

Telecommunications engineering

J. Dunlop
and
D.G. Smith



Telecommunications engineering

**J. Dunlop
and
D.G. Smith**

Department of Electronic
and Electrical Engineering,
University of Strathclyde,
Glasgow



130
Van Nostrand Reinhold (UK) Co. Ltd

8750130

© 1984 J. Dunlop and D.G. Smith

All rights reserved. No part of this work covered by the copyright hereon may be reproduced or used in any form or by any means – graphic, electronic, or mechanical, including photocopying, recording, taping, or information storage or retrieval systems – without the written permission of the publishers.

First published in 1984 by
Van Nostrand Reinhold (UK) Co. Ltd
Molly Millars Lane, Wokingham, Berkshire, England

Typeset in 9/11 pt Times by Thomson Press (India) Ltd, New Delhi

Printed and bound in Hong Kong.

Library of Congress Cataloging in Publication Data

Dunlop, J.

Telecommunications engineering.

Includes bibliographies and index.

1. Telecommunication. I. Smith, D.G. II. Title.

TK5101.D845 1984 621.38 84-3531

ISBN 0-442-30585-0

ISBN 0-442-30586-9 (pbk.)

207/102

Preface

The influence of telecommunications has increased steadily since the introduction of telegraphy, radio and telephony. Now, most of us are directly dependent on one or more of its many facets for the efficient execution of our work, at home, or in our leisure.

Consequently, as a subject for study it has become more and more important, finding its way into a large range of higher education courses, given at a variety of levels. For many students, telecommunications will be presented as an area of which they should be aware. The course they follow will include the essential features and principles of communicating by electro-magnetic energy, without developing them to any great depth. For others, however, the subject is of more specialized interest; they will start with an overview course and proceed to specialise in some aspects at a later time. We have written our book with both types of student in mind. We have brought together a broader range of material than is usually found in one text, and we have tried to combine an analytical approach to important concepts with a descriptive account of system design. In several places we have stressed the approximate nature of analysis, and the need to exercise engineering judgement in its application. The intention has been to avoid too much detail, so that the text will stand on its own as a general undergraduate level introduction, and it will also provide a strong foundation for those who will eventually develop more specialized interests.

We have assumed that the reader is familiar with basic concepts in electronic engineering, electromagnetic theory, probability theory and differential calculus.

Chapter 1 begins with the theoretical description of signals and the channels through which they are transmitted. Emphasis is placed on numerical methods of analysis such as the discrete Fourier transform, and the relationship between the time and frequency domain representations is covered in detail. This chapter also deals with the description and transmission of information bearing signals.

Chapter 2 is concerned with analogue modulation theory. In this chapter there is a strong link between the theoretical concepts of modulation theory and the practical significance of this theory. This chapter assumes that the reader has a realistic knowledge of electronic circuit techniques.

Chapter 3 is devoted to discrete signals and in particular the coding and transmission of analogue signals in digital format. This chapter also emphasises the relationship between the theoretical concepts and their practical significance.

Chapters 4 and 5 are concerned with the performance of telecommunications systems in noise. Chapter 4 covers the performance of analogue systems and concentrates on the spectral properties of noise. Chapter 5 covers the performance

of digital systems and is based on the statistical properties of noise. This chapter also deals in detail with the practical implication of error correction codes, a topic which is often ignored by more specialised texts in digital communications.

In Chapter 6 the elements of high-frequency transmission line theory are discussed, with particular emphasis on loss-less lines. The purpose is to introduce the concepts of impedance, reflection and standing-waves, and to show how the designer can influence the behaviour of the line.

Basic antenna analysis, and examples of some commonly used arrays and microwave antennas, are introduced in Chapter 7, while Chapters 8 and 9 describe the essential features of waveguide-based microwave components. A fairly full treatment of the propagation of signals along a waveguide is considered from both the descriptive and field-theory analysis points of view.

