Radio Wave Propagation

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An Introduction for the Non-Specialist

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Preface

Understanding the propagation of radio waves in the vicinity of the earth's surface can be quite complex, especially if detailed theoretical knowledge is required. The transmission path is complicated by atmospheric, tropospheric and ionospheric effects, and the earth's surface itself, and other obstacles, can interact with the passage of radiation between a transmitter and receiver. Time of day and season of the year can also be important.

A full treatment of these aspects usually requires a detailed understanding of electromagnetic theory and Maxwell's celebrated equations and yet many practitioners, even electrical engineers, may not have that background in sufficient depth. Nevertheless, with the proliferation of wireless applications, particularly in the VHF and UHF ranges, there is often the need for the non-specialist to gain a working knowledge of the properties of radio waves and how they are affected by factors such as those outlined above. That is the purpose of this book. It treats the essential elements of radio wave propagation without requiring recourse to advanced electromagnetic concepts and equations; however it provides sufficient detail to allow those concerned with wireless systems to acquire quickly a practical working knowledge of the important concepts.

The treatment commences with an analysis of how *energy* (and power) is conveyed in free space, taking essentially a radiative transfer approach and thus avoiding the need to understand electric and magnetic field propagation at the outset. It then examines in some detail how the proximity of the earth and the atmosphere cause the radiation travelling from a transmitter to a receiver to follow one or more of three mechanisms – the surface, sky and space waves. Most attention is given to the space wave since it is the mechanism most commonly encountered in contemporary applications.

Radio wave propagation is placed in a practical context by considering the design aspects of communications systems at microwave frequencies. That requires an understanding of noise and its importance in systems design.

We take the unusual step of including a fuller consideration of the electromagnetic properties of materials late in the book rather than as an introductory chapter as found in more theoretical treatments. It is placed here so that the contexts in which the knowledge of material properties is important have already been established.

The material is based on a single semester overview course suitable for later year undergraduate students in engineering or science.

Canberra, Australia 2007 *John A. Richards*

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Chapter 1
Fundamental Concepts: Propagation in Free Space

1.1 Free Space Versus Guided Propagation of Radio Waves

Radio waves can travel between two points either by propagating in free space or by being guided in a medium such as a coaxial cable, waveguide or optical fibre. In the former, the spectrum available must be shared with all users. To ensure compatible operation, allocation of the free space radio spectrum is subject to regulation by internationally agreed charters, and directional antennas are often employed to minimise interference of services operating on similar frequencies in close geographical proximity.

In principle, if radiation is carried inside a guiding medium there is not likely to be any interference with other users. Instead, the full range of frequencies able to be supported by the medium is available to the user. Often the spectrum again is regulated, but now according to the specifications of a service provider rather than through treaty.

This book is concerned with radiation in free space. It examines, with a minimum of complex mathematical theory, the mechanisms by which propagation can take place between points in space, and places the material in the context of telecommunications systems. We commence with an understanding of how energy radiates.

1.2 The Concept of Power Density

A detailed understanding of methods of radio wave propagation would ordinarily commence with a treatment of Maxwell's equations and their combination into the wave equation. However, a good practical appreciation can be obtained by starting with a simple understanding of how power propagates outwards from a source of energy, such as a radio transmitter.

Consider a point source of energy, such as that depicted in Fig. 1.1. It could be a source of light, heat, sound or electrical energy. Often we characterise it by the

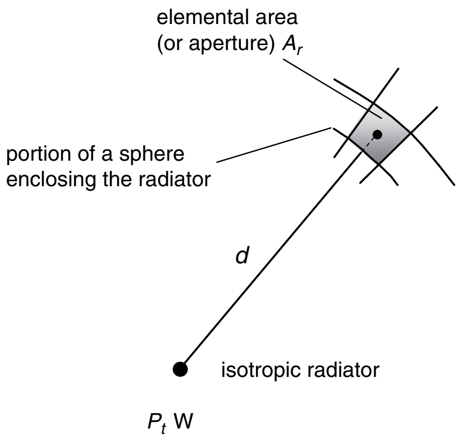

Fig. 1.1 The concept of an isotropic radiator and spherical propagation

power it radiates – i.e. the energy per second emanating from it – which is measured in watts (W). If the source radiates uniformly in all directions it is called *isotropic*, or an *isotropic radiator*. A point source must be isotropic since there is nothing to bias the flow of energy in any particular direction.

The energy from an isotropic source propagates outward in a spherical fashion. If we placed ourselves at a given distance d from the radiator and enclosed it by a sphere of that radius then we could intersect all of the power emanating from the source. While it originated from a point source isotropic radiator, the power is now smeared or distributed over the whole surface area of the sphere. It is convenient now to define the *power density* over the surface of the sphere as the power transmitted divided by the surface area of the sphere. It has units of watts per square metre, and is given by

$$p = \frac{P_t}{4\pi d^2} \quad \mathrm{Wm}^{-2} \tag{1.1}$$

Note that this is the classical *inverse square law* found in many other fields of physics.

