Optimisation of Wire Antennas

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Editorial Preface

One frequently hears the remark that the use of digital computers in antenna design often denies the user of the need to obtain an in depth appreciation of the physical action taking place. This comment is not unexpected since one of the main aims of modern computer design is to evolve accurate theoretical models, particularly for electromagnetic configurations that present measurement difficulties. In reality however the most powerful approach is likely to be a skilful blend of both theory and physical appreciation, and this monograph is presented in just this spirit. Despite the fact that the common wire dipole or monopole is probably the oldest known and most exhaustively treated antenna, the authors have revealed a variety of shapes that give enhanced gain. Modern computer methods for field solution and optimisation are used throughout but the keystone is the good understanding of field lines, power flow, formation of the far from the nearfield zones and many other physical effects taking place around the wire conductors. Several practical results for specially shaped Yagi and log-periodic arrays with additional sidelobe constraints, are presented to round off this interesting monograph which should appeal to both experts and students who are concerned with the behaviour and optimisation of wire antennas.

J.R. James

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List of Symbols

$\hat{a}$	unit vector defining direction as given by spherical coordinates θ and ϕ
$\vec{A}$	vector potential
A	constant in Hallén's integral equation
A_{eff}	effective area
A_{SL}	sidelobe attenuation
$b_n(z')$	basis (expansion) function
B_r	relative bandwidth
$\vec{c}$	position vector
C	capacitance
C_1	dead capacitance
C_2	radiation capacitance
d	distance
d_o	distance of antenna base from reflecting wall
D	directivity
$D(z)$	right hand side of integral equation
D_m	matrix vector
$\vec{e}$	instantaneous electrical fieldstrength
e_ρ , e_z	components of instantaneous electrical fieldstrength
$\vec{E}$	vector of electrical fieldstrength
E_{tan}	tangential electrical fieldstrength
$\vec{E}_i$	incident electrical fieldstrength
$F(\theta)$	radiation characteristic
G	isotropic gain

$\vec{G}$	gradient vector
h	antenna dimension
h_ϕ	component of instantaneous magnetic fieldstrength
h_{eff}	effective height
$\vec{H}$	vector of magnetic fieldstrength
I_n	current coefficient of expansion function
IM	imaginary part of function
j_D	instantaneous displacement current density
$\vec{J}$	vector of current filament
$J(z')$	antenna current
J_A	antenna input current
J_{max}	current anti node
J_n	current expansion function
$K(z,z')$	kernel of integral equation
L	antenna (arc-) length
ℓ_{eff}	effective length
M	figure of merit
M_D	individual figure of merit (for directivity)
$P(z')$	pulse function
P_{av}	available power
r	radius (also in spherical coordinates)
r_o	radius to a point on the antenna conductor surface
R_n	distance from the apex of a LPA-antenna
R_A	antenna resistance
R_r	radiation resistance
R_{ro}	intrinsic radiation resistance
RE	real part of a function
$\vec{s}$	vector of instantaneous power flux density, Poynting vector
$\vec{S}$	vector of power flux density, Poynting vector
$\vec{S}^{(r)}$	real part of Poynting vector
$\vec{S}^{(i)}$	imaginary part of Poynting vector
S_{max}	power flux density (absolute value of Poynting's vector) into direction of main radiation

$\hat{t}$	unit vector parallel to wire surface
$T_m(z)$	test or weighting function
$TR(z')$	triangle function
$\hat{u}$	unit vector parallel to current element
$\hat{v}$	unit vector complemental to $\hat{u}$
$\vec{v}$	vector of energy velocity
V	voltage
$V^{(n)}$	n-th interval
V_A	antenna input voltage
V_o	open circuit voltage
w	energy density
W	energy
W_D	weighting factor for directivity
x	rectangular coordinate
$\hat{x}$	unit vector in x-direction
X	reactance
X_A	antenna reactance
y	rectangular coordinate
$\hat{y}$	unit vector in y-direction
z	rectangular coordinate
$\hat{z}$	unit vector in z-direction
z'	(arc-) length coordinate
Z	impedance
Z_A	antenna impedance
Z_c	characteristic impedance
Z_L	load impedance
Z_{mn}	matrix impedance coefficient
Z_o	characteristic field impedance

<u>Greek Letters</u>

α	included angle
$\alpha(z')$	inclination angle
α_n	inclination angle of n-th segment
β_o	phase constant of free space
δ	delta (Dirac-) function
Δh	length of segment with straight-line dipole

Δs	length of segment with curvilinear antenna
ε_0	dielectric constant of free space
θ	spherical coordinate
λ_0	free space wavelength
μ_0	permeability constant of free space
ν	number of segment
$\vec{\Pi}$	Hertzian vector
ρ	cylindrical coordinate
ρ_0	wire radius
σ	spacing factor
τ	scaling factor
ϕ	spherical coordinate
ϕ_0	magnetic flux
ψ	angle determining antenna geometry in spherical coordinates (see Fig. 4.12)
ω	angular frequency
Ω	Hallén's parameter

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CHAPTER 1
Introduction

Antennas, being a vital and integral part of any wireless transmission system, have received much attention from the early beginnings of radiocommunications. In particular, linear or wire antennas, which represent one of the simplest configurations able to radiate and receive electromagnetic fields, have been dealt with in a large number of books and monographs, among which references [1] to [9] and [68] to [71] constitute only a small and incomplete selection. In contrast to their simple geometry, a rigorous theory for linear antennas was not found until the late thirties, and even modern computer solutions are debatable when realistic antenna input regions have to be taken into account. On the other hand, practical approximation theories - e.g. the transmission-line theory - have been known for quite a while and have served their purpose well in providing antenna engineers with simple concepts and reliable data, at least for moderately thin antennas.

