Statistical communication theory and its applications

Edited by Prof. B. R. Levin

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The Greek Alphabet

Αα	Alpha	Ιι	Iota	Ρρ	Rho
Ββ	Beta	Κϰ	Kappa	Σσ	Sigma
Γγ	Gamma	Λλ	Lambda	Ττ	Tau
Δδ	Delta	Μμ	Mu	Υυ	Upsilon
Εε	Epsilon	Νν	Nu	Φφ	Phi
Ζζ	Zeta	Ξξ	Xi	Χχ	Chi
Ηη	Eta	Οο	Omicron	Ψψ	Psi
Θθϑ	Theta	Ππ	Pi	Ωω	Omega

На английском языке

Contents

Preface

Rather hair-splittingly, the title of this book might be "Statistical Communication Theory: Selected Topics and Applications to High-priority Problems in Telecommunications".

The idea to publish the book emerged at the First CMEA Workshop on Statistical Communication Theory and its Applications held in Pushchino near Moscow in September 1977. The participants were scientists and engineers from Bulgaria, GDR, Hungary, Poland and the Soviet Union. Three Corresponding Members of the Academies, 39 Professors and Doctors of Science, 60 Candidates of Science represented the leading science centers and universities of the member-countries. The main objectives of the Workshop were to listen to reviewing reports on the major research areas of the theory, to exchange applicational experience, and to work out recommendations concerning the strategy of further research and applications.

The reviewing reports delivered at the Workshop make up the body of the book. Yet, it should not be viewed as a collection of abridged papers (nonabridged form would require a volume twice as large). The authors agreed that the contributions to the book should be selected, arranged and presented according to a preset structure and methodology, that unified terms and symbols should be used throughout the text as far as possible, and, finally, that the book should have a common list of references. The editor working in contact with the authors tried to make his best in achieving these not unlaborious goals.

The book has an introduction, nine chapters, and a list of references with more than 500 entries published mainly in the last decade.

The introduction outlines the methodologic principles and gives a historical survey of statistical communication theory paralleling the sequence of the papers in the book. Basically, every chapter discusses theoretical issues within the framework of applications. Yet, to be more specific, the first five chapters focus on theoretical aspects, and the last four on applications.

Chapter 1 is devoted to stochastic models of signals, interference and communication channels, and to the measurement of statistical parameters of these objects.

Chapter 2 presents an original approach to the description of stochastic system behavior, evaluates interesting parallels between the description of the deterministic and stochastic systems. For the latter, two ways of presentation are given.

Chapter 3 treats methods of coding and decoding, with main emphasis on difficulties in their realization.

Chapter 4 deals with the theory and application of large time-bandwidth product signals.

Chapter 5 illustrates what can be done for the synthesis of information systems under uncertainty by statistical methods.

Chapter 6 gives an analysis of interference and crosstalk in multichannel radio communication systems.

Chapter 7 shows how statistical communication theory is embodied in practical developments exemplified by satellite, troposcatter and optical communication systems and electromagnetic compatibility of radio systems.

The last two chapters discuss computer-communication networks.

On the whole, the book covers a significant part of modern statistical communication theory along with vast areas of its application in telecommunications, giving the state of the art by the end of 1977.

B. R. Levin

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List of Principal Symbols

A = event
a = amplitude of a signal
$A(t)$ = quadrature component of a narrowband process
B = time-bandwidth product of a signal
$B(t)$ = quadrature component of a narrowband process
C^1 = space of continuous functions
D = signal distance
E = experiment; energy in a signal
$\mathrm{E}[\ ]$ = expected value of the quantity in brackets
F = spectrum bandwidth
$F(x)$ = normal (Gaussian) distribution function
$F(\omega)$ = power spectrum
$F_1(x, t)$ = one-dimensional probability distribution function
$F(\mathbf{x}_1^n, \mathbf{t}_1^n)$ = joint probability distribution function
f_0 = carrier frequency
GF = Galois field
h = signal-to-noise ratio (S/N)
$h(u, v)$ = impulse response of a linear system
$I_0(x)$ = zero-order modified Bessel function
$\mathbf{I}$ = identity (unit) matrix
$K(u, v)$ = covariance function
$\mathbf{K}$ = covariance matrix
$K(i\omega), K(s)$ = transfer function of a linear network
m = mean value of a random variable
n = size of a sample; code word length
$n(t)$ = white noise
N = number of trials; number of scatter elements in multipath propagation
N_0 = spectral density of white noise
p = probability
$\mathrm{P}\{A\}$ = probability of an event A
P_s = power of a signal
P_n = power of noise
R = transmission rate
$R(t)$ = normalized autocorrelation function
$s(t)$ = desired signal
T = duration of an observation inverval; signal length; set of time points
t, τ = time variables
$w(\mathbf{x}_1^n, \mathbf{t}_1^n)$ = joint probability density
$W(t)$ = Wiener process
$\mathscr{X}$ = ensemble of realizations