Telephone system equipment represents the largest part of a country's investment in telecommunications, yet teletraffic theory and basic system design do not always form part of a telecommunications class syllabus. Chapter 10 is a comprehensive chapter on traditional switching systems and the techniques used in their analysis. Care has been taken to limit the theoretical discussion to simple cases, to enable the underlying concepts to be emphasised.

Chapter 11 is devoted to television systems. In a text of this nature such a coverage must be selective. We have endeavoured to cover the main topics in modern colour television systems from the measurement of light to the transmission of teletext information. The three main television systems, NTSC, PAL and SECAM, are covered but the major part of this chapter is devoted to the PAL system.

One of the outstanding major developments in recent years has been the production of optical fibres of extremely low loss, making optical communication systems very attractive, both technically and commercially. Chapter 12 discusses the main features of these systems, without introducing any of the analytical techniques used by specialists. The chapter is intended to give an impression of the exciting future for this new technology.

We cannot claim to have produced a universal text! some omissions will not turn out to be justified, and topics which appear to be of only specialised interest now may suddenly assume a much more general importance. However, we hope that we have provided in one volume a coverage which will find acceptance by many students who are taking an interest in this stimulating and expanding field of engineering.

List of symbols

C	capacitance per unit length of transmission line
A	telephone traffic, in erlangs
α	attenuation coefficient on a transmission line
α	traffic offered per free source
B	bandwidth of a signal or channel
B	call congestion
β	phase constant on a transmission line
β	modulation index
c	velocity of light in free space
$C(n)$	discrete spectrum
C_n	n th harmonic in a Fourier series
δ_s	skin depth
$\delta(t - t_0)$	impulse function at t_0
DFT	discrete Fourier transform
E	time congestion
$E(f)$	energy density spectrum
$E_N(A)$	Erlang's loss function
$E(N, s, \alpha)$	Engset's loss function
ϵ	permittivity
ϵ_0	permittivity of free space
η_0	free space characteristic impedance
η	Single sided power spectral density of white noise
F	noise figure of a network
f_0	fundamental frequency of a periodic wave
f_c	cut-off frequency
$f(t), h(t)$	general function of time
$F_c(v)$	cumulative distribution function
G	conductance per unit length of transmission line
γ	propagation coefficient on a transmission line
$G(f)$	power spectral density
$G(i)$	probability of any i devices being busy
H	magnetic field
H_m	entropy of a message (bits/symbol)
$H(f)$	Fourier transform of $h(t)$
$H(i)$	probability of a particular i devices being busy
$h(k)$	discrete signal

$[i]$	probability that a network is in state i
IDFT	inverse discrete Fourier transform
IF	intermediate frequency
$I_0(x)$	modified Bessel function
$J_n(\beta)$	Bessel functions of the first kind
k_c	$2\pi/\lambda_c$
L	inductance per unit length of transmission line
λ	likelihood ratio
λ	wavelength
λ_c	cut-off wavelength
λ_{cm}	cut-off wavelength of the TE_{mn} or TM_{mn} mode
λ_g	guide wavelength
λ_i	call arrival rate in state i
λ_0	free space wavelength
$L(f)$	frequency domain output of a network
$l(t)$	time domain output of a network
m	depth of modulation
μ	permeability
μ_i	call departure rate in state i
μ_0	permeability of free space
N	number of devices
n	refractive index of glass fibre
N_i	normalised noise power at the input of a network
N_o	normalised noise power at the output of a network
n_0	refractive index of free space
$n(t)$	elemental noise voltage
P	power in a signal
P_e	error probability
$P(f)$	transfer function of a network
p'_{nm}	root of $J'_n(k_c, a)$
ψ	angle of reflection coefficient
$p(t)$	impulse response of a network
$p_v(v)$	probability density function
R	resistance per unit length of transmission line
$R_h(\tau)$	autocorrelation function of $h(t)$
ρ	reflection coefficient at transmission line load
s	mean call holding time
S	number of traffic sources
S	voltage standing wave ratio (VSWR)
S_c	normalized carrier power
S_i	normalized signal power at the input of a network
σ	rms voltage of a random signal
S_o	normalised signal power at the output of a network
SNR	signal to noise ratio (power)
T	period of a periodic wave

