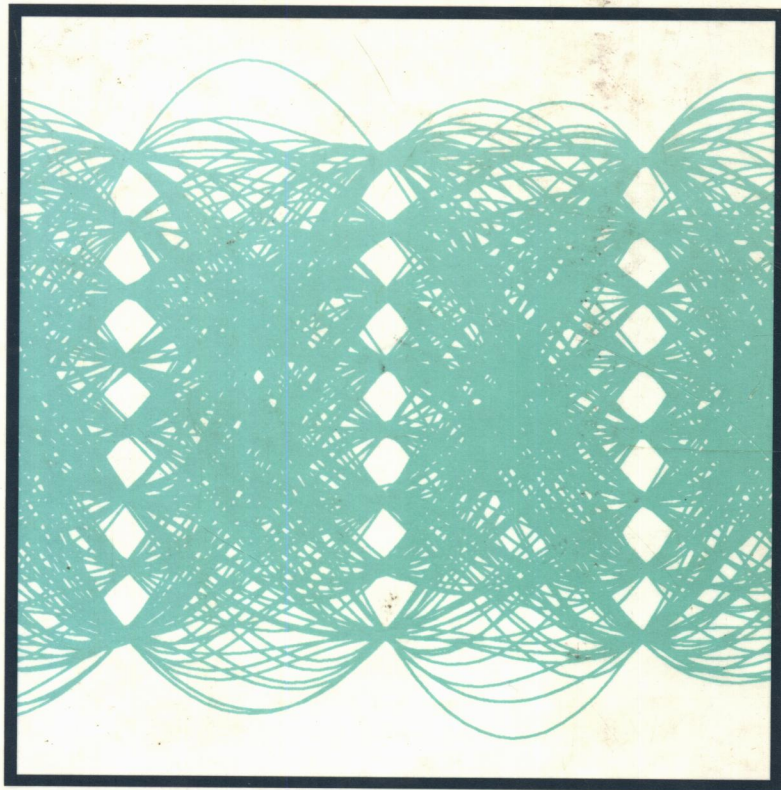
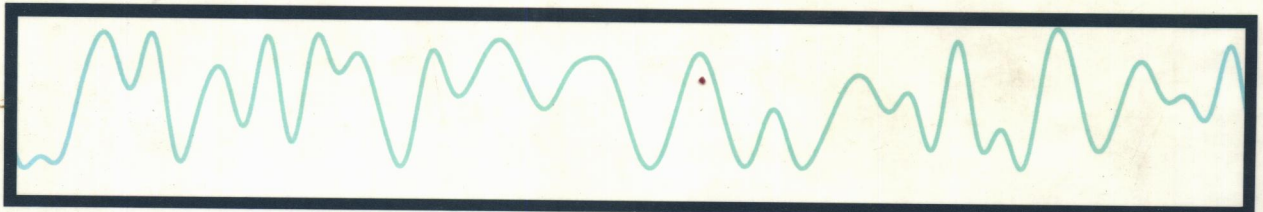


# **DIGITAL COMMUNICATION**

— **Second Edition** —



**Edward A. Lee**  
**David G. Messerschmitt**



# CONTENTS

---

PREFACE  
NOTES TO THE INSTRUCTOR

## PART I: THE BASICS

<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
1.1	APPLICATIONS OF DIGITAL COMMUNICATION	2
1.2	DIGITAL vs. ANALOG COMMUNICATIONS	5
1.3	PLAN OF THE BOOK	7
1.4	FURTHER READING	8
<b>2</b>	<b>DETERMINISTIC SIGNAL PROCESSING</b>	<b>11</b>
2.1	SIGNALS	11
2.2	LTI SYSTEMS AND FOURIER TRANSFORMS	13
2.3	THE NYQUIST SAMPLING THEOREM	15
2.4	PASSBAND SIGNALS and MODULATION	17
2.5	Z TRANSFORMS AND RATIONAL TRANSFER FUNCTIONS	21
2.6	SIGNAL SPACE REPRESENTATIONS	31
2.7	FURTHER READING	39
2-A	SUMMARY OF FOURIER TRANSFORM PROPERTIES	39
2-B	SPECTRAL FACTORIZATION	41
<b>3</b>	<b>STOCHASTIC SIGNAL PROCESSING</b>	<b>48</b>
3.1	RANDOM VARIABLES	48
3.2	RANDOM PROCESSES	57
3.3	MARKOV CHAINS	68
3.4	THE POISSON PROCESS AND QUEUEING	75
3.5	FURTHER READING	85