x = threshold value; an independent variable
$x(t)$ = realization of a random process
$\mathbf{X}$ = set of input values
$X(t)$ = process
$Y(t)$ = process
$\mathcal{Y}$ = set of conditions
$\mathbf{Y}$ = set of output values
z = state-variable
$\delta(\tau)$ = Dirac delta function
Δ = frequency band
$\hat{\theta}$ = estimate of a parameter θ
π = conditional probability matrix
σ^2 = variance
Φ = phase of a signal
φ = phase
τ = delay time
Ω, ω = angular frequency
ξ, η, ζ, ν = random variables
$\xi(t)$ = interference, noise
$\in$ = "belongs in" or "falls in"
$\triangleq$ = equal by definition
$\forall$ = "for all"
sgn $(\cdot)$ = sign function, equal to $+1$ for positive argument and to -1 for negative argument

Abbreviations

Modulation and Multiplexing

ADM = adaptive delta modulation
AM = amplitude modulation
DPSK = differential phase-shift keying
FDM = frequency-division multiplex
FM = frequency modulation
FSK = frequency-shift keying
PAM = pulse-amplitude modulation
PCM = pulse-code modulation
PM = phase modulation
PPM = pulse-position modulation
PSK = phase-shift keying
PWM = pulse-width modulation
SSB = single-sideband (AM)
TDM = time division multiplex

Organisations

CCIR = Comité Consultatif International de Radio
CCITT = Comité Consultatif International de Télégraphie et Téléphonie
CMEA = Council for Mutual Economic Assistance

Others

ACF = autocorrelation function
CCF = cross-correlation function
CVP = channel with variable parameters
DFT = discrete Fourier transform
DSC = discrete symmetric memoryless channel
FFT = fast Fourier transform
IF = intermediate frequency
LSC = linear stochastic channel
PLL = phase-lock loop
RF = radio frequency
RSC = random structure channel

Introduction

A Historical Survey of Statistical Communication Theory

I.1. Pioneering the Statistical Communication Theory

In 1947, V. A. Kotel'nikov, Vice-President of the USSR Academy of Sciences at this writing, presented to the Moscow Power Institute the dissertation headed "A theory of potential noise immunity". In the submitted thesis he formulated the objectives of optimal statistical synthesis of communication receivers in the presently known form. From the new positions he analyzed various communication systems to found out the bounds for feasible methods of modulation [151].

Over a year later, the Bell System Technical Journal published Claude Shannon's papers "A mathematical theory of communication" [478] where he set forth his two famous theorems. The first is on message source encoding to offset redundancy and the second on the maximum amount of information which by a suitable coding procedure can be transmitted through the discrete noisy channel with arbitrary small error rate. This work initiated coding theory as another active area in communications research.

The fundamental results by Kotel'nikov and Shannon have been widely recognized as basic contribution into the building of statistical communication theory. Three past decades have seen substantial progress in the methods of the theory and their applications in the research and development work.

I.2. General Methodology

Consider shortly the historical backgrounds to statistical communication theory which may serve another illustration of the knowledge continuity and interrelation principles in science.

Philosophical concepts. Since the time of Newton and Laplace physical processes were studied predominantly using deterministic principles. Although skilful and consistent in their use, they, however, could not embrace all the aspects of real phenomena. So, for example, the methods of classical mechanics, which had seemed adequate to sufficiently describe microcosmic processes, had to give up their place to a probabilistic approach that in the cource of an elaborated study proved a powerful alternative to the deterministic techniques.

At the turn of this century the well-balanced structure of determinism in physics suffered a first deep break. In 1902, American theoretical physisist J. Willard Gibbs published his work on the general principles of statistical mechanics [78]. These principles paved the way for the quantum theory of elementary particles, which is based on the known principle to determine only the probability of an experimental outcome. Max Born, one of the founders of quantum mechanics, wrote that casuality of classical physics had always been interpreted as determinism (even by Immanuael Kant) and that new quantum mechanics turned out to be statistical rather than deterministic, and its success in all fields of physics was a fact [31].

First applied at a microscopic level, the probabilistic and statistical concepts of physics penetrated deep into the natural sciences to interprete manifold macroscopic phenomena and to describe them clearly and exactly even in continuous media. In the 1940s, these concepts gained a reliable foothold in radio engineering and communication theory. It became obvious that in designing a communication system one had to reckon with the effect of noise although it could not be exactly predicted and deterministically corrected due to its stochastic nature. On the other hand, transmission of information in a communication system is sensible only when the transmitted message is not known a priory to the recepient. This pragmatic approach led to the choice of a stochastic model for the message source and communication channel; it also suggested that instead of an individual signal an ensemble of signals should be considered using a probability measure specified on this ensemble.

