
THE LEVINSON–DURBIN ALGORITHM

The Levinson–Durbin algorithm is an order-recursive method for determining the solution to the set of linear equations

$$\Phi_p \mathbf{a}_p = \phi_p \quad (\text{A-1})$$

where Φ_p is a $p \times p$ Toeplitz matrix, \mathbf{a}_p is the vector of predictor coefficients expressed as

$$\mathbf{a}_p' = [a_{p1} \quad a_{p2} \quad \dots \quad a_{pp}]$$

and ϕ_p is a p -dimensional vector with elements

$$\phi_p' = [\phi(1) \quad \phi(2) \quad \dots \quad \phi(p)]$$

For a first-order ($p = 1$) predictor, we have the solution

$$\begin{aligned} \phi(0)a_{11} &= \phi(1) \\ a_{11} &= \phi(1)/\phi(0) \end{aligned} \quad (\text{A-2})$$

The residual mean square error (MSE) for the first-order predictor is

$$\begin{aligned} \mathcal{E}_1 &= \phi(0) - a_{11}\phi(1) \\ &= \phi(0) - a_{11}^2\phi(0) \\ &= \phi(0)(1 - a_{11}^2) \end{aligned} \quad (\text{A-3})$$

In general, we may express the solution for the coefficients of an m th-order

predictor in terms of the coefficients of the $(m-1)$ th-order predictor. Thus, we express \mathbf{a}_m as the sum of two vectors, namely,

$$\mathbf{a}_m = \begin{bmatrix} a_{m1} \\ a_{m2} \\ \vdots \\ a_{mm} \end{bmatrix} = \begin{bmatrix} \mathbf{a}_{m-1} \\ 0 \end{bmatrix} + \begin{bmatrix} \mathbf{d}_{m-1} \\ k_m \end{bmatrix} \quad (\text{A-4})$$

where the vector \mathbf{d}_{m-1} and the scalar k_m are to be determined. Also, Φ_m may be expressed as

$$\Phi_m = \begin{bmatrix} \Phi_{m-1} & \Phi'_{m-1} \\ \Phi'_{m-1} & \phi(0) \end{bmatrix} \quad (\text{A-5})$$

where Φ'_{m-1} is just the vector Φ_{m-1} in reverse order.

Now

$$\begin{bmatrix} \Phi_{m-1} & \Phi'_{m-1} \\ \Phi'_{m-1} & \phi(0) \end{bmatrix} \left(\begin{bmatrix} \mathbf{a}_{m-1} \\ 0 \end{bmatrix} + \begin{bmatrix} \mathbf{d}_{m-1} \\ k_m \end{bmatrix} \right) = \begin{bmatrix} \Phi_{m-1} \\ \phi(m) \end{bmatrix} \quad (\text{A-6})$$

From (A-6), we obtain two equations. The first is the matrix equation

$$\Phi_{m-1} \mathbf{a}_{m-1} + \Phi_{m-1} \mathbf{d}_{m-1} + k_m \Phi'_{m-1} = \Phi_{m-1} \quad (\text{A-7})$$

But $\Phi_{m-1} \mathbf{a}_{m-1} = \Phi_{m-1}$. Hence, (A-7) simplifies to

$$\Phi_{m-1} \mathbf{d}_{m-1} + k_m \Phi'_{m-1} = 0 \quad (\text{A-8})$$

This equation has the solution

$$\mathbf{d}_{m-1} = -k_m \Phi_{m-1}^{-1} \Phi'_{m-1} \quad (\text{A-9})$$

But Φ'_{m-1} is just Φ_{m-1} in reverse order. Hence, the solution in (A-9) is simply \mathbf{a}_{m-1} in reverse order multiplied by $-k_m$. That is,

$$\mathbf{d}_{m-1} = -k_m \begin{bmatrix} a_{m-1, m-1} \\ a_{m-1, m-2} \\ \vdots \\ a_{m-1, 1} \end{bmatrix} \quad (\text{A-10})$$

The second equation obtained from (A-6) is the scalar equation

$$\Phi'_{m-1} \mathbf{a}_{m-1} + \Phi'_{m-1} \mathbf{d}_{m-1} + \phi(0) k_m = \phi(m) \quad (\text{A-11})$$

We eliminate \mathbf{d}_{m-1} from (A-11) by use of (A-10). The resulting equation gives us k_m . That is,

$$\begin{aligned} k_m &= \frac{\phi(m) - \Phi'_{m-1} \mathbf{a}_{m-1}}{\phi(0) - \Phi'_{m-1} \Phi_{m-1}^{-1} \Phi'_{m-1}} \\ &= \frac{\phi(m) - \Phi'_{m-1} \mathbf{a}_{m-1}}{\phi(0) - \mathbf{a}'_{m-1} \Phi_{m-1}} \\ &= \frac{\phi(m) - \Phi'_{m-1} \mathbf{a}_{m-1}}{\mathcal{E}_{m-1}} \end{aligned} \quad (\text{A-12})$$

where \mathcal{E}_{m-1} is the residual MSE given as

$$\mathcal{E}_{m-1} = \phi(0) - \mathbf{a}_{m-1}' \boldsymbol{\phi}_{m-1} \quad (\text{A-13})$$

By substituting (A-10) for \mathbf{d}_{m-1} in (A-4), we obtain the order-recursive relation

$$a_{mk} = a_{m-1,k} - k_m a_{m-1,m-k}, \quad k = 1, 2, \dots, m-1, \quad m = 1, 2, \dots, p \quad (\text{A-14})$$

and

$$a_{mm} = k_m$$

The minimum MSE may also be computed recursively. We have

$$\mathcal{E}_m = \phi(0) - \sum_{k=1}^m a_{mk} \phi(k) \quad (\text{A-15})$$

Using (A-14) in (A-15), we obtain

$$\mathcal{E}_m = \phi(0) - \sum_{k=1}^{m-1} a_{m-1,k} \phi(k) - a_{mm} \left[\phi(m) - \sum_{k=1}^{m-1} a_{m-1,m-k} \phi(k) \right] \quad (\text{A-16})$$

But the term in square brackets in (A-16) is just the numerator of k_m in (A-12). Hence,

$$\begin{aligned} \mathcal{E}_m &= \mathcal{E}_{m-1} - a_{mm}^2 \mathcal{E}_{m-1} \\ &= \mathcal{E}_{m-1} (1 - a_{mm}^2) \end{aligned} \quad (\text{A-17})$$

ERROR PROBABILITY FOR MULTICHANNEL BINARY SIGNALS

In multichannel communication systems that employ binary signaling for transmitting information over the AWGN channel, the decision variable at the detector can be expressed as a special case of the general quadratic form

$$D = \sum_{k=1}^L (A |X_k|^2 + B |Y_k|^2 + CX_k Y_k^* + C^* X_k^* Y_k) \quad (\text{B-1})$$

in complex-valued gaussian random variables. A , B , and C are constants; X_k and Y_k are a pair of correlated complex-valued gaussian random variables. For the channels considered, the L pairs $\{X_k, Y_k\}$ are mutually statistically independent and identically distributed.

The probability of error is the probability that $D < 0$. This probability is evaluated below.

The computation begins with the characteristic function, denoted by $\psi_D(jv)$, of the general quadratic form. The probability that $D < 0$, denoted here as the probability of error P_b , is

$$P_b = P(D < 0) = \int_{-\infty}^0 p(D) dD \quad (\text{B-2})$$

where $p(D)$, the probability density function of D , is related to $\psi_D(jv)$ by the Fourier transform, i.e.,

$$p(D) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \psi_D(jv) e^{-jvD} dv$$

Hence,

$$P_b = \int_{-\infty}^0 dD \frac{1}{2\pi} \int_{-\infty}^{\infty} \psi_D(jv) e^{-jvD} dv \quad (\text{B-3})$$

Let us interchange the order of integration and carry out first the integration with respect to D . The result is

$$P_b = -\frac{1}{2\pi j} \int_{-\infty-j\epsilon}^{\infty-j\epsilon} \frac{\psi_D(jv)}{v} dv \quad (\text{B-4})$$

where a small positive number ϵ has been inserted in order to move the path of integration away from the singularity at $v = 0$ and which must be positive in order to allow for the interchange in the order of integration.

Since D is the sum of statistically independent random variables, the characteristic function of D factors into a product of L characteristic functions, with each function corresponding to the individual random variables d_k , where

$$d_k = A |X_k|^2 + B |Y_k|^2 + C X_k Y_k^* + C^* X_k^* Y_k$$

The characteristic function of d_k is

$$\phi_{d_k}(jv) = \frac{v_1 v_2}{(v + jv_1)(v - jv_2)} \exp \left[\frac{v_1 v_2 (-v^2 \alpha_{1k} + jv \alpha_{2k})}{(v + jv_1)(v - jv_2)} \right] \quad (\text{B-5})$$

where the parameters v_1 , v_2 , α_{1k} , and α_{2k} depend on the means \bar{X}_k and \bar{Y}_k and the second (central) moments μ_{xx} , μ_{yy} , and μ_{xy} of the complex-valued gaussian variables X_k and Y_k through the following definitions ($|C|^2 - AB > 0$):

$$\begin{aligned} v_1 &= \sqrt{w^2 + \frac{1}{4(\mu_{xx}\mu_{yy} - |\mu_{xy}|^2)(|C|^2 - AB)}} - w \\ v_2 &= \sqrt{w^2 + \frac{1}{4(\mu_{xx}\mu_{yy} - |\mu_{xy}|^2)(|C|^2 - AB)}} + w \\ w &= \frac{A\mu_{xx} + B\mu_{yy} + C\mu_{xy}^* + C^*\mu_{xy}}{4(\mu_{xx}\mu_{yy} - |\mu_{xy}|^2)(|C|^2 - AB)} \\ \alpha_{1k} &= 2(|C|^2 - AB)(|\bar{X}_k|^2 \mu_{yy} + |\bar{Y}_k|^2 \mu_{xx} - \bar{X}_k^* \bar{Y}_k \mu_{xy} - \bar{X}_k \bar{Y}_k^* \mu_{xy}^*) \\ \alpha_{2k} &= A |\bar{X}_k|^2 + B |\bar{Y}_k|^2 + C \bar{X}_k^* \bar{Y}_k + C^* \bar{X}_k \bar{Y}_k^* \\ \mu_{xy} &= \frac{1}{2} E[(X_k - \bar{X}_k)(Y_k - \bar{Y}_k)^*] \end{aligned} \quad (\text{B-6})$$

Now, as a result of the independence of the random variables d_k , the characteristic function of D is

$$\begin{aligned} \psi_D(jv) &= \prod_{k=1}^L \psi_{d_k}(jv) \\ \psi_D(jv) &= \frac{(v_1 v_2)^L}{(v + jv_1)^L (v - jv_2)^L} \exp \left[\frac{v_1 v_2 (jv \alpha_2 - v^2 \alpha_1)}{(v + jv_1)(v - jv_2)} \right] \end{aligned} \quad (\text{B-7})$$

where

$$\alpha_1 = \sum_{k=1}^L \alpha_{1k}, \quad \alpha_2 = \sum_{k=1}^L \alpha_{2k} \quad (\text{B-8})$$

The result (B-7) is substituted for $\psi_D(jv)$ in (B-4), and we obtain

$$P_b = -\frac{(v_1 v_2)^L}{2\pi j} \int_{-\infty + j\epsilon}^{\infty + j\epsilon} \frac{dv}{v(v + jv_1)^L(v - jv_2)^L} \exp \left[\frac{v_1 v_2 (jv\alpha_2 - v^2\alpha_1)}{(v + jv_1)(v - jv_2)} \right] \quad (\text{B-9})$$

This integral is evaluated as follows.

The first step is to express the exponential function in the form

$$\exp \left(-A_1 + \frac{jA_2}{v + jv_1} - \frac{jA_3}{v - jv_2} \right)$$

where one can easily verify that the constants A_1 , A_2 , and A_3 are given as

$$\begin{aligned} A_1 &= \alpha_1 v_1 v_2 \\ A_2 &= \frac{v_1^2 v_2}{v_1 + v_2} (\alpha_1 v_1 + \alpha_2) \\ A_3 &= \frac{v_1 v_2^2}{v_1 + v_2} (\alpha_1 v_2 - \alpha_2) \end{aligned} \quad (\text{B-10})$$

Second, a conformal transformation is made from the v plane onto the p plane via the change in variable

$$p = -\frac{v_1}{v_2} \frac{v - jv_2}{v + jv_1} \quad (\text{B-11})$$

In the p plane, the integral given by (B-9) becomes

$$P_b = \frac{\exp [v_1 v_2 (-2\alpha v_1 v_2 + \alpha_2 v_1 - \alpha_2 v_2) / (v_1 + v_2)^2]}{(1 + v_2/v_1)^{2L-1}} \frac{1}{2\pi j} \int_{\Gamma} f(p) dp \quad (\text{B-12})$$

where

$$f(p) = \frac{[1 + (v_2/v_1)p]^{2L-1}}{p^L(1-p)} \exp \left[\frac{A_2(v_2/v_1)}{v_1 + v_2} p + \frac{A_3(v_1/v_2)}{v_1 + v_2} \frac{1}{p} \right] \quad (\text{B-13})$$

and Γ is a circular contour of radius less than unity that encloses the origin.

The third step is to evaluate the integral

$$\begin{aligned} \frac{1}{2\pi j} \int_{\Gamma} f(p) dp &= \frac{1}{2\pi j} \int_{\Gamma} \frac{[1 + (v_2/v_1)p]^{2L-1}}{p^L(1-p)} \\ &\quad \times \exp \left[\frac{A_2(v_2/v_1)}{v_1 + v_2} p + \frac{A_3(v_1/v_2)}{v_1 + v_2} \frac{1}{p} \right] dp \end{aligned} \quad (\text{B-14})$$

In order to facilitate subsequent manipulations, the constants $a \geq 0$ and $b \geq 0$ are introduced and defined as follows:

$$\frac{1}{2}a^2 = \frac{A_3(v_1/v_2)}{v_1 + v_2}, \quad \frac{1}{2}b^2 = \frac{A_2(v_2/v_1)}{v_1 + v_2} \quad (\text{B-15})$$

Let us also expand the function $[1 + (v_2/v_1)p]^{2L-1}$ as a binomial series. As a result, we obtain

$$\begin{aligned} \frac{1}{2\pi j} \int_{\Gamma} f(p) dp &= \sum_{k=0}^{2L-1} \binom{2L-1}{k} \left(\frac{v_2}{v_1}\right)^k \\ &\times \frac{1}{2\pi j} \int_{\Gamma} \frac{p^k}{p^{L-k}(1-p)} \exp\left(\frac{\frac{1}{2}a^2}{p} + \frac{1}{2}b^2p\right) dp \end{aligned} \quad (\text{B-16})$$

The contour integral given in (B-16) is one representation of the Bessel function. It can be solved by making use of the relations

$$I_n(ab) = \begin{cases} \frac{1}{2\pi j} \left(\frac{a}{b}\right)^n \int_{\Gamma} \frac{1}{p^{n+1}} \exp\left(\frac{\frac{1}{2}a^2}{p} + \frac{1}{2}b^2p\right) dp \\ \frac{1}{2\pi j} \left(\frac{b}{a}\right)^n \int_{\Gamma} p^{n-1} \exp\left(\frac{\frac{1}{2}a^2}{p} + \frac{1}{2}b^2p\right) dp \end{cases}$$

where $I_n(x)$ is the n th order modified Bessel function of the first kind and the series representation of Marcum's Q function in terms of Bessel functions, i.e.,

$$Q_1(a, b) = \exp[-\frac{1}{2}(a^2 + b^2)] + \sum_{n=0}^{\infty} \left(\frac{a}{b}\right)^n I_n(ab)$$

First, consider the case $0 \leq k \leq L-2$ in (B-16). In this case, the resulting contour integral can be written in the form†

$$\frac{1}{2\pi j} \int_{\Gamma} \frac{1}{p^{L-k}(1-p)} \exp\left(\frac{\frac{1}{2}a^2}{p} + \frac{1}{2}b^2p\right) dp = Q_1(a, b) \exp[\frac{1}{2}(a^2 + b^2)] + \sum_{n=1}^{L-k} \left(\frac{b}{a}\right)^n I_n(ab) \quad (\text{B-17})$$

Next, consider the term $k = L-1$. The resulting contour integral can be expressed in terms of the Q function as follows:

$$\frac{1}{2\pi j} \int_{\Gamma} \frac{1}{p(1-p)} \exp\left(\frac{\frac{1}{2}a^2}{p} + \frac{1}{2}b^2p\right) dp = Q_1(a, b) \exp[\frac{1}{2}(a^2 + b^2)] \quad (\text{B-18})$$

Finally, consider the case $L \leq k \leq 2L-1$. We have

$$\begin{aligned} &\frac{1}{2\pi j} \int_{\Gamma} \frac{p^{k-L}}{1-p} \exp\left(\frac{\frac{1}{2}a^2}{p} + \frac{1}{2}b^2p\right) dp \\ &= \sum_{n=0}^{\infty} \frac{1}{2\pi j} \int_{\Gamma} p^{k-L+n} \exp\left(\frac{\frac{1}{2}a^2}{p} + \frac{1}{2}b^2p\right) dp \\ &= \sum_{n=k+1-L}^{\infty} \left(\frac{a}{b}\right)^n I_n(ab) = Q_1(a, b) \exp[\frac{1}{2}(a^2 + b^2)] - \sum_{n=0}^{k-L} \left(\frac{a}{b}\right)^n I_n(ab) \end{aligned} \quad (\text{B-19})$$

Collecting the terms that are indicated on the right-hand side of (B-16) and using

† This contour integral is related to the generalized Marcum Q function, defined as

$$Q_m(a, b) = \int_0^{\infty} x(x/a)^{m-1} \exp[-\frac{1}{2}(x^2 + a^2)] I_{m-1}(ax) dx, \quad m \geq 1$$

in the following manner:

$$Q_m(a, b) \exp[\frac{1}{2}(a^2 + b^2)] = \frac{1}{2\pi j} \int_{\Gamma} \frac{1}{p^m(1-p)} \exp\left(\frac{\frac{1}{2}a^2}{p} + \frac{1}{2}b^2p\right) dp$$

the results given in (B-17)–(B-19), the following expression for the contour integral is obtained after some algebra:

$$\begin{aligned} \frac{1}{2\pi j} \int_{\Gamma} f(p) dp = & \left(1 + \frac{v_2}{v_1}\right)^{2L-1} [\exp[\frac{1}{2}(a^2 + b^2)] Q_1(a, b) - I_0(ab)] \\ & + I_0(ab) \sum_{k=0}^{L-1} \binom{2L-1}{k} \left(\frac{v_2}{v_1}\right)^k \\ & + \sum_{n=1}^{L-1} I_n(ab) \sum_{k=0}^{L-1-n} \binom{2L-1}{k} \left[\left(\frac{b}{a}\right)^n \left(\frac{v_2}{v_1}\right)^k - \left(\frac{a}{b}\right)^n \left(\frac{v_2}{v_1}\right)^{2L-1-k} \right] \quad (\text{B-20}) \end{aligned}$$

Equation (B-20) in conjunction with (B-12) gives the result for the probability of error. A further simplification results when one uses the following identity, which can easily be proved:

$$\exp \left[\frac{v_1 v_2}{(v_1 + v_2)^2} (-2\alpha_1 v_1 v_2 + \alpha_2 v_1 - \alpha_2 v_2) \right] = \exp \left[-\frac{1}{2}(a^2 + b^2) \right]$$

Therefore, it follows that

$$\begin{aligned} P_b = & Q_1(a, b) - I_0(ab) \exp \left[-\frac{1}{2}(a^2 + b^2) \right] \\ & + \frac{I_0(ab) \exp \left[-\frac{1}{2}(a^2 + b^2) \right]}{(1 + v_2/v_1)^{2L-1}} \sum_{k=0}^{L-1} \binom{2L-1}{k} \left(\frac{v_2}{v_1}\right)^k + \frac{\exp \left[-\frac{1}{2}(a^2 + b^2) \right]}{(1 + v_2/v_1)^{2L-1}} \\ & \times \sum_{n=1}^{L-1} I_n(ab) \sum_{k=0}^{L-1-n} \binom{2L-1}{k} \\ & \times \left[\left(\frac{b}{a}\right)^n \left(\frac{v_2}{v_1}\right)^k - \left(\frac{a}{b}\right)^n \left(\frac{v_2}{v_1}\right)^{2L-1-k} \right] \quad (L > 1) \\ P_b = & Q_1(a, b) - \frac{v_2/v_1}{1 + v_2/v_1} I_0(ab) \exp \left[-\frac{1}{2}(a^2 + b^2) \right] \quad (L = 1) \end{aligned} \quad (\text{B-21})$$

This is the desired expression for the probability of error. It is now a simple matter to relate the parameters a and b to the moments of the pairs $\{X_k, Y_k\}$. Substituting for A_2 and A_3 from (B-10) into (B-15), we obtain

$$\begin{aligned} a = & \left[\frac{2v_1^2 v_2 (\alpha_1 v_2 - \alpha_2)}{(v_1 + v_2)^2} \right]^{1/2} \\ b = & \left[\frac{2v_1 v_2^2 (\alpha_1 v_1 + \alpha_2)}{(v_1 + v_2)^2} \right]^{1/2} \end{aligned} \quad (\text{B-22})$$

Since v_1 , v_2 , α_1 , and α_2 have been given in (B-6) and (B-8) directly in terms of the moments of the pairs X_k and Y_k , our task is completed.

ERROR PROBABILITIES FOR ADAPTIVE RECEPTION OF M -PHASE SIGNALS

In this appendix, we derive probabilities of error for two- and four-phase signaling over an L -diversity-branch time-invariant additive gaussian noise channel and for M -phase signaling over an L -diversity-branch Rayleigh fading additive gaussian noise channel. Both channels corrupt the signaling waveforms transmitted through them by introducing additive white gaussian noise and an unknown or random multiplicative gain and phase shift in the transmitted signal. The receiver processing consists of cross-correlating the signal plus noise received over each diversity branch by a noisy reference signal, which is derived either from the previously received information-bearing signals or from the transmission and reception of a pilot signal, and adding the outputs from all L -diversity branches to form the decision variable.