Rather than collect the outgoing power density over the full surface area of the sphere, we could instead intercept only that portion over the small cross-sectional area shown in Fig. 1.1. Then we will be able to extract

$$P_r = pA_r \quad \mathrm{W} \tag{1.2}$$

watts of power from the outgoing wavefront. We have used subscripts r in this last equation to imply "received". The intersecting cross-section A_r is generally referred to as an *aperture*, as though it were a hole through which power is received.

The point source isotropic radiator of Fig. 1.1 is fictional. Real radiators are designed to focus their transmitted power in preferred directions as depicted in Fig. 1.2. We now introduce a definition to continue with the discussion of power density: the *gain* of the radiator G_t is a measure of how much more power density

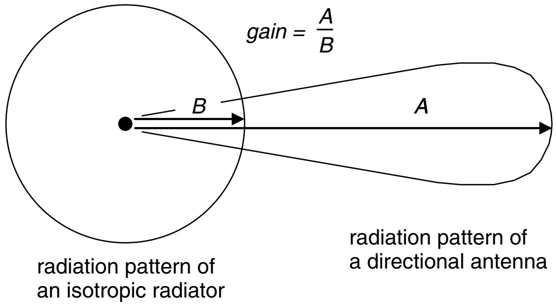

Fig. 1.2 The concept of antenna gain, based on how much more power density can be radiated in a preferred direction compared with an isotropic source

the real radiator is able to transmit in the preferred direction (usually by employing an antenna) than can the equivalent isotropic source. Thus the power density at distance d from the transmitter, and the power received, are now given respectively by

$$p_r = \frac{P_t G_t}{4\pi d^2} \quad \text{Wm}^{-2} \tag{1.3}$$

$$P_r = \frac{P_t G_t A_r}{4\pi d^2} \quad \text{W} \tag{1.4}$$

1.3 Electric and Magnetic Field Components

We have described the propagation of the radio wave so far in terms of the power density conveyed. In reality however it travels as the combination of electric and magnetic field vectors as illustrated in Fig. 1.3. Both fields are at right angles to the direction of propagation and at right angles also to each other.[1] The wave is therefore referred to as transverse electromagnetic (TEM). When referred to the earth's surface two orientations are defined – by reference to the orientation of the electric field vector – as noted in Fig. 1.3. They allow us to describe the radiation as *horizontally* or *vertically* polarised.[2]

It is important to recognise that the vectors shown illustrate the plane in which the respective fields oscillate (at the frequency of the transmitted radiation). Strictly

[1] This is only true in the case of free space propagation and well away from the transmitting antenna. Inside guiding media such as a waveguide there can be components of electric and magnetic field in the direction of propagation as there will also be in the very near vicinity of an antenna in free space.

[2] The radiation can also be elliptically or, as a special case, circularly polarised. In these cases there are both vertical and horizontal components with different magnitudes and with a relative phase difference.

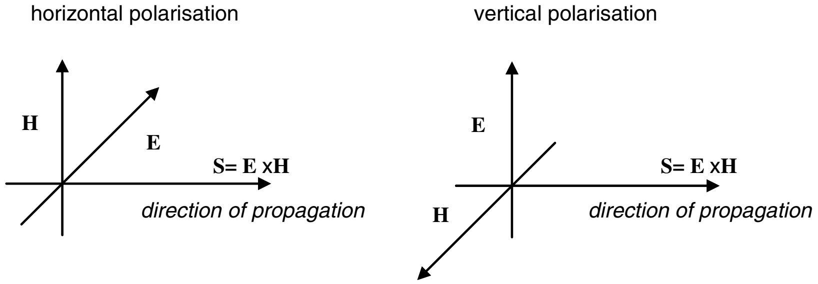

Fig. 1.3 Transverse electric and magnetic field components, and the Poynting vector, for a travelling wave

they are vector-phasors in that they contain information on the geometric orientation of the field, its magnitude and its relative phase angle.

The vector cross product of the electric and magnetic field vectors defines a new vector that points in the direction of propagation. Called the Poynting Vector, **S**, it has units of watts per square metre, since electric and magnetic fields have units respectively of volts per metre (Vm^{-1}) and amps per metre (Am^{-1}). Thus the Poynting Vector has units of power density; even though a vector quantity, its magnitude is precisely power density. From the definition of vector cross product,[3] the magnitude of the Poynting vector is the product of the magnitudes of the electric and magnetic fields. Thus we have another expression for power density, in addition to that used in (1.1) and (1.3), viz:

$$p = |\mathbf{S}| = |\mathbf{E}|\,|\mathbf{H}| \quad \mathrm{Wm}^{-2} \tag{1.5}$$

In free space it can be shown[4] that the electric and magnetic field intensities are related by

$$|\mathbf{E}| = \eta\,|\mathbf{H}| = 120\pi\,|\mathbf{H}| \approx 377\,|\mathbf{H}| \tag{1.6}$$

in which $\eta = 120\pi = 377\Omega$ is the impedance of free space.