Following statistical mechanics and statistical physics, the middle of the century saw the advent of statistical radio physics, statistical radio engineering, statistical communication theory, and theory of information. The concept of indeterminism is that joins all of them.

Mathematics involved. To deduce the quantitative characteristics of the studied process the scientist needs an adequate body of mathematics. Now that the deterministic principles had to be abandoned a need arose to expand the mathematical methods to include first of all those of theory of probability and mathematical statistics. Gaining new applications, however, mathematics itself had to adapt to the new needs. For example, random process theory branched off probability theory, and decision theory branched off mathematical statistics.

These disciplines were given a far-reaching impetus by several outstanding mathematicians. In the early 1930s, Khinchin and Wiener developed the theory of harmonic analysis of random functions. So, the Wiener-Khinchin theorem relates the autocorrelation function and power spectrum of a wide-sense stationary random process. In 1939, Kolmogorov published—first abroad [417], then in the USSR [140]— a paper which laid a foundation for further work on random process filtering.

In 1942, Wiener wrote a report on random process filtering, which was made public in 1949 [500]. At this time he was already aware of the Kolmogorov's findings. Later in his book 'I am a Mathematician' Wiener wrote, "My research at this time received a ready reception in Russia and was in close relation with the work of some of the Russian mathematicians, although I had never met any of them nor, I believe, ever been in correspondence with them. Khinchin and Kolmogorov, the two chief Russian exponents of the theory of probability, have long been involved in the same field in which I was working. For more than twenty years, we have been on one another's heels; either they had proved a theorem which I was about to prove, or I had been ahead of them by the narrowest of margine. This contact between our work came not from any definite program on my part, nor I believe, from any of theirs but was due to the fact that we had come into our greatest activity at about the same time, with about the same intellectual equipment."

Problems and objectives. Any classification arranges things according to some attributes. With regard to problems and objectives of statistical communication theory this may be done with recourse to a block diagram where a communication system is presented as a sequence of "black boxes" running from source to sink (see, e.g. [96]).

Two basic groups of objectives are those of analysis and synthesis. In analysis, the objective is to study and deduce the system or subsystem of interest assuming that the system algorithm is given along with the probability distribution of signals and noise on the input side. In synthesis, the objective is to develop a system or subsystem algorithm complying with a specified performance criterion.

Synthesis may be based on a complete a priori information, when the probability distributions of the signals and noise and the additional constraints are known. Alternatively, it may be attempted under conditions of uncertainty when some of the a priori data used as the performance criterion are not known. For a more detailed classification, one or more "black boxes" must be isolated from the block diagram. Then several groups of problems and objectives may be visualized in statistical communication theory:

model buildings for signals, noise, and communication channels;
coding and decoding;
multiplexing in a multichannel system;

choice of signal waveforms and modulation methods;
analysis of noise, interference and distortion in a system;
choice of a reception algorithm and demodulation methods.

Consider first the methodology of noise immunity as applied to data transmission and then retrospectively review the milestones which some divisions of statistical communication theory have passed in their development.

I.3. Methodology of Noise Immunity

It is essential to draw a clear demarcation line between the reliability and noise immunity of a system. This is especially important because of the fast progress in microelectronics and integrated circuit technology.

There are two types of system failure to distinguish—irreversible failures and reversible failures. An irreversible failure is caused by such factors as ageing, corrosion, inadequate structural strength, etc. The evaluation of probability characteristics when estimating a non-failure operating time, given a possibility of irreversible failures, pertaines to reliability theory. Reliability can be improved by better technology, equipment redundancy, and some other means. A reversible failure is brought about by interference. In this case, the system recovers its serviceability as soon as the interference vanishes. Matters of optimal design leading to a noise-immune system relate to the theory of noise immunity.

Information transmission and reception involves both reliability and noise immunity. However, either may have an optimal solution different from that of the other. Let us consider the matter of noise immunity in more detail.

Often its objective is stated as filtering, that is separation of the desired information from the undesired. Accordingly, principal aspects are considered.

1. Separation of the desired information from interference without loss of the former. It is the fundamental objective of communication. If it cannot be achieved, for instance due to a limited bandwidth, then one usually seeks at least to minimize distortion so as to satisfy some optimality criterion.

2. Separation of a part of the desired information from the remaining useful information and interference, which entails the loss of some information. This is the fundamental objective of measurements. Here some distortion of a desired signal is not objectionable, such as when functionals of the primary information flow are measured. The information flow is reduced to functions and variables which describe the original process in some way.

There certainly may exist cases that do not fit the above classification or are intersection of the above two objectives.