

INDEX

- 2-D Fourier transform, 333
- 2-D sampling theorem, 334
- A/D converter, 320
 - MATLAB functions, 323
 - parallel or flash, 322
 - serial or integrating, 321
 - successive approximation, 321
- Absolute specifications, 538, 608
- Accumulated window amplitude function, 560, 608
- ACRS, 885
- ACVS, 885
- Adder, 486, 522
- adder, 35
- additivity property, 33
- Adjustable windows, 608
- Affine estimator, 793, 885
- aliasing, 295, 301
 - in nonbandlimited signals, 307
 - in sinusoidal signals, 302
 - time-domain, 367
- aliasing distortion, 295, 340
- allpass reverberator unit, 252
- allpass systems, 216, 249, 275
- All-pole lattice structure, 516, 522
- All-pole signal modeling, 866
- All-pole speech signal modeling, 875
- All-pole system, 522
- All-zero lattice structure, 511, 522
- All-zero system, 522
- Alternation theorem, 585
 - for FIR filters, 588
- Amplitude response function, 549, 608
 - computation, 551
 - unified representation, 552
- amplitude spectrum, 189
- analog frequency, 189
- Analog lowpass filters, design of, 627
 - specifications, 628
 - system function from magnitude response, 628
- analog representation, 7, 20
- analog signal, 4
- Analog Specifications, 608
- analog-to-digital (A/D) converter, 20
 - ideal, 12
- analog-to-digital conversion, 318
- Analysis filter, 810
- Analysis filter bank, 746, 764
- Angle response, 608
- ANSI/IEEE standard 754-1985, 909
- Antialiasing filter, 727
- Anti-imaging postfilter, 727
- Antialiasing filter, 953
- Antialiasing filter design in oversampling, 920
- apparent frequency, 302, 304, 340
- AR modeling, 866
- arbitrary band positioning, 340
- audio analog recording system, 3
- audio signals, 30
- autocorrelation sequence, 187, 189
- Autocorrelation sequence (ACRS), 799, 816
- Autocovariance sequence (ACVS), 799, 816
- Autoregressive (AR) process, 811, 812, 816
- Autoregressive moving average (ARMA) processes, 810, 816
- Average power, 807, 822
- Backward linear predictor, 871
- Band-edges, 608
- bandlimited bandpass signal, 340
- bandlimited lowpass signal, 340
- bandwidth, 404
- Bartlett estimator, the, 855
- Bartlett window, 560
- Basic elements, 522

- Bessel function, zeroth-order modified, 567
- Best uniform approximation, 543
- Bi-orthogonal filter bank, 751, 764
- Bias of an estimator, 831, 885
- Bilinear transformation, 660, 687
 - design procedure, 666
 - frequency warping, 664
 - mapping properties, 663
 - MATLAB functions, 662
 - realizability, 661
- binary code, 8, 20
- Binary fixed-point number representation, 903, 953
- Binary floating-point representation, 953
- Binary number representation, 953
- Binary point, 953
- Binary representation range, 904
- Binary representation resolution, 904
- bit-reversed ordering, 470
- Blackman window, 561
- Blackman-Tukey method, the, 849
 - computation of, 852
 - mean of, 851
 - variance of, 852
- Blackman-Tukey PSD estimator, the, 849, 885
- Block diagram, 486, 522
- block-processing, 57
- butterfly computation, 470
- Butterworth approximation, 543, 608
- Butterworth approximation, the analog, 629, 687
 - definition and properties, 629
 - design procedure, 631
 - MATLAB functions, 632
 - pole locations, 630
- Butterworth filter, 687

- Canonical direct form structure, 491
- Canonical structure, 522
- Cascade form structure, 522
 - FIR, 501, 502
 - IIR, 488, 494
- Cauer approximation, the, 648
- Cauer filters, 649, 687
- Chebyshev approximation, 543, 608
- Chebyshev approximation, the analog, 687
 - Chebyshev filter, 688
 - Chebyshev I approximation, the analog, 634
 - definition and properties, 635
 - design procedure, 640
 - MATLAB functions, 640
 - pole locations, 637
 - Chebyshev II approximation, the analog, 643
 - design procedure, 644
 - MATLAB functions, 645
- Chebyshev polynomials, 582, 608
 - definition and properties, 582
- Chebyshev's theorem, 584
- chirp signal, 206, 470
- chirp transform algorithm, 470
 - computation, 464
 - definition, 462
- chirp z-transform, 464, 470
- circular addressing, 419
- circular buffer, 419
- circular convolution, 419
- circular folding, 419
- circular shift, 419
- circular-even symmetry, 419
- circular-odd symmetry, 419
- Coloring filter, 810, 868
- comb filters, 242, 275
- comb reverberator unit, 242
- Commutator structure, 733
- complex bandpass filters, 244
- complex exponentials
 - harmonically related, 137
 - orthogonality property, 137
- complex reciprocal zero, 249
- Compressor, 706
- Computation of ripple, 558
- Computational complexity, 488
- computational cost or complexity, 470
- Condition for perfect reconstruction, 750
- Conditional pdf, 787
- Conjugate quadrature filters (CQF), 752
 - design procedure, 754
- Consistency, 831
- Consistent estimator, 831
- continuous phase function, 207, 275
- Continuous random variable, 780, 816

