the radius of the service area of this receiver at a transmission frequency of 800 MHz?

To answer this question, we first note that –90dBm is equivalent to 10^{-9} milliwatts of power. From Eq. (2.5), the maximum tolerable path loss is

$$L_p = \frac{P_T(\text{mW})}{P_R(\text{mW})} = \frac{100}{10^{-9}} = 10^{11}$$

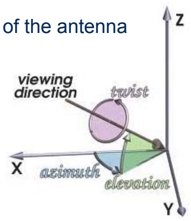
Consequently, observing that $\lambda = c/f$, where c is the speed of light, and using Eq. (2.6), we find that the maximum range is given by

$$R = \frac{\lambda}{4\pi}\sqrt{L_p} = \frac{c}{4\pi f}\sqrt{L_p} = \frac{3\times 10^8\,\text{m/s}}{4\pi\times 800\times 10^6\,\text{s}^{-1}}\sqrt{10^{11}} = 9.2\text{km}$$

The conclusion drawn from this example is that it takes very little transmit power to provide a large service area under free-space propagation conditions. ■

2.2.2 Directional Radiation

- Most of the antennas have *gain* or *directivity* G(θ,Φ) that is a function of *azimuth* angle θ and the *elevation* angle Φ:
  - The azimuth angle θ is the look angle in the horizontal plane of the antenna relative to a reference horizontal direction
  - The elevation angle Φ is the look angle of the antenna above the horizontal plane



2.2.2 Directional Radiation

- Transmit gain of an antenna is defined as

$$G_T(\theta,\phi) = \frac{\text{Power flux density in direction } (\theta,\phi)}{\text{Power flux density of an isotropic antenna}} \qquad (2.7)$$

- The corresponding definition for the receive antenna gain is

$$G_R(\theta,\phi) = \frac{\text{Effectivearea in direction } (\theta,\phi)}{\text{Effectivearea of an istopic antenna}} \qquad (2.8)$$

2.2.2 Directional Radiation

- Principle of reciprocity
  Signal transmission over a radio path is reciprocal in the sense that the locations of the transmitter and receiver can be interchanged without changing the transmission characteristics.
- From the principle of reciprocity and definition for the receive antenna gain, the maximum transmit or receive gain of an antenna in any direction is given by

$$G = \frac{4\pi}{\lambda^2} A_e \qquad (2.9)$$

EXAMPLE 2.2 Parabolic Antenna Gain

For a parabolic antenna, looking directly at the antenna boresight, we find that the area is simply $\pi D^2/4$, where D is the diameter of the dish. Consequently, the effective area of the antenna is given by

$$A_e = \eta \frac{\pi D^2}{4}$$

and the corresponding antenna gain (both transmit and receive) is

$$G = \frac{A_e}{A_{\text{isotropic}}} = \frac{\eta \pi D^2/4}{\lambda^2/4\pi} = \eta\left(\frac{\pi D}{\lambda}\right)^2$$

This equation illustrates that the antenna gain depends on the wavelength of transmission. For example, a 0.6-m parabolic dish used for receiving a direct broadcast satellite television signal at 12 GHz has a gain of

$$G = \eta\left(\frac{\pi D}{\lambda}\right)^2 = 0.5\left(\frac{\pi \times 0.6 \times f}{c}\right)^2 = 2842.4$$

If we express this gain in decibels, it corresponds to a gain of 34.5 dB. We have assumed an antenna efficiency of 50%. ■

2.2.3 The Friis Equation

- When nonisotropic antennas are used, the free-space loss relating the received and transmitted power for general antennas is

$$P_R = \frac{P_T G_T G_R}{L_P} \qquad (2.11)$$

- Rewrite it as decibel equation

$$P_R(dB) = P_T(dB) + G_R(dB) + G_T(dB) - L_T(dB) \qquad (2.12)$$

- Friis equation is the fundamental *link budget* equation.
- *Closing the link* refers to the requirement that the right-hand side provide enough power at the receiver to detect the transmitted information reliably.

2.2.4 Polarization

- Electromagnetic waves are transmitted in two orthogonal dimensions, referred to as polarizations. Two commonly used orthogonal sets of polarizations are:
  - *Horizontal and vertical polarization*.
    - Vertical polarization is used for terrestrial mobile radio communications.
    - At frequencies in the VHF band, vertical polarization is better than horizontal polariza ion.
  - *Left-hand and right-hand circular polarizations*.
    - It used in satellite communication.
    - For well designed fixed communication link, two orthogonal polarizations can be used to double the transmission capacity in a given frequency band.