C-1 MATHEMATICAL MODEL FOR AN M -PHASE SIGNALING COMMUNICATIONS SYSTEM

In the general case of M -phase signaling, the signaling waveforms at the transmitter are†

$$s_n(t) = \text{Re} \{ s_m(t) e^{j2\pi f_c t} \}$$

† The complex representation of real signals is used throughout. Complex conjugation is denoted by an asterisk.

where

$$s_m(t) = g(t) \exp \left[j \frac{2\pi}{M} (n-1) \right], \quad n = 1, 2, \dots, M, \quad 0 \leq t \leq T \quad (\text{C-1})$$

and T is the time duration of the signaling interval.

Consider the case in which one of these M waveforms is transmitted, for the duration of the signaling interval, over L channels. Assume that each of the channels corrupts the signaling waveform transmitted through it by introducing a multiplicative gain and phase shift, represented by the complex-valued number g_k , and an additive noise $z_k(t)$. Thus, when the transmitted waveform is $s_m(t)$, the waveform received over the k th channel is

$$r_{ik}(t) = g_k s_m(t) + z_k(t), \quad 0 \leq t \leq T, \quad k = 1, 2, \dots, L \quad (\text{C-2})$$

The noises $\{z_k(t)\}$ are assumed to be sample functions of a stationary white gaussian random process with zero mean and autocorrelation function $\phi_z(\tau) = N_0 \delta(\tau)$, where N_0 is the value of the spectral density. These sample functions are assumed to be mutually statistically independent.

At the demodulator, $r_{ik}(t)$ is passed through a filter whose impulse response is matched to the waveform $g(t)$. The output of this filter, sampled at time $t = T$, is denoted as

$$X_k = 2\mathcal{E} g_k \exp \left[j \frac{2\pi}{M} (n-1) \right] + N_k \quad (\text{C-3})$$

where \mathcal{E} is the transmitted signal energy per channel and N_k is the noise sample from the k th filter. In order for the demodulator to decide which of the M phases was transmitted in the signaling interval $0 \leq t \leq T$, it attempts to undo the phase shift introduced by each channel. In practice, this is accomplished by multiplying the matched filter output X_k by the complex conjugate of an estimate \hat{g}_k of the channel gain and phase shift. The result is a weighted and phase-shifted sampled output from the k th-channel filter, which is then added to the weighted and phase-shifted sampled outputs from the other $L-1$ channel filters.

The estimate \hat{g}_k of the gain and phase shift of the k th channel is assumed to be derived either from the transmission of a pilot signal or by undoing the modulation on the information-bearing signals received in previous signaling intervals. As an example of the former, suppose that a pilot signal, denoted by $s_{pk}(t)$, $0 \leq t \leq T$, is transmitted over the k th channel for the purpose of measuring the channel gain and phase shift. The received waveform is

$$g_k s_{pk}(t) + z_{pk}(t), \quad 0 \leq t \leq T$$

where $z_{pk}(t)$ is a sample function of a stationary white gaussian random process with zero mean and autocorrelation function $\phi_p(\tau) = N_0 \delta(\tau)$. This signal plus noise is passed through a filter matched to $s_{pk}(t)$. The filter output is sampled at time $t = T$ to yield the random variable $X_{pk} = 2\mathcal{E}_p g_k + N_{pk}$, where \mathcal{E}_p is the energy in the pilot signal, which is assumed to be identical for all channels, and N_{pk} is the additive noise sample. An estimate of g_k is obtained by properly normalizing X_{pk} , i.e., $\hat{g}_k = X_{pk} / 2\mathcal{E}_p$.

On the other hand, an estimate of g_k can be obtained from the information-bearing signal as follows. If one knew the information component contained in the matched filter output then an estimate of g_k could be obtained by properly normalizing this

output. For example, the information component in the filter output given by (C-3) is $2\mathcal{E}g_k \exp[j(2\pi/M)(n-1)]$, and hence, the estimate is

$$\hat{g}_k = \frac{X_k}{2\mathcal{E}} \exp\left[-j\frac{2\pi}{M}(n-1)\right] = g_k + \frac{N'_k}{2\mathcal{E}}$$

where $N'_k = N_k \exp[-j(2\pi/M)(n-1)]$ and the pdf of N'_k is identical to the pdf of N_k . An estimate that is obtained from the information-bearing signal in this manner is called a *clairvoyant estimate*. Although a physically realizable receiver does not possess such clairvoyance, it can approximate this estimate by employing a time delay of one signaling interval and by feeding back the estimate of the transmitted phase in the previous signaling interval.

Whether the estimate of g_k is obtained from a pilot signal or from the information-bearing signal, the estimate can be improved by extending the time interval over which it is formed to include several prior signaling intervals in a way that has been described by Price (1962a, b). As a result of extending the measurement interval, the signal-to-noise ratio in the estimate of g_k is increased. In the general case where the estimation interval is the infinite past, the normalized *pilot signal estimate* is

$$\hat{g}_k = g_k + \sum_{i=1}^{\infty} c_i N_{pki} / 2\mathcal{E}_p \sum_{i=1}^{\infty} c_i \quad (\text{C-4})$$

where c_i is the weighting coefficient on the subestimate of g_k derived from the i th prior signal interval and N_{pki} is the sample of additive gaussian noise at the output of the filter matched to $s_{pk}(t)$ in the i th prior signaling interval. Similarly, the clairvoyant estimate that is obtained from the information-bearing signal by undoing the modulation over the infinite past is

$$\hat{g}_k = g_k + \sum_{i=1}^{\infty} c_i N_{ki} / 2\mathcal{E} \sum_{i=1}^{\infty} c_i \quad (\text{C-5})$$

As indicated, the demodulator forms the product between \hat{g}_k^* and X_k and adds this to the products of the other $L-1$ channels. The random variable that results is

$$\begin{aligned} z &= \sum_{k=1}^L X_k \hat{g}_k^* = \sum_{k=1}^L X_k Y_k^* \\ &= z_r + jz_i \end{aligned} \quad (\text{C-6})$$

where, by definition, $Y_k = \hat{g}_k$, $z_r = \text{Re}(z)$, and $z_i = \text{Im}(z)$. The phase of z is the decision variable. This is simply

$$\theta = \tan^{-1}\left(\frac{z_i}{z_r}\right) = \tan^{-1}\left[\frac{\text{Im}\left(\sum_{k=1}^L X_k Y_k^*\right)}{\text{Re}\left(\sum_{k=1}^L X_k Y_k^*\right)}\right] \quad (\text{C-7})$$

C-2 CHARACTERISTIC FUNCTION AND PROBABILITY DENSITY FUNCTION OF THE PHASE θ

The following derivation is based on the assumption that the transmitted signal phase is zero, i.e., $n=1$. If desired, the pdf of θ conditional on any other transmitted signal phase can be obtained by translating $p(\theta)$ by the angle $2\pi(n-1)/M$. We also assume

that the complex-valued numbers $\{g_k\}$, which characterize the L channels, are mutually statistically independent and identically distributed zero-mean gaussian random variables. This characterization is appropriate for slowly Rayleigh fading channels. As a consequence, the random variables (X_k, Y_k) are correlated, complex-valued, zero-mean, gaussian, and statistically independent, but identically distributed with any other pair (X_i, Y_i) .

The method that has been used in evaluating the probability density $p(\theta)$ in the general case of diversity reception is as follows. First, the characteristic function of the joint probability distribution function of z_r and z_i , where z_r and z_i are two components that make up the decision variable θ , is obtained. Second, the double Fourier transform of the characteristic function is performed and yields the density $p(z_r, z_i)$. Then the transformation

$$r = \sqrt{z_r^2 + z_i^2}, \quad \theta = \tan^{-1} \left(\frac{z_i}{z_r} \right) \quad (\text{C-8})$$

yields the joint pdf of the envelope r and the phase θ . Finally, integration of this joint pdf over the random variable r yields the pdf of θ .

The joint characteristic function of the random variables z_r and z_i can be expressed in the form

$$\psi(jv_1, jv_2) = \left[\frac{\frac{4}{m_{xx}m_{yy}(1-|\mu|^2)}}{\left(v_1 - j \frac{2|\mu| \cos \epsilon}{\sqrt{m_{xx}m_{yy}(1-|\mu|^2)}} \right)^2} + \left(v_2 - j \frac{2|\mu| \sin \epsilon}{\sqrt{m_{xx}m_{yy}(1-|\mu|^2)}} \right)^2 + \frac{4}{m_{xx}m_{yy}(1-|\mu|^2)^2} \right]^L \quad (\text{C-9})$$

where, by definition,

$$\begin{aligned} m_{xx} &= E(|X_k|^2) && \text{identical for all } k \\ m_{yy} &= E(|Y_k|^2) && \text{identical for all } k \\ m_{xy} &= E(X_k Y_k^*) && \text{identical for all } k \end{aligned} \quad (\text{C-10})$$

$$\mu = \frac{m_{xy}}{\sqrt{m_{xx}m_{yy}}} = |\mu| e^{j\epsilon}$$

The result of Fourier-transforming the function $\psi(jv_1, jv_2)$ with respect to the variables v_1 and v_2 is

$$\begin{aligned} p(z_r, z_i) &= \frac{(1-|\mu|^2)^L}{(L-1)! \pi 2^L} (\sqrt{z_r^2 + z_i^2})^{L-1} \\ &\times \exp [|\mu| (z_r \cos \epsilon + z_i \sin \epsilon)] K_{L-1}(\sqrt{z_r^2 + z_i^2}) \end{aligned} \quad (\text{C-11})$$

where $K_n(x)$ is the modified Hankel function of order n . Then the transformation of random variables, as indicated in (C-8) yields the joint pdf of the envelope r and the phase θ in the form

$$p(r, \theta) = \frac{(1-|\mu|^2)^L}{(L-1)! \pi 2^L} r^L \exp [|\mu| r \cos(\theta - \epsilon)] K_{L-1}(r) \quad (\text{C-12})$$

Now, integration over the variable r yields the marginal pdf of the phase θ . We have evaluated the integral to obtain $p(\theta)$ in the form

$$p(\theta) = \frac{(-1)^{L-1}(1-|\mu|^2)^L}{2\pi(L-1)!} \left\{ \frac{\partial^{L-1}}{\partial b^{L-1}} \left[\frac{1}{b-|\mu|^2 \cos^2(\theta-\varepsilon)} + \frac{|\mu| \cos(\theta-\varepsilon)}{[b-|\mu|^2 \cos^2(\theta-\varepsilon)]^{3/2}} \cot^{-1} \left(-\frac{|\mu| \cos(\theta-\varepsilon)}{b^{1/2}} \right) \right] \right\} \Big|_{b=1} \quad (\text{C-13})$$

In this equation, the notation

$$\frac{\partial^L}{\partial b^L} f(b, \mu) \Big|_{b=1}$$

denotes the L th partial derivative of the function $f(b, \mu)$ evaluated at $b = 1$.

C-3 ERROR PROBABILITIES FOR SLOWLY RAYLEIGH FADING CHANNELS

In this section, the probability of a character error and the probability of a binary digit error are derived for M -phase signaling. The probabilities are evaluated via the probability density function and the probability distribution function of θ .

The Probability Distribution Function of the Phase In order to evaluate the probability of error, we need to evaluate the definite integral

$$P(\theta_1 \leq \theta \leq \theta_2) = \int_{\theta_1}^{\theta_2} p(\theta) d\theta$$

where θ_1 and θ_2 are limits of integration and $p(\theta)$ is given by (C-13). All subsequent calculations are made for a real cross-correlation coefficient μ . A real-valued μ implies that the signals have symmetric spectra. This is the usual situation encountered. Since a complex-valued μ causes a shift of ε in the pdf of θ , i.e., ε is simply a bias term, the results that are given for real μ can be altered in a trivial way to cover the more general case of complex-valued μ .

In the integration of $p(\theta)$, only the range $0 \leq \theta \leq \pi$ is considered, because $p(\theta)$ is an even function. Furthermore, the continuity of the integrand and its derivatives and the fact that the limits θ_1 and θ_2 are independent of b allow for the interchange of integration and differentiation. When this is done, the resulting integral can be evaluated quite readily and can be expressed as follows:

$$\begin{aligned} \int_{\theta_1}^{\theta_2} p(\theta) d\theta &= \frac{(-1)^{L-1}(1-\mu^2)^L}{2\pi(L-1)!} \\ &\times \frac{\partial^{L-1}}{\partial b^{L-1}} \left\{ \frac{1}{b-\mu^2} \left[\frac{\mu \sqrt{1-(b/\mu^2-1)x^2}}{b^{1/2}} \cot^{-1} x \right. \right. \\ &\left. \left. - \cot^{-1} \left(\frac{xb^{1/2}\mu}{\sqrt{1-(b/\mu^2-1)x^2}} \right) \right] \right\} \Big|_{x_1}^{x_2} \end{aligned} \quad (\text{C-14})$$

where, by definition,

$$x_i = \frac{-\mu \cos \theta_i}{\sqrt{b-\mu^2 \cos \theta_i}}, \quad i = 1, 2 \quad (\text{C-15})$$

Probability of a Symbol Error The probability of a symbol error for any M -phase signaling system is

$$P_M = 2 \int_{\pi/M}^{\pi} p(\theta) d\theta$$

When (C-14) is evaluated at these two limits, the result is

$$P_M = \frac{(-1)^{L-1}(1-\mu^2)^L}{\pi(L-1)!} \frac{\partial^{L-1}}{\partial b^{L-1}} \left\{ \frac{1}{b-\mu^2} \left[\frac{\pi}{M}(M-1) - \frac{\mu \sin(\pi/M)}{\sqrt{b-\mu^2 \cos^2(\pi/M)}} \cot^{-1} \left(\frac{-\mu \cos(\pi/M)}{\sqrt{b-\mu^2 \cos^2(\pi/M)}} \right) \right] \right\} \Big|_{b=1} \quad (C-16)$$

Probability of a Binary Digit Error First, let us consider two-phase signaling. In this case, the probability of a binary digit error is obtained by integrating the pdf $p(\theta)$ over the range $\frac{1}{2}\pi < \theta < 3\pi$. Since $p(\theta)$ is an even function and the signals are a priori equally likely, this probability can be written as

$$P_2 = 2 \int_{\pi/2}^{\pi} p(\theta) d\theta$$

It is easily verified that $\theta_1 = \frac{1}{2}\pi$ implies $x_1 = 0$ and $\theta_2 = \pi$ implies $x_2 = \mu/\sqrt{b-\mu^2}$. Thus,

$$P_2 = \frac{(-1)^{L-1}(1-\mu^2)^L}{2(L-1)!} \frac{\partial^{L-1}}{\partial b^{L-1}} \left[\frac{1}{b-\mu^2} - \frac{\mu}{b^{1/2}(b-\mu^2)} \right] \Big|_{b=1} \quad (C-17)$$

After performing the differentiation indicated in (C-17) and evaluating the resulting function at $b = 1$, the probability of a binary digit error is obtained in the form

$$P_2 = \frac{1}{2} \left[1 - \mu \sum_{k=0}^{L-1} \binom{2k}{k} \left(\frac{1-\mu^2}{4} \right)^k \right] \quad (C-18)$$

Next, we consider the case of four-phase signaling in which a Gray code is used to map pairs of bits into phases. Assuming again that the transmitted signal is $s_{it}(t)$, it is clear that a single error is committed when the received phase is $\frac{1}{4}\pi < \theta < \frac{3}{4}\pi$, and a double error is committed when the received phase is $\frac{3}{4}\pi < \theta < \pi$. That is, the probability of a binary digit error is

$$P_{4b} = \int_{\pi/4}^{3\pi/4} p(\theta) d\theta + 2 \int_{3\pi/4}^{\pi} p(\theta) d\theta \quad (C-19)$$

It is easily established from (C-14) and (C-19) that

$$P_{4b} = \frac{(-1)^{L-1}(1-\mu^2)^L}{2(L-1)!} \frac{\partial^{L-1}}{\partial b^{L-1}} \left[\frac{1}{b-\mu^2} - \frac{\mu}{(b-\mu^2)(2b-\mu^2)^{1/2}} \right] \Big|_{b=1}$$

Hence, the probability of a binary digit error for four-phase signaling is

$$P_{4b} = \frac{1}{2} \left[1 - \frac{\mu}{\sqrt{2-\mu^2}} \sum_{k=0}^{L-1} \binom{2k}{k} \left(\frac{1+\mu^2}{4-2\mu^2} \right)^k \right] \quad (C-20)$$

Note that if one defines the quantity $\rho = \mu/\sqrt{2-\mu^2}$, the expression for P_{4b} in terms of ρ is

$$P_{4b} = \frac{1}{2} \left[1 - \rho \sum_{k=0}^{L-1} \binom{2k}{k} \left(\frac{1-\rho^2}{4} \right)^k \right] \quad (C-21)$$

In other words, P_{ab} has the same form as P_2 given in (C-18). Furthermore, note that ρ , just like μ , can be interpreted as a cross-correlation coefficient, since the range of ρ is $0 \leq \rho \leq 1$ for $0 \leq \mu \leq 1$. This simple fact will be used in Section C-4.

The above procedure for obtaining the bit error probability for an M -phase signal with a Gray code can be used to generate results for $M = 8, 16$, etc., as shown by Proakis (1968).

Evaluation of the Cross-Correlation Coefficient The expressions for the probabilities of error given above depend on a single parameter, namely, the cross-correlation coefficient μ . The clairvoyant estimate is given by (C-5), and the matched filter output, when signal waveform $s_1(t)$ is transmitted, is $X_k = 2\mathcal{E}g_k + N_k$. Hence, the cross-correlation coefficient is

$$\mu = \frac{\sqrt{v}}{\sqrt{(\bar{\gamma}_c^{-1} + 1)(\bar{\gamma}_c^{-1} + v)}} \quad (\text{C-22})$$

where, by definition,

$$v = \frac{\left| \sum_{i=1}^{\infty} c_i \right|^2}{\sum_{i=1}^{\infty} |c_i|^2} \quad (\text{C-23})$$

$$\bar{\gamma}_c = \frac{\mathcal{E}}{N_0} E(|g_k|^2), \quad k = 1, 2, \dots, L$$

The parameter v represents the effective number of signaling intervals over which the estimate is formed, and $\bar{\gamma}_c$ is the average SNR per channel.

In the case of differential phase signaling, the weighing coefficients are $c_1 = 1$, $c_i = 0$ for $i \neq 1$. Hence, $v = 1$ and $\mu = \bar{\gamma}_c / (1 + \bar{\gamma}_c)$.

When $v = \infty$, the estimate is perfect and

$$\lim_{v \rightarrow \infty} \mu = \sqrt{\frac{\bar{\gamma}_c}{\bar{\gamma}_c + 1}}$$

Finally, in the case of a pilot signal estimate, given by (C-4) the cross-correlation coefficient is

$$\mu = \left[\left(1 + \frac{r+1}{r\bar{\gamma}_i} \right) \left(1 + \frac{r+1}{v\bar{\gamma}_i} \right) \right]^{-1/2} \quad (\text{C-24})$$

where, by definition,

$$\bar{\gamma}_i = \frac{\mathcal{E}_i}{N_0} E(|g_k|^2)$$

$$\mathcal{E}_i = \mathcal{E} + \mathcal{E}_p$$

$$r = \mathcal{E}/\mathcal{E}_p$$

The values of μ given above are summarized in Table C-1.

C-4 ERROR PROBABILITIES FOR TIME-INVARIANT AND RICEAN FADING CHANNELS

In Section C-2, the complex-valued channel gains $\{g_k\}$ were characterized as zero-mean gaussian random variables, which is appropriate for Rayleigh fading channels. In this section, the channel gains $\{g_k\}$ are assumed to be nonzero-mean gaussian random variables. Estimates of the channel gains are formed by the demodulator and are used

TABLE C-1 RAYLEIGH FADING CHANNEL

| Type of estimate | Cross-correlation coefficient μ |
|------------------------------|--|
| Clairvoyant estimate | $\frac{\sqrt{v}}{\sqrt{(\bar{\gamma}_c^{-1} + 1)(\bar{\gamma}_c^{-1} + v)}}$ |
| Pilot signal estimate | $\frac{\sqrt{rv}}{(r+1)\sqrt{\left(\frac{1}{\bar{\gamma}_t} + \frac{r}{r+1}\right)\left(\frac{1}{\bar{\gamma}_t} + \frac{v}{r+1}\right)}}$ |
| Differential phase signaling | $\frac{\bar{\gamma}_c}{\bar{\gamma}_c + 1}$ |
| Perfect estimate | $\sqrt{\frac{\bar{\gamma}_c}{\bar{\gamma}_c + 1}}$ |

as described in Section C-1. Moreover, the decision variable θ is defined again by (C-7). However, in this case, the gaussian random variables X_k and Y_k , which denote the matched filter output and the estimate, respectively, for the k th channel, have nonzero means, which are denoted by \bar{X}_k and \bar{Y}_k . Furthermore, the second moments are

$$\begin{aligned} m_{xx} &= E(|X_k - \bar{X}_k|^2) && \text{identical for all channels} \\ m_{yy} &= E(|Y_k - \bar{Y}_k|^2) && \text{identical for all channels} \\ m_{xy} &= E[(X_k - \bar{X}_k)(Y_k^* - \bar{Y}_k^*)] && \text{identical for all channels} \end{aligned}$$

and the normalized covariance is defined as

$$\mu = \frac{m_{xy}}{\sqrt{m_{xx}m_{yy}}}$$

Error probabilities are given below only for two- and four-phase signaling with this channel model. We are interested in the special case in which the fluctuating component of each of the channel gains $\{g_k\}$ is zero, so that the channels are time-invariant. If, in addition to this time invariance, the noises between the estimate and the matched filter output are uncorrelated then $\mu = 0$.