- continuous-time Fourier series (CTFS), 143, 189
 - amplitude spectrum, 144
 - Dirichlet conditions, 147
 - discrete or line spectrum, 144
 - Gibbs phenomenon, 149
 - magnitude spectrum, 144
 - Parseval's relation, 144
 - phase spectrum, 144
 - power spectrum, 144
 - rectangular pulse train, 145
 - spectrum, 143
- continuous-time Fourier transform (CTFT), 150, 189
 - convergence, 153
 - CTFT pair, 153
 - direct, 152
 - energy-density spectrum, 154
 - inverse, 153
 - Parseval's relation, 154
 - spectrum, 153
- Continuous-time lowpass filters, design of, 627
- continuous-time LTI systems
 - allpass, 270
 - eigenfunctions, 259
 - eigenvalues, 259
 - frequency response function, 259
 - frequency response, geometric computation, 266
 - frequency response, MATLAB computation, 267
 - ideal filters, 273
 - minimum-phase, 270
 - minimum-phase and allpass decomposition, 273
 - poles, 263
 - rational system function, 263
 - stability, 266
 - system function, 259
 - zeros, 263
- continuous-time signal, 4
- continuous-time sinusoids, 135
- Continuous-time stochastic process, 797
- Continuous-time to discrete-time filter transformations, 653
- Conversion
 - structure, 519
- convolution, 75
 - associative property, 46
 - commutative property, 45
 - distributive property, 47
 - periodic sequences, 49
- convolution integral, 70
- convolution sum, 40
 - analytical evaluation, 50
 - numerical computation, 55
- corelation of signals
 - computation in MATLAB, 187
- Correlation, 788, 790, 792, 816
 - properties, 801
- Correlation coefficient, 789, 816
- correlation coefficient, 186, 189
- Correlation matrix, 792
- correlation of signals, 186
- correlation sequence, 189
- Correlation window, 846
- Cosine-modulated filter bank, 762
- Covariance, 788, 792, 816
 - properties, 801
- Covariance matrix, 791, 816
- Cross-correlation sequence, 800
- Cross-covariance sequence, 800
- CTFS, 419
- CTFT, 419
- Cumulative distribution function (CDF), 782, 816
- Cutoff frequency, 608
- D/A converter
 - characteristic pulse, 324
 - example, sinusoidal signals, 325
 - MATLAB functions, 327
 - practical, 324
- DAC compensation, 598
- Data, 885
- Data window, 846
- data window, 419
- Decimation, 713, 764
 - MATLAB functions for, 713
 - two stage, 741
- decimation-in-frequency (DIF) FFT, 470
- decimation-in-time (DIT) FFT, 470
- Decimator, 713
- delay distortion, 275
- Delay element, unit, 486

- Design of continuous-time lowpass filters, 627
- Desired filter, 541
- Deterministic ACRS, 805
- Deterministic signals, 778
- DFS, 419
- DFT, 419
- DFT matrix, 419, 471
- Differentiators, discrete-time, 601
- Digital differentiator, 608
- Digital Hilbert transformer, 608
- digital image, 59
- digital recording system, 3
- digital representation, 7, 20
- digital signal, 5
- digital signal processing, 14, 21
 - applications, 16
- digital-to-analog (D/A) converter, 12, 21
 - ideal, 12
- direct DFT algorithm, 471
- Direct form for linear-phase FIR systems, 503
- Direct form I structure, 488, 522
- Direct form II structure, 490, 522
- Direct form structure, 522
 - FIR, 501
 - IIR, 488
- Dirichlet's conditions, 189
- Dirichlet's function, 189
- discrete Fourier series (DFS)
 - definition, 363
 - inverse, 363
- Discrete Fourier Transform (DFT), 471
- discrete Fourier transform (DFT), 353, 357
 - algebraic formulation, 358
 - circular buffer, 376
 - circular convolution, 385
 - circular correlation, 389
 - circular folding or reversal, 376
 - circular shift, 383
 - circular symmetry, 378
 - computation, 361
 - computing linear convolution, 392
 - computing the CTFS, 355
 - computing the CTFT, 354
 - computing the DTFT, 355
 - decomposition into symmetric components, 380
 - definition, 358
 - DFT matrix, 360
 - fast Fourier transform or FFT, 358
 - implementation of FIR filters using, 394
 - inverse, 358
 - linearity, 374
 - matrix formulation, 360
 - modulo-N operations, 375
 - of two real valued sequences, 382
 - overlap-add method, 395
 - overlap-save method, 395
 - periodicity, 362
 - properties, 374
 - relationship to other transforms, 372
 - roots of unity, 359
 - stretched and sampled sequences, 390
 - summary of properties, 391
 - symmetry properties, 378
 - twiddle factor, 358
- Discrete random variable, 780, 816
- Discrete wavelet transform, 763
- discrete-time Fourier series (DTFS), 157, 189
 - Dirichlet's function, 161
 - DTFS pair, 158
 - numerical computation, 162
 - Parseval's relation, 158
 - periodic impulse train, 159
 - power spectrum, 159
 - rectangular pulse train, 160
- discrete-time Fourier transform (DTFT), 163, 190
 - conjugation of complex sequence, 183
 - convergence, 168
 - convolution of sequences, 183
 - differentiation in frequency, 183
 - DTFT pair, 166
 - energy-density spectrum, 167
 - frequency shifting, 181
 - ideal low-pass sequence, 177
 - linearity, 181
 - magnitude spectrum, 166
 - modulation, 181
 - multiplication of sequences, 184
 - numerical computation, 168
 - Parseval's relation, 167
 - Parseval's theorem, 184
 - phase spectrum, 166
 - properties, 171
 - reconstruction from samples, 369
 - relationship to z-transform, 172