From (1.3), (1.5) and (1.6) we can see that the electric field strength created at the distance d from the transmitter is

$$|\mathbf{E}| = \frac{\sqrt{30P_tG_t}}{d} \quad \mathrm{Vm}^{-1} \tag{1.7}$$

which shows that the field strength follows an *inverse distance law*, whereas we saw that power density follows an inverse square law.

[3] For a very good vector treatment of electromagnetic propagation, including the fundamental concepts from vector algebra see J.D. Kraus, *Electromagnetism*, 5th ed., N.Y., McGraw-Hill, 1995.

[4] Ibid.

1.4 Velocity of Propagation and Frequency-Wavelength Relationship

From Maxwell's equations we can show that the velocity of radio waves in a medium is given by

$$v = \frac{1}{\sqrt{\mu\varepsilon}} \tag{1.8}$$

where μ and ε are the absolute permeability and permittivity of the medium respectively; they are two of the medium's electromagnetic properties. In free space

$$\mu = \mu_o = 400\pi \quad \text{nHm}^{-1}$$
$$\varepsilon = \varepsilon_o = 8.85 \quad \text{pFm}^{-1}$$

which, when substituted into (1.8), give the velocity of radio waves (and light) in free space as

$$v = c = 299.8 \approx 300\,\text{Mms}^{-1}$$

In a medium with *relative permeability* μ_r and *relative permittivity* ε_r (also called *dielectric constant*) the absolute permeability and permittivity of the medium are

$$\mu = \mu_r\mu_o \quad \text{Hm}^{-1}$$
$$\varepsilon = \varepsilon_r\varepsilon_o \quad \text{Fm}^{-1}$$

Most media in which we are interested are non-magnetic, so that $\mu_r = 1$.

In a medium with dielectric constant ε_r the velocity of the radio waves is

$$v = \frac{1}{\sqrt{\mu_o\varepsilon_r\varepsilon_o}} = \frac{c}{\sqrt{\varepsilon_r}} = \frac{c}{n} \tag{1.9}$$

where $n = \sqrt{\varepsilon_r}$ is, by definition, the *refractive index* of the medium.

Since, for any wave motion, the wavelength and frequency are related by velocity according to

$$v = f\lambda$$

a very useful relationship can be derived for radio waves in free space. Based on the value for the velocity of light, we can see that

$$f(\text{MHz}) = \frac{300}{\lambda(\text{m})} \tag{1.10}$$

This is one of the most useful and important expressions in telecommunications and in the study of propagation of radio waves.

1.5 Friis' Radiation Formula

Imagine we want to transmit a signal between two points spaced d apart, well away from any effect of the earth's surface. The transmitting antenna is characterised by a gain G_t; the receiving antenna can be described by an aperture A_r. If the transmitter delivers a power of P_t watts to the transmitting antenna then the power density at the receiving antenna is

$$p = \frac{G_t P_t}{4\pi d^2} \quad \mathrm{Wm}^{-2}$$

from which the receiving antenna extracts a power (delivered at its terminals) of

$$P_r = pA_r = \frac{A_r G_t P_t}{4\pi d^2} \quad \mathrm{W} \tag{1.11}$$

There is a relationship between the gain of an antenna when used for transmission and the aperture of the same antenna when used for reception. As seen in Appendix A, the aperture of the receiving antenna can be written

$$A_r = \frac{\lambda^2 G_r}{4\pi} \quad \mathrm{m}^2$$

which, when substituted into (1.11), gives

$$P_r = \frac{G_r G_t P_t \lambda^2}{(4\pi d)^2} = G_r G_t P_t \left(\frac{\lambda}{4\pi d}\right)^2 \quad \mathrm{W} \tag{1.12}$$

This last expression is known as *Friis' Radiation Formula*.

It is convenient now to take $10\log_{10}$ of (1.12) to give

$$10\log_{10} P_r = 10\log_{10} G_r + 10\log_{10} G_t + 10\log_{10} P_t + 20\log_{10} \frac{\lambda}{4\pi d}$$

or

$$10\log_{10} P_r = 10\log_{10} G_r + 10\log_{10} G_t + 10\log_{10} P_t - 20\log_{10} \frac{4\pi d}{\lambda} \tag{1.13}$$

Now what do expressions like $10\log_{10} G_t$ mean? We can write this expression as

$$10\log_{10} \frac{G_t}{1}$$

The "1" in the denominator can be regarded as the gain of an isotropic radiator (since the isotropic source radiates uniformly in all directions, and gain is defined in relation to isotropic behaviour). Thus, the last expression can be viewed as the gain of the transmitting antenna, expressed in decibels with respect to an isotropic radiator. This is written