τ	dummy time variable
T_e	effective noise temperature of a network or antenna
TE_{mn}	transverse electric waveguide mode
TM_{mn}	transverse magnetic waveguide mode
T_s	standard noise temperature (290 K)
V	peak voltage of a waveform
v	transmission line wave velocity
V_1	incident (forward) voltage on a transmission line
V_2	reflected (backward) voltage on a transmission line
v_g	group velocity
$V_n(t)$	bandlimited noise voltage
v_{ph}	phase velocity
W	highest frequency component in a signal
$x(t)$	amplitude of in-phase noise component
y	mean call arrival rate
$y(t)$	amplitude of quadrature noise component
Z_L	transmission line load impedance
Z_0	characteristic impedance of a transmission line

Contents

Preface	v
List of Symbols	xv
1 Signals and channels	1
1.1 Introduction	1
1.2 The frequency and time domains	1
1.3 Continuous Fourier analysis	2
1.4 Odd and even functions	7
1.5 Waveform synthesis	9
1.6 The Fourier integral	10
1.7 Power and energy density spectrum	13
1.8 Signal transmission through linear systems	13
1.9 The impulse function	15
1.10 The discrete Fourier transform (DFT)	17
1.11 Time domain analysis	22
1.12 Correlation functions	25
1.13 Information content of signals	28
1.14 Information transmission	34
1.15 Conclusion	39
References	39
Problems	39
2 Analogue modulation theory	43
2.1 Double sideband amplitude modulation (DSB-AM)	44
2.2 Double sideband suppressed carrier amplitude modulation (DSB-SC-AM)	46
2.3 Single sideband amplitude modulation (SSB-AM)	47
2.4 Vestigial sideband amplitude modulation (VSB-AM)	47
2.5 DSB-AM modulators	48
2.6 DSB-SC-AM modulators	49
2.7 SSB-AM modulators	49
2.8 VSB-AM modulators	51
2.9 DSB-AM detection	51
2.10 DSB-SC-AM detection	56
2.11 SSB-AM detection	57
2.12 VSB-AM detection	58

2.13	Economic factors affecting the choice of AM systems	59
2.14	Angle modulation	59
2.15	Phase modulation (PM)	60
2.16	Frequency modulation (FM)	61
2.17	Frequency modulators	67
2.18	Demodulation of an FM wave	69
2.19	Frequency division multiplex (FDM) transmission	74
2.20	Conclusion	74
	References	75
	Problems	75
3	Discrete signals	77
3.1	Sampling of continuous signals	77
3.2	Reconstruction of the continuous signal	79
3.3	Low-pass filtering of a sampled signal	81
3.4	Time division multiplex (TDM) transmission	82
3.5	Pulse code modulation (PCM)	83
3.6	PCM line signals	88
3.7	Bandwidth of a PCM signal	90
3.8	Synchronization of PCM links	93
3.9	Delta modulation	94
3.10	Data communications	96
3.11	Spectral properties of data signals	98
3.12	Amplitude shift keying (ASK)	98
3.13	Frequency shift keying (FSK)	100
3.14	Phase shift keying (PSK)	101
3.15	Practical data systems	101
3.16	Differential phase shift keying (DPSK)	103
3.17	Advanced modulation methods	104
3.18	Packet-switched networks	105
3.19	Conclusion	10
	References	105
	Problems	109
4	Noise in analogue communications systems	111
4.1	Introduction	112
4.2	Physical sources of noise	112
4.3	Noise properties of networks	114
4.4	Algebraic representation of band-limited noise	119
4.5	SNR characteristics of envelope detected DSB-AM	121
4.6	SNR characteristics of coherently detected DSB-AM	123
4.7	SNR characteristics of DSB-SC-AM	123
4.8	SNR characteristics of SSB-AM	123
4.9	SNR characteristics of FM	124
4.10	Pre-emphasis and de-emphasis	128