- sampling, 363
- sampling, example, 367
- spectrum, 166
- symmetry, 173
- time reversal, 183
- time shifting, 181
- windowing theorem, 184
- zero padding, 369
- discrete-time oscillator, 275
- discrete-time resonator, 275
- discrete-time resonators, 238
- Discrete-time sampling rate, 764
- discrete-time signal, 4
- discrete-time sinusoidal oscillators, 240
- discrete-time sinusoids, 138
 - orthogonality property, 140
- Discrete-time stochastic process, 797
- distortionless system, 275
- divide-and-conquer approach, 471
- Downsampler, 706, 764
- downsampler, 34
- Downsampling, 707
- DTFS, 419
- DTFT, 419
- echo generation, 68
- effective continuous-time filter, 314, 340
- Effective number of bits (ENOB), 914
- eigenfunctions of LTI systems, 275
- Elliptic approximation, the analog, 688
 - MATLAB functions, 650
- Elliptic filters, 649, 688
- energy density spectrum, 190
- energy or power gain, 275
- equalizers, 257
- Equiripple optimum design method, 586
 - FDATool, 599
 - obtaining the optimum approximation, 590
 - practical considerations, 592
 - problem formulation, 586
 - specification, 588
- Equiripple property, 584, 609
- Ergodicity, 835, 885
- Estimate, 793, 830, 885
- Estimation of ACVS/ACRS, 836
- Estimation of mean, 836
- Estimation of mean, variance, and covariance, 830
- Estimation of variance, 838
- Estimator, 793, 830, 885
 - affine, 793
 - consistent, 831
 - linear, 794
 - optimum linear mse, 864
- Events, 779, 816
- Excess mse, 864
- Expectation, mathematical, 783, 816
 - joint, 787
 - marginal, 783
- Extraripple FIR filter, 590, 609
- Extremal frequencies, 609
- Failure of the periodogram, 848
- Fast Fourier Transform (FFT), 471
- Fast Fourier Transform (FFT) algorithms, 434
 - algebraic approach, 440
 - bit reversed order, 445
 - bit-reversed ordering, 444
 - bit-reversed shuffling, 457
 - butterfly computations, 457
 - decimation-in-frequency, 451
 - decimation-in-frequency butterfly, 453
 - decimation-in-time, 441
 - decimation-in-time butterfly, 443
 - direct computation, 435
 - divide-and-conquer approach, 436
 - fastest Fourier transform in the west, 458
 - generalized FFTs, 454
 - Goertzel's algorithm, 460
 - identical geometry, 450
 - indexing, 457
 - MATLAB function, 448
 - MATLAB native functions, 458
 - matrix approach, 436
 - memory management, 457
 - merging, 444
 - mixed radix FFTs, 456
 - natural order, 445, 448
 - prime factor algorithms, 456
 - recursive computation, 439
 - reverse carry algorithm, 446
 - shuffling, 443
 - split radix FFTs, 456
 - transposed FFT structures, 454
 - twiddle factors, 457
 - Winograd Fourier transform algorithms, 456

- FDATool, 609
- FDATool for equiripple filter design
 - for equiripple filter design, 599
- FDATool for IIR filter design
 - for IIR filter design, 685
- FDATool for special FIR filter designs
 - for special FIR filter designs, 606
- FDATool for window design
 - for window design, 572
- FTW algorithms, 471
- filter, 31
- Filter bank, 746, 764
 - analysis, 746
 - bi-orthogonal, 751
 - cosine-modulated, 762
 - maximally decimated, 747
 - modulated, 760
 - multichannel, 759
 - near-perfect reconstruction, 751, 761
 - nonuniform, 746
 - orthogonal, 751, 753
 - para-unitary, 751
 - Perfect reconstruction orthogonal FIR, 751
 - pseudo-QMF, 762
 - quadrature-mirror, 756, 757
 - synthesis, 746
 - tree-structured, 762
 - two-channel, 746
 - uniform, 746
 - uniform DFT, 761
- filter design
 - by pole-zero placement, 237
- Filter design problem, the, 538
- Filter specifications, 538
 - continuous-time, 540
- Filter structures
 - polyphase, 730
- filters
 - bandwidth, 221
 - cutoff frequencies, 221
 - frequency-selective, 221
 - ideal bandpass, 221
 - ideal bandstop, 222
 - ideal frequency-selective, 221
 - ideal highpass, 222
 - ideal lowpass, 222
- finite impulse response (FIR) systems, 45
- Finite precision, 953
- Finite precision arithmetic, 488
- Finite wordlength effects, 902, 953
 - digital filters, 936
 - FFT algorithms, 950
- FIR filter design, 537
 - equiripple optimum Chebushev, 586
 - frequency-sampling, 573
 - optimality criteria, 542
 - special filters, 601
 - using adjustable Kaiser window, 566
 - using fixed windows, 564
 - windowing, 556
- FIR filters
 - real-time implementation, 57
- FIR linear-phase filters, 544
 - amplitude response function, 549
 - type-I, 546
 - type-II, 547
 - type-III, 548
 - type-IV, 549
 - zero locations, 552
- FIR spatial filters, 59
- FIR system, 76
- FIR system structures, 501
- FIR versus IIR filters, 626
- Fixed windows, 609
- Fixed-point format, 903
- Floating-point representation, 909
- folding frequency, 296, 305, 340
- Formant frequencies, 875
- Formants, 876
- Forward linear predictor, 866
- Fourier analysis using the DFT, 396
- Fourier representation
 - continuous-time signals, 142
 - discrete-time signals, 157
 - summary, 169
- Fourier series
 - continuous-time periodic signals, 143
- Fractional delay, 724, 764
- fractional delay, 216
- frame-processing, 57
- frequency, 135
 - angular or radian, 135
 - fundamental range, 140
 - negative, 135
 - normalized, 138