In the general case, the probability of error for two-phase signaling over L statistically independent channels characterized in the manner described above can be obtained from the results in Appendix B. In its most general form, the expression for the binary error rate is

$$\begin{aligned} P_2 &= Q_1(a, b) - I_0(a) \exp[-\tfrac{1}{2}(a^2 + b^2)] \\ &\quad + \frac{I_0(ab) \exp[-\tfrac{1}{2}(a^2 + b^2)]}{[2/(1-\mu)]^{2L-1}} \sum_{k=0}^{L-1} \binom{2L-1}{k} \left(\frac{1+\mu}{1-\mu}\right)^k \\ &\quad + \frac{\exp[-\tfrac{1}{2}(a^2 + b^2)]}{[2/(1-\mu)]^{2L-1}} \\ &\quad \times \sum_{k=1}^{L-1} I_n(ab) \sum_{n=0}^{L-1-k} \binom{2L-1}{k} \left[\left(\frac{b}{a}\right)^n \left(\frac{1+\mu}{1-\mu}\right)^k - \left(\frac{a}{b}\right)^n \left(\frac{1+\mu}{1-\mu}\right)^{2L-1-k} \right] \quad (L \geq 2) \\ P_2 &= Q_1(a, b) - \tfrac{1}{2}(1+\mu)I_0(ab) \exp[-\tfrac{1}{2}(a^2 + b^2)] \quad (L = 1) \end{aligned} \tag{C-25}$$

where, by definition,

$$\begin{aligned} a &= \left(\frac{1}{2} \sum_{k=1}^L \left| \frac{\bar{X}_k}{\sqrt{m_{xx}}} - \frac{\bar{Y}_k}{\sqrt{m_{yy}}} \right|^2 \right)^{1/2} \\ b &= \left(\frac{1}{2} \sum_{k=1}^L \left| \frac{\bar{X}_k}{\sqrt{m_{xx}}} + \frac{\bar{Y}_k}{\sqrt{m_{yy}}} \right|^2 \right)^{1/2} \\ Q_1(a, b) &= \int_0^\infty x \exp[-\frac{1}{2}(a^2 + x^2)] I_0(ax) dx \end{aligned} \quad (C-26)$$

$I_n(x)$ is the modified Bessel function of the first kind and of order n .

Let us evaluate the constants a and b when the channel is time-invariant, $\mu = 0$, and the channel gain and phase estimates are those given in Section C-1. Recall that when signal $s_1(t)$ is transmitted, the matched filter output is $X_k = 2\mathcal{E}g_k + N_k$. The clairvoyant estimate is given by (C-5). Hence, for this estimate, the moments are $\bar{X}_k = 2\mathcal{E}g_k$, $\bar{Y}_k = g_k$, $m_{xx} = 4\mathcal{E}N_0$, and $m_{yy} = N_0/\mathcal{E}v$, where \mathcal{E} is the signal energy, N_0 is the value of the noise spectral density, and v is defined in (C-23). Substitution of these moments into (C-26) results in the following expressions for a and b :

$$\begin{aligned} a &= \sqrt{\frac{1}{2}\gamma_b} |\sqrt{v} - 1| \\ b &= \sqrt{\frac{1}{2}\gamma_b} |\sqrt{v} + 1| \\ \gamma_b &= \frac{\mathcal{E}}{N_0} \sum_{k=1}^L |g_k|^2 \end{aligned} \quad (C-27)$$

This is a result originally derived by Price (1962).

The probability of error for differential phase signaling can be obtained by setting $v = 1$ in (C-27).

Next, consider a pilot signal estimate. In this case, the estimate is given by (C-4) and the matched filter output is again $X_k = 2\mathcal{E}g_k + N_k$. When the moments are calculated and these are substituted into (C-26), the following expressions for a and b are obtained:

$$\begin{aligned} a &= \sqrt{\frac{\gamma_t}{2}} \left| \sqrt{\frac{v}{r+1}} - \sqrt{\frac{r}{r+1}} \right| \\ b &= \sqrt{\frac{\gamma_t}{2}} \left(\sqrt{\frac{v}{r+1}} + \sqrt{\frac{r}{r+1}} \right) \end{aligned} \quad (C-28)$$

where

$$\begin{aligned} \gamma_t &= \frac{\mathcal{E}_t}{N_0} \sum_{k=1}^L |g_k|^2 \\ \mathcal{E}_t &= \mathcal{E} + \mathcal{E}_p \\ r &= \mathcal{E}/\mathcal{E}_p \end{aligned}$$

Finally, we consider the probability of a binary digit error for four-phase signaling over a time-invariant channel for which the condition $\mu = 0$ obtains. One approach that can be used to derive this error probability is to determine the pdf of θ and then to integrate this over the appropriate range of values of θ . Unfortunately, this approach proves to be intractable mathematically. Instead, a simpler, albeit roundabout, method may be used that involves the Laplace transform. In short, the integral in (14-4-14) of the text that relates the error probability $P_2(\gamma_b)$ in an AWGN channel to the error

TABLE C-2 TIME-INVARIANT CHANNEL

| Type of estimate | a | b |
|------------------------------|---|---|
| Two-phase signaling | | |
| Clairvoyant estimate | $\sqrt{\frac{1}{2}\gamma_b}(\sqrt{v}-1)$ | $\sqrt{\frac{1}{2}\gamma_b}(\sqrt{v}+1)$ |
| Differential phase signaling | 0 | $\sqrt{2\gamma_b}$ |
| Pilot signal estimate | $\sqrt{\frac{\gamma_t}{2}} \left \sqrt{\frac{v}{r+1}} - \sqrt{\frac{r}{r+1}} \right $ | $\sqrt{\frac{\gamma_t}{2}} \left(\sqrt{\frac{v}{r+1}} + \sqrt{\frac{r}{r+1}} \right)$ |
| Four-phase signaling | | |
| Clairvoyant estimate | $\sqrt{\frac{1}{2}\gamma_b} \left \sqrt{v+1+\sqrt{v^2+1}} - \sqrt{v+1-\sqrt{v^2+1}} \right $ | $\sqrt{\frac{1}{2}\gamma_b} \left(\sqrt{v+1+\sqrt{v^2+1}} + \sqrt{v+1-\sqrt{v^2+1}} \right)$ |
| Differential phase signaling | $\sqrt{\frac{1}{2}\gamma_b}(\sqrt{2+\sqrt{2}}-\sqrt{2-\sqrt{2}})$ | $\sqrt{\frac{1}{2}\gamma_b}(\sqrt{2+\sqrt{2}}+\sqrt{2-\sqrt{2}})$ |
| Pilot signal estimate | $\sqrt{\frac{\gamma_t}{4(r+1)}} \left \sqrt{v+r+\sqrt{v^2+r^2}} - \sqrt{v+r-\sqrt{v^2+r^2}} \right $ | $\sqrt{\frac{\gamma_t}{4(r+1)}} \left(\sqrt{v+r+\sqrt{v^2+r^2}} + \sqrt{v+r-\sqrt{v^2+r^2}} \right)$ |

probability P_2 in a Rayleigh fading channel is a Laplace transform. Since the bit error probabilities P_2 and P_{ab} for a Rayleigh fading channel, given by (C-18) and (C-21), respectively, have the same form but differ only in the correlation coefficient, it follows that the bit error probabilities for the time-invariant channel also have the same form. That is, (C-25) with $\mu = 0$ is also the expression for the bit error probability of a four-phase signaling system with the parameters a and b modified to reflect the difference in the correlation coefficient. The detailed derivation may be found in the paper by Proakis (1968). The expressions for a and b are given in Table C-2.

SQUARE-ROOT FACTORIZATION

Consider the solution of the set of linear equations

$$\mathbf{R}_N \mathbf{C}_N = \mathbf{U}_N \quad (\text{D-1})$$

where \mathbf{R}_N is an $N \times N$ positive-definite symmetric matrix, \mathbf{C}_N is an N -dimensional vector of coefficients to be determined, and \mathbf{U}_N is an arbitrary N -dimensional vector. The equations in (D-1) can be solved efficiently by expressing \mathbf{R}_N in the factored form

$$\mathbf{R}_N = \mathbf{S}_N \mathbf{D}_N \mathbf{S}_N' \quad (\text{D-2})$$

where \mathbf{S}_N is a lower triangular matrix with elements $\{s_{ik}\}$ and \mathbf{D}_N is a diagonal matrix with diagonal elements $\{d_k\}$. The diagonal elements of \mathbf{S}_N are set to unity, i.e., $s_{ii} = 1$. Then we have

$$\begin{aligned} r_{ij} &= \sum_{k=1}^j s_{ik} d_k s_{jk}, \quad 1 \leq j \leq i-1, \quad i \geq 2 \\ r_{11} &= d_1 \end{aligned} \quad (\text{D-3})$$

where $\{r_{ij}\}$ are the elements of \mathbf{R}_N . Consequently, the elements $\{s_{ik}\}$ and $\{d_k\}$ are determined from (D-3) according to the equations

$$\begin{aligned} d_1 &= r_{11} \\ s_{ij} d_j &= r_{ij} - \sum_{k=1}^{j-1} s_{ik} d_k s_{jk}, \quad 1 \leq j \leq i-1, \quad 2 \leq i \leq N \\ d_i &= r_{ii} - \sum_{k=1}^{i-1} s_{ik}^2 d_k, \quad 2 \leq i \leq N \end{aligned} \quad (\text{D-4})$$

Thus, (D-4) define \mathbf{S}_N and \mathbf{D}_N in terms of the elements of \mathbf{R}_N .

The solution to (D-1) is performed in two steps. With (D-2) substituted into (D-1) we have

$$\mathbf{S}_N \mathbf{D}_N \mathbf{S}_N' \mathbf{C}_N = \mathbf{U}_N$$

Let

$$\mathbf{Y}_N = \mathbf{D}_N \mathbf{S}_N' \mathbf{C}_N \quad (\text{D-5})$$

Then

$$\mathbf{S}_N \mathbf{Y}_N = \mathbf{U}_N \quad (\text{D-6})$$

First we solve (D-6) for \mathbf{Y}_N . Because of the triangular form of \mathbf{S}_N , we have

$$\begin{aligned} y_1 &= u_1 \\ y_i &= u_i - \sum_{j=1}^{i-1} s_{ij} y_j, \quad 2 \leq i \leq N \end{aligned} \quad (\text{D-7})$$

Having obtained \mathbf{Y}_N , the second step is to compute \mathbf{C}_N . That is,

$$\begin{aligned} \mathbf{D}_N \mathbf{S}_N' \mathbf{C}_N &= \mathbf{Y}_N \\ \mathbf{S}_N' \mathbf{C}_N &= \mathbf{D}_N^{-1} \mathbf{Y}_N \end{aligned}$$

Beginning with

$$c_N = y_N / d_N \quad (\text{D-8})$$

the remaining coefficients of \mathbf{C}_N are obtained recursively as follows:

$$c_i = \frac{y_i}{d_i} - \sum_{j=i+1}^N s_{ij} c_j, \quad 1 \leq i \leq N-1 \quad (\text{D-9})$$

The number of multiplications and divisions required to perform the factorization of \mathbf{R}_N is proportional to N^3 . The number of multiplications and divisions required to compute \mathbf{C}_N , once \mathbf{S}_N is determined, is proportional to N^2 . In contrast, when \mathbf{R}_N is Toeplitz the Levinson–Durbin algorithm should be used to determine the solution of (D-1), since the number of multiplications and divisions is proportional to N^2 . On the other hand, in a recursive least-squares formulation, \mathbf{S}_N and \mathbf{D}_N are not computed as in (D-3), but they are updated recursively. The update is accomplished with N^2 operations (multiplications and divisions). Then the solution for the vector \mathbf{C}_N follows the steps (D-5)–(D-9). Consequently, the computational burden of the recursive least-squares formulation is proportional to N^2 .

REFERENCES AND BIBLIOGRAPHY

- Abend, K. and Fritchman, B. D. (1970). "Statistical Detection for Communication Channels with Intersymbol Interference," *Proc. IEEE*, pp. 779-785, May.
- Abramson, N. (1963). *Information Theory and Coding*, McGraw-Hill, New York.
- Abramson, N. (1970). "The ALOHA System—Another Alternative for Computer Communications," *1970 Fall Joint Comput. Conf., AFIDS Conf. Proc.*, vol. 37, pp. 281-285, AFIPS Press, Montvale, N.J.
- Abramson, N. (1977). "The Throughput of Packet Broadcasting Channels," *IEEE Trans. Commun.*, vol. COM-25, pp. 117-128, January.
- Abramson, N. (1993). *Multiple Access Communications*, IEEE Press, New York.
- Adler, R. L., Coppersmith, D., and Hassner, M. (1983). "Algorithms for Sliding Block Codes," *IEEE Trans. Inform. Theory*, vol. IT-29, pp. 5-22, January.
- Al-Hussaini, E. and Al-Bassiouni (1985). "Performance of MRC Diversity Systems for the Detection of Signals with Nakagami Fading," *IEEE Trans. Commun.*, vol. COM-33, pp. 1315-1319, December.
- Altekar, S. A. and Beaulieu, N. C. (1993). "Upper Bounds on the Error Probability of Decision Feedback Equalization," *IEEE Trans. Inform. Theory*, vol. IT-39, pp. 145-156, January.
- Anderberg, M. R. (1973). *Cluster Analysis for Applications*, Academic, New York.
- Anderson, J. B., Aulin, T., and Sundberg, C. W. (1986). *Digital Phase Modulation*, Plenum, New York.
- Anderson, R. R. and Salz, J. (1965). "Spectra of Digital FM," *Bell Syst. Tech. J.*, vol. 44 pp. 1165-1189, July-August.
- Ash, R. B. (1965). *Information Theory*, Interscience, New York.
- Aulin, T. (1980). "Viterbi Detection of Continuous Phase Modulated Signals," *Nat. Telecommun. Conf. Record*, pp. 14.2.1-14.2.7, Houston, Texas, November.
- Aulin, T., Rydbeck, N., and Sundberg, C. W. (1981). "Continuous Phase Modulation—Part II: Partial Response Signaling," *IEEE Trans. Commun.*, vol. COM-29, pp. 210-225, March.
- Aulin, T. and Sundberg, C. W. (1981). "Continuous Phase Modulation—Part I: Full Response Signaling," *IEEE Trans. Commun.*, vol. COM-29, pp. 196-209, March.
- Aulin, T. and Sundberg, C. W. (1982a). "On the Minimum Euclidean Distance for a Class of Signal Space Codes," *IEEE Trans. Inform. Theory*, vol. IT-28, pp. 43-55, January.

- Aulin, T. and Sundberg, C. W. (1982b). "Minimum Euclidean Distance and Power Spectrum for a Class of Smoothed Phase Modulation Codes with Constant Envelope," *IEEE Trans. Commun.*, vol. COM-30, pp. 1721-1729, July.
- Aulin, T. and Sundberg, C. W. (1984). "CPM—An Efficient Constant Amplitude Modulation Scheme," *Int. J. Satellite Commun.*, vol. 2, pp. 161-186.
- Austin, M. E. (1967). "Decision-Feedback Equalization for Digital Communication Over Dispersive Channels," MIT Lincoln Laboratory, Lexington, Mass., Tech. Report No. 437, August.
- Barrow, B. (1963). "Diversity Combining of Fading Signals with Unequal Mean Strengths," *IEEE Trans. Commun., Syst.*, vol. CS-11, pp. 73-78, March.
- Beaulieu, N. C. (1990). "An Infinite Series for the Computation of the Complementary Probability Distribution Function of a Sum of Independent Random Variables and Its Application to the Sum of Rayleigh Random Variables," *IEEE Trans. Commun.*, vol. COM-38, pp. 1463-1474, September.
- Beaulieu, N. C. and Abu-Dayya, A. A. (1991). "Analysis of Equal Gain Diversity on Nakagami Fading Channels," *IEEE Trans. Commun.*, vol. COM-39, pp. 225-234, February.
- Bekir, N. E., Scholtz, R. A., and Welch, L. R. (1978). "Partial-Period Correlation Properties of PN Sequences," 1978 *Nat. Telecommun. Conf. Record*, pp. 35.1.1-25.1.4, Birmingham, Alabama, November.
- Belfiore, C. A. and Park, J. H., Jr. (1979). "Decision-Feedback Equalization," *Proc. IEEE*, vol. 67, pp. 1143-1156, August.
- Bellini, J. (1986). "Busgang Techniques for Blind Equalization," *Proc. GLOBECOM'86*, pp. 46.1.1-46.1.7, Houston, Texas, December.
- Bello, P. A. and Nelin, B. D. (1962a). "Predetection Diversity Combining with Selectivity Fading Channels," *IRE Trans. Commun. Syst.*, vol. CS-10, pp. 32-42, March.
- Bello, P. A. and Nelin, B. D. (1962b). "The Influence of Fading Spectrum on the Binary Error Probabilities of Incoherent and Differentially Coherent Matched Filter Receivers," *IRE Trans. Commun. Syst.*, vol. CS-10, pp. 160-168, June.
- Bello, P. A. and Nelin, B. D. (1963). "The Effect of Frequency Selective Fading on the Binary Error Probabilities of Incoherent and Differentially Coherent Matched Filter Receivers," *IEEE Trans. Commun. Syst.*, vol. CS-11, pp. 170-186, June.
- Bennett, W. R. and Davey, J. R. (1965). *Data Transmission*, McGraw-Hill, New York.
- Bennett, W. R. and Rice, S. O. (1963). "Spectral Density and Autocorrelation Functions Associated with Binary Frequency-Shift Keying," *Bell Syst. Tech. J.*, vol. 42, pp. 2355-2385, September.
- Benveniste, A. and Goursat, M. (1984). "Blind Equalizers," *IEEE Trans. Commun.*, vol. COM-32, pp. 871-883, August.
- Berger, T. (1971). *Rate Distortion Theory*, Prentice-Hall, Englewood Cliffs, N.J.
- Berger, T. and Tufts, D. W. (1967). "Optimum Pulse Amplitude Modulation, Part I: Transmitter-Receiver Design and Bounds from Information Theory," *IEEE Trans. Inform. Theory*, vol. IT-13, pp. 196-208.
- Bergmans, P. P. and Cover, T. M. (1974). "Cooperative Broadcasting," *IEEE Trans. Inform. Theory*, vol. IT-20, pp. 317-324, May.
- Berlekamp, E. R. (1968). *Algebraic Coding Theory*, McGraw-Hill, New York.
- Berlekamp, E. R. (1973). "Goppa Codes," *IEEE Trans. Inform. Theory*, vol. IT-19, pp. 590-592.
- Berlekamp, E. R. (1974). *Key Papers in the Development of Coding Theory*, IEEE Press, New York.
- Bierman, G. J. (1977). *Factorization Methods for Discrete Sequential Estimation*, Academic, New York.
- Biglieri, E., Divsalar, D., McLane, P. J., and Simon, M. K. (1991). *Introduction to Trellis-Coded Modulation with Applications*, Macmillan, New York.
- Bingham, J. A. C. (1990). "Multicarrier Modulation for Data Transmission: An Idea Whose Time Has Come," *IEEE Commun. Mag.*, vol. 28, pp. 5-14, May.

- Blahut, R. E. (1983). *Theory and Practice of Error Control Codes*, Addison-Wesley, Reading, Mass.
- Blahut, R. E. (1987). *Principles and Practice of Information Theory*, Addison-Wesley, Reading, Mass.
- Bose, R. C. and Ray-Chaudhuri, D. K. (1960a). "On a Class of Error Correcting Binary Group Codes," *Inform. Control*, vol. 3, pp. 68-79, March.
- Bose, R. C. and Ray-Chaudhuri, D. K. (1960b). "Further Results in Error Correcting Binary Group Codes," *Inform. Control*, vol. 3, pp. 279-290, September.
- Brennan, D. G. (1959). "Linear Diversity Combining Techniques," *Proc. IRE.*, vol. 47, pp. 1075-1102.
- Busgang, J. J. (1952). "Crosscorrelation Functions of Amplitude-Distorted Gaussian Signals," MIT RLE Tech. Report 216.
- Bucher, E. A. (1980). "Coding Options for Efficient Communications on Non-Stationary Channels," *Rec. IEEE Int. Conf. Commun.*, pp. 4.1.1-4.1.7.
- Burton, H. O. (1969). "A Class of Asymptotically Optimal Burst Correcting Block Codes," *Proc. ICC.* Boulder, Col., June.
- Buzo, A., Gray, A. H., Jr., Gray, R. M., and Markel, J. D. (1980). "Speech Coding Based Upon Vector Quantization," *IEEE Trans. Acoust., Speech, Signal Processing*, Vol. ASSP-28 pp. 562-574, October.
- Cahn, C. R. (1960). "Combined Digital Phase and Amplitude Modulation Communication Systems," *IRE Trans. Commun. Syst.*, vol. CS-8, pp. 150-155, September.
- Calderbank, A. R. and Sloane, N. J. A. (1987). "New Trellis Codes Based on Lattices and Cosets," *IEEE Trans. Inform. Theory*, vol. IT-33, pp. 177-195, March.
- Campanella, S. J. and Robinson, G. S. (1971). "A Comparison of Orthogonal Transformations for Digital Speech Processing," *IEEE Trans. Commun.*, vol. COM-19, pp. 1045-1049, December.
- Campopiano, C. N. and Glazer, B. G. (1962). "A Coherent Digital Amplitude and Phase Modulation Scheme," *IRE Trans. Commun. Syst.*, vol. CS-10, pp. 90-95, June.
- Capetanakis, J. I. (1979). "Tree Algorithms for Packet Broadcast Channels," *IEEE Trans. Inform. Theory*, vol. IT-25, pp. 505-515, September.
- Caraiscos, C. and Liu, B. (1984). "A Roundoff Error Analysis of the LMS Adaptive Algorithm," *IEEE Trans. Acoust., Speech, Signal Processing*, Vol. ASSP-32, pp. 34-41, January.
- Carayannis, G., Manolakis, D. G., and Kalouptsidis, N. (1983). "A Fast Sequential Algorithm for Least-Squares Filtering and Prediction," *IEEE Trans. Acoust., Speech, Signal Processing*, Vol. ASSP-31, pp. 1394-1402, December.
- Carayannis, G., Manolakis, D. G., and Kalouptsidis, N. (1986). "A Unified View of Parametric Processing Algorithms for Prewindowed Signals," *Signal Processing*, vol. 10, pp. 335-368, June.
- Carleial, A. B. and Hellman, M. E. (1975). "Bistable Behavior of ALOHA-Type Systems," *IEEE Trans. Commun.*, vol. COM-23, pp. 401-410, April 1975.
- Carlson, A. B. (1975). *Communication Systems*, McGraw-Hill, New York.
- Chang, D. Y., Gersho, A., Ramamurthi, B., and Shohan, Y. (1984). "Fast Search Algorithms for Vector Quantization and Pattern Matching," *Proc. IEEE Int. Conf. Acoust., Speech, Signal Processing*, paper 9.11, San Diego, Calif., March.
- Chang, R. W. (1966). "Synthesis of Band-Limited Orthogonal Signals for Multichannel Data Transmission," *Bell Syst. Tech. J.*, vol. 45, pp. 1775-1796, December.
- Charash, U. (1979). "Reception Through Nakagami Fading Multipath Channels with Random Delays," *IEEE Trans. Commun.*, vol. COM-27, pp. 657-670, April.
- Chase, D. (1972). "A Class of Algorithms for Decoding Block Codes With Channel Measurement Information," *IEEE Trans. Inform. Theory*, vol. IT-18, pp. 170-182, January.
- Chase, D. (1976). "Digital Signal Design Concepts for a Time-Varying Ricean Channel," *IEEE Trans. Commun.*, vol. COM-24, pp. 164-172, February.
- Chien, R. T. (1964). "Cyclic Decoding Procedures for BCH Codes," *IEEE Trans. Inform. Theory*, vol. IT-10, pp. 357-363, October.