4.11	Conclusion	130
	References	130
	Problems	130
5	Noise in digital communications systems	134
5.1	The amplitude distribution function of white noise	134
5.2	Statistical decision theory	137
5.3	Decision errors in PCM	141
5.4	Decision errors in carrier modulated data signals	141
5.5	Matched filtering and correlation detection	145
5.6	Error detection and correction	148
5.7	Multiple decisions	156
5.8	Conclusion	157
	References	157
	Problems	157
6	High-frequency transmission lines	160
6.1	Voltage and current relationships on the line	160
6.2	Line parameters	163
6.3	Characteristic impedance	164
6.4	Reflection from the load	165
6.5	Reflection coefficient ρ	165
6.6	Sending-end impedance	168
6.7	Lines of low loss	170
6.8	Loss-less lines	171
6.9	Quarter-wave transformer	171
6.10	Stubs	172
6.11	Standing waves	172
6.12	Voltage standing wave ratio (VSWR)	174
6.13	Impedance at a voltage minimum and at a voltage maximum	175
6.14	Load impedance on a loss-less line	175
6.15	Smith transmission line chart	177
6.16	Stub matching	186
6.17	Single-stub matching	187
6.18	Double-stub matching	189
6.19	Derivation of the Smith chart	193
6.20	Travelling waves on a loss-less line	195
6.21	Wave equation for a loss-less transmission line	195
6.22	Conclusion	197
	References	197
	Problems	197
7	Antennas	200
7.1	Radiation pattern (polar diagram)	200
7.2	Lobes	202

7.3	Beamwidth.....	202
7.4	Antenna impedance and bandwidth.....	202
7.5	Gain.....	203
7.6	Field due to a filament of current.....	204
7.7	Induction field.....	206
7.8	Radiation field.....	206
7.9	Power radiated from a current element.....	206
7.10	Radiation pattern of a short dipole.....	209
7.11	Antenna arrays.....	210
7.12	Two-element array.....	210
7.13	Linear arrays.....	211
7.14	Pattern multiplication.....	213
7.15	Antenna matching.....	214
7.16	Parasitic elements.....	215
7.17	Microwave antennas.....	216
7.18	Parabolic reflector.....	216
7.19	Horn antennas.....	219
7.20	Dielectric lens.....	221
7.21	Conclusion.....	222
	References.....	223
	Appendix 7.1: Field components produced by a short current element	223
	Problems.....	225
8	Active microwave devices.....	227
8.1	Klystron.....	227
8.2	Two-cavity klystron.....	227
8.3	Reflex klystron.....	230
8.4	Magnetron.....	234
8.5	Travelling-wave tube (TWT).....	237
8.6	Solid-state devices.....	240
8.7	Gunn diode.....	241
8.8	IMPATT diode.....	245
8.9	Field-effect transistors.....	248
8.10	Conclusion.....	253
	References.....	253
9	Passive microwave devices.....	254
9.1	Waveguides.....	254
9.2	Rectangular waveguide.....	254
9.3	Interference of two plane waves.....	255
9.4	Cut-off wavelength.....	256
9.5	Phase velocity.....	257
9.6	Group velocity.....	258
9.7	Rectangular waveguide modes.....	258
9.8	Field theory of propagation along a rectangular waveguide.....	259