- normalized angular, 138
- variables and units, 141
- Frequency band transformations, 673, 688
 - continuous-time, 674
 - discrete-time, 676
- Frequency domain effects of truncation, 556
- frequency response for rational system
 - functions, 224
 - computation, 226
 - geometrical evaluation, 231
 - group delay computation, 227
 - interactive visualization tool, 228
 - time-, frequency-, and z-domain, 236
- frequency response function, 275
- Frequency sampling design method
 - basic design approach, 573
 - better design approaches, 574
 - design procedure, 577
 - linear-phase FIR filter design, 574
 - MATLAB functions, 580
 - non-rectangular window design approach, 576
 - optimal design approach, 575
 - smooth transition band approach, 575
- Frequency sampling form structure, 501, 508, 522
- Frequency Selective Filters, 537, 609
- frequency transformations, 243, 246
- Frequency transformations of lowpass filters, 673
- Frequency warping, 688
- frequency-domain sampling effects, 408
- fundamental frequency, 190
- fundamental harmonic, 190
- fundamental period, 27, 76, 190
- Gaussian distribution, 784
 - unit, 785
- Gaussian noise process, 810
- Gaussian pulse, 419
- Generalized linear phase, 551
- Goertzel's algorithm, 471
- Granular limit cycles, 949, 953
- Granular noise, 910, 953
- group delay, 275
- guard band, 296, 340
- Half-band filter, 736, 764
- Half-band filter design, 738
- Half-band FIR filters, 736
- Hamming window, 561
- Hann window, 561
- harmonic frequencies or harmonics, 190
- Harmonic process models, 814, 816
- harmonically-related complex exponentials, 190
- Hilbert transform, discrete, 542
- Hilbert transformers, discrete-time, 603
- Histogram, 780
- homogeneity property, 33, 76
- Horner's rule, 460, 471
- Hotelling transform, 880
- ideal ADC, 311
- ideal analog-to-digital converter (ADC), 293
- ideal bandlimited interpolation, 299, 340
- ideal bandlimited interpolator, 315
- ideal DAC, 314
- ideal digital-to-analog converter (DAC), 340
- Ideal discrete-time interpolator, 764
- ideal frequency-selective filters, 275
- Ideal half-band filters, 736
- ideal sampler, 293
- ideal sampling, 340
- IDFS, 419
- IDFT, 419
- IFIR filter design, 744
- IIR filter design, 624
 - FDATool, 685
 - introduction, 625
- IIR system structures, 488
- Image polynomial, 513
 - image reconstruction, 333
- image sampling
 - 2-D interpolation function, 337
 - aliasing, 335
 - ideal reconstruction, 337
 - Moire patterns, 335
 - visual effects, 335
- Impulse response, multiband filter, 570
- Impulse-invariance transformation, 653, 688
 - design procedure, 657
 - mapping, 654
 - MATLAB functions, 656
- impulse-invariance transformation, 340
- in-place algorithm, 471

- infinite impulse response (IIR) systems, 45, 76
- Infinite precision (accuracy), 902, 953
- inherent periodicity, 419
- Input A/D quantization noise through
 - discrete-time systems, 916
- instantaneous frequency, 206
- integer-band positioning, 340
- Integral of window amplitude function, 563
- Interpolated FIR (IFIR) filters, 742, 744, 764
- interpolation, 764
- Interpolation, 298, 340
 - linear, 722
 - MATLAB functions for, 719
- interpolation function, 298
- Interpolator, 718
- inverse system, 254
- inversion of nonminimum phase systems, 257
- invertible system, 275

- Joint pdf, 786, 816
- Jointly distributed random variables, 786
- Jointly wide-sense stationary random process, 800

- K*th-band filter, 737, 765
- K*th-band FIR filters, 736
- Kaiser window, 566
- Kaiser window empirical design equations, 567
- Karhunen-Loeve transform (KLT), 877, 878, 880, 885
 - geometric interpretation, 882
 - in practice, 881