- Chow, J. S., Tu, J. C., and Cioffi, J. M. (1991). "A Discrete Multitone Transceiver System for HDSL Applications," *IEEE J. Selected Areas Commun.*, vol. SAC-9, pp. 895-908, August.
- Chyi, G. T., Proakis, J. G., and Keller, C. M. (1988). "Diversity Selection/Combining Schemes with Excess Noise-Only Diversity Reception Over a Rayleigh-Fading Multipath Channel." *Proc. Conf. Inform. Sci. Syst.*, Princeton University, Princeton, N.J. March.
- Cioffi, J. M. and Kailath, T. (1984). "Fast Recursive-Least Squares Transversal Filters for Adaptive Filtering," *IEEE Trans. Acoust., Speech, Signal Processing*, vol. ASSP-32, pp. 304-337, April.
- Cook, C. E., Eilersick, F. W., Milstein, L. B., and Schilling, D. L. (1983). *Spread Spectrum Communications*, IEEE Press, New York.
- Costas, J. P. (1956). "Synchronous Communications," *Proc. IRE*, vol. 44, pp. 1713-1718, December.
- Cover, T. M. (1972). "Broadcast Channels," *IEEE Trans. Inform. Theory*, vol. IT-18, pp. 2-14, January.
- Cramér, H. (1946). *Mathematical Methods of Statistics*, Princeton University Press, Princeton, N.J.
- Daut, D. G., Modestino, J. W., and Wismer, L. D. (1982). "New Short Constraint Length Convolutional Code Construction for Selected Rational Rates," *IEEE Trans. Inform. Theory*, vol. IT-28, pp. 793-799, September.
- Davenport, W. B., Jr. (1970). *Probability and Random Processes*, McGraw-Hill, New York.
- Davenport, W. B. Jr. and Root, W. L. (1958). *Random Signals and Noise*, McGraw-Hill, New York.
- Davisson, L. D. (1973). "Universal Noiseless Coding," *IEEE Trans. Inform. Theory*, vol. IT-19, pp. 783-795.
- Davisson, L. D., McEliece, R. J., Pursley, M. B., and Wallace, M. S. (1981). "Efficient Universal Noiseless Source Codes," *IEEE Trans. Inform. Theory*, vol. IT-27, pp. 269-279.
- deBuda, R. (1972). "Coherent Demodulation of Frequency Shift Keying with Low Deviation Ratio," *IEEE Trans. Commun.*, vol. COM-20, pp. 429-435, June.
- Deller, J. P., Proakis, J. G., and Hansen, H. L. (1993). *Discrete-Time Processing of Speech Signals*, MacMillan, New York.
- Ding, Z. (1990). *Application Aspects of Blind Adaptive Equalizers in QAM Data Communications*, Ph.D. Thesis, Department of Electrical Engineering, Cornell University.
- Ding, Z., Kennedy, R. A., Anderson, B. D. O., and Johnson, C. R. (1989). "Existence and Avoidance of Ill-Convergence of Godard Blind Equalizers in Data Communication Systems," *Proc. 23rd Conf. on Inform. Sci. Systems*, Baltimore, Md.
- Divsalar, D., Simon, M. K., and Yuen, J. H. (1987). "Trellis Coding with Asymmetric Modulation," *IEEE Trans. Commun.*, vol. COM-35, pp. 130-141, February.
- Divsalar, D. and Yuen, J. H. (1984). "Asymmetric MPSK for Trellis Codes," *Proc. GLOBECOM'84*, pp. 20.6.1-20.6.8, Atlanta, Georgia, November.
- Dixon, R. C. (1976). *Spread Spectrum Techniques*, IEEE Press, New York.
- Doelz, M. L., Heald, E. T., and Martin, D. L. (1957). "Binary Data Transmission Techniques for Linear Systems," *Proc. IRE*, vol. 45, pp. 656-661, May.
- Drouilhet, P. R., Jr. and Bernstein, S. L. (1969). "TATS—A Bandspread Modulation-Demodulation System for Multiple Access Tactical Satellite Communication," *1969 IEEE Electronics and Aerospace Systems (EASCON) Conv. Record*, Washington, D.C., pp. 126-132, October 27-29.
- Duffy, F. P. and Tratcher, T. W. (1971). "Analog Transmission Performance on the Switched Telecommunications Network," *Bell Syst. Tech. J.*, vol. 50, pp. 1311-1347, April.
- Durbin, J. (1959). "Efficient Estimation of Parameters in Moving-Average Models," *Biometrika*, vol. 46, parts 1 and 2, pp. 306-316.
- Duttweiler, D. L., Mazo, J. E., and Messerschmitt, D. G. (1974). "Error Propagation in Decision-Feedback Equalizers," *IEEE Trans. Inform. Theory*, vol. IT-20, pp. 490-497, July.
- Eleftheriou, E. and Falconer, D. D. (1987). "Adaptive Equalization Techniques for HF Channels," *IEEE J. Selected Areas Commun.*, vol. SAC-5 pp. 238-247, February.

- El Gamal, A. and Cover, T. M. (1980). "Multiple User Information Theory," *Proc. IEEE*, vol. 68, pp. 1466-1483, December.
- Elias, P. (1954). "Error-Free Coding," *IRE Trans. Inform. Theory*, vol. IT-4, pp. 29-37, September.
- Elias, P. (1955). "Coding for Noisy Channels," *IRE Convention Record*, vol. 3, part 4, 37-46.
- Esposito, R. (1967). "Error Probabilities for the Nakagami Channel," *IEEE Trans. Inform. Theory*, vol. IT-13, pp. 145-148, January.
- Eyuboglu, V. M. (1988). "Detection of Coded Modulation Signals on Linear, Severely Distorted Channels Using Decision-Feedback Noise Prediction with Interleaving," *IEEE Trans. Commun.*, vol. COM-36, pp. 401-409, April.
- Falconer, D. D. (1976). "Jointly Adaptive Equalization and Carrier Recovery in Two-Dimensional Digital Communication Systems," *Bell Syst. Tech. J.*, vol. 55, pp. 317-334, March.
- Falconer, D. D. and Ljung, L. (1978). "Application of Fast Kalman Estimation to Adaptive Equalization," *IEEE Trans. Commun.*, vol. COM-26, pp. 1439-1446, October.
- Falconer, D. D. and Salz, J. (1977). "Optimal Reception of Digital Data Over the Gaussian Channel with Unknown Delay and Phase Jitter," *IEEE Trans. Inform. Theory*, vol. IT-23, pp. 117-126, January.
- Fano, R. M. (1961). *Transmission of Information*, MIT Press, Cambridge, Mass.
- Fano, R. M. (1963). "A Heuristic Discussion of Probabilistic Coding," *IEEE Trans. Inform. Theory*, vol. IT-9, pp. 64-74, April.
- Feinstein, A. (1958). *Foundations of Information Theory*, McGraw-Hill, New York.
- Fire, P. (1959). "A Class of Multiple-Error-Correcting Binary Codes for Non-Independent Errors," Sylvania Report No. RSL-E-32, Sylvania Electronic Defense Laboratory, Mountain View, Calif., March.
- Flanagan, J. L., et al. (1979). "Speech Coding," *IEEE Trans. Commun.*, vol. COM-27, pp. 710-736, April.
- Forney, G. D., Jr. (1965). "One Decoding BCH Codes," *IEEE Trans. Inform. Theory*, vol. IT-11, pp. 549-557, October.
- Forney, G. D., Jr. (1966a). *Concatenated Codes*, MIT Press, Cambridge, Mass.
- Forney, G. D., Jr. (1966b). "Generalized Minimum Distance Decoding," *IEEE Trans. Inform. Theory*, vol. IT-12, pp. 125-131, April.
- Forney, G. D., Jr. (1968). "Exponential Error Bounds for Erasure, List, and Decision-Feedback Schemes," *IEEE Trans. Inform. Theory*, vol. IT-14, pp. 206-220, March.
- Forney, G. D., Jr. (1970a). "Coding and Its Application in Space Communications," *IEEE Spectrum*, vol. 7, pp. 47-58, June.
- Forney, G. D., Jr. (1970b). "Convolutional Codes I: Algebraic Structure," *IEEE Trans. Inform. Theory*, vol. IT-16, pp. 720-738, November.
- Forney, G. D., Jr. (1971). "Burst Correcting Codes for the Classic Bursty Channel," *IEEE Trans. Commun. Tech.*, vol. COM-19, pp. 772-781, October.
- Forney, G. D., Jr. (1972). "Maximum-Likelihood Sequence Estimation of Digital Sequences in the Presence of Intersymbol Interference," *IEEE Trans. Inform. Theory*, vol. IT-18, pp. 363-378, May.
- Forney, G. D., Jr. (1974). "Convolutional Codes III: Sequential Decoding," *Inform. Control*, vol. 25, pp. 267-297, July.
- Forney, G. D., Jr. (1988). "Coset Codes I: Introduction and Geometrical Classification," *IEEE Trans. Inform. Theory*, vol. IT-34, pp. 671-680, September.
- Forney, G. D., Jr., Gallager, R. G., Lang, G. R., Longstaff, F. M., and Qureshi, S. U. (1984). "Efficient Modulation for Band-Limited Channels," *IEEE J. Selected Areas Commun.*, vol. SAC-2, pp. 632-647, September.
- Foschini, G. J. (1984). "Contrasting Performance of Faster-Binary Signaling with QAM," *Bell Syst. Tech. J.*, vol. 63, pp. 1419-1445, October.
- Foschini, G. J. (1985). "Equalizing Without Altering or Detecting Data," *Bell Syst. Tech. J.*, vol. 64, pp. 1885-1911, October.

- Foschini, G. J., Gitlin, R. D., and Weinstein, S. B. (1974). "Optimization of Two-Dimensional Signal Constellations in the Presence of Gaussian Noise," *IEEE Trans. Commun.*, vol. COM-22, pp. 28-38, January.
- Franaszek, P. A. (1968). "Sequence-State Coding for Digital Transmission," *Bell Syst. Tech. J.*, vol. 27, p. 143.
- Franaszek, P. A. (1969). "On Synchronous Variable Length Coding for Discrete Noiseless Channels," *Inform. Control*, vol. 15, pp. 155-164.
- Franaszek, P. A. (1970). "Sequence-State Methods for Run-Length-Limited Coding," *IBM J. Res. Dev.*, pp. 376-383, July.
- Franks, L. E. (1969). *Signal Theory*, Prentice-Hall, Englewood Cliff, N.J.
- Franks, L. E. (1983). "Carrier and Bit Synchronization in Data Communication—A Tutorial Review," *IEEE Trans. Commun.*, vol. COM-28, pp. 1107-1121, August.
- Franks, L. E. (1981). "Synchronization Subsystems: Analysis and Design," in *Digital Communications, Satellite/Earth Station Engineering*, K. Feher (ed.), Prentice-Hall, Englewood Cliffs, N.J.
- Fredricsson, S. (1975). "Pseudo-Randomness Properties of Binary Shift Register Sequences," *IEEE Trans. Inform. Theory*, vol. IT-21, pp. 115-120, January.
- Freiman, C. E. and Wyner, A. D. (1964). "Optimum Block Codes for Noiseless Input Restricted Channels," *Inform. Control*, vol. 7, pp. 398-415.
- Gardner, N. T. (1971). "Signal Design for Fast-Fading Gaussian Channels," *IEEE Trans. Inform. Theory*, vol. IT-17, pp. 247-256, May.
- Gabor, A. (1967). "Adaptive Coding for Self Clocking Recording," *IEEE Trans. Electronic Comp.* vol. EC-16, p. 866.
- Gallager, R. G. (1965). "Simple Derivation of the Coding Theorem and Some Applications," *IEEE Trans. Inform. Theory*, vol. IT-11, pp. 3-18, January.
- Gallager, R. G. (1968). *Information Theory and Reliable Communication*, Wiley, New York.
- Gardner, F. M. (1979). *Phaselock Techniques*, Wiley, New York.
- Gardner, W. A. (1984). "Learning Characteristics of Stochastic-Gradient Descent Algorithms: A General Study, Analysis, and Critique," *Signal Processing*, vol. 6, pp. 113-133, April.
- George, D. A., Bowen, R. R., and Storey, J. R. (1971). "An Adaptive Decision-Feedback Equalizer," *IEEE Trans. Commun. Tech.*, vol. COM-19, pp. 281-293, June.
- Gersho, A. (1982). "On the Structure of Vector Quantizers," *IEEE Trans. Inform. Theory*, vol. IT-28, pp. 157-166, March.
- Gersho, A. and Gray, R. M. (1992). *Vector Quantization and Signal Compression*, Kluwer Academic Publishers, Boston.
- Gersho, A. and Lawrence, V. B. (1984). "Multidimensional Signal Constellations for Voiceband Data Transmission," *IEEE J. Selected Areas Commun.*, vol. SAC-2, pp. 687-702, September.
- Gerst, I. and Diamond, J. (1961). "The Elimination of Intersymbol Interference by Input Pulse Shaping," *Proc. IRE*, vol. 53, July.
- Ghez, S., Verdu, S., and Schwartz, S. C. (1988). "Stability Properties of Slotted Aloha with Multipacket Reception Capability," *IEEE Trans. Autom. Control*, vol. 33, pp. 640-649, July.
- Ghosh, M. and Weber, C. L. (1991). "Maximum likelihood Blind Equalization," *Proc. 1991 SPIE Conf.*, San Diego, Calif. July.
- Gilbert, E. N. (1952). "A Comparison of Signaling Alphabets," *Bell Syst. Tech. J.*, vol. 31, pp. 504-522, May.
- Gilhausen, K. S., Jacobs, I. M., Podovani, R., Viterbi, A. J., Weaver, L. A., and Wheatley, G. E. III (1991). "On the Capacity of a Cellular CDMA System," *IEEE Trans. Vehicular Tech.*, vol. 40, pp. 303-312, May.
- Gitlin, R. D., Meadors, H. C., and Weinstein, S. B. (1982). "The Tap Leakage Algorithm: An Algorithm for the Stable Operation of a Digitally Implemented Fractionally Spaced, Adaptive Equalizer," *Bell Syst. Tech. J.*, vol. 61, pp. 1817-1839, October.
- Gitlin, R. D. and Weinstein, S. B. (1979). "On the Required Tap-Weight Precision for Digitally Implemented Mean-Squared Equalizers," *Bell Syst. Tech. J.*, vol. 58, pp. 301-321, February.

- Gitlin, R. D. and Weinstein, S. B. (1981). "Fractionally-Spaced Equalization: An Improved Digital Transversal Equalizer," *Bell Syst. Tech. J.*, vol. 60, pp. 275-296, February.
- Glave, F. E. (1972). "An Upper Bound on the Probability of Error due to Intersymbol Interference for Correlated Digital Signals," *IEEE Trans. Inform. Theory*, vol. IT-18, pp. 356-362, May.
- Goblick, T. J., Jr. and Holsinger, J. L. (1967). "Analog Source Digitization: A Comparison of Theory and Practice," *IEEE Trans. Inform. Theory*, vol. IT-13, pp. 323-326, April.
- Godard, D. N. (1974). "Channel Equalization Using a Kalman Filter for Fast Data Transmission," *IBM J. Res. Dev.*, vol. 18, pp. 267-273, May.
- Godard, D. N. (1980). "Self-Recovering Equalization and Carrier Tracking in Two-Dimensional Data Communications Systems," *IEEE Trans. Commun.*, vol. COM-28, pp. 1867-1875, November.
- Golay, M. J. E. (1949). "Note on Digital Coding," *Proc. IRE*, vol. 37, p. 657, June.
- Gold, R. (1967). "Optimal Binary Sequences for Spread Spectrum Multiplexing," *IEEE Trans. Inform. Theory*, vol. IT-13, pp. 619-621, October.
- Gold, R. (1968). "Maximal Recursive Sequences with 3-Valued Recursive Cross Correlation Functions," *IEEE Trans. Inform. Theory*, vol. IT-14, pp. 154-156, January.
- Golomb, S. W. (1967). *Shift Register Sequences*, Holden-Day, San Francisco, Calif.
- Goppa, V. D. (1970). "New Class of Linear Correcting Codes," *Probl. Peredach. Inform.*, vol. 6, pp. 24-30.
- Goppa, V. D. (1971). "Rational Presentation of Codes and (L, g) -Codes," *Probl. Peredach. Inform.*, vol. 7, pp. 41-49.
- Gray, R. M. (1975). "Sliding Block Source Coding," *IEEE Trans. Inform. Theory*, vol. IT 21, pp. 357-368, July.
- Gray, R. M. (1990). *Source Coding Theory*, Kluwer Academic Publishers, Boston.
- Greefkes, J. A. (1970). "A Digitally Companded Delta Modulation Modem for Speech Transmission," *Proc. IEEE Int. Conf. on Commun.* pp. 7.33-7.48, June.
- Green, P. E., Jr. (1962). "Radar Astronomy Measurement Techniques," MIT Lincoln Laboratory, Lexington, Mass., Tech. Report No. 282, December.
- Gronemeyer, S. A. and McBride, A. L. (1976). "MSK and Offset QPSK Modulation," *IEEE Trans. Commun.*, vol. COM-24, pp. 809-820, August.
- Gupta, S. C. (1975). "Phase-Locked Loops," *Proc. IEEE*, vol. 63, pp. 291-306, February.
- Hahn, P. M. (1962). "Theoretical Diversity Improvement in Multiple Frequency Shift Keying," *IRE Trans. Commun. Syst.*, vol. CS-10, pp. 177-184, June.
- Hamming, R. W. (1950). "Error Detecting and Error Correcting Codes," *Bell Syst. Tech. J.*, vol. 29, pp. 147-160, April.
- Hamming, R. W. (1986). *Coding and Information Theory*, Prentice-Hall, Englewood Cliffs, N.J.
- Hancock, J. C. and Lucky, R. W. (1960). "Performance of Combined Amplitude and Phase-Modulated Communication Systems," *IRE Trans. Commun. Syst.*, vol. CS-8, pp. 232-237, December.
- Hartley, R. V. (1928). "Transmission of Information," *Bell Syst. Tech. J.*, vol. 7, p. 535.
- Hatzinakos, D. and Nikias, C. L. (1991). "Blind Equalization Using a Tricepstrum-Based Algorithm," *IEEE Trans. Commun.*, vol. COM-39, pp. 669-682, May.
- Hecht, M. and Guida, A. (1969). "Delay Modulation," *Proc. IEEE*, vol. 57, pp. 1314-1316, July.
- Heller, J. A. (1968). "Short Constraint Length Convolutional Codes," Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Calif., *Space Program Summary* 37-54, vol. 3, pp. 171-174, December.
- Heller, J. A. (1975). "Feedback Decoding of Convolutional Codes," in *Advances in Communication Systems*, vol. 4, A. J. Viterbi (ed.), Academic, New York.
- Heller, J. A. and Jacobs, I. M. (1971). "Viterbi Decoding for Satellite and Space Communication," *IEEE Trans. Commun. Tech.*, vol. COM-19, pp. 835-848, October.
- Helstrom, C. W. (1955). "The Resolution of Signals in White Gaussian Noise," *Proc. IRE*, vol. 43, pp. 1111-1118, September.