9.9	Transverse electric (TE) modes	263
9.10	Transverse magnetic (TM) modes	267
9.11	Field equations for the fundamental TE_{10} mode	268
9.12	Attenuation in rectangular waveguide	269
9.13	Evanescient modes	270
9.14	Rectangular mode patterns	270
9.15	Circular waveguides	271
9.16	Circular waveguide (TE) modes	273
9.17	Circular mode cut-off frequency	277
9.18	Attenuation in circular waveguide	278
9.19	Rectangular cavity	279
9.20	Cavity Q – TE_{101} mode	282
9.21	Circular cavity	284
9.22	Rectangular waveguide components – TE_{10} mode	285
9.23	Waveguide – coaxial transformer	286
9.24	Attenuator	287
9.25	Directional coupler	288
9.26	Tee junctions	289
9.27	Wavemeter	290
9.28	Matched load	291
9.29	Short-circuit	291
9.30	Isolator	292
9.31	Conclusion	293
	References	294
	Problems	294
10	Telephony	296
10.1	Telephone traffic	296
10.2	Inter-arrival and call-holding times	297
10.3	Traffic variation	298
10.4	Busy hour	299
10.5	Lost-calls-cleared systems	299
10.6	Equations of state	299
10.7	Statistical equilibrium	301
10.8	State probability	301
10.9	Full-availability models	302
10.10	Erlang distribution: $S \gg N$	302
10.11	Time congestion	304
10.12	Call congestion	305
10.13	Bernoulli distribution: $S \leq N$	305
10.14	Engset distribution: $S > N$	307
10.15	Probability of occupancy of particular devices	308
10.16	Link systems	311
10.17	Probability of blocking	312
10.18	Delay system	316

10.19	Simulation	319
10.20	Switching and signalling	320
10.21	Types of signalling system	322
10.22	Loop disconnect pulsing	324
10.23	Voice-frequency signalling	328
10.24	Outband signalling	332
10.25	Switching networks	334
10.26	Basic analogue switching systems	337
10.27	Step-by-step	337
10.28	Common control	338
10.29	Multi-frequency signalling	340
10.30	Common-channel signalling	341
10.31	The telephone network	343
10.32	Numbering schemes	344
10.33	Routing calls	346
10.34	Digital systems	347
10.35	Conclusion	352
	References	352
	Problems	353
11	Television systems	356
11.1	Introduction	356
11.2	Measurement of light and the response of the eye	356
11.3	The monochrome television waveform	357
11.4	Bandwidth of a television waveform	360
11.5	Choice of number of lines	361
11.6	Synchronizing pulses	361
11.7	The television receiver	365
11.8	Colorimetry	368
11.9	Requirements of a colour television system	370
11.10	The PAL colour television system	371
11.11	Transmission of the chrominance signals	372
11.12	The transmitted PAL signal	375
11.13	Gamma correction	376
11.14	The NTSC chrominance signal	376
11.15	The PAL receiver	379
11.16	The SECAM system	380
11.17	Display devices and television cameras	381
11.18	Teledata	83
11.19	Teletext transmission	384
11.20	Viewdata	389
11.21	Conclusion	390
	References	390
	Problems	391

12	Optical fibre communications	394
12.1	Optical fibre	394
12.2	Stepped-index fibre	395
12.3	Skew rays	396
12.4	Modes	397
12.5	Graded-index fibre	397
12.6	Loss mechanisms	399
12.7	Absorption	399
12.8	Scatter	400
12.9	Radiation from bends	400
12.10	Single-mode fibre	401
12.11	Detectors	401
12.12	PIN diode	402
12.13	APD device	403
12.14	Speed of response and quantum efficiency	403
12.15	Reliability	403
12.16	Noise	404
12.17	Optical sources	404
12.18	Light emitting diodes (LEDs)	406
12.19	Lasers	407
12.20	Communications systems	410
12.21	Conclusion	413
	References	41
Appendix 1	Four-figure Bessel functions	15
Appendix 2	Useful trigonometric identities	416
Appendix 3	Normal error function tables	417
Index		419

1 Signals and channels

1.1 Introduction

Telecommunication engineering is concerned with the transmission of information between two distant points. Intuitively we may say that a signal contains information if it tells us something we did not already know. This definition is too imprecise for telecommunications studies, and we shall devote a section of this chapter to a formal description of information. For the present it is sufficient to say that a signal that contains information varies in an unpredictable or random manner. We have thus specified a primary character of the signals in telecommunications systems; they are random in nature.