- Lag variable, 799
- Lag window, 846
- Lagrange interpolation, 372
- Laplace transform
 - convolution property, 262
 - definition, 260
 - differentiation property, 262
 - integration property, 262
 - linearity property, 261
 - region of convergence (ROC), 260
 - time-delay property, 262
- latency, 57
- Lattice structure, 511, 523
- Lattice structure for linear prediction, 870
- Lattice-ladder structure, 519, 523

- leakage, 403
- Leakage
 - spectral, 844
- Least significant bit (LSB), 903
- Levinson-Durbin algorithm, 812, 813, 868
- Limit cycle oscillations, 949, 953
- linear constant coefficient difference equation
 - (LCCDE), 66, 76, 110
 - all-pole system, 113
 - all-zero system, 113
 - analysis with MATLAB, 114
 - computation, 67
 - finite impulse response (FIR) system, 113
 - infinite impulse response (IIR) system, 113
 - initially at rest, 65, 110
 - nonrecursive system, 113
 - order of, 66
 - recursive system, 113
 - steady-state response, 64, 76
 - time-invariant, 66
 - transient response, 64, 77
 - zero-input response, 63, 77
 - zero-state response, 63, 77
- Linear estimation, 792
- Linear estimator, 885
- linear FM pulse, 206, 275
- linear FM signal, 414
- Linear interpolation, 765
- Linear minimum mse estimator, 794
- Linear prediction, 866
 - in practice, 873
 - non-windowing method, 875
 - windowing method, 874
- Linear predictor, 885
- Linear processes, 810, 816
- Linear vs affine estimator, 794
- Linear-phase filters, 609
- Linear-phase form structure, 501, 523
- Linear-phase system, 523
 - Direct form, 503
- lowpass antialiasing filter, 340
- LTI system
 - all-pole, 122
 - all-zero, 122
 - causal, 47, 74
 - continuous-time, 69
 - FIR, 122

- IIR, 122
 - impulse response, 122
 - stable, 47, 74
 - step response, 49
 - causal and stable system, 109
 - causality, 108
 - distortionless response, 215
 - eigenfunction of continuous-time, 136
 - eigenfunctions, 90, 202
 - eigenvalues, 90, 136
 - energy or power gain, 214
 - frequency response function, 202
 - gain response, 204
 - generalized linear phase, 219
 - group delay, 218
 - magnitude distortion, 216
 - magnitude response, 204
 - phase or delay distortion, 217
 - phase response, 204
 - response to aperiodic inputs, 212
 - response to periodic inputs, 210
 - stability, 108
 - steady-state response, 208
 - system function, 106
 - transform analysis, 201
 - transient response, 208
-
- magnetic tape system, 2
 - magnitude distortion, 275
 - magnitude response, 275
 - magnitude spectrum, 190
 - Matched filter, 860, 885
 - MATLAB functions for analog Butterworth approximation, 632
 - MATLAB functions for analog ChebYshev I approximation, 640
 - MATLAB functions for analog Chebyshev II approximation, 645
 - MATLAB functions for analog elliptic approximation, 650
 - MATLAB functions for Bilinear transformation, 662
 - MATLAB functions for decimation, 713
 - MATLAB functions for frequency-sampling design, 580
 - MATLAB functions for impulse-invariance, 656
 - MATLAB functions for interpolation, 719
 - MATLAB functions for pairing and ordering, 946
 - MATLAB functions for rational rate conversions, 735
 - MATLAB functions for window design, 571
 - Maximally decimated multirate filter bank, 747
 - maximally flat magnitude filters, 630
 - Maximally flat multirate filter bank, 765
 - Maximally-flat approximation, 543, 609
 - maximum phase system, 256
 - maximum-phase system, 275
 - Mean sequence, 817
 - Mean squared error, 831
 - Mean squared error (mse), 793
 - Mean value, 782, 816
 - Mean vector, 791
 - Mean-squared-error approximation, 542
 - merging formula, 471
 - Method of principal components, 880
 - Minimax approximation, 543, 582, 609
 - optimality, 584
 - minimum delay property, 255
 - minimum phase and allpass decomposition, 254
 - minimum-phase system, 254, 275
 - Mirroe-image symmetry, 553
 - Mirror-image polynomial, 553, 609
 - mixed phase system, 256
 - mixed radix FFT algorithms, 471
 - mixed-phase system, 275
 - mixed-signal processing, 16
 - Modified periodogram, the, 845
 - Modulated filter bank, 765
 - modulo-N operation, 419
 - Moire pattern, 340
 - Most significant bit (MSB), 903
 - Moving average (MA) process, 811, 817
 - MSE approximation, 609
 - Multiband filter impulse response, 570
 - Multichannel filter bank, 759
 - Multiplier, 523
 - multiplier, 35
 - Multirate identities, the, 729, 765
 - Multirate signal processing, 705
 - Multirate systems, 705, 765
 - filter design, 736
 - implementation, 727
 - Multistage decimation and interpolation, 739