3-A	POWER SPECTRUM OF A CYCLOSTATIONARY PROCESS	86
3-B	POWER SPECTRUM OF A MARKOV CHAIN	87
3-C	DERIVATION OF POISSON PROCESS	90
3-D	MOMENT GENERATING FUNCTION OF SHOT NOISE	91

## **4 LIMITS OF COMMUNICATION 97**

4.1	JUST ENOUGH INFORMATION ABOUT ENTROPY	99
4.2	CAPACITY OF DISCRETE-TIME CHANNELS	102
4.3	FURTHER READING	110
4-A	ASYMPTOTIC EQUIPARTITION THEOREM	110

## **5 PHYSICAL MEDIA AND CHANNELS 115**

5.1	COMPOSITE CHANNELS	116
5.2	TRANSMISSION LINES	119
5.3	OPTICAL FIBER	127
5.4	MICROWAVE RADIO	142
5.5	TELEPHONE CHANNELS	160
5.6	MAGNETIC RECORDING CHANNELS	167
5.7	FURTHER READING	171

# **PART II: MODULATION AND DETECTION**

## **6 MODULATION 178**

6.1	AN OVERVIEW OF BASIC PAM TECHNIQUES	179
6.2	PULSE SHAPES	187
6.3	BASEBAND PAM	191
6.4	PASSBAND PAM	199
6.5	ALPHABET DESIGN	213
6.6	THE MATCHED FILTER — ISOLATED PULSE CASE	224
6.7	SPREAD SPECTRUM	229
6.8	ORTHOGONAL MULTIPULSE MODULATION	230
6.9	COMBINED PAM AND MULTIPULSE MODULATION	249
6.10	OPTICAL FIBER RECEPTION	261
6.11	MAGNETIC RECORDING	262
6.12	FURTHER READING	263
6-A	MODULATING RANDOM PROCESSES	263
6-B	THE GENERALIZED NYQUIST CRITERION	266

## 7 SIGNAL and RECEIVER DESIGN 279

- 7.1 SIGNAL MODEL 282
- 7.2 SPECIFIC MODULATION TECHNIQUES 286
- 7.3 PAM WITH INTERSYMBOL INTERFERENCE 294
- 7.4 BANDWIDTH and SIGNAL DIMENSIONALITY 304
- 7.5 FURTHER READING 307

## 8 NOISE 311

- 8.1 COMPLEX-VALUED GAUSSIAN PROCESSES 311
- 8.2 FUNDAMENTAL RESULTS 316
- 8.3 PERFORMANCE of PAM 320
- 8.4 PERFORMANCE of MINIMUM-DISTANCE RECEIVERS 329
- 8.5 PAM with ISI 334
- 8.6 SPREAD SPECTRUM 337
- 8.7 CAPACITY AND MODULATION 344
- 8.8 QUANTUM NOISE in OPTICAL SYSTEMS 360
- 8.9 FURTHER READING 371

## 9 DETECTION 378

- 9.1 DETECTION OF A SINGLE REAL-VALUED SYMBOL 380
- 9.2 DETECTION OF A SIGNAL VECTOR 385
- 9.3 KNOWN SIGNALS IN GAUSSIAN NOISE 390
- 9.4 OPTIMAL INCOHERENT DETECTION 402
- 9.5 OPTIMAL DETECTORS for PAM WITH ISI 406
- 9.6 SEQUENCE DETECTION: THE VITERBI ALGORITHM 409
- 9.7 SHOT NOISE SIGNAL WITH KNOWN INTENSITY 424
- 9.8 FURTHER READING 427
  - 9-A KARHUNEN-LOEVE EXPANSION 428
  - 9-B GENERAL ML AND MAP SEQUENCE DETECTORS 430
  - 9-C BIT ERROR PROBABILITY FOR SEQUENCE DETECTORS 432