These random signals can be broadly subdivided into discrete signals that have a fixed number of possible values, and continuous signals that have any value between given limits. Whichever type of signal we deal with, the telecommunication system that it uses can be represented by the generalized model of Fig. 1.1. The central feature of this model is the transmission medium or channel. Some examples of channels are coaxial cables, radio links, optical fibres and ultrasonic transmission through solids and liquids. It is clear from these examples that the characteristics of channels can vary widely. The common feature of all channels, however, is that they modify or distort the waveform of the transmitted signal. In some cases the distortion can be so severe that the signal becomes totally unrecognizable.

In many instances it is possible to minimize distortion by careful choice of the transmitted signal waveform. To do this the telecommunications engineer must be able to define and analyse the properties of both the signals and the channels over which they are transmitted. In this chapter we shall concentrate on the techniques used in signal and linear systems analysis, although we should point out that many telecommunications systems do have non-linear characteristics.

1.2 The Frequency and Time Domains

The analysis of linear systems is relatively straightforward if the applied signals are sinusoidal. We have already indicated that the signals encountered in telecommunications systems are random in nature and, as such, are non-deterministic. It is often possible to approximate such signals by periodic functions that themselves can be decomposed into a sum of sinusoidal components. The signal waveforms are functions of time and the variation of signal amplitude with time is known as the 'time domain representation' of the signal. Alternatively, if a signal is decomposed

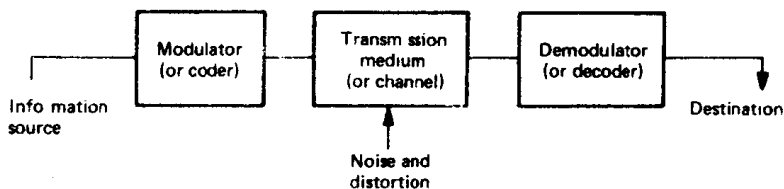


Fig. 1.1 Basic elements of a telecommunications system.

into a sum of sinusoidal components, the amplitude and phase of these components can be expressed as a function of frequency. This leads us to the 'frequency domain representation' of the signal.

The relationship between frequency domain and time domain is an extremely important one and is specified by Fourier's theorem. The response of a linear system to a signal can be determined in the time domain by using the principles of convolution, and in the frequency domain by applying the principle of superposition to the responses produced by the individual sinusoidal components. We will consider the frequency domain first, as this makes use of the theorems of linear network analysis which will be familiar to readers with an electronics background. Time domain analysis is considered in detail in Section 1.11. Frequency domain analysis will be introduced using traditional Fourier methods and we will then develop the discrete Fourier transform (DFT) which is now an essential tool in computer aided analysis of modern telecommunications systems.

1.3 Continuous Fourier Analysis

Fourier's theorem states that any single valued periodic function, which has a repetition interval T , can be represented by an infinite series of sine and cosine terms which are harmonics of $f_0 = 1/T$. The theorem is given by Eqn (1.1).

$$h(t) = \frac{a_0}{T} + \sum_{n=1}^{\infty} (a_n \cos 2\pi n f_0 t + b_n \sin 2\pi n f_0 t) \quad (1.1)$$

where $f_0 = 1/T$ is the fundamental frequency. The response of a linear system to a waveform $h(t)$ that is not a simple harmonic function is found by summing the responses produced by the individual sinusoidal components. The term a_0/T is known as the dc component and is the mean value of $h(t)$.

$$\frac{a_0}{T} = \frac{1}{T} \int_{-T/2}^{T/2} h(t) dt$$

i.e

$$a_0 = \int_{-T/2}^{T/2} h(t) dt \quad (1.2)$$