- Multistage noise shaping (MASH), 926
- Mulyiplier, 486
- n-domain, 89
- natural order, 471
- Near-perfect reconstruction filter bank, 751, 761
- Noise shaping converter, 953
- Nominal value, 609
- Nonnegative definite, 792
- Nonnegative definite matrix, 817
- Nonuniform filter bank, 746
- Normal distribution, 784, 817
- Normal equations, 863, 864, 885
- Normal form structure, 487, 523
- Normal random vector, 792, 817
- Normalized FIR system, 513
- normalized frequency, 190
- Normalized PARCOR coefficients, 873
- notch filters, 240, 275
- Number representation, 903, 953
- Nyquist filter, 737, 765
- Nyquist frequency, 296, 340
- Nyquist rate, 296, 340

- Octave-band filter bank, 765
- Octave-band tree structure, 762
- Optimum FIR filtering, 864
- Optimum linear filters, 858
- Optimum linear mse estimator, 864
- Optimum orthogonal transforms, 877
- Orthogonal filter bank, 765
- Orthogonal random variables, 789, 817
- Orthogonal transforms, 877
- Orthogonality principle, 864, 885
- orthogonality property, 190
- Outcome, 817
- Output round-off noise variance, 938
- Output signal-to-noise ratio (SNR), 859
- Overflow condition, 906, 953
- Overflow limit cycles, 949, 950, 953
- overlap-add method, 419
- overlap-save method, 420
- Overload distortion, 910
- Overload noise, 953

- Oversampled A/D conversion, 919, 953
 - resolution, 922
 - with direct quantization, 919
 - with noise shaping, 923
- Oversampled D/A conversion, 953
 - with noise shaping, 927
- Oversampling ratio (OSR), 920

- Pairing and ordering in cascade form, 945, 953
 - MATLAB functions, 946
- Paley-Wiener condition, 810
- Paley-Wiener theorem, 541
- Para-unitary filter bank, 751
- Parallel form structure, 497, 523
 - IIR, 488
- Parks-McClellan algorithm, 586, 590, 609
 - flow-chart, 593
- Parseval's relation for the DFT, 892
- Partial correlation (PARCOR), 873
- partial fraction expansion, 122
- Parzen window, 850
- Passband, 609
- passband ripple, 539
- Perfect reconstruction, 765
- Perfect reconstruction orthogonal FIR filter bank, 751
 - periodic extension, 366, 420
 - periodic replication, 366
 - periodization, 366
- Periodogram, the, 839, 885
 - averaging, 855
 - covariance of, 845
 - failure of, 848
 - mean of, 843
 - modified, 845
 - smoothing, 849
 - statistical properties, 841
 - variance of, 845
- phase distortion, 275
- phase response, 275
- phase spectrum, 190
- picture element, 5
- pixel, 5, 59
- pole-zero pattern rotation, 243
- Polyphase filter structures, 765
 - for decimation and interpolation, 731
- Polyphase representation, 765
- Post aliasing distortion, 718

- Power complementary filters, 752
- Power spectral density, 806, 817
 - auto-, 806
 - cross-, 808
- power spectrum, 190
- practical DAC, 340
- Practical filter, 541
- practical or nonideal filters, 275
- Prediction error filter, 868
- Prewarping, 665, 688
- prime factor algorithm (PFA), 471
- Principal component transform, 877
- principal phase function, 207, 275
- principal value of angle, 180
- principle of superposition, 33, 76
- Probability, 780, 817
- Probability distributions, 780
 - Gaussian, 784
 - normal, 784
 - uniform, 784
- Probability functions, 786
- Probability models, 778
- Probability density function (pdf), 781, 817
 - conditional, 787
 - joint, 786
 - marginal, 787
- Product filter, 750, 765
- Prolate spheroidal wave functions, 566
- Properties of commonly used windows, 563
- PSD, 885
- Pseudo-QMF bank, 770
- Quadrature mirror filter (QMF) bank, 765
- quantization, 11, 21, 340
 - interval, 320
 - level, 320
 - noise, 322
 - SQNR, 323
 - step, 320
- Quantization error, 910
 - statistical analysis, 909
- Quantization interval, 910, 953
- Quantization levels, 910, 953
- quantization noise, 340
- Quantization of filter coefficients, 928
 - FIR, 933
 - IIR, 929
 - pole and zero locations, 929
 - Sensitivity formula, 931
- Quantization process, 905, 953
- Quantization step, 911, 953
- quick Fourier transform, 467
- quick Fourier transform (QFT), 471
- radix-2 FFT algorithms, 471
- radix-R FFT algorithms, 471
- Raised-cosine pulse-shaping filter, 609
- Raised-cosine pulse-shaping filter design, 605
- Random experiments, 778, 817
- Random process, 796, 817
 - AR, 811, 812
 - ARMA, 810
 - Gaussian, 810
 - Harmonic, 814
 - jointly wide-sense, 800
 - MA, 811
 - regular, 810
 - response to LTI systems, 802
 - second-order, 799
 - stationary, 799
 - statistical specification, 797
 - strictly stationary, 799
 - white noise, 809
 - wide-sense stationary, 799
- Random signal processing, 829
- Random signals, 777, 778
- Random variables, 780, 817
 - continuous, 780
 - discrete, 780
 - jointly distributed, 786
 - linear combinations, 790
 - linear relationship, 789
 - orthogonal, 789
 - statistically independent, 787
 - uncorrelated, 788
- Random vector, 791
 - normal, 792
- Rational Chebishev function, 649
- real bandpass filters, 246
- Rectangular window, 556, 560
- Reflection coefficients, 849, 872
- Regular processes, 817
- Relative frequency, 779, 817
- Relative specifications, 539, 609
- Remez exchange algorithm, 585