- Helstrom, C. W. (1968). *Statistical Theory of Signal Detection*, Pergamon, London.
- Helstrom, C. W. (1991). *Probability and Stochastic Processes for Engineers*, Macmillan, New York.
- Hildebrand, F. B. (1960). *Methods of Applied Mathematics*, Prentice-Hall, Englewood Cliffs, N.J.
- Hirosaki, B. (1981). "An Orthogonality Multiplexed QAM System Using the Discrete Fourier Transform," *IEEE Trans. Commun.*, vol. COM-29, pp. 982-989, July.
- Hirosaki, B., Hasegawa, S., and Sabato, A. (1986). "Advanced Group-Band Modem Using Orthogonally Multiplexed QAM Techniques," *IEEE Trans. Commun.*, vol. COM-34, pp. 587-592, June.
- Ho, E. Y. and Yeh, Y. S. (1970). "A New Approach for Evaluating the Error Probability in the Presence of Intersymbol Interference and Additive Gaussian Noise," *Bell Syst. Tech. J.*, vol. 49, pp. 2249-2265, November.
- Hocquenghem, A. (1959). "Codes Correcteurs d'Erreurs," *Chiffres*, vol. 2, pp. 147-156.
- Holmes, J. K. (1982). *Coherent Spread Spectrum Systems*, Wiley-Interscience, New York.
- Horwood, D. and Gagliardi, R. (1975). "Signal Design for Digital Multiple Access Communications," *IEEE Trans. Commun.*, vol. COM-23, pp. 378-383, March.
- Hsu, F. M. (1982). "Square-Root Kalman Filtering for High-Speed Data Received over Fading Dispersive HF Channels," *IEEE Trans. Inform. Theory*, vol. IT-28, pp. 753-763, September.
- Huffman, D. A. (1952). "A Method for the Construction of Minimum Redundancy Codes," *Proc. IRE*, vol. 40, pp. 1098-1101, September.
- Hui, J. Y. N. (1984). "Throughput Analysis for Code Division Multiple Accessing of the Spread Spectrum Channel," *IEEE J. Selected Areas Commun.*, vol. SAC-2, pp. 482-486, July.
- Immink, K. A. S. (1990). "Runlength-Limited Sequences," *Proc. IEEE*, vol. 78, pp. 1745-1759, November.
- Itakura, F. (1975). "Minimum Prediction Residual Principle Applied to Speech Recognition," *IEEE Trans. Acoust., Speech, Signal Processing*, vol. ASSP-23, pp. 67-72, February.
- Itakura, F. and Saito, S. (1968). "Analysis Synthesis Telephony Based on the Maximum-Likelihood Methods," *Proc. 6th Int. Congr. Acoust.*, Tokyo, Japan, pp. C17-C20.
- Jacobs, I. M. (1974). "Practical Applications of Coding," *IEEE Trans. Inform. Theory*, vol. IT-20, pp. 305-310, May.
- Jacoby, G. V. (1977). "A New Look-Ahead Code for Increased Data Density," *IEEE Trans. Magnetics*, vol. MAG-13, 1202-1204.
- Jayant, N. S. (1970). "Adaptive Delta Modulation with a One-Bit Memory," *Bell Syst. Tech. J.*, pp. 321-342, March.
- Jayant, N. S. (1974). "Digital Coding of Speech Waveforms: PCM, DPCM, and DM Quantizers," *Proc. IEEE*, vol. 62, pp. 611-632, May.
- Jayant, N. S. (1976). *Waveform Quantization and Coding*, IEEE Press, New York.
- Jayant, N. S. and Noll, P. (1984). *Digital Coding of Waveforms*, Prentice-Hall, Englewood Cliffs, N.J.
- Jelinek, F. (1968). *Probabilistic Information Theory*, McGraw-Hill, New York.
- Jelinek, F. (1969). "Fast Sequential Decoding Algorithm Using a Stack," *IBM J. Res. Dev.*, vol. 13, pp. 675-685, November.
- Johnson, C. R. (1991). "Admissibility in Blind Adaptive Channel Equalization," *IEEE Control Syst. Mag.*, pp. 3-15, January.
- Jones, S. K., Cavin, R. K. and Reed, W. M. (1982). "Analysis of Error-Gradient Adaptive Linear Equalizers for a Class of Stationary-Dependent Processes," *IEEE Trans. Inform. Theory*, vol. IT-28, pp. 318-329, March.
- Jordan, K. L. Jr. (1966). "The Performance of Sequential Decoding in Conjunction with Efficient Modulation," *IEEE Trans. Commun. Syst.*, vol. CS-14, pp. 283-287, June.
- Justesen, J. (1972). "A Class of Constructive Asymptotically Good Algebraic Codes," *IEEE Trans. Inform. Theory*, vol. IT-18, pp. 652-656, September.
- Kailath, T. (1960). "Correlation Detection of Signals Perturbed by a Random Channel," *IRE Trans. Inform. Theory*, vol. IT-6, pp. 361-366, June.

- Kailath, T. (1961). "Channel Characterization: Time-Variant Dispersive Channels, In *Lectures on Communication System Theory*, Chap. 6, E. Baghdady (ed.), McGraw-Hill, New York.
- Kalet, I. (1989). "The Multitone Channel," *IEEE Trans. Commun.*, vol. COM-37, pp. 119-124, February.
- Karabed, R. and Siegel, P. H. (1991). "Matched-Spectral Null Codes for Partial-Response Channels," *IEEE Trans. Inform. Theory*, vol. IT-37, pp. 818-855, May.
- Kasami, T. (1966). "Weight Distribution Formula for Some Class of Cyclic Codes," Coordinated Science Laboratory, University of Illinois, Urbana, Ill., Tech. Report No. R-285, April.
- Kaye, A. R. and George, D. A. (1970). "Transmission of Multiplexed PAM Signals over Multiple Channel and Diversity Systems," *IEEE Trans. Commun.*, vol. COM-18, pp. 520-525, October.
- Kelly, E. J., Reed, I. S., and Root, W. L. (1960). "The Detection of Radar Echoes in Noise, Pt. I," *J. SIAM*, vol. 8, pp. 309-341, September.
- Kleinrock, L. and Tobagi, F. A. (1975). "Packet Switching in Radio Channels: Part I—Carrier Sense Multiple-Access Modes and Their Throughput-Delay Characteristics," *IEEE Trans. Commun.*, vol. COM-23, pp. 1400-1416, December.
- Kobayashi, H. (1971). "Simultaneous Adaptive Estimation and Decision Algorithm for Carrier Modulated Data Transmission Systems," *IEEE Trans. Commun. Tech.*, vol. COM-19, pp. 268-280, June.
- Kotelnikov, V. A. (1947). "The Theory of Optimum Noise Immunity," Ph.D. Dissertation, Molotov Energy Institute, Moscow. [Translated by R. A. Silverman, McGraw-Hill, New York.]
- Kretzmer, E. R. (1966). "Generalization of a Technique for Binary Data Communication," *IEEE Trans. Commun. Tech.*, vol. COM-14, pp. 67-68, February.
- Larsen, K. J. (1973). "Short Convolutional Codes with Maximal Free Distance for Rates 1/2, 1/3, and 1/4," *IEEE Trans. Inform. Theory*, vol. IT-19, pp. 371-372, May.
- Lender, A. (1963). "The Duobinary Technique for High Speed Data Transmission," *AIEE Trans. Commun. Electronics*, vol. 82, pp. 214-218.
- Leon-Garcia, A. (1994). *Probability and Random Processes for Electrical Engineering*, Addison-Wesley, Reading, Mass.
- Levinson, N. (1947). "The Wiener RMS (Root Mean Square) Error Criterion in Filter Design and Prediction," *J. Math. and Phys.*, vol. 25, pp. 261-278.
- Lin, S. and Costello, D. J., Jr. (1983). *Error Control Coding: Fundamentals and Applications*, Prentice-Hall, Englewood Cliffs, N.J.
- Linde, Y., Buzo, A., and Gray, R. M. (1980). "An Algorithm for Vector Quantizer Design," *IEEE Trans. Commun.* vol. COM-28, pp. 84-95, January.
- Lindell, G. (1985). "On Coded Continuous Phase Modulation," Ph.D. Dissertation, Telecommunication Theory, University of Lund, Lund, Sweden, May.
- Lindholm, J. H. (1968). "An Analysis of the Pseudo-Randomness Properties of Subsequences of Long m -Sequences," *IEEE Trans. Inform. Theory*, vol. IT-14, pp. 569-576, July.
- Lindsey, W. C. (1964). "Error Probabilities for Ricean Fading Multichannel Reception of Binary and N -Ary Signals," *IEEE Trans. Inform. Theory*, vol. IT-10, pp. 339-350, October.
- Lindsey, W. C. (1972). *Synchronization Systems in Communications*, Prentice-Hall, Englewood Cliffs, N.J.
- Lindsey, W. C. and Chie, C. M. (1981). "A Survey of Digital Phase-Locked Loops," *Proc. IEEE*, vol. 69, pp. 410-432.
- Lindsey, W. C. and Simon, M. K. (1973). *Telecommunication Systems Engineering*, Prentice-Hall, Englewood Cliffs, N.J.
- Ling, F. (1988). "Convergence Characteristics of LMS and LS Adaptive Algorithms for Signals with Rank-Deficient Correlation Matrices," *Proc. Int. Conf. Acoust., Speech, Signal Processing*, New York, 25.D.4.7, April.
- Ling, F., Manolakis, D. G., and Proakis, J. G. (1986a). "Finite Word-Length Effects in Recursive Least Squares Algorithms with Application to Adaptive Equalization," *Annales des Telecommunications*, vol. 41, pp. 1-9, May-June.

- Ling, F., Manolakis, D. G., and Proakis, J. G. (1986b). "Numerically Robust Least-Squares Lattice-Ladder Algorithms with Direct Updating of the Reflection Coefficients," *IEEE Trans. Acoust., Speech, Signal Processing*, vol. ASSP-34, pp. 837-845, August.
- Ling, F. and Proakis, J. G. (1982). "Generalized Least Squares Lattice and Its Applications to DFE," *Proc. 1982, IEEE Int. Conf. on Acoustics, Speech, Signal Processing*, Paris, France, May.
- Ling, F. and Proakis, J. G. (1984a). "Numerical Accuracy and Stability: Two Problems of Adaptive Estimation Algorithms Caused by Round-Off Error," *Proc. Int. Conf. Acoust., Speech, Signal Processing*, pp. 30.3.1-30.3.4, San Diego, Calif., March.
- Ling, F. and Proakis, J. G. (1984b). "Nonstationary Learning Characteristics of Least Squares Adaptive Estimation Algorithms," *Proc. Int. Conf. Acoust., Speech, Signal Processing*, pp. 3.7.1-3.7.4, San Diego, Calif., March.
- Ling, F. and Proakis, J. G. (1984c). "A Generalized Multichannel Least-Squares Lattice Algorithm with Sequential Processing Stages," *IEEE Trans. Acoust., Speech, Signal Processing*, vol. ASSP-32, pp. 381-389, April.
- Ling, F. and Proakis, J. G. (1985). "Adaptive Lattice Decision-Feedback Equalizers—Their Performance and Application to Time-Variant Multipath Channels," *IEEE Trans. Commun.*, vol. COM-33, pp. 348-356, April.
- Ling, F. and Proakis, J. G. (1986). "A Recursive Modified Gram-Schmidt Algorithm," *IEEE Trans. Acoust., Speech, Signal Processing*, vol. ASSP-34, pp. 829-836, August.
- Ling, F. and Quershi, S. U. H. (1986). "Lattice Predictive Decision-Feedback Equalizer for Digital Communication Over Fading Multipath Channels," *Proc. GLOBECOM '86*, Houston, Texas, December.
- Ljung, S. and Ljung, L. (1985). "Error Propagation Properties of Recursive Least-Squares Adaptation Algorithms," *Automatica*, vol. 21, pp. 159-167.
- Lloyd, S. P. (1982). "Least Squares Quantization in PCM," *IEEE Trans. Inform. Theory*, vol. IT-28, pp. 129-137, March.
- Loeve, M. (1955). *Probability Theory*, Van Nostrand, Princeton, N.J.
- Long, G., Ling, F., and Proakis, J. G. (1987). "Adaptive Transversal Filters with Delayed Coefficient Adaptation," *Proc. Int. Conf. Acoust., Speech, Signal Processing*, Dallas, Texas, March.
- Long, G., Ling, F., and Proakis, J. G. (1988a). "Fractionally-Spaced Equalizers Based on Singular-Value Decomposition," *Proc. Int. Conf. Acoust., Speech, Signal Processing*, New York, 25.D.4.10, April.
- Long, G., Ling, F., and Proakis, J. G. (1988b). "Applications of Fractionally-Spaced Decision-Feedback Equalizers to HF Fading Channels," *Proc. MILCOM*, San Diego, Calif., October.
- Long, G., Ling, F., and Proakis, J. G. (1989). "The LMS Algorithm with Delayed Coefficient Adaptation," *IEEE Trans. Acoust., Speech, Signal Processing*, vol. ASSP-37, October.
- Lucky, R. W. (1965). "Automatic Equalization for Digital Communications," *Bell Syst. Tech. J.*, vol. 44, pp. 547-588, April.
- Lucky, R. W. (1966). "Techniques for Adaptive Equalization of Digital Communication," *Bell Syst. Tech. J.*, vol. 45, pp. 255-286.
- Lucky, R. W. and Hancock, J. C. (1962). "On the Optimum Performance of N -ary Systems Having Two Degrees of Freedom," *IRE Trans. Commun. Syst.*, vol. CS-10, pp. 185-192, June.
- Lucky, R. W., Salz, J., and Weldon, E. J., Jr. (1968). *Principles of Data Communication*, McGraw-Hill, New York.
- Lugannani, R. (1969). "Intersymbol Interference and Probability of Error in Digital Systems," *IEEE Trans. Inform. Theory*, vol. IT-15, pp. 682-688, November.
- Lundgren, C. W. and Rummier, W. D. (1979). "Digital Radio Outage Due to Selective Fading—Observation vs. Prediction from Laboratory Simulation," *Bell Syst. Tech. J.*, vol. 58, pp. 1074-1100, May-June.
- Lupas, R. and Verdu, S. (1989). "Linear Multiuser Detectors for Synchronous Code-Division Multiple-Access Channels," *IEEE Trans. Inform. Theory*, vol. IT-35, pp. 123-136, January.

- Lupas, R. and Verdu, S. (1990). "Near-Far Resistance of Multiuser Detectors in Asynchronous Channels," *IEEE Trans. Commun.*, vol. COM-38, pp. 496-508, April.
- MacKenzie, L. R. (1973). "Maximum Likelihood Receivers for Channels Having Memory," Ph.D. Dissertation, Department of Electrical Engineering, University of Notre Dame, Notre Dame, Ind., January.
- MacWilliams, F. J. and Sloane, J. J. (1977). *The Theory of Error Correcting Codes*, North Holland, New York.
- Magee, F. R. and Proakis, J. G. (1973). "Adaptive Maximum-Likelihood Sequence Estimation for Digital Signaling in the Presence of Intersymbol Interference," *IEEE Trans. Inform. Theory*, vol. IT-19, pp. 120-124, January.
- Makhoul, J. (1978). "A Class of All-Zero Lattice Digital Filters: Properties and Applications," *IEEE Trans. Acoust., Speech, Signal Processing*, vol. ASSP-26, pp. 304-314, August.
- Makhoul, J., Roucos, S., and Gish, H. (1985). "Vector Quantization in Speech Coding," *Proc. IEEE*, vol. 73, pp. 1551-1587, November.
- Martin, D. R. and McAdam, P. L. (1980). "Convolutional Code Performance with Optimal Jamming," *Conf. Rec. Int. Conf. Commun.*, pp. 4.3.1-4.3.7, May.
- Massey, J. L. (1963). *Threshold Decoding*, MIT Press, Cambridge, Mass.
- Massey, J. L. (1965). "Step-by-Step Decoding of the BCH Codes," *IEEE Trans. Inform. Theory*, vol. IT-11, pp. 580-585, October.
- Massey, J. L. (1988). "Some New Approaches to Random Access Communications," *Performance '87*, pp. 551-569. [Reprinted 1993 in *Multiple Access Communications*, N. Abramson (ed.), IEEE Press, New York.]
- Massey, J. L. and Sain, M. (1968). "Inverses of Linear Sequential Circuits," *IEEE Trans. Comput.*, vol. C-17, pp. 330-337, April.
- Matis, K. R. and Modestino, J. W. (1982). "Reduced-State Soft-Decision Trellis Decoding of Linear Block Codes," *IEEE Trans. Inform. Theory*, vol. IT-28, pp. 61-68, January.
- Max, J. (1960). "Quantizing for Minimum Distortion," *IRE Trans. Inform. Theory*, vol. IT-6, pp. 7-12, March.
- Mazo, J. E. (1975). "Faster-Than-Nyquist Signaling," *Bell Syst. Tech. J.*, vol. 54, pp. 1451-1462, October.
- Mazo, J. E. (1979). "On the Independence Theory of Equalizer Convergence," *Bell Syst. Tech. J.*, vol. 58, pp. 963-993, May.
- McMahon, M. A. (1984). *The Making of a Profession—A Century of Electrical Engineering in America*, IEEE Press, New York.
- Mengali, U. (1977). "Joint Phase and Timing Acquisition in Data Transmission," *IEEE Trans. Commun.*, vol. COM-25, pp. 1174-1185, October.
- Meyers, M. H. and Franks, L. E. (1980). "Joint Carrier Phase and Symbol Timing for PAM Systems," *IEEE Trans. Commun.*, vol. COM-28, pp. 1121-1129, August.
- Meyr, H. and Ascheid, G. (1990). *Synchronization in Digital Communications*, Wiley Interscience, New York.
- Miller, K. S. (1964). *Multidimensional Gaussian Distributions*, Wiley, New York.
- Millman, S. (ed.) (1984). *A History of Engineering and Science in the Bell System—Communication Sciences (1925-1980)*, AT&T Bell Laboratories.
- Miyagaki, Y., Morinaga, N., and Namekawa, T. (1978). "Error Probability Characteristics for CPSK Signal Through m-Distributed Fading Channel," *IEEE Trans. Commun.*, vol. COM-26, pp. 88-100, January.
- Monsen, P. (1971). "Feedback Equalization for Fading Dispersive Channels," *IEEE Trans. Inform. Theory*, vol. IT-17, pp. 56-64, January.
- Morf, M. (1977). "Ladder Forms in Estimation and System Identification," *Proc. 11th Annual Asilomar Conf. on Circuits, Systems and Computers*, Monterey, Calif., Nov. 7-9.
- Morf, M., Dickinson, B., Kailath, T., and Vieira, A. (1977). "Efficient Solution of Covariance Equations for Linear Prediction," *IEEE Trans. Acoust., Speech, Signal Processing*, vol. ASSP-25, pp. 429-433, October.
- Morf, M. and Lee, D. (1979). "Recursive Least Squares Ladder Forms for Fast Parameter

- Tracking," *Proc. 1978 IEEE Conf. on Decision and Control*, San Diego, Calif., pp. 1362-1367, January 12.
- Morf, M., Lee, D., Nickolls, J. and Vieira, A. (1977). "A Classification of Algorithms for ARMA Models and Ladder Realizations," *Proc. 1977 IEEE Int. Conf. on Acoustics, Speech, Signal Processing*, Hartford, Conn., pp. 13-19, May.
- Morf, M., Vieira, A., and Lee, D. (1977). "Ladder Forms for Identification and Speech Processing," *Proc. 1977 IEEE Conf. on Decision and Control*, New Orleans, La, pp. 1074-1078, December.
- Mueller, K. H. and Muller, M. S. (1976). "Timing Recovery in Digital Synchronous Data Receivers," *IEEE Trans. Commun.*, vol. COM-24, pp. 516-531, May.
- Muller, D. E. (1954). "Application of Boolean Algebra to Switching Circuit Design and to Error Detection," *IRE Trans. Electronic Comput.*, vol. EC-3, pp. 6-12, September.
- Mulligan, M. G. (1988). "Multi-Amplitude Continuous Phase Modulation with Convolutional Coding," Ph.D. Dissertation, Department of Electrical and Computer Engineering, Northeastern University, June.
- Nakagami, M. (1960). "The m-Distribution—A General Formula of Intensity Distribution of Rapid Fading," in *Statistical Methods of Radio Wave Propagation*, W. C. Hoffman (ed.), pp. 3-36, Pergamon Press, New York.
- Natali, F. D. and Walbesser, W. J. (1969). "Phase-Locked Loop Detection of Binary PSK Signals Utilizing Decision Feedback," *IEEE Trans. Aerospace Electronic Syst.*, vol. AES-5, pp. 83-90, January.
- Neyman, J. and Pearson, E. S. (1933). "On the Problem of the Most Efficient Tests of Statistical Hypotheses," *Phil. Trans. Roy. Soc. London, Series A*, vol. 231, 289-337.
- North, D. O. (1943). "An Analysis of the Factors Which Determine Signal/Noise Discrimination in Pulse-Carrier Systems," RCA Tech. Report No. 6 PTR-6C.
- Nyquist, H. (1924). "Certain Factors Affecting Telegraph Speed," *Bell Syst. Tech. J.*, vol. 3, pp. 324.
- Nyquist, H. (1928). "Certain Topics in Telegraph Transmission Theory," *AIEE Trans.*, vol. 47, pp. 617-644.
- Odenwalder, J. P. (1970). "Optimal Decoding of Convolutional Codes," Ph.D. Dissertation, Department of Systems Sciences, School of Engineering and Applied Sciences, University of California, Los Angeles.
- Odenwalder, J. P. (1976). "Dual- k Convolutional Codes for Noncoherently Demodulated Channels," *Proc. Int. Telemetry Conf.* vol. 12, pp. 165-174, September.
- Olsen, J. D. (1977). "Nonlinear Binary Sequences with Asymptotically Optimum Periodic Cross Correlation," Ph.D. Dissertation, University of Southern California, December.
- Omura, J. (1971). "Optimal Receiver Design for Convolutional Codes and Channels with Memory Via Control Theoretical Concepts," *Inform. Sci.*, vol. 3, pp. 243-266.
- Omura, J. K. and Levitt, B. K. (1982). "Code Error Probability Evaluation for Antijam Communication Systems," *IEEE Trans. Commun.*, vol. COM-30, pp. 896-903, May.
- Osborne, W. P. and Luntz, M. B. (1974). "Coherent and Noncoherent Detection of CPFSK," *IEEE Trans. Commun.*, vol. COM-22, pp. 1023-1036, August.
- Paaske, E. (1974). "Short Binary Convolutional Codes with Maximal Free Distance for Rates $2/3$ and $3/4$," *IEEE Trans. Inform. Theory*, vol. IT-20, pp. 683-689, September.
- Paez, M. D. and Glisson, T. H. (1972). "Minimum Mean Squared Error Quantization in Speech PCM and DPCM Systems," *IEEE Trans. Commun.*, vol. COM-20, pp. 225-230, April.
- Pahlavan, K. (1985). "Wireless Communications for Office Information Networks," *IEEE Commun. Mag.*, vol. 23, pp. 18-27, June.
- Papoulis, A. (1984). *Probability, Random Variables, and Stochastic Processes*, McGraw-Hill, New York.
- Paul, D. B. (1983). "An 800bps Adaptive Vector Quantization Vocoder Using a Preceptual Distance Measure," *Proc. IEEE Int. Conf. Acoust., Speech, Signal Processing*, Boston, Mass, pp. 73-76, April.
- Pearson, K., (1965). *Tables of the Incomplete Γ -Function*, Cambridge University Press, London.

