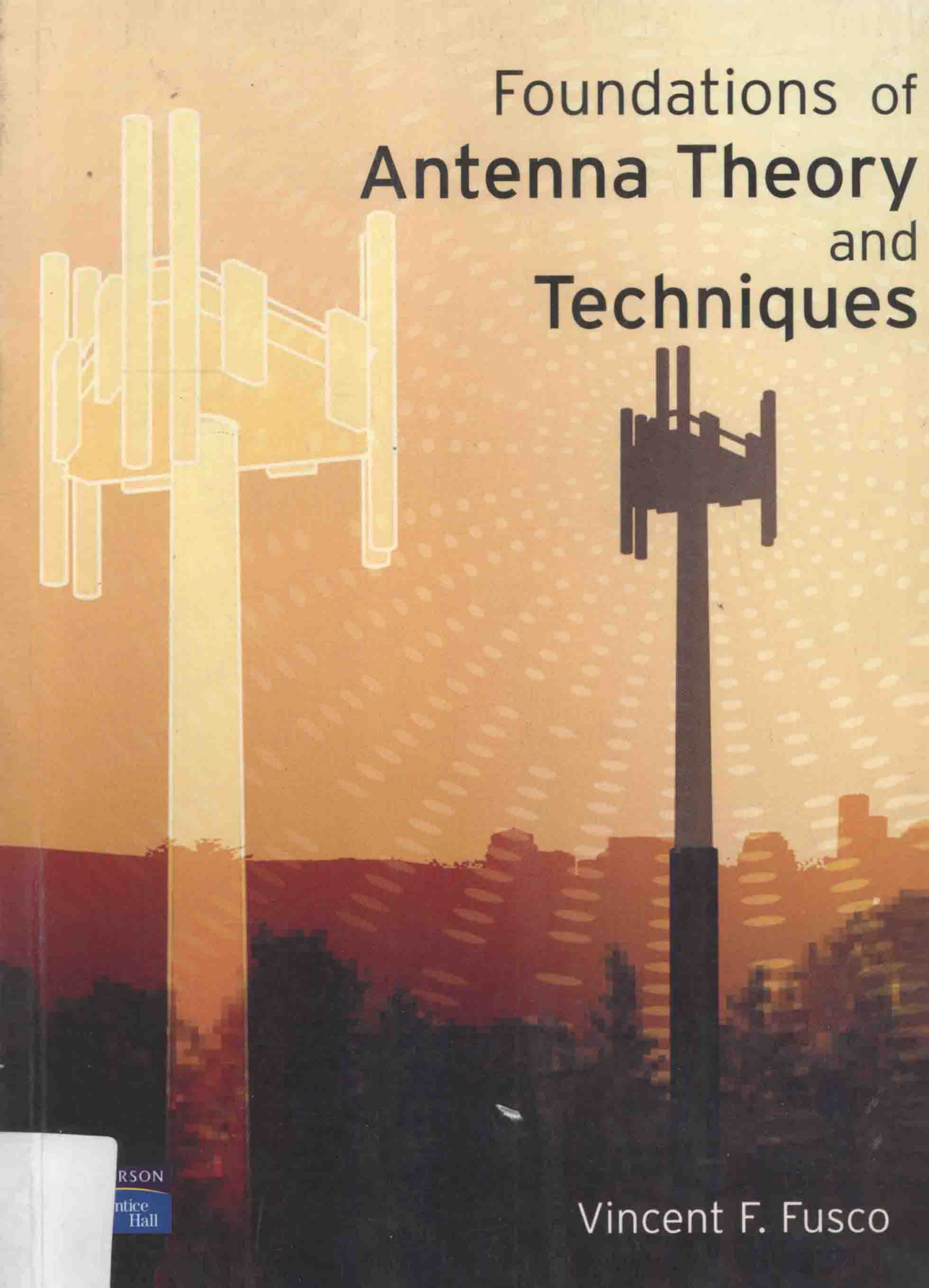
Foundations of Antenna Theory and Techniques



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Foundations of Antenna Theory and Techniques

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Preface

This book is designed as a set of topics that interlock in order to give the reader a reasonably paced introduction to the theory that underpins antenna design techniques.

The earliest recorded pioneer of studies related to the creation and detection of electromagnetic radiation through free space was Heinrich Rudolf Hertz (1857–1894). Hertz demonstrated by a series of experiments around 1886 that electromagnetic waves transmitted through the air had wave-like characteristics. By good fortune, the spark gap means by which he created his electromagnetic energy generated centimetre wavelengths. This involved creating a discharge of a Leyden jar (a capacitor) through one coil while causing a spark to pass across a short air gap between the ends of the other coil. Oliver Heaviside had pointed out in 1877 that such a discharge of a capacitor in association with an inductor, the coil, would lead to oscillatory current. In effect, Hertz created a broadband signal generator producing energy over a very wide range of frequencies. Working at centimetre wavelengths meant that he could conveniently reflect these waves by dielectric prisms and metal parabolic mirrors in much the same way as light can be manipulated.