- Resampling, 706, 765
- resolvability, 420
- Response of LTI systems to random process
 - frequency-domain analysis, 806
 - time-domain analysis, 803
- reverberation, 68
- reverse carry algorithm, 471
- Ripple, 609
- Roll-off, 609
- Round-off noise effects, 954
 - direct-form FIR filters, 937
 - IIR filters, 940
 - normal direct-form II, 940
 - scaling to avoid overflow, FIR filters, 939
 - scaling to avoid overflow, IIR filters, 943
 - transposed direct-form II, 941
- Rounding operation, 905, 954
- Sample correlation coefficient, 834
- Sample covariance, 834
- Sample function, 797
- Sample mean, 832
 - bias, 832
 - variance, 832
- Sample space, 778, 817
- Sample variance, 833
- sample-and-hold circuit, 319, 340
- sampling, 4, 11, 21
 - frequency, 24
 - in frequency domain, 364
 - linear FM signal, 306
 - of periodic signals, 309
 - period, 21, 24
 - periodic or uniform, 293
 - reconstruction from samples, 298
 - sampling frequency, 5, 293
 - sampling period, 5, 76, 293
 - sampling rate, 5, 76, 293
 - interval, 24
 - practical, 318
 - practical reconstruction from samples, 318
 - rate, 21, 24
- sampling ADC, 319, 341
- Sampling distribution, 830, 885
- sampling frequency, 341
- sampling of bandpass signals, 327
 - arbitrary band positioning, 330
 - guard bands, 332
 - integer band positioning, 328
 - reconstruction from samples, 329
- sampling rate, 341
- Sampling rate change, 706, 765
 - decrease by an integer, 706
 - increase by an integer, 715
 - noninteger factor, 725
- Sampling rate compressor, 706, 727, 765
- Sampling rate conversion, 706
 - MATLAB functions for, 735
- Sampling rate expander, 717, 728, 765
- Sampling rate, discrete-time, 712
- sampling theorem, 296, 341
- Scaling operation, 954
- Second-order moments, 809
- Second-order sections, 523
- Sensitivity formula, 954
- sensor, 14
- sequence, 24
 - anticausal, 122
 - causal, 48, 122
 - complex sinusoidal, 27
 - exponential, 26
 - left-sided, 122
 - noncausal, 122
 - periodic, 27
 - right-sided, 122
 - sinusoidal, 26
 - two-sided, 122
 - unit pulse, 25
 - unit step, 25
- short-time DFT, 413, 420
- shuffling operation, 471
- Sigma-delta modulator, 926
- Signa and magnitude format, 903, 954
- signal, 2, 21
 - amplitude, 4
 - analog, 20
 - continuous-time, 20
 - decomposition into impulses, 39
 - deterministic, 8, 20
 - digital, 21
 - discrete-time, 24, 76
 - duration, 24
 - elementary, 76
 - energy, 25, 76
 - periodic, 76
 - plotting in MATLAB, 30

- random, 8, 21
- representation, 24
- support, 24
- time, 4
- addition, 29
- bounded, 75
- division, 29
- folding, 29
- generation in MATLAB, 28
- length, 24
- multiplication, 29
- power, 25, 76
- scaling, 29
- subtraction, 29
- time-reversal, 29
- time-shifting, 29
- Signal flow graph, 486, 523
- signal processing, 1, 13, 21
 - analog, 13, 20
- signal-flow graph
 - directed branch, 36
 - pick-off node, 36
 - summing node, 36
- signals
 - Fourier representation, 134
- Simulation and verification
 - structure, 519
- sinc function, 145
- Sine integral function, 558
- sliding DFT, 468
- sliding DFT (SDFT), 471
- smearing, 403
- spatial frequency, 333
- Special FIR filter designs, 601
 - FDATool, 606
- Spectral analysis of stationary processes, 834
- Spectral decomposition, 881
- Spectral factorization, 688, 753, 817
- spectral factorization, 248
- Spectral leakage, 843
- spectral leakage, 400, 420
- Spectral resolution, 843
- spectral resolution, 400
- Spectral smearing, 843
- spectral spreading or smearing, 400, 420
- spectrogram, 413, 420, 472
 - MATLAB computation, 416
- Spectrum expansion, 709
- split-radix FFT algorithm, 471
- SQNR, 954
- Standard deviation, 783, 817
- Stationary random process
 - correlation-ergodic, 835
 - mean-ergodic, 835
- Statistical averages, 782
- Statistical analysis of quantization error, 909
- Statistical independence, 787, 817
- Statistical regularity, 780
- Statistically independent random variables, 787
- steady-state response, 276
- Spectral factorization, 810
- Stochastic process, 796
 - continuous-time, 797
 - discrete-time, 797
 - realization, 797
- Stopband, 609
- stopband ripple, 539
- stream processing, 57
- Strict-sense stationary random process, 817
- Structures for discrete-time systems,
 - 485, 486, 523
 - conversion, 519
 - FIR, 501
 - IIR, 488
 - simulation and verification, 519
- Sub-band signals, 746, 765
- superposition summation, 40
- Synthesis filter, 810
- Synthesis filter bank, 765
- system, 9, 21
 - additivity property, 75
 - analog, 9, 20
 - block diagram, 35
 - causal, 32, 75
 - continuous-time, 9, 20
 - digital, 10, 21
 - discrete-time, 10, 21, 31, 76
 - dynamic, 35, 76
 - fixed, 34
 - impulse response, 38, 76
 - interface, 10
 - linear, 33, 76
 - LTI, 76
 - memoryless, 35, 76
 - noncausal, 32, 76
 - nonlinear, 33