- Peebles, P. Z. (1987). *Probability, Random Variables, and Random Signal Principles*, McGraw-Hill, New York.
- Peterson, W. W. (1960). "Encoding and Error-Correction Procedures for Bose-Chaudhuri Codes," *IRE Trans. Inform. Theory*, vol. IT-6, pp. 459-470, September.
- Peterson, W. W. and Weldon, E. J., Jr. (1972). *Error-Correcting Codes*, 2d ed., MIT Press, Cambridge, Mass.
- Picci, G. and Prati, G. (1987). "Blind Equalization and Carrier Recovery Using a Stop-and-Go Decision Directed Algorithm," *IEEE Trans. Commun.*, vol. COM-35, pp. 877-887, September.
- Picinbono, B. (1978). "Adaptive Signal Processing for Detection and Communication," in *Communication Systems and Random Process Theory*, J. K. Skwirzynski (ed.), Sijthoff & Nordhoff, Alphen aan den Rijn, The Netherlands.
- Pickholtz, R. L., Schilling, D. L., and Milstein, L. B. (1982). "Theory of Spread Spectrum Communications—A Tutorial," *IEEE Trans. Commun.*, vol. COM-30, pp. 855-884, May.
- Pieper, J. F., Proakis, J. G., Reed, R. R., and Wolf, J. K. (1978). "Design of Efficient Coding and Modulation for a Rayleigh Fading Channel," *IEEE Trans. Inform. Theory*, vol. IT-24, pp. 457-468, July.
- Pierce, J. N. (1958). "Theoretical Diversity Improvement in Frequency-Shift Keying," *Proc. IRE*, vol. 46, pp. 903-910, May.
- Pierce, J. N. and Stein, S. (1960). "Multiple Diversity with Non-Independent Fading," *Proc. IRE*, vol. 48, pp. 89-104, January.
- Plotkin, M. (1960). "Binary Codes with Specified Minimum Distance," *IRE Trans. Inform. Theory*, vol. IT-6, pp. 445-450, September.
- Poor, H. V. and Verdu, S. (1988). "Single-User Detectors for Multiuser Channels," *IEEE Trans. Commun.*, vol. 36, pp. 50-60, January.
- Price, R. (1954). "The Detection of Signals Perturbed by Scatter and Noise," *IRE Trans. Inform. Theory*, vol. PGIT-4, pp. 163-170, September.
- Price, R. (1956). "Optimum Detection of Random Signals in Noise, with Application to Scatter-Multipath Communication," *IRE Trans. Inform. Theory*, vol. IT-2, pp. 125-135, December.
- Price, R. (1962a). "Error Probabilities for Adaptive Multichannel Reception of Binary Signals," MIT Lincoln Laboratory, Lexington, Mass., Tech. Report No. 258, July.
- Price, R. (1962b). "Error Probabilities for Adaptive Multichannel Reception of Binary Signals," *IRE Trans. Inform. Theory*, vol. IT-8, pp. 305-316, September.
- Price, R. (1972). "Nonlinearly Feedback-Equalized PAM vs. Capacity," *Proc. 1972 IEEE Int. Conf. on Commun.* Philadelphia, Penn., pp. 22.12-22.17, June.
- Price, R. and Green, P. E., Jr. (1958). "A Communication Technique for Multipath Channels," *Proc. IRE*, vol. 46, pp. 555-570, March.
- Price, R. and Green, P. E., Jr. (1960). "Signal Processing in Radar Astronomy—Communication via Fluctuating Multipath Media," MIT Lincoln Laboratory, Lexington, Mass., Tech. Report No. 234, October.
- Proakis, J. G. (1968). "Probabilities of Error for Adaptive Reception of M -Phase Signals," *IEEE Trans. Commun. Tech.*, vol. COM-16, pp. 71-81, February.
- Proakis, J. G. (1975). "Advances in Equalization for Intersymbol Interference," in *Advances in Communication Systems*, vol. 4, A. J. Viterbi (ed.), Academic, New York.
- Proakis, J. G., Drouilhet, P. R., Jr., and Price, R. (1964). "Performance of Coherent Detection Systems Using Decision-Directed Channel Measurement," *IEEE Trans. Commun. Syst.*, vol. CS-12, pp. 54-63, March.
- Proakis, J. G. and Ling, F. (1984). "Recursive Least Squares Algorithms for Adaptive Equalization of Time-Variant Multipath Channels," *Proc. Int. Conf. Commun.* Amsterdam, The Netherlands, May.
- Proakis, J. G. and Manolakis, D. G. (1988). *Introduction to Digital Processing*, Macmillan, New York.
- Proakis, J. G. and Miller, J. H. (1969). "Adaptive Receiver for Digital Signaling through

- Channels with Intersymbol Interference," *IEEE Trans. Inform. Theory*, vol. IT-15, pp. 484-497, July.
- Proakis, J. G. and Rahman, I. (1979). "Performance of Concatenated Dual- k Codes on a Rayleigh Fading Channel with a Bandwidth Constraint," *IEEE Trans. Commun.*, vol. COM-27, pp. 801-806, May.
- Pursley, M. B. (1979). "On the Mean-Square Partial Correlation of Periodic Sequences," *Proc. 1979 Conf. Inform. Science and Systems*, Johns Hopkins University, Baltimore, Md., pp. 377-379, March.
- Qureshi, S. U. H. (1976). "Timing Recovery for Equalized Partial Response Systems," *IEEE Trans. Commun.*, vol. COM-24, pp. 1326-1331, December.
- Qureshi, S. U. H. (1985). "Adaptive Equalization," *Proc. IEEE*, vol. 53, pp. 1349-1387, September.
- Qureshi, S. U. H. and Forney, G. D., Jr. (1977). "Performance and Properties of a $T/2$ Equalizer," *Natl. Telecom. Conf. Record*, pp. 11.1.1-11.1.14, Los Angeles, Calif., December.
- Rabiner, L. R. and Schafer, R. W. (1978). *Digital Processing of Speech Signals*, Prentice-Hall, Englewood Cliffs, N.J.
- Raheli, R., Polydoros, A., and Tzou, C.-K. (1995). "The Principle of Per-Survivor Processing: A General Approach to Approximate and Adaptive MLSE," *IEEE Trans. Commun.*, vol. COM-43 (to appear).
- Rahman, I. (1981). "Bandwidth Constrained Signal Design for Digital Communication over Rayleigh Fading Channels and Partial Band Interference Channels," Ph.D. Dissertation, Department of Electrical Engineering, Northeastern University, Boston, Mass.
- Ramsey, J. L. (1970). "Realization of Optimum Interleavers," *IEEE Trans. Inform. Theory*, vol. IT-16, pp. 338-345.
- Reed, I. S. (1954). "A Class of Multiple-Error Correcting Codes and the Decoding Scheme," *IRE Trans. Inform.*, vol. IT-4, pp. 38-49, September.
- Reed, I. S. and Solomon, G. (1960). "Polynomial Codes Over Certain Finite Fields," *SIAM J.*, vol. 8, pp. 300-304, June.
- Rizos, A. D., Proakis, J. G., and Nguyen, T. Q. (1994). "Comparison of DFT and Cosine Modulated Filter Banks in Multicarrier Modulation," *Proc. Globecom '94*, pp. 687-691, San Francisco, Calif., November.
- Roberts, L. G. (1975). "Aloha Packet System with and without Slots and Capture," *Comp. Commun. Rev.*, vol. 5, pp. 28-42, April.
- Roucos, S., Schwartz, R., and Makhoul, J. (1982). "Segment Quantization for Very-Low-Rate Speech Coding," *Proc. Int. Conf. Acoust., Speech, Signal Processing*, Paris, France, pp. 1565-569, May.
- Rowe, H. E. and Prabhu, V. K. (1975). "Power Spectrum of a Digital Frequency Modulation Signal," *Bell Syst. Tech. J.*, vol. 54, pp. 1095-1125, July-August.
- Rummler, W. D. (1979). "A New Selective Fading Model: Application to Propagation Data," *Bell Syst. Tech. J.*, vol. 58, pp. 1037-1071, May-June.
- Ryder, J. D. and Fink, D. G. (1984). *Engineers and Electronics*, IEEE Press, New York.
- Saltzberg, B. R. (1967). "Performance of an Efficient Parallel Data Transmission System," *IEEE Trans. Commun.*, vol. COM-15, pp. 805-811, December.
- Saltzberg, B. R. (1968). "Intersymbol Interference Error Bounds with Application to Ideal Bandlimited Signaling," *IEEE Trans. Inform. Theory*, vol. IT-14, pp. 563-568, July.
- Salz, J. (1973). "Optimum Mean-Square Decision Feedback Equalization," *Bell Syst. Tech. J.*, vol. 52, pp. 1341-1373, October.
- Salz, J., Sheehan, J. R., and Paris, D. J. (1971). "Data Transmission by Combined AM and PM," *Bell Syst. Tech. J.*, vol. 50, pp. 2399-2419, September.
- Sarwate, D. V. and Pursley, M. B. (1980). "Crosscorrelation Properties of Pseudorandom and Related Sequences," *Proc. IEEE*, vol. 68, pp. 593-619, May.
- Sato, Y. (1975). "A Method of Self-Recovering Equalization for Multilevel Amplitude-Modulation Systems," *IEEE Trans. Commun.*, vol. COM-23, pp. 679-682, June.
- Sato, Y. et al. (1986). "Blind Suppression of Time Dependency and its Extension to Multi-Dimensional Equalization," *Proc. ICC'86*, pp. 46.4.1-46.4.5.

- Satorius, E. H. and Alexander, S. T. (1979). "Channel Equalization Using Adaptive Lattice Algorithms," *IEEE Trans. Commun.*, vol. COM-27, pp. 899-905, June.
- Satorius, E. H. and Pack, J. D. (1981). "Application of Least Squares Lattice Algorithms to Adaptive Equalization," *IEEE Trans. Commun.*, vol. COM-29, pp. 136-142, February.
- Savage, J. E. (1966). "Sequential Decoding—The Computation Problem," *Bell Syst. Tech. J.*, vol. 45, pp. 149-176, January.
- Scholtz, R. A. (1977). "The Spread Spectrum Concept," *IEEE Trans. Commun.*, vol. COM-25, pp. 748-755, August.
- Scholtz, R. A. (1979). "Optimal CDMA Codes," *1979 Nat. Telecommun. Conf. Rec.*, Washington, D.C., pp. 54.2.1-54.2.4, November.
- Scholtz, R. A. (1982). "The Origins of Spread Spectrum," *IEEE Trans. Commun.*, vol. COM-30, pp. 822-854, May.
- Schonhoff, T. A. (1976). "Symbol Error Probabilities for M -ary CPFSK: Coherent and Noncoherent Detection," *IEEE Trans. Commun.*, vol. COM-24, pp. 644-652, June.
- Seshadri, N. (1994). "Joint Data and Channel Estimation Using Fast Blind Trellis Search Techniques," *IEEE Trans. Commun.*, vol. COM-42, pp. 1000-1011, March.
- Shalvi, O. and Weinstein, E. (1990). "New Criteria for Blind Equalization of Nonminimum Phase Systems Channels," *IEEE Trans. Inform. Theory*, vol. IT-36, pp. 312-321, March.
- Shannon, C. E. (1948a). "A Mathematical Theory of Communication," *Bell Syst. Tech. J.*, vol. 27, pp. 379-423, July.
- Shannon, C. E. (1948b). "A Mathematical Theory of Communication," *Bell Syst. Tech. J.*, vol. 27, pp. 623-656, October.
- Shannon, C. E. (1949). "Communication in the Presence of Noise," *Proc. IRE*, vol. 37, pp. 10-21, January.
- Shannon, C. E. (1959a). "Coding Theorems for a Discrete Source with a Fidelity Criterion," *IRE Nat. Conv. Rec.*, pt. 4, pp. 142-163, March.
- Shannon, C. E. (1959b). "Probability of Error for Optimal Codes in a Gaussian Channel," *Bell Syst. Tech. J.*, vol. 38, pp. 611-656, May.
- Shannon, C. E., Gallager, R. G., and Berlekamp, E. R. (1967). "Lower Bounds to Error Probability for Coding on Discrete Memoryless Channels, I and II," *Inform. Control.*, vol. 10, pp. 65-103, January; pp. 527-552, May.
- Shimbo, O. and Celebiler, M. (1971). "The Probability of Error due to Intersymbol Interference and Gaussian Noise in Digital Communication Systems," *IEEE Trans. Commun. Tech.*, vol. COM-19, pp. 113-119, April.
- Simon, M. K. and Divsalar, D. (1985). "Combined Trellis Coding with Asymmetric MPSK Modulation," *JPL Publ. 85-24*, Pasadena, Calif, May.
- Simon, M. K., Omura, J. K., Scholtz, R. A., and Levitt, B. K. (1985). *Spread Spectrum Communications Vol. I, II, III*, Computer Science Press, Rockville, Md.
- Simon, M. K. and Smith, J. G. (1973). "Hexagonal Multiple Phase-and-Amplitude-Shift Keyed Signal Sets," *IEEE Trans. Commun.*, vol. COM-21, pp. 1108-1115, October.
- Slepian, D. (1956). "A Class of Binary Signaling Alphabets," *Bell Syst. Tech. J.*, vol. 35, pp. 203-234, January.
- Slepian, D. (1974). *Key Papers in the Development of Information Theory*, IEEE Press, New York.
- Slepian, D. and Wolf, J. K. (1973). "A Coding Theorem for Multiple Access Channels with Correlated Sources," *Bell Syst. Tech. J.*, vol. 52, pp. 1037-1076.
- Sloane, N. J. A. and Wyner, A. D. (1993). *The Collected Papers of Shannon*, IEEE Press, New York.
- Slock, D. T. M. and Kailath, T. (1988). "Numerically Stable Fast Recursive Least-Squares Transversal Filters," *Proc. Int. Conf. Acoust., Speech, Signal Processing*, pp. 1365-1368, New York, April.
- Smith, J. W. (1965). "The Joint Optimization of Transmitted Signal and Receiving Filter for Data Transmission Systems," *Bell Syst. Tech. J.*, vol. 44, pp. 1921-1942, December.
- Stenbit, J. P. (1964). "Table of Generators for BCH Codes," *IEEE Trans. Inform. Theory*, vol. IT-10, pp. 390-391, October.

- Stiffler, J. J. (1971). *Theory of Synchronous Communications*, Prentice-Hall, Englewood Cliffs, N.J.
- Sundberg, C. E. (1986). "Continuous Phase Modulation," *IEEE Commun. Mag.*, vol. 24, pp. 25-38, April.
- Suzuki, H. (1977). "A Statistical Model for Urban Multipath Channels with Random Delay," *IEEE Trans. Commun.*, vol. COM-25, pp. 673-680, July.
- Tang, D. L. and Bahl, L. R. (1970). "Block Codes for a Class of Constrained Noiseless Channels," *Inform. Control*, vol. 17, pp. 436-461.
- Titsworth, R. C. and Welch, L. R. (1961). "Power Spectra of Signals Modulated by Random and Pseudorandom Sequences," *JPL Tech. Rep. 32-140*, October 10.
- Thomas, C. M., Weidner, M. Y., and Durrani, S. H. (1974). "Digital Amplitude-Phase-Keying with M -ary Alphabets," *IEEE Trans. Commun.*, vol. COM-22, pp. 168-180, February.
- Tong, L. Xu, G., and Kailath, T. (1994). "Blind Identification and Equalization Based on Second-Order Statistics," *IEEE Trans. Inform. Theory*, vol. IT-40, pp. 340-349, March.
- Tufts, D. W. (1965). "Nyquist's Problem—The Joint Optimization of Transmitter and Receiver in Pulse Amplitude Modulation," *Proc. IEEE*, vol. 53, pp. 248-259, March.
- Turin, G. L. (1961). "On Optimal Diversity Reception," *IRE Trans. Inform. Theory*, vol. IT-7, pp. 154-166, July.
- Turin, G. L. (1962). "On Optimal Diversity Reception II," *IRE Trans. Commun. Syst.*, vol. CS-12, pp. 22-31, March.
- Turin, G. L. *et al.* (1972). "Simulation of Urban Vehicle Monitoring Systems," *IEEE Trans. Vehicular Tech.*, pp. 9-16, February.
- Tzannes, M. A., Tzannes, M. C., Proakis, J. G., and Heller, P. N. (1994). "DMT Systems, DWMT Systems and Digital Filter Banks," *Proc. Int. Conf. Commun.*, pp. 311-315, New Orleans, Louisiana, May 1-5.
- Ungerboeck, G. (1972). "Theory on the Speed of Convergence in Adaptive Equalizers for Digital Communication," *IBM J. Res. Dev.*, vol. 16, pp. 546-555, November.
- Ungerboeck, G. (1974). "Adaptive Maximum-Likelihood Receiver for Carrier-Modulated Data-Transmission Systems," *IEEE Trans. Commun.*, vol. COM-22, pp. 624-636, May.
- Ungerboeck, G. (1976). "Fractional Tap-Spacing Equalizer and Consequences for Clock Recovery in Data Modems," *IEEE Trans. Commun.*, vol. COM-24, pp. 856-864, August.
- Ungerboeck, G. (1982). "Channel Coding with Multilevel/Phase Signals," *IEEE Trans. Inform. Theory*, vol. IT-28, pp. 55-67, January.
- Ungerboeck, G. (1987). "Trellis-Coded Modulation with Redundant Signal Sets, Parts I and II," *IEEE Commun. Mag.*, vol. 25, pp. 5-21, February.
- Ungerboeck, G. and Csajka, I. (1976). "On Improving Data-Link Performance by Increasing the Channel Alphabet and Introducing Sequence Coding, 1976 Int. Conf. Inform. Theory, Ronneby, Sweden, June.
- Vaidyanathan, P. P. (1993). *Multirate Systems and Filter Banks*, Prentice-Hall, Englewood Cliffs, N.J.
- Van Etten, W. (1975). "An Optimum Linear Receiver for Multiple Channel Digital Transmission Systems," *IEEE Trans. Commun.*, vol. COM-23, pp. 828-834, August.
- Van Etten, W. (1976). "Maximum Likelihood Receiver for Multiple Channel Transmission Systems," *IEEE Trans. Commun.*, vol. COM-24, pp. 276-283, February.
- Van Trees, H. L. (1968). *Detection, Estimation, and Modulation Theory, Part I*, Wiley, New York.
- Varsharmov, R. R. (1957). "Estimate of the Number of Signals in Error Correcting Codes," *Doklady Akad. Nauk, S.S.S.R.*, vol. 117, pp. 739-741.
- Verdu, S. (1986a). "Minimum Probability of Error for Asynchronous Gaussian Multiple-Access Channels," *IEEE Trans. Inform. Theory*, vol. IT-32, pp. 85-96, January.
- Verdu, S. (1986b). "Multiple-Access Channels with Point-Process Observation: Optimum Demodulation," *IEEE Trans. Inform. Theory*, vol. IT-32, pp. 642-651, September.
- Verdu, S. (1986c). "Optimum Multiuser Asymptotic Efficiency," *IEEE Trans. Commun.*, vol. COM-34, pp. 890-897, September.
- Verdu, S. (1989). "Recent Progress in Multiuser Detection," *Advances in Communications and Signal Processing*, Springer-Verlag, Berlin. [Reprinted in *Multiple Access Communications*, N. Abramson (ed.), IEEE Press, New York.]

- Viterbi, A. J. (1966). *Principles of Coherent Communication*, McGraw-Hill, New York.
- Viterbi, A. J. (1967). "Error Bounds for Convolutional Codes and an Asymptotically Optimum Decoding Algorithm," *IEEE Trans. Inform. Theory*, vol. IT-13, pp. 260-269, April.
- Viterbi, A. J. (1969). "Error Bounds for White Gaussian and Other Very Noisy Memoryless Channels with Generalized Decision Regions," *IEEE Trans. Inform. Theory*, vol. IT-15, pp. 279-287, March.
- Viterbi, A. J. (1971). "Convolutional Codes and Their Performance in Communication Systems," *IEEE Trans. Commun. Tech.*, vol. COM-19, pp. 751-772, October.
- Viterbi, A. J. (1978). "A Processing Satellite Transponder for Multiple Access by Low-Rate Mobile Users," *Proc. Fourth Int. Conf. on Digital Satellite Communications*, Montreal, Canada, pp. 166-174, October.
- Viterbi, A. J. (1979). "Spread Spectrum Communication—Myths and Realities," *IEEE Commun. Mag.*, vol. 17, pp. 11-18, May.
- Viterbi, A. J. (1985). "When Not to Spread Spectrum—A Sequel," *IEEE Commun. Mag.*, vol. 23, pp. 12-17, April.
- Viterbi, A. J. and Jacobs, I. M. (1975). "Advances in Coding and Modulation for Noncoherent Channels Affected by Fading, Partial Band, and Multiple-Access Interference," in *Advances in Communication Systems*, vol. 4, A. J. Viterbi (ed.), Academic, New York.
- Viterbi, A. J. and Omura, J. K. (1979). *Principles of Digital Communication and Coding*, McGraw-Hill, New York.
- Wainberg, S. and Wolf, J. K. (1970). "Subsequences of Pseudo-Random Sequences," *IEEE Trans. Commun. Tech.*, vol. COM-18, pp. 606-612, October.
- Wainberg, S. and Wolf, J. K. (1973). "Algebraic Decoding of Block Codes Over a q -ary Input, Q -ary Output Channel, $Q > q$," *Inform. Control*, vol. 22, pp. 232-247, April.
- Wald, A. (1947). *Sequential Analysis*, Wiley, New York.
- Ward, R. B. (1965). "Acquisition of Pseudonoise Signals by Sequential Estimation," *IEEE Trans. Commun. Tech.*, vol. COM-13, pp. 474-483, December.
- Ward, R. B. and Yiu, K. P. (1977). "Acquisition of Pseudonoise Signals by Recursion-Aided Sequential Estimation," *IEEE Trans. Commun.*, vol. COM-25, pp. 784-794, August.
- Weber, W. J., III, Stanton, P. H., and Sumida, J. T. (1978). "A Bandwidth Compressive Modulation System Using Multi-Amplitude Minimum-Shift Keying (MAMSK)," *IEEE Trans. Commun.*, vol. COM-26, pp. 543-551, May.
- Wei, L. F. (1984a). "Rotationally Invariant Convolutional Channel Coding with Expanded Signal Space, Part I: 180°," *IEEE J. Selected Areas Commun.*, vol. SAC-2, pp. 659-671, September.
- Wei, L. F. (1984b). "Rotationally Invariant Convolutional Channel Coding with Expanded Signal Space, Part II: Nonlinear Codes," *IEEE J. Selected Areas Commun.*, vol. SAC-2, pp. 672-686, September.
- Wei, L. F. (1987). "Trellis-Coded Modulation with Multi-Dimensional Constellations," *IEEE Trans. Inform. Theory*, vol. IT-33, pp. 483-501, July.
- Weinstein, S. B. and Ebert, P. M. (1971). "Data Transmission by Frequency-Division Multiplexing Using the Discrete Fourier Transform," *IEEE Trans. Commun.*, vol. COM-19, pp. 628-634, October.
- Welch, L. R. (1974). "Lower Bounds on the Maximum Cross Correlation of Signals," *IEEE Trans. Inform. Theory*, vol. IT-20, pp. 397-399, May.
- Weldon, E. J., Jr. (1971). "Decoding Binary Block Codes on Q -ary Output Channels," *IEEE Trans. Inform. Theory*, vol. IT-17, pp. 713-718, November.
- Widrow, B. (1966). "Adaptive Filters, I: Fundamentals," Stanford Electronics Laboratory, Stanford University, Stanford, Calif., Tech Report No. 6764-6, December.
- Widrow, B. (1970). "Adaptive Filters," *Aspects of Network and System Theory*, R. E. Kalman and N. DeClaris (eds.), Holt, Rinehart and Winston, New York.
- Widrow, B. and Hoff, M. E., Jr. (1960). "Adaptive Switching Circuits," *IRE WESCON Conv. Rec.*, pt. 4, pp. 96-104.
- Widrow, B. et al. (1975). "Adaptive Noise Cancelling: Principles and Applications," *Proc. IEEE*, vol. 63, pp. 1692-1716, December.