## 10 EQUALIZATION 442

- 10.1 OPTIMAL ZERO-FORCING EQUALIZATION 445
- 10.2 GENERALIZED EQUALIZATION METHODS 464
- 10.3 FRACTIONALLY SPACED EQUALIZER 482
- 10.4 TRANSVERSAL FILTER EQUALIZERS 486
- 10.5 ISI and CHANNEL CAPACITY 487
- 10.6 FURTHER READING 511
  - 10-A DFE ERROR PROPAGATION 511

## **11 ADAPTIVE EQUALIZATION** **517**

- 11.1 CONSTRAINED-COMPLEXITY EQUALIZERS 519
- 11.2 ADAPTIVE LINEAR EQUALIZER 532
- 11.3 ADAPTIVE DFE 541
- 11.4 FRACTIONALLY SPACED EQUALIZER 543
- 11.5 PASSBAND EQUALIZATION 546
- 11.6 FURTHER READING 549
  - 11-A SG ALGORITHM ERROR VECTOR NORM 549

## **PART III: CODING**

## **12 SPECTRUM CONTROL** **555**

- 12.1 GOALS OF LINE CODES 556
- 12.2 LINE CODE OPTIONS 558
- 12.3 FILTERING FOR SPECTRUM CONTROL 573
- 12.4 CONTINUOUS-PHASE MODULATION 589
- 12.5 SCRAMBLING 591
- 12.6 FURTHER READING 597
  - 12-A MAXIMAL-LENGTH FEEDBACK SHIFT REGISTERS 598

## **13 ERROR CONTROL** **609**

- 13.1 BLOCK CODES 613
- 13.2 CONVOLUTIONAL CODES 626
- 13.3 HISTORICAL NOTES AND FURTHER READING 636
  - 13-A LINEARITY OF CODES 637
  - 13-B PATH ENUMERATORS 642

## **14 SIGNAL-SPACE CODING** **650**

- 14.1 MULTIDIMENSIONAL SIGNAL CONSTELLATIONS 652
- 14.2 TRELLIS CODES 668
- 14.3 COSET CODES 684
- 14.4 SIGNAL-SPACE CODING AND ISI 688
- 14.5 FURTHER READING 694

# PART IV: SYNCHRONIZATION

## 15 PHASE-LOCKED LOOPS 700

- 15.1 IDEAL CONTINUOUS-TIME PLL 702
- 15.2 DISCRETE-TIME PLLs 709
- 15.3 PHASE DETECTORS 713
- 15.4 VARIATIONS ON A THEME: VCOs 718
- 15.5 FURTHER READING 720

## 16 CARRIER RECOVERY 725

- 16.1 DECISION-DIRECTED CARRIER RECOVERY 726
- 16.2 POWER OF N CARRIER RECOVERY 733
- 16.3 FURTHER READING 734

## 17 TIMING RECOVERY 737

- 17.1 TIMING RECOVERY PERFORMANCE 739
- 17.2 SPECTRAL-LINE METHODS 741
- 17.3 MMSE TIMING RECOVERY AND APPROXIMATIONS 748
- 17.4 BAUD-RATE TIMING RECOVERY 754
- 17.5 ACCUMULATION OF TIMING JITTER 756
- 17.6 FURTHER READING 759
  - 17-A THE POISSON SUM FORMULA 759
  - 17-B DISCRETE-TIME DERIVATIVE 760

# PART V: MULTIPLE ACCESS

## 18 MULTIPLE ACCESS ALTERNATIVES 765

- 18.1 MEDIUM TOPOLOGY FOR MULTIPLE ACCESS 767
- 18.2 MULTIPLE ACCESS BY TIME DIVISION 770
- 18.3 MULTIPLE ACCESS BY FREQUENCY DIVISION 787
- 18.4 MULTIPLE ACCESS BY CODE DIVISION 789
- 18.5 THE CELLULAR CONCEPT 792

## 19 ECHO CANCELLATION 797

- 19.1 PRINCIPLE OF THE ECHO CANCELER 798
- 19.2 BASEBAND CHANNEL 801
- 19.3 PASSBAND CHANNEL 804
- 19.4 ADAPTATION 809
- 19.5 FAR-END ECHO 815
- 19.6 FURTHER READING 818
  - 19-A REAL-ERROR CANCELER CONVERGENCE 819

EXERCISE SOLUTIONS 825

PERMUTED INDEX 865