- system (*cont.*)
 - nonrecursive, 76
 - practically realizable, 37, 76
 - recursive, 76
 - signal-flow graph, 35
 - stable, 32, 76
 - state, 62, 76
 - step response, 76
 - time-invariant, 34, 77
 - time-varying, 34
- system function, 90, 122
 - pole, 112, 122
 - rational function, 111
 - stability, 113
 - zero, 112, 122
- system gain, 276
- talk-through system, 301, 341
- Tapped-delay line, 501, 523
- The Bartlett-Welch method, 855
- time and frequency scaling, 403
- time duration, 404
- time-dependent DFT, 413
- time-domain, 89
- time-domain aliasing, 420
- Toeplitz matrix, 802
- Tolerance, 609
- Tolerance diagram, 538
- transfer function, 90, 122
- Transformations, continuous-time to
 - discrete-time filter, 653
- transient response, 276
- Transition band, 609
- Transition bandwidth, 558
- Transposed direct form I structure, 490
 - direct form I, 490
- Transposed direct form II structure, 492
- Transposed form structure, 487, 523
 - direct form II, 492
- Transposition, 487
- Transposition of signal flow graph, 487
- Transposition procedure, 523
- Transversal line, 501, 523
- Transposition theorem, 487
- Tree-structured filter banks, 765
- Triangular window, 560
- Truncation operation, 905, 954
- twiddle factor, 472
- Two-channel filter bank
 - condition for perfect reconstruction, 749
 - input-output description, 747
- Two-stage decimation, 741
- Two's-complement format, 904, 954
- Type-I FIR filter, 609
- Type-II FIR filter, 609
- Type-III FIR filter, 609
- Type-IV FIR filter, 609
- uncertainty principle, 403, 420
- Uncorrelated random variables, 817
- Uniform DFT filter bank, 765
- Uniform distribution, 817
- Uniform filter bank, 765
- Uniform-band tree structure, 762
- unit delay, 35
- Unit delay element, 523
- unit impulse, 25
- unit impulse function, 70
 - distribution, 72
 - generalized function, 72
 - operational definition, 73
- unwrapped phase function, 276
- Upsampler, 765
- Upsampling, 715
- Variance, 783, 817
- Variance of an estimator, 831, 885
- Variance-gain, 918, 954
- Weighted error, 590
- Welch method, 856, 885
 - computation, 857
- White noise process, 817
- Whitening filter, 810, 868
- Wide-sense stationary (WSS) random
 - process, 817
- Wiener filter, 865, 885
- Window
 - Bartlett, 560
 - Blackman, 561
 - correlation, 846
 - Hamming, 561
 - Hann, 561
 - Kaiser, 566
 - lag, 846

- Parzen, 850
 - rectangular, 556, 560
 - triangular, 560
- Window closing, 853, 855
- Window design method, 556
 - FDATool, 572
 - MATLAB functions, 571
- windowing, 356
 - data window, 397
 - of sinusoidal signals, 397
- windows
 - MATLAB tool, 410
 - types, 405
- Winograd Fourier transform algorithm (WFTA), 472
- Wold-decomposition theorem, 815
- wrapped phase function, 276

- Yule-Walker equations, 812

- z-transform
 - anticausal exponential sequence, 94
 - bilateral, 118
 - causal exponential sequence, 93
 - complex conjugate distinct poles, 101
 - conjugation of complex sequence, 105
 - convolution, 104
 - differentiation, 105
 - exponential pulse sequence, 93
 - exponentially oscillating sequence, 95
 - initial value theorem, 106
 - inverse, 99
 - linearity, 103
 - long division, 99
 - multiplication by an exponential sequence, 105
 - one-sided, 118, 122
 - partial fraction expansion, 99
 - partial fraction expansion in MATLAB, 102
 - poles, 91
 - polynomial multiplication in MATLAB, 104
 - polynomial representation in MATLAB, 98
 - proper rational function, 99
 - properties, 103
 - real and distinct poles, 99
 - reconstruction from samples, 371
 - region of convergence (ROC), 91, 122
 - residue, 122
 - square pulse sequence, 93
 - time reversal, 106
 - time shifting, 103
 - two-sided, 118, 122
 - two-sided exponential sequence, 95
 - unilateral, 118
 - unit sample sequence, 92
 - zeros, 91
- zero-padding, 420
- Zero-phase IIR filtering, 627, 688
- zero-state response, 276
- zoom FFT, 465
- zoom FFT algorithm, 472