- Wiener, N. (1949). *The Extrapolation, Interpolation, and Smoothing of Stationary Time Series with Engineering Applications*, Wiley, New York (reprint of original work published as an MIT Radiation Laboratory Report in 1942).
- Wintz, P. A. (1972). "Transform Picture Coding," *Proc. IEEE*, vol. 60, pp. 880-920, July.
- Wolf, J. K. (1978). "Efficient Maximum Likelihood Decoding of Linear Block Codes Using a Trellis," *IEEE Trans. Inform. Theory*, vol. IT-24, pp. 76-81, January.
- Wozencraft, J. M. (1957). "Sequential Decoding for Reliable Communication," *IRE Nat. Conv. Rec.*, vol. 5, pt. 2, pp. 11-25.
- Wozencraft, J. M. and Jacobs, I. M. (1965). *Principles of Communication Engineering*, Wiley, New York.
- Wozencraft, J. M. and Kennedy, R. S. (1966). "Modulation and Demodulation for Probabilistic Decoding," *IEEE Trans. Inform. Theory*, vol. IT-12, pp. 291-297, July.
- Wozencraft, J. M. and Rieffen, B. (1961). *Sequential Decoding*, MIT Press, Cambridge, Mass.
- Wyner, A. D. (1965). "Capacity of the Band-Limited Gaussian Channel," *Bull. Syst. Tech. J.*, vol. 45, pp. 359-371, March.
- Xie, Z., Rushforth, C. K., and Short, R. T. (1990a). "Multiuser Signal Detection Using Sequential Decoding," *IEEE Trans. Commun.*, vol. COM-38, pp. 578-583, May.
- Xie, Z., Short, R. T., and Rushforth, C. K. (1990b). "A Family of Suboptimum Detectors for Coherent Multiuser Communications," *IEEE J. Selected Areas Commun.*, vol. SAC-8, pp. 683-690, May.
- Yao, K. (1972). "On Minimum Average Probability of Error Expression for Binary Pulse-Communication System with Intersymbol Interference," *IEEE Trans. Inform. Theory*, vol. IT-18, pp. 528-531, July.
- Yao, K. and Tobin, R. M. (1976). "Moment Space Upper and Lower Error Bounds for Digital Systems with Intersymbol Interference," *IEEE Trans. Inform. Theory*, vol. IT-22, pp. 65-74, January.
- Yue, O. (1983). "Spread Spectrum Mobile Radio 1977-1982," *IEEE Trans. Vehicular Tech.*, vol. VT-32, pp. 98-105, February.
- Zelinski, P. and Noll, P. (1977). "Adaptive Transform Coding of Speech Signals," *IEEE Trans. Acoustics, Speech, Signal Processing*, vol. ASSP-25, pp. 299-309, August.
- Zervas, E., Proakis, J. G., and Eyuboglu, V. (1991). "A Quantized Channel Approach to Blind Equalization," *Proc. ICC'91*, Chicago, IL, June.
- Zhang, X. and Brady, D. (1993). "Soft-Decision Multistage Detection of Asynchronous AWGN Channels," *Proc. 31st Allerton Conf. on Commun., Contr., Comp.* Allerton, IL, October.
- Zhou, K. and Proakis, J. G. (1988). "Coded Reduced-Bandwidth QAM with Decision-Feedback Equalization," *Conf. Rec. IEEE Int. Conf. Commun.*, Philadelphia, Penn., pp. 12.6.1-12.6.5, June.
- Zhou, K., Proakis, J. G., and Ling, F. (1987). "Decision-Feedback Equalization of Fading Dispersive Channels with Trellis-Coded Modulation," *Int. Conf. Commun. Tech.*, Nanjing, China, November.
- Zhou, K., Proakis, J. G., and Ling, F. (1990). "Decision-Feedback Equalization of Time-Dispersive Channels with Coded Modulation," *IEEE Trans. Commun.*, vol. COM-38, pp. 18-24, January.
- Ziemer, R. E. and Peterson, R. L. (1985). *Digital Communications and Spread Spectrum Systems*, Macmillan, New York.
- Zigangirov, K. S. (1966). "Some Sequential Decoding Procedures," *Probl. Peredach. Inform.*, vol. 2, pp. 13-25.
- Ziv, J. (1985). "Universal Quantization," *IEEE Trans. Inform. Theory*, vol. 31, pp. 344-347.
- Ziv, J. and Lempel, A. (1977). "A Universal Algorithm for Sequential Data Compression," *IEEE Trans. Inform. Theory*, vol. IT-23, pp. 337-343.
- Ziv, J. and Lempel, A. (1978). "Compression of Individual Sequences via Variable-Rate Coding," *IEEE Trans. Inform. Theory*, vol. IT-24, pp. 530-536.
- Zvonar, Z. and Brady, D. (1995). "Differentially Coherent Multiuser Detection in Asynchronous CDMA Flat Rayleigh Fading Channels," *IEEE Trans. Commun.*, vol. COM-43, to appear.

- Adaptive equalization, 636–676
- Adaptive equalizers, 636–676 (*See also* Equalizers)
 - blind, 664–675
 - decision-feedback, 621–625, 649–650
 - linear, 584–601, 648–649
 - baseband, 648
 - passband, 648–649
 - maximum likelihood sequence estimator, 607–616, 652–654
- Adaptive transform coding, 137
- Algorithm:
 - Constant-modulus, 670
 - Godard, 670–673
 - Huffman, 99–103
 - K means, 122
 - Lempel–Ziv, 106–108
 - Levinson–Durbin, 128, 139, 879–881
 - LMS (MSE), 639–642
 - recursive least-squares (RLS), 654–664
 - RLS (fast), 660
 - RLS (Kalman), 656–658
 - RLS lattice, 660–664
 - RLS square-root, 660
 - stochastic gradient, 668
 - zero-forcing, 637–638
- Amplitude distortion, 535
- Analog sources, 82
 - quantization of, 108–125
 - optimum, 113
 - scalar, 113–118
 - vector, 118
 - sampling of, 72–73
- Antenna:
 - beamwidth, 317
 - effective area, 316
 - effective radiated power, 316
 - illumination efficiency factor, 317
- A posteriori probability, 21
- A priori probability, 21
- Autocorrelation function, 64
 - at output of linear system, 68–70
 - of cyclostationary process, 75–76
- Autocovariance function, 64
- Automatic gain control (AGC), 336
- Average power density spectrum, 77
- Averages, 33–37
 - central moments, 33
 - characteristic function, 35–37
 - for sum of statistically independent random variables, 36
 - correlation, 34
 - covariance, 34
 - covariance matrix, 34
 - expected value (mean), 33
 - joint moments, 34
 - of stochastic processes, 64–67
 - variance, 33
- AWGN (additive white Gaussian noise) channel, 233–234
- Band-limited channels, 534–540 (*See also* Channels)
- Bandpass signals, 152–157
 - complex envelope of, 159
 - envelope of, 155

Bandpass signals (Cont.):

- phase of, 155
- quadrature components, 155

Bandpass system, 157–159

- response of, 157–159

Bandwidth efficiency, 283–284**Bandwidth expansion factor, 444, 807****Baseband signals, 176**

- delay modulation, 188
- Miller, 188
- NRZ, 187
- NRZI, 187
- power spectra of, 220–223

Baudot code, 13**Bayes' theorem, 21****BCH (Bose–Chaudhuri–Hocquenghem) codes, 435–436****Bibliography, 899–916****Binary symmetric channel (BSC), 381**

- capacity of, 381
- transition probability, 376–377

Binomial distribution, 37–38**Biorthogonal signals, 183****Bit interval, 174****Blind equalization, 664–675**

- constant modulus algorithm*, 670
- Godard algorithm, 670–673
- joint data and channel estimation, 667–668
- maximum-likelihood algorithms, 664–667
- stochastic gradient algorithms, 668–669
- with second-order moments, 673–675

Block codes, 413–468

- binary, 4
- concatenated, 467–468
- cyclic, 423–436
 - Bose–Chaudhuri–Hocquenghem (BCH), 435–436
 - encoders for, 430–435
 - generator polynomial for, 437–438
 - Golay, 433
 - Hamming, 433
 - maximum-length shift-register (MLSR), 433–435
 - table of MLSR connections, 435
- dual code, 426
- equivalent, 418
- error correction capability, 451–452
- error detection capability, 451–452
- extended, 420
- fixed-weight, 414
- generator matrix, 417
- generator polynomial, 424
- Golay, 423, 433
 - extended, 423
 - generator polynomial of, 433
 - performance on AWGN channel, 454–455
 - weight distribution, 423

Block codes (Cont.):

- Hadamard, 422–423
- Hamming, 421–422
- hard-decision decoding, 445–456
- linear, 413–468
- maximum-distance-separable, 461
- message polynomial, 424
- minimum distance bounds, 461–464
 - Elias, 463
 - Gilbert–Varsharmov, 463
 - Hamming, 462
 - Plotkin, 462
- nonbinary, 464–468
- nonsystematic, 418
- null space, 416
- parity-check matrix, 419
- parity polynomial, 426
- perfect, 453
- quasi-perfect, 454
- rate, 2, 414
- reciprocal polynomial, 426
- Reed–Solomon, 464–466
- shortened, 421
- soft-decision decoding, 436–445
- standard array, 447
- syndrome, 449–451
- systematic, 418

Block length, 414**Burst errors, 469****Burst error correction capability, 469****Capacity (see Channel capacity)****Carrier, 159****Carrier phase estimation**

- Costas loop, 355–356
- decision-directed, 347–350
- ML methods, 339–341
- nondecision directed, 350–358
- phase-locked loop, 341–346
- squaring loop, 353–355

Carrier recovery, 336–358**Canchy–Schwartz inequality, 165****Central limit theorem, 61–62****Central moments, 33****Channel:**

- additive white gaussian noise (AWGN), 233–234
- band-limited, 534–540
- binary symmetric, 375–376
- capacity, 380–386
 - AWGN, 381–386
 - band limited AWGN, 383–386
 - DMC, 376–377
 - infinite bandwidth AWGN, 385
- coherence bandwidth, 764

Channel (*Cont.*):

- coherence time, 765
- cutoff rate, 394
 - for system design, 400–406
- discrete memoryless (DMC), 376–377
- discrete-time model, 586–588
- distortion, 534–540
 - amplitude, 535
 - envelope delay, 535
 - frequency offset, 538
 - impulse noise, 538
 - nonlinear, 537
 - phase jitter, 535
 - squared-error, 108
 - thermal noise, 538
- Distortion-rate function, 110
- Doppler power spectrum, 765
- Doppler spread, 765
- encoder, 1–2
 - code rate, 2, 414
 - code word, 2
- fading multipath: characterization of, 759–769
 - correlation functions for, 763–767
 - impulse response, 760–761
 - models for, 767–769
 - transfer function, 763
- fiber optic, 5
- frequency nonselective, 764, 772–795
 - digital signaling over, 772–795
- frequency selective, 764, 798–806
 - digital signaling over, 795–806
 - error rate for, 798–806
 - RAKE demodulator for, 797–806
 - tap weight estimation of, 801–803
 - tapped delay line model of, 795–797
- microwave LOS, 767–769
- models for, 11–13, 375–380
 - additive noise, 11
 - binary symmetric, 375–376
 - discrete memoryless, 376–377
 - discrete-time, 586–588
 - linear filter, 11
 - linear, time-variant filter, 12
 - waveform, 378–380
- multipath spread, 763
- Nakagami fading, 762
- overspread, 771
- Rayleigh fading, 761
 - binary signaling over, 772–776
 - coded waveforms for, 806–832
 - cutoff rate for, 825–832
 - frequency nonselective, 764
 - M -ary orthogonal signaling over, 787–792
 - multiphase signaling over, 785–787

Channel (*Cont.*):

- Ricean fading, 761
- scattering function, 766
- spread factor, 771
 - table, 772
- storage, 10
- underspread, 771
- underwater acoustic, 9
- wireless, 5
- wireline, 4
- Channel encoder, 2
- Channel reliability function, 389
- Characteristic function, 35–37
 - of binomial, 38
 - of chi-square, 42–44
 - of gaussian, 41
 - of multivariate gaussian, 49–52
 - of uniform, 39
- Chebyshev inequality, 52–54
- Chernoff bound, 53–57
 - for BSC, 455
 - for Rayleigh fading channel, 792–794
- Chi-square distribution, 41–45
 - central, 42–43
 - noncentral, 42–44
- Code division multiple access (CDMA)
 - asynchronous, 852–854
 - effective SNR, 861
 - efficiency of, 861
 - optimum receiver for, 851–854
 - suboptimum detectors for, 854–861
 - decorrelating, 855–857
 - MMSE, 858–859
 - performance, 859
 - single user, 854
 - synchronous, 851–852
- Code rate, 2
- Code word, 2
 - fixed length, 94
 - variable length (Huffman), 96–103
- Coded modulation, 511–526
- Codes:
 - source:
 - instantaneously decodable, 96
 - uniquely decodable, 96
- (*See also* Block codes; Convolutional codes)
- Coding:
 - entropy, 97, 117
 - for AWGN channel: block codes, 413–468
 - convolutional codes, 470–511
 - for BSC (*see* Block codes; Convolutional codes)
 - for Rayleigh fading channel, 806–832
 - concatenated, 814–825
 - constant-weight codes, 814–825

- Coding (Cont.):**
 for Rayleigh fading channel (*Cont.*):
 convolutional codes, 811–814
 cutoff rate, 825–829
 linear block codes, 808–814
 trellis codes, 830–832
 Huffman (entropy), 96–103
 noiseless, 93–108
 speech, 143–144
- Coding gain**, 441, 507, 733
- Compandor**, 127
- Comparison of digital modulation**, 282–284
- Complementary error function**, 40
- Complete orthonormal functions**, 165–168
- Complex envelope**, 155
 of narrowband process, 155
- Computational cutoff rate**, 503
 (*See also* cutoff rate)
- Concatenated block codes**, 467–468
- Concatenated convolutional codes**, 449–500
- Conditional cdf (cumulative distribution function)**, 26–28
- Conditional pdf (probability density function)**, 25
- Conditional probability**, 20
- Consistent estimate (see Estimate)**
- Constraint length**, 470
- Continuous-phase frequency-shift keying (CPFSK)**, 190–191
 performance of, 284–301
 power density spectrum of, 209–219
 representation of, 284–285
- Continuous-phase modulation (CPM)**, 191–203
 demodulation:
 maximum-likelihood sequence estimation, 284–289
 multiamplitude, 200–203
 multi- h , 295
 performance of, 290–296
 symbol-by-symbol, 296–300
 full response, 192
 minimum-shift keying (MSK), 196–199
 modulation index, 191
 multiamplitude, 200–203
 multi- h , 295
 partial response, 192
 phase cylinder, 195
 phase trees of, 192
 power spectrum of, 209–219
 representation of, 190–196
 signal space diagram for, 199–200
 state trellis, 196
 trellis of, 195
- Continuously variable slope delta modulation (CVSD)**, 135
- Convolutional codes**, 470–511
 applications of, 506–511
 binary, 470–476
- Convolutional codes (Cont.):**
 catastrophic error propagation, 482
 concatenated, 492, 499–500
 constraint length, 470
 decoding, 483–486
 Fano algorithm, 500–503
 feedback, 505–506
 sequential, 500–502
 stack algorithm, 503–504
 Viterbi, 483–486
 distance properties of, 492–496
 dual- k , 492–499
 encoder, 470–478
 generators, 471–472
 hard-decision decoding, 489–492
 minimum free distance, 479
 nonbinary, 492–499
 optimum decoding of, 483–485
 performance on AGWN channel, 486–492
 performance on BSC, 489–491
 performance on Rayleigh fading channel, 811–814
 quantized metrics, 508–510
 soft-decision decoding, 486–489
 state diagram, 474–477
 table of generators for maximum free distance, 493–497
 transfer function, 477–480
 tree diagram, 472
 trellis diagram, 473
- Correlation demodulator**, 234–238
 metrics for, 246
- Correlative state vector**, 286
- Coset**, 447
- Coset leader**, 447
- Covariance**, 34
- Covariance function**, 65
- Cross-correlation function**, 65
- Cross-power density spectrum**, 68
- Cumulative distribution function (cdf)**, 23
- Cutoff rate**, 394
 comparison with channel capacity, 399–400
 for binary coded signals, 396
 for M -ary input, M -ary output vector channel, 403
 for multiamplitude signals, 397–399
 for noncoherent channel, 405–406
 for q -ary input Q -ary output channel, 400–401
 system design with, 400–406
- CW jamming**, 706
- Cyclic codes (see Block codes, cyclic)**
- Cyclostationary process**, 75–76, 205
- Data compression**, 1
- Data translation codes**, 566
- Decision-feedback equalizer (see Equalizers, decision-feedback)**

- Decoding of block codes:
 - for fading channels: hard-decision, 811
 - soft-decision, 808–811
 - hard-decision, 445–456
 - bounds on performance for BSC, 452–455
 - Chernoff bound, 455
 - syndrome, 449–451
 - table lookup method, 447–448
 - soft-decision, 436–445
 - bounds on performance for AWGN, 440–443
 - comparison with hard-decision decoding, 456–461
- Decoding of convolutional codes:
 - for fading channel, performance, 811–814
 - feedback, 505–506
 - hard-decision, 489–492
 - performance on AWGN channel, 486–492
 - performance on BSC, 489–491
 - sequential, 500–502
 - soft decision, 486–489
 - stack algorithm, 503–504
 - Viterbi algorithm, 483–486
- Delay distortion, 535
- Delay power spectrum, 762
- Delta modulation (*see* Source, encoding)
- Demodulation/Detection
 - carrier recovery for, 337–358
 - Costas loop, 355–356
 - decision-directed, 347–350
 - ML methods, 339–341
 - non-decision-directed, 350–358
 - squaring PLL, 353–355
 - coherent:
 - of binary signals, 257–260
 - of biorthogonal signals, 264–266
 - comparison of, 282–284
 - of DPSK signals, 274–278
 - of equicorrelated signals, 266
 - of M -ary binary coded signals, 266–267
 - optimum, 244–257
 - of orthogonal signals, 260–264
 - of PAM signals, 267–269
 - of PSK signals, 269–274
 - of QAM signals, 278–282
 - correlation-type, 234–238
 - of CPFSK, 284–289
 - performance, 289–301
 - for intersymbol interference, 584–627
 - matched filter-type, 238–244
 - maximum-likelihood, 244–254
 - maximum likelihood sequence, 249–254
 - noncoherent, 302–313
 - of binary signals, 302–308
 - of M -ary orthogonal signals, 308–312
 - multichannel, 680–686
- Demodulation/Detection (*Cont.*):
 - noncoherent (*Cont.*):
 - optimum, 302–312
 - symbol-by-symbol, 254–256
 - Differential encoding, 187
 - Differential entropy, 92
 - Differential phase-shift keying (DPSK), 274–278
 - Digital communication system model, 1–3
 - Digital modulator, 2
 - Direct sequence (*see* Spread spectrum signals)
 - Discrete memoryless channel (DMC), 376–377
 - Discrete random variable, 23
 - Distance (*see* Block codes; Convolutional codes, minimum free distance)
 - Distortion (*See also* Channel distortion):
 - from quantization, 113–125
 - granular noise, 134
 - slope overload, 134
 - Distortion rate function, 110
 - Distributions (*see* Probability distributions)
 - Diversity:
 - antenna, 777
 - frequency, 777
 - performance of, 777–795
 - polarization, 778
 - RAKE, 778
 - time, 777
 - Double-sideband modulation, 176
 - DPCM (Differential pulse code modulation) (*see* Source, encoding)
 - DPSK (differential phase-shift keying), 274–278
 - Dual code, 426
 - Dual- k codes, 492–499
 - Duobinary signal, 548–549
 - Early-late gate synchronizer, 362–365
 - Effective antenna area, 316
 - Effective radiated power, 316
 - Eigenvalue, 164
 - Eigenvector, 164
 - Elias bound, 461–463
 - Encoding (*see* Block codes; Conventional codes)
 - Energy, 156
 - Ensemble averages, 64–65
 - Entropy, 88
 - conditional, 88
 - differential, 92
 - discrete memoryless sources, 94–103
 - discrete stationary sources, 103–106
 - Entropy coding, 96, 117
 - Envelope, 155
 - Envelope detection, 306
 - Equalizers (*See also* Adaptive equalizers)
 - decision-feedback, 621–627, 649–650