Hertz went on to show, using the principle of resonance, that with identical transmit and receive circuits he could considerably increase the free-space transmission distance between transmitter and receiver. In addition, he realised that the relationship between electromagnetic wave propagation amplitude and distance obeyed the inverse distance relationship. It is this property that makes wireless communication attractive as a virtual wire communication means.

Among Hertz's many key discoveries was the linear oscillator, comprising two metal rods terminating in metal spheres. In fact, he had created a dipole antenna similar in many respects to that much used in today's communication systems. Using this dipole, he showed that the electromagnetic waves he was producing had their electric field component parallel to his rod antennas, i.e. they were linearly polarised. This principle is used today to reduce interference between radio communication systems that share the same frequency response. Hertz's seminal work ultimately led to the creation of wireless communication across all the frequency ranges in use today.

The work of Hertz went a long way towards validating the set of mathematical relationships postulated by James Clerk Maxwell (1831–1879). Maxwell's equations give the coherent framework within which it is possible to establish the relationships between electricity, magnetism and electromagnetic wave propagation. Maxwell proved that radio waves were an electromagnetic phenomenon and that their maximum speed of propagation in a vacuum was the same as that of light, 3×10^8 m/s. His work showed theoretically that, like light, electromagnetic waves could be focused using a parabolic reflector. Maxwell's equations are the starting point for RF and microwave designers in their attempts to quantify and control electromagnetic wave phenomena in order to produce useful engineering artefacts such as antennas.

Samuel Morse had invented the printing telegraph in 1835, while Alexander Graham Bell had patented his telephone transmitter and receiver in 1876 and distant communication over wires was established. The theoretical work of Maxwell, underpinned by the supporting experimental evidence provided by Hertz, had by the 1890s led to the idea that Hertzian waves as they were by that time known might be used as an alternative to wire in order to transmit telegraphic or telephone signals over large distances. The major thrust to providing realisation of these assertions came about as a consequence of the work of Guglielmo Marconi (1874–1937), who from 1894 onwards began to demonstrate wireless communication over useful distances.

A key breakthrough came when Marconi used transmit and receive antennas, which were elevated above the ground. This dramatically improved free-space operating distance from a few hundred metres to several kilometres. Encouraged by these results and realising that one of the most commercially attractive uses for wireless communications at that time was in facilitating ships in distress to summon assistance, Marconi was granted the world's first patent for a wireless telegraph in 1897.

Marconi then formed 'The Wireless Telegraph and Signal Company Ltd' later to become 'The Marconi Company'. A further significant technical breakthrough for Marconi came in 1900, when he obtained a patent for a resonant tuner with a variable capacitor, which could bring the transmitter and receiver into resonance. An extension to this work meant that multiple antennas could be connected to a single transmitter and receiver. With these improvements, Marconi's company had a number of commercial successes with shipboard coastal radio. His major success came in December 1901, when he managed to receive a signal in Newfoundland that had been sent from Cornwall in England. With this, the monopoly control by the British Post Office of transatlantic submarine cable telephony was broken. In the period 1902 to the 1920s, many key developments related to long-wave wireless telephony occurred; for example, valves were invented, which improved transmitter power and receiver sensitivity. Short-wave transatlantic radio communications were pioneered in the 1930s at AT&T, Western Electric and Bell Laboratories in the United States. Engineers such as H.T. Friis and E. Bruce developed theories and antenna types that are still widely used today.

The seminal work of these and other pioneers is constantly evolving, through developments in radar in the 1950s to satellite communications in the 1960s and 1970s and with the aid of miniaturisation in electronics to modern developments in adaptive antennas for base station and multiband antennas for personal mobile communication wireless handsets that are currently taking place.

The motivation for this book is the recent huge expansion in mobile telecommunications, with the resultant scarcity of qualified RF specialists. One of the key areas of these systems and perhaps the least understood is the point of entry or exit of a wireless signal to and from the system, i.e. the antenna. Engineers with a working knowledge of the basic fundamentals of these structures are increasingly in demand. Their scarcity is compounded by the fact that many university undergraduate programmes have dropped electromagnetic field courses in favour of more digital signal-processing type of activities. Consequently, this book is intended to act as an interpretational guide to the many volumes of excellent (but for the beginner sometimes hard to digest) material that exist in classical textbooks on the subject of electromagnetic waves. Thus it is hoped that this book will facilitate the basis for a study of the concepts that underpin antenna theory and techniques.

The structure of the material is broadly as follows:

- basic concept of radiation and the elementary building block for linear antenna modelling;
- plane wave propagation and power flow;
- basic antenna definitions and the concept of the linear dipole antenna;
- single and multiple dipole antenna radiation pattern formation;
- antenna systems and related characterisation methods;
- basic antenna-matching techniques;
- some popular antenna types.

The text is not meant to be a replacement for the many excellent textbooks on antenna theory that currently exist. It is meant to act as a detailed first reference or as the core of a training tool for those undergraduates, postgraduates or engineers wishing to receive the fundamental theoretical underpinning required for a fruitful appreciation of this rewarding subject.