The purpose of this book does not consist in adding one more so-called 'exact solution' to the numerous ones already described in the literature or in summing up all the techniques in use for solving wire-antenna problems by approximations, but in providing the reader with the latest results concerning the nearfield of conventional straight-line dipoles or monopoles and in particular in showing the capabilities of optimisation techniques for synthesising wire antennas with new unconventional geometries and surprising qualities.

In order to obtain these results, different computation techniques were employed, ranging from the 'method of moments' to a simple sinusoidal approximation of the antenna-current distribution. The particular computation method used for a specific problem was chosen in such a way that computational effort and computer time became a minimum without sacrificing accuracy to a degree that would render the results unrealistic.

After a discussion of the special simplifications which can be used when dealing with wire antennas, Chapter 3 is concerned with conventional straight-line dipoles and monopoles. It is shown that the sinusoidal current distribution can be derived as an asymptotic solution of Hallén's integral equation for infinitely thin wires. Then the method of moments is presented and applied for evaluating the current distribution, farfield radiation pattern and nearfield properties of moderately thin antennas. Particular attention is paid to the physical background of wave detachment from an antenna. The way in which electromagnetic waves are launched from a monopole is described in Section 3.3.1 by means of a sequence of instantaneous pictures of the electrical fieldlines for an electrically short, for a quarter wave and for an electrically long monopole.

While electrical fieldlines and charges serve their purpose well in demonstrating how waves detach from the antenna wire, some basic insights into the nature of antenna radiation can only be obtained by taking a closer look at the power flow. In Section 3.3.2, energy transport within the nearfield of straight-line monopoles is presented in three different ways, namely plots of the time-average Poynting-vector, time-average flowlines of energy and ellipses of the instantaneous Poynting-vector. For the transmitting case, it is shown how energy emerging from the feedline is guided by the antenna rod and deflected to the farfield. The antenna rod itself does not radiate but acts in guiding the energy and in improving the matching conditions. By computing the energy flowlines for a matched receiving monopole at greater distance from the antenna, it becomes possible to construct the shape of the effective area of this antenna.

Considering the instantaneous energy transport, a new equivalent circuit for electrically short radiators can be derived. This equivalent circuit proves to be helpful for estimating the properties of antennas which are too complicated for a straightforward analysis.

Chapter 4 deals with shaping wire antennas in order to achieve optimum performance data. The basic procedure applied is outlined using the effective length as the one parameter to be maximised. It is shown that the shape of a single-wire antenna synthesised for maximum effective length is also a first-order approximation to the antenna shape for maximum directivity. Direct synthesis of a maximum-directivity antenna is described in the subsequent section and results obtained with the method of moments as well as those based on the sinusoidal current distribution are compared with measurements. Shaped $1.5\lambda_0$-dipoles seem to be particularly attractive as they offer 7.2 dB of isotropic gain, in a special split-wire version even 10.5 dB.

The basic optimisation techniques used are outlined in Section 4.3, while the energy flow within the nearfield of the shaped wire antennas is discussed in Section 4.4.

The combination of optimised radiators to form arrays, as proposed in the subsequent paragraph, yields new and promising antennas. In particular an optimised Yagi-Uda array with three elements and different short-backfire arrays with shaped feeders are presented.

While optimisation so far was applied to one performance parameter only, the next sections deal with multiparameter optimisation. Among the examples discussed are wires shaped in the vicinity of large reflecting walls with the aim of simultaneously maximising directivity and sidelobe attenuation and in a further example additionally providing minimum mismatch to a given feedline. The last chapter is devoted to arrays that combine the broadband capabilities of log-periodic arrays with the increased gain of shaped elements.

CHAPTER 2
General Assumptions with Thin-Wire Antennas

Antennas dealt with in this book are exclusively of the thin-wire type, i.e. their length L is much greater than their diameter $2\rho_0$ (Fig. 2.1). In order to characterise

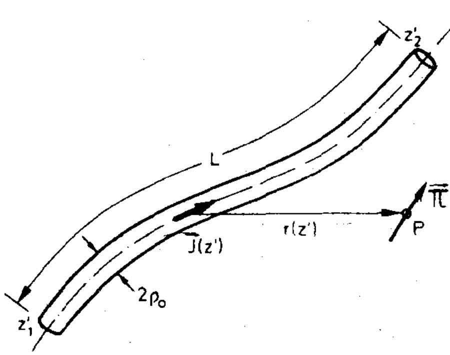

Fig. 2.1 Linear antenna of general shape

the dimensions of such antennas it is convenient to use Hallen's parameter

$$\Omega = 2 \ln \frac{L}{\rho_0} \quad , \tag{2.1}$$

where L is the length and ρ_0 the radius of the antenna conductor. For the purpose of this book, antennas will be called 'thin' or 'moderately thin' if

$$\Omega \geq 6 \quad . \tag{2.2}$$