- Equalizers (*Cont.*):
- decision-feedback (*Cont.*):
 - adaptive, 649–652
 - examples of performance, 622–623
 - of trellis-coded signals, 650–652
 - minimum MSE, 622
 - predictive form, 626–627
 - linear, 601–620, 648–649
 - adaptive, 636–644
 - convergence of MSE algorithm, 642–644
 - error probability, 613–617
 - examples of performance, 613–617
 - excess MSE, 644–648
 - fractionally spaced, 617–620
 - LMS (MSE) algorithm, 639–642
 - limit on step size, 645–646
 - mean-square error (MSE) criterion, 607–620
 - minimum MSE, 610–611
 - output SNR for, 605, 610
 - peak distortion, 602
 - peak distortion criterion, 602–607
 - zero-forcing, 603–604, 637–638
 - maximum-likelihood sequence estimation, 584–586, 589–593, 607–616
 - self-recovering (blind), 644–675
 - with trellis-coded modulation, 650–652
 - using the Viterbi algorithm, 589–593
 - channel estimator for, 652–654
 - performance of, 593–601
- Equivalent codes, 418
- Equivalent lowpass impulse response, 157–158
- Equivalent lowpass signal, 155
- Equivocation, 90
- Error function, 40
- Error probability:
- coherent demodulation:
 - binary coded, 266–267
 - for binary signals, 257–260
 - for DPSK, 274–278
 - for M -ary biorthogonal, 264–265
 - for M -ary equicorrelated, 266
 - for M -ary orthogonal, 260–263
 - for M -ary PAM, 267–269
 - for PSK, 269–274
 - for QAM, 278–282
 - union bound for, 263–264
 - multichannel, 680–686
 - noncoherent demodulation, 301–313
 - for binary signals, 301–308
 - for M -ary orthogonal, 308–312
- Estimate:
- biased, 367
 - consistent, 59, 368
 - efficient, 368
- Estimate (*Cont.*):
- unbiased, 367
- Estimate of phase (*See also* Carrier phase estimation)
- clairvoyant, 889
 - pilot signal, 889
- Estimation, maximum-likelihood sequence (MLSE), 249–254
- Estimation:
- maximum likelihood, 334–335
 - of carrier phase, 337–358
 - of signal parameters, 333–335
 - of symbol timing, 358–365
 - of symbol timing and carrier phase, 365–371
 - performance of, 367–370
- Euclidean:
- distance, 251
 - weight, 595
- Events, 18
- intersection of, 19
 - joint, 19
 - mutually exclusive, 19
 - null, 19
 - probability of, 19
 - union of, 19
- Excess bandwidth, 546
- Excess MSE, 644–648
- Expected value, 33
- Expurgated codes, 816–817
- Extended code, 420
- Extension field, 415
- Eye pattern, 541
- Fading channels, 8, 758–839 (*See also* Channels)
- Feedback decoding, 505–506
- FH spread spectrum signals (*see* Spread spectrum signals)
- Filter:
- integrator, 238
 - matched, 239
- Folded spectrum, 606
- Follower jammer, 731
- Fourier transform, 35
- Free euclidian distance, 517
- Free-space path loss, 317
- Frequency diversity, 777
- Frequency division multiple access (FDMA), 842–844
- Frequency-hopped (FH) spread spectrum (*see* Spread spectrum signals)
- Frequency-shift keying (FSK), 181–183, 190–191
- continuous-phase (CPFSK): performance of, 284–301
 - power density spectrum of, 213–217
 - representation of, 190–191
- Functions of random variables, 28–32

- Galois field, 415
- Gamma function, 42
- Gaussian distribution, 39–41
 - multivariate, 49–52
- Gaussian noise, 11
- Gaussian random process, 65
- Gaussian random variables, linear transformation of, 50–52
- Generator matrix, 417
- Generator polynomial, 424
- Gilbert–Varsharmov bound, 463
- Golay codes, 423, 433
 - extended, 423
 - generator polynomial of, 433
 - performance on AWGN channel, 454–455
- Gold sequences, 727
- Gram–Schmidt procedure, 167–173
- Granular noise, 134
- Gray encoding, 175

- Hadamard codes, 422–423, 817–821
- Hamming bound on minimum distance, 462
- Hamming codes, 421–422, 433
- Hamming distance, 415
- Hard-decision decoding:
 - block codes, 445–456
 - convolutional codes, 489–492
- Hilbert transform, 154
- Huffman coding, 96–103

- Illumination efficiency factor, 317
- Impulse noise, 538
- Impulse response, 68
- Independent events, 21
- Independent random variables, 28
- Information, 84–85
 - equivocation, 90
 - measure of, 84–91
 - mutual, 84
 - average, 87
 - self-, 85
 - average (entropy), 88
 - sequence, 3, 83
- Interleaving, 468–470
 - block, 469
 - convolutional, 470
- Intersymbol interference, 536–537
 - controlled (*see* Partial response signals)
 - discrete-time model for, 586–589
 - equivalent white noise filter model, 588
 - optimum demodulator for, 584–593
- Inverse filter, 603

- Jacobian, 32
- Jamming margin, 707
- Joint cdf (cumulative distribution function), 25
- Joint pdf (probability density function), 25
- Joint processes, 65

- Kalman (RLS) algorithm, 656–658
 - fast, 660
- Kasami sequences, 729
- Kraft inequality, 97–98

- Laplace probability density function, 56
- Lattice:
 - filter, 660–664
 - recursive least-squares, 664
- Law of large numbers (weak), 59
- Least favorable pdf, 305
- Least-squares algorithms, 654–664
- Lempel–Ziv algorithm, 106–108
- Levinson–Durbin algorithm, 128, 139, 879–881
- Likelihood ratio, 304
- Line codes, 566
- Linear codes (*see* Block codes, linear; Convolutional codes)
- Linear equalization (*see* Equalizers, linear)
- Linear-feedback shift-register, maximal length, 433–435, 724–727
- Linear prediction, 128–130, 138–144, 660–664
 - backward, 661–662
 - forward, 661–662
 - residuals, 663
- Linear predictive coding (LPC):
 - speech, 138–144
- Linear time-invariant system, 68–69
 - response to stochastic input, 68–72
- Linear transformation of random variables, 28–29, 50–52
- Link budget analysis, 316–319
- Link margin, 319
- Lloyd–Max quantizer, 113
- Lowpass signal, 155
- Lowpass system, 157
- Low probability of intercept, 696, 715–716

- Magnetic recording, 567–568
 - normalized density, 567
- Majority logic decoder, 506
- Mapping by set partitioning, 512
- Marginal probability density, 26
- Marcum's Q -function, 44
- Markov chain, 189
 - transition probability matrix of, 189
- Matched filter, 238–244
- Maximal ratio combining, 779
 - performance of, 780–782

- Maximum a posteriori probability (MAP)
 - criterion, 245, 254–257
- Maximum free distance codes, tables of, 492–496
- Maximum length shift-register codes, 433–435, 724–727
- Maximum likelihood:
 - parameter estimation, 333–335, 339–341
 - for carrier phase, 339–341
 - for joint carrier and symbol, 365–367
 - for symbol timing, 358–364
 - performance of, 367–370
- Maximum-likelihood criterion, 245–246
- Maximum-likelihood receiver, 233–257
- Maximum-likelihood sequence estimation (MLSE), 249–254
- Mean-square error (MSE) criterion, 607–617
- Mean value, 33
- Microwave LOS channel, 768–769
- Miller code, 188, 575
- Minimum distance:
 - bounds on, 461–464
 - definition, 416
 - Euclidean, 173
 - Hamming, 416
- Minimum-shift keying (MSK), 196–199
 - power spectrum of, 213–219
- Models:
 - channel, 375–386
 - source, 82–84, 93–95
- Modified duobinary signal, 549–550
- Modulation:
 - binary, 257–260
 - biorthogonal, 264–266
 - comparison of, 282–284
 - continuous-phase FSK (CPFSK), 190–191
 - power spectrum, 213–219
 - DPSK, 274–278
 - equicorrelated (simplex), 266
 - index, 191
 - linear, 174–186
 - power spectrum of, 204–209
 - M -ary orthogonal, 260–264
 - multichannel, 680–686
 - nonlinear, 190–203
 - offset QPSK, 198
 - PAM (ASK), 267–269
 - PSK, 269–274
 - QAM, 278–282
- Modulation codes, 566–576 (*See also* Partial response signals)
 - capacity of, 569
 - Miller code, 573
 - NRZ, 574
 - NRZI, 566, 568, 574–575
 - run-length limited, 568–576
- Modulation codes (*Cont.*):
 - run-length limited (*Cont.*):
 - fixed rate, 572
 - state dependent, 571
 - state independent, 571
- Modulator:
 - binary, 2
 - digital, 2
 - M -ary, 2
- Moments, 33
- Morse Code, 13
- Multicarrier communications
 - capacity of, 687–689
 - FFT-based system, 689–692
- Multichannel communications, 680–686
 - with binary signals, 682–684
 - with M -ary orthogonal signals, 684–686
- Multipath channels, 8, 758–839
- Multipath intensity profile, 762
- Multipath spread, 763
- Multiple access methods, 840–849
 - capacity of, 843–849
 - CDMA, 843, 849–862
 - FDMA, 842
 - random access, 962–872
 - TDMA, 842
- Multiuser communications, 840–872
- Multivariate gaussian distribution, 49–52
- Mutual information, 84
 - average, 87–88
- Mutually exclusive events, 18
- Narrowband interference, 704–706
- Narrowband process, 152
 - carrier frequency of, 153
- Narrowband signal, 152
- Noise:
 - gaussian, 162
 - white, 162–163
- Noisy channel coding theorem, 386–387
- Noncoherent combining loss 683–684
- Nonlinear distortion, 537
- Nonlinear modulation, 190
- Nonstationary stochastic process, 63
- Norm, 165
- Normal equations, 128
- Normal random variables (*see* Gaussian distribution)
- Null event, 18
- Null space, 416
- Nyquist criterion, 542–547
- Nyquist rate, 14, 72
- Offset quadrature PSK (OQPSK), 198
- On-off signalling (OOK), 321

- Optimum demodulation: (*see* Demodulation/Detection)
- Orthogonal signals, 165–166
- Orthogonality principle, mean-square estimation, 608
- Orthonormal:
 - expansion, 165–173
 - functions, 165–166
- Parity check, 417
 - matrix, 419
- Parity polynomial, 426
- Partial-band interference, 734–741
- Partial response signals, 548–560
 - duobinary, 548–549
 - error probability of, 562–565
 - modified duobinary, 549
 - precoding for, 551–555
- Partial-time (pulsed) jamming, 717–724
- Peak distortion criterion, 602–607
- Peak frequency deviation, 190
- Perfect codes, 453–454
- Periodically stationary, wide sense, 75–76, 205
- Phase jitter, 538
- Phase-locked loop (PLL), 341–346
 - Costas, 355–356
 - decision-directed, 347–350
 - M*-law type, 356–358
 - non-decision-directed, 350–351
 - square-law type, 353–355
- Phase-shift keying (PSK), 177–178, 269–274
 - adaptive reception of, 887–896
 - pdf of phase, 270–271
 - performance for AWGN channel, 271–274
 - performance for Rayleigh fading channel, 780–787, 887–894
- Plotkin bound on minimum distance, 462
- Power density spectrum, 67–68, 204–223
 - at output of linear system, 69
 - of digitally modulated signals, 204–223
- Prediction (*see* Linear prediction)
- Preferred sequences, 727
- Prefix condition, 96
- Probability:
 - a priori, 21
 - a posteriori, 21
 - conditional, 20, 26–28
 - of events, 18
 - joint, 19, 25–26
- Probability density function (pdf), 24
- Probability distribution function, 23
- Probability distributions, 37–52
 - binomial, 37–38
 - chi-square, 41–45
 - central, 42–43
 - noncentral, 42–44
- Probability distributions (*Cont.*):
 - gamma, 43
 - gaussian, 39–41
 - multivariate gaussian, 49–52
 - Nakagami, 48–49
 - Rayleigh, 45–46
 - Rice, 47–48
 - uniform, 39
- Probability transition matrix, 377
- Processing gain, 707
- Pseudo-noise (PN) sequences:
 - autocorrelation function, 725–726
 - generation via shift register, 724–729
 - Gold, 727
 - Kasami, 729
 - maximal-length, 725–726
 - peak cross-correlation, 726–727
 - preferred, 727
 - (*See also* Spread spectrum signals)
- Pulse amplitude modulation (PAM), 174–176, 267–269
- Pulse code modulation (PCM), 125–133
 - adaptive (ADPCM), 131–133
 - differential (DPCM), 127–129
- Pulsed interference, 717
 - effect on error rate performance, 717–724
- Quadrature amplitude modulation (QAM), 178–180, 278–282
- Quadrature components, 155
 - of narrowband process, 155–156
 - properties of, 161–162
- Quantization, 108–125
 - block, 118–125
 - optimization (Lloyd–Max), 113–118
 - scalar, 113–118
 - vector, 118–125
- Quantization error, 125–133
- Quasiperfect codes, 454
- Raised cosine spectrum, 546
 - excess bandwidth, 546
 - rolloff parameter, 546
- RAKE correlator, 797–798
- RAKE receiver:
 - for binary antipodal signals, 798–803
 - for binary orthogonal signals, 801–802
 - for DPSK signals, 804
 - for noncoherent detection of orthogonal signals, 805
- RAKE matched filter, 799–800
- Random access, 862–872
 - ALOHA, 863–867
 - carrier sense, 867–872
 - with collision detection, 868
 - non persistent, 868

- Random access (*Cont.*):
 - carrier sense (*Cont.*):
 - 1-persistent, 869
 - p -persistent, 869
 - offered channel traffic, 864
 - slotted ALOHA, 864
 - throughput, 865–867
 - unslotted, 864
- Random coding, 390–400
 - binary coded signals, 390–397
 - multiampitude signals, 397–399
- Random Processes (*see* Stochastic processes)
- Random variables, 22–28
 - function of, 28–32
 - multiple, 25
 - orthogonal, 35
 - single, 22–24
 - statistically independent, 28
 - sums of, 58–63
 - central limit theorem, 61–62
 - transformation of, 28–32
 - Jacobian of, 32
 - linear, 28, 32, 49–52
 - uncorrelated, 34
- Rate:
 - code, 2, 414
 - of encoded information (*see* Source encoding)
- Rate distortion function, 108–113
 - of bandlimited gaussian source, 112
 - of memoryless gaussian source, 109–110
 - table of, 112
- Rayleigh distribution, 45–46
- Rayleigh fading (*see* Channel, fading multipath; Channel, Rayleigh fading)
- Reciprocal polynomial, 426
- Recursive least squares (RLS) algorithms, 654–664
 - fast RLS, 660
 - RLS Kalman, 656–660
 - RLS lattice, 660–664
- Reed-Solomon codes, 464–466
- References, 899–916
- Reflection coefficients, 140
- Regenerative repeaters, 314–316
- Residuals, 663
- Rice distribution, 47–48
- Ricean fading channel, 761
- Run-length limited codes, 568–576
 - fixed rate, 572
 - state dependent, 571
 - state independent, 571
- Sample function, 63
- Sample mean, 58
- Sample space, 17–18
- Sampling theorem, 72–73
- Scattering function, 766
- Self-information, 85
 - average (entropy), 88
- Sequential decoding, 501–503
- Set partitioning, 512
- Shannon limit, 264
- Shortened code, 421
- Signal constellations:
 - PAM, 174–176
 - PSK, 177–178
 - QAM, 178–180
- Signal design, 540–576
 - for band-limited channel, 540–551
 - for channels with distortion, 557–560
 - for no intersymbol interference, 540–547
 - with partial response pulses, 548–551
 - with raised cosine spectral pulse, 546–547
- Signal-to-noise ratio (SNR), 258
- Signals:
 - bandpass, 152–157
 - baseband, 176, 186–189
 - binary antipodal, 257
 - binary coded, 266–267
 - binary orthogonal, 258
 - biorthogonal, 183–184, 264–266
 - carrier of, 159
 - characterization of, 152–163
 - complex envelope of, 155
 - digitally modulated, 173–209
 - cyclostationary, 204–206
 - representation of, 173–202
 - spectral characteristics of, 202–223
 - discrete-time, 74–76
 - energy of, 156
 - envelope of, 155
 - equivalent lowpass, 155
 - lowpass, 155
 - M -ary orthogonal, 181–183
 - multiampitude, 174–176
 - multidimensional, 180–181
 - multiphase, 177–178
 - narrowband, 152
 - optimum demodulation of, 233–257
 - quadrature amplitude modulated (QAM), 178–180
 - quadrature components of, 155–156
 - properties of, 161–162
 - simplex, 184, 266
 - speech, 143–144
 - stochastic, 62–77, 159–163
 - autocorrelation of, 64, 68–70, 75–76
 - autocovariance, 64
 - bandpass stationary, 159–163
 - cross correlation of, 65

Signals (*Cont.*):stochastic (*Cont.*):

- ensemble averages of, 64–65
- power density spectrum, 67–68, 204–223
- properties of quadrature components, 161–162
- white noise, 162–163

Signature sequence, 843

Simplex signals, 266

Single-sideband modulation, 176

Skin depth, 9

Slope overload distortion, 134

Slope overload distortion, 134

Soft decision decoding:

- block codes, 436–445
- convolutional codes, 486–489

Source:

- analog, 82–83
- binary, 83
- discrete memoryless (DMS), 82–83
- discrete stationary, 103–106
- encoding, 93–144
 - adaptive DM, 135–136
 - adaptive DPCM, 131–133
 - adaptive PCM, 131–133
 - delta modulation (DM), 133–136
 - differential pulse code modulation (DPCM), 127–129
 - discrete memoryless, 94–103
 - Huffman, 99–103
 - Lempel–Ziv, 106–108
 - linear predictive coding (LPC), 138–142
 - pulse code modulation (PCM), 125–127
- models, 82–84
- speech, 143–144
- spectral, 136–138
- waveform, 125–144

Source coding, 82–144

Spaced-frequency, spaced-time correlation function, 763

Spectrum:

- of CPFSK and CPM, 209–219
- of digital signals, 203–223
- of linear modulation, 204–209
- of signals with memory, 220–223

Spread factor, 771

table of, 771

Spread spectrum multiple access (SSMA), 716

Spread spectrum signals:

- acquisition of, 774–748
- for antijamming, 712–715
- for code division multiple access (CDMA), 696, 716–717, 741–743
- concatenated codes for, 711–712, 740–741
- direct sequence, 697–700
 - applications of, 712–717
 - coding for, 710–712

Spread spectrum signals (*Cont.*):direct sequence (*Cont.*):

- demodulation of, 701–702
 - performance of, 702–712
 - with pulse interference, 717–724
- examples of DS, 712–717
- frequency-hopped (FH), 729–743
- block hopping, 731
 - follower jammer for, 731
 - performance of, 732–734
 - with partial-band interference, 734, 741
- hybrid combinations, 743–744
- for low-probability of intercept (LPI), 696, 715–716
- for multipath channels, 795–806
- synchronization of, 744–752
- time-hopped (TH), 743
- tracking of, 748
- uncoded PN, 708

Spread spectrum system model, 697–698

Square-law detection, 306

Square-root factorization, 660, 897–898

Staggered quadrature PSK (SQPSK), 198

State diagram, 196, 474–477

Stationary stochastic processes, 63–64

- strict-sense, 63–64
- wide-sense, 64

Statistical averages, 64–67

Steepest-descent (gradient) algorithm, 639–642

Stochastic process, 62–72, 159–163

- cyclostationary, 75–76
- discrete-time, 74–76
- narrowband, 159
- nonstationary, 63
- strict-sense stationary, 63–64
- wide-sense stationary, 64

Storage channel, 10

Strict-sense stationary, 63–64

Subband coding, 137

Symbol interval, 174

Synchronization:

- carrier, 337–358
 - effect of noise, 343–346
 - for multiphase signals, 356–358
 - with Costas loop, 355–356
 - with decision-feedback loop, 347–350
 - with phase-locked loop (PLL), 341–346
 - with squaring loop, 353–355
- of spread spectrum signals, 744–752
- sliding correlator, 747
- symbol, 336–337

Syndrome, 446

Syndrome decoding, 446–451

System, linear, 68–72

autocorrelation function at output, 69

- System, linear (*Cont.*):
 - bandpass, response of, 157–159
 - power density spectrum at output, 69–70
- Systematic code, 418
- Tail probability bounds, 53–57
 - Chebyshev inequality, 53–54
 - Chernoff bound, 54–57
- TATS (tactical transmission system), 741–743
- Telegraphy, 13
- Telephone channels, 4, 563–538
- Thermal noise, 3, 11
- Threshold decoder, 506
- Time diversity, 777
- Time division multiple access (TDMA), 842–844
- Toeplitz matrix, 879
- Transfer function:
 - of convolutional code, 477–483
 - of linear system, 68–72
- Transformation of random variables, 29–32, 49–52
- Transition probabilities, 189
- Transition probability matrix, 189
 - for channel, 375–378
 - for delay modulation, 189–190
- Tree diagram, 192–195, 471–472
- Trellis-coded modulation, 511–526
 - free Euclidean distance, 517
 - subset decoding, 519
 - tables of coding gains for, 522–523
- Trellis diagram, 473
- Uncorrelated random variables, 34
- Uniform distribution, 39
- Union bound, 263–264, 387–389
- Union of events, 18
- Uniquely decodable, 96
- Universal source coding, 106
- Variable-length encoding, 95–103
- Variance, 33
- Vector space, 163–165
- Vector quantization, 118–125
- Viterbi algorithm, 251, 287–289, 483–486
- Vocal tract, 141–143
- Voltage-controlled oscillator (VCO), 341–343
- Weak law of large numbers, 59
- Weight:
 - of code word, 414
 - distribution, 414
 - for Golay, 423
- Welch bound, 728
- White noise, 162–163
- Whitening filter, 587–588
- Wide-sense stationary, 64
- Wiener filter, 14
- Yule–Walker equations, 128
- Z transform, 587
- Zero-forcing equalizer, 602–605
- Zero-forcing filter, 603–604