2.3 Terrestrial Propagation: Physical Models

- In terrestrial communication, buildings, terrain or vegetation may obstruct the line-of-sight path between transmit and receive antennas.
  - Communication relies on either reflection or diffraction.
  - Multitude of possible paths arise.
- *Multipath* propagation:
  - With multiple waves arriving at the same location and either *destructive* or *constructive* interference happened.

2.3 Terrestrial Propagation: Physical Models

- *Ducting* occurs when the physical characteristics of the environments create a waveguide like effect.
- High frequency radio has carrier frequencies range from 3 to 30MHz.
- Differences between the layers of the atmosphere are most pronounced and the layers act like different media to the transmission.
- The HF signal can be trapped within a layer of ionosphere.
  - This allows signal to travel long distances with very little attenuation and is sometimes called *skywaves*.

2.3.1 Reflection and the Plane-Earth Model

- The flat-Earth model shows a fixed transmitter with an antenna of height h_T transmit ing to fixed receiving antenna of height h_R.

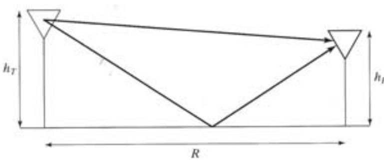


FIGURE 2.5 Plane-Earth reflection model.

2.3.1 Reflection and the Plane-Earth Model

- Power flux density and he *field strength* E:

$$\phi = \frac{|E|^2}{\eta_0} \qquad (2.13)$$

- The field strength is measured in volts per meter and η_0 is the characteristic wave impedance of free space.
- The antenna acts as impedance transformer. Assume electric field is generated by continuous wave signal with frequency *f*, at given point of space,

$$E(t) = \sqrt{2}E_0\cos(2\pi f t+\theta) = \sqrt{2}\,\mathrm{Re}\{E_0 e^{j(2\pi f t+\theta)}\} \qquad (2.14)$$

where field streng h E_0 and phase θ depends on the loca ion in space and Re{ } denotes the real part of the quan ity inside the parentheses.

2.3.1 Reflection and the Plane-Earth Model

- For simplification, we define the complex phasor

$$\tilde{E} = E_0 e^{j\theta} \qquad (2.15)$$

- In he case of the reflection of a single ray, if $\tilde{E}_d$ is the reflected field, the relationship between the two fields is given by

$$\tilde{E} = \tilde{E}_d \rho e^{j\psi} \qquad (2.16)$$

where ρ is the attenuation of the electric field and ψ is the phase change caused by reflection

2.3.1 Reflection and the Plane-Earth Model

- Differences between the direct and reflected paths depends on path length differences. By Pythagorean theorem, the *length of direct paths* is

$$R_d = \sqrt{R^2 + (h_T - h_R)^2} \qquad (2.17)$$

- Similarly, the *length of the reflected path* is

$$R_r = \sqrt{R^2 + (h_T + h_R)^2} \qquad (2.18)$$

2.3.1 Reflection and the Plane-Earth Model

- To calculate the field streng h at receiving antenna, we assume difference in attenua ion between direct and ground-reflected wave is negligible. That is,

$$|\tilde{E}_r| = |\tilde{E}_d| \qquad (2.19)$$

- The phase difference between two paths is sensitive to the path length and it cannot be neglected. The path difference between the reflected and incident rays is

$$\Delta R = R_r - R_d \qquad (2.20)$$

2.3.1 Reflection and the Plane-Earth Model

- If R is large compared with both h_t and h_R, he length of the direct path can be approximated by

$$R_d = R\sqrt{1+\frac{(h_T-h_R)^2}{R^2}} = R\left(1+\frac{(h_T-h_R)^2}{2R^2}\right) \qquad (2.21)$$

- From the above equation, approxima ion $\sqrt{1+x} = (1+X/2)$ for x<<1. Using the same technique for R_r, we have,

$$\Delta R = \frac{(h_T+h_R)^2-(h_T-h_R)^2}{2R} = 2\frac{h_T h_R}{R} \qquad (2.22)$$