V.F. Fusco
November 2004

List of principle symbols

α	attenuation coefficient, phase lead or lag used to steer an antenna pattern
β, k	wave number
Δ	power splitter coupling coefficient
ε_r	relative delectric constant
ε_o	permittivity of free space 8.85×10^{-12} F/m
μ_o	permeability of free space $4\pi \times 10^{-7}$ H/m
ϕ	asimuth angle
Γ	reflection coefficient
λ	free-space wavelength
θ	elevation angle
σ	conductivity
τ	tilt angle for polarisation ellipse
η	wave impedance of free space, white noise power, antenna radiation efficiency
ω	angular frequency in rads/sec
ψ	phase delay due to spatially displayed elements, transmission line propagation constant wavelength
*	complex conjugate
A_e	effective antenna aperture
$\|AR\|$	axial ratio of an ellipse
B	bandwidth in Hertz, shunt admittance
B', B_N	noise equivalent bandwidth
c	velocity of electromagnetic wave propagation, 3×10^8 m/s
C	capacitance
D	antenna directivity
d	array element separation
dBi	decibels relative to an isotropic source

dBm	decibels relative to 1 mW
EIRP	effective isotropic radiated power
E_{max}	maximum radiated electric field
E_r	radial component of electric field
$E_{x,y}$	x,y directed component of electric field
E_θ	elevation component of electric field
E_ϕ	azimuth component of electric field
F	noise factor
$F(\theta)$	pattern multiplication factor
G	antenna gain, shunt conductance
G_R	gain of receive antenna
G_T	gain of transmit antenna
G/T	gain to equivalent noise temperature ratio
$G^x(f)$	Noise power at filter input
h	height of microstrip substrate
h_e	effective length of antenna
$H(f)$	filter impulse response
Hz	Hertz
H_ϕ	azimuthal component of magnetic field
$I_0, I(o)$	antenna terminal current excitation
$I(z)$	wire antenna current distribution
k	Boltzmann's constant, 1.38×10^{-23} J/K
l_{eff}	effective length of antenna
L	attenuator loss, inductance
L_I	insertion loss
MDS	minimum discernible signal level
n_a	added noise power
n_o	output noise power
N_f	noise figure
P_{inc}	incident power
P_n	available noise power
P_R	power received by antenna
P_T	power transmitted by antenna
q	charge on electron
Q	quality factor
r	distance to observation point
r_n	*n*th clearance radius in Fresnel region
R	conductor resistance, series resistance
R_L	antenna ohmic loss
R_{rad}	radiation resistance
S_{ij}	s- parameter for port ij
S/N	signal-to-noise ratio
T	absolute temperature in Kelvin
T_e	effective noise temperature
T_N	Tchebyscheff polynomial
T_{sys}	system noise temperature

v_p	phase velocity
V_{ij}	open circuit voltage induced on antenna i by a signal from antenna j
V_{oc}	antenna open-circuit terminal voltage
VSWR	voltage standing wave ratio
x_n	*n*th antenna array element separation
Y	noise power ratio
Z	antenna input impedance
Z_{ij}	mutual impedance between two antennas
Z_0	characteristic impedance
Z_s	sending end impedance
Z_T	terminating impedance
$\boldsymbol{B}$	magnetic flux density
$\boldsymbol{E}$	electric field vector
$\boldsymbol{H}$	magnetic field vector
$\boldsymbol{J}$	current density

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Contents

Chapter 1

Basic concepts

In order to understand the basic principles upon which the operation of antennas rely, it is essential to have an appreciation of how radiation occurs. A simple explanation that shows how an accelerated charge gives rise to radiation is therefore presented first.

This concept is then extended to demonstrate how in the presence of a conductor of short but finite length the radiation from the conductor will be distributed preferentially in space. Examination of this apparently simple structure will yield considerable insight into the behaviour of more complex antennas and arrays of antennas. This basic study also aids the comprehension of the field behaviour close to and far from the basic radiation element, the Hertzian dipole, named after Henrich Hertz (1857–94), who demonstrated the propagation of electromagnetic waves through space [1] and who is credited with the invention of the first antennas.

1.1 Radiation

When a time-varying voltage or current is applied to a conductor, free electrons are accelerated. These electrons are able to travel in the spaces between atoms under the influence of the exciting voltage, or current, applied to the conductor. If the current or voltage is alternating, then electrons at a given location on the conductor move back and forward in sympathy with the disturbing force. The acceleration (or deceleration) of these electrons causes radiation to occur [2]. To see why this happens, consider the effect of a single electron with charge $-q$ C moving along a straight piece of wire. As the charge is accelerated a current will be formed, since by definition current is the rate of change of charge.

As this current flows then a magnetic field, H, will be set up whose sense is defined by the right-hand screw rule (Figure 1.1). Here the magnetic field lines, H, form closed loops. Electric field lines, E, come from infinity to the charge, $-q$, as lines of flux,