More Information

# Index

Abuelma'atti model, 157-61 adjacent-channel error power ratio (ACEPR) FOM, 98, 99, 225 adjacent-channel interference, 249 adjacent-channel power ratio (ACPR), 99, 224, 240, 241 adjacent-channel power ratio difference (AACPR) FOM, 98, 99, 224 amplifier-based properties of behavioural models. 35-45 bias-circuitry-based memory effects, 36-9 class A amplifiers, 43-4 distortion studies on HEMTs, 39 low-frequency feedback, 37 memory effects, short and long term, 35-40, 93 memoryless PAs and circuits, 35-6, 92-140 nonlinearity classification, 42-5 Pearson's classification of nonlinearities, 43 - 5quasi-memoryless descriptions, 40-2 self-heating mechanisms, 39-40 simplified FET-based PA circuit, 38 trap-related memory effects, 39-40 see also nonlinear dynamic systems classification (Pearson) amplifier characterisation, 45-79 broadband-amplifier characterisation setup (BBACS), 65-9 models extracted, 70 structural comparison, 65-6 typical configuration, 68 deficient models, 47 excitation signal design, 47-50 figures of merit (FOMs), 62, 104, 215-32, 240large-signal network analyser (LSNA), 62model validation, 47 multisine signals, 48 nonlinear vector network analyser (NVNA), 62 parsimony models, 47 persistent excitation, 46 single-tone measurement setups, 57–62 models extracted, 63 system identification, 45-7 two-tone measurement setups, 62-5

disadvantages, 64 models extracted, 66 vector network analyser (VNA) application, 57 - 62see also multisine amplifier characterisation amplifier response to excitation, 50-7 amplifier response, 50-1 measurement results, 52-7 3G WCDMA signals, 98 two-tone measurements, 53-5, 57, 60, 240 WiMax modulated signal, 55, 58 measurement setup, 53, 61 nonlinear dynamic model responses, 51-2 nonlinear static model responses, 51 analogue-signal sampling and processing, 244-8 continuous-in-time simulation, 246-7 finite-time-window and finite-time-block simulation, 247 Hilbert transform, 245 mixed frequency- and time-domain (MFTD) signal representation, 247 multirate sampling, 246 nonlinearity, 245 sampling rate, 94, 245-6 statistical techniques, 247-8 time-domain mode sampling, 246 time-driven simulation, 246 analogue-signal simulators for wireless communication, 235-8 analogue-digital interfaces, 235-6 design, 237 distortion in high-powered PA systems, 92-6, 237 narrowband nonlinear PA systems, 94-5, 237 - 8system or circuit simulation, 236-7, 241-4 application-based properties of behavioural models, 30-5 band-pass-low-pass relationship, 31-5 band-pass nonlinear systems, 32-5, 94, 95 baseband output, 34, 94 describing functions, 35 for solving ODEs, 30-1 low-pass nonlinear systems, 33-4, 94-8 memoryless systems, 34, 92-138 microwave PA modelling, 31, 92-138

## More Information

# Index

arbitrary memoryless nonlinearity, 14, 128 artificial neural networks (ANNs), 4, 6-9, 168 - 72artificial neurons, 170 multilayer perception (MLP), 170-2 sigmoid function, 171 band-pass nonlinear systems, 32-5, 94-8 baseband memory polynomial model, see memory polynomial model baseband output, 34 behavioural modelling most important properties, 27-8 principles of, 2, 27-8, 92-6, 237-9 see also amplifier characterisation; amplifier-based properties of behavioural models; application-based properties of behavioural models; memoryless nonlinear models; model-based-structure properties of behavioural models Berman and Mahle models, 106, 127, 133 comparisons, 96, 106 Bessel-Fourier (BF) memoryless behavioural models, 96, 106, 117-25, 158 as decomposable models, 117-18, 131-2 as extensible models, 117, 132 comparisons, 96, 106, 137-8 model extraction, 118-23 BF coefficients (rounded), 119-23 goodness of fit, 122 instability beyond the dynamic range, 122 - 3measurement curves, 119-21 measurement error, 121 parameter,  $\alpha$ , 117, 119–23 multicarrier-input models, 118, 131-2 Bessel functions, 94, 106, 118 bias-circuitry-based memory effects, 36-9 bilinear recursive nonlinear filter, 6 bit error rate (BER), 238, 248 branch memoryless nonlinearities, 8 broadband-amplifier characterisation setups (BBACS), 65-70 advantages, 67 concerns, 67 models extracted, 70 structural comparison, 65-6 typical configuration, 68 Chebyshev polynomials, 144 complementary cumulative distribution function (CCDF), 238

complex envelope, xvi, 1, 10, 11, 16, 31–5, 89–93, 154, 158, 165, 177, 179, 193, 196, 203, 206–10, 218–19, 240, 245 circuit-envelope simulation. 240-1 circuit-level PA models, 20-3 artificial neural networks (ANNs), 21-2 behavioural models, 21-3 equivalent circuit models, 20 polyharmonic distortion model, 22 two-slice Walker model, 22 Volterra input-output map (VIOMAP), 21 circuit-level simulation, 88, 239-42 circuit-envelope simulation, 240-1 harmonic-balance (HB) simulation, 240 mixed-signal high-frequency IC simulation, 241 - 2Spice simulator, 239 coherence function FOM, 223-4 communication-network simulation, see system simulation comparison of PAs, see validation and comparison of PA models complex power series models, 90, 99-103, 132 comparisons, 96 equivalent RF model, 100 extracted coefficient sets, 102 harmonic and IMP analysis, 100-3 model error results, 102, 104 Volterra series relationship, 100 continuous-in-time simulation, 246-7 continuous- or discrete-time models, 29 deficient models, 47 describing functions, 35 deterministic behavioural model properties, 30 digital-logic simulation, 242, 244 see also analogue signal sampling and processing; analogue-signal simulators direct time-domain (DTD) simulations, 132 discrete- or continuous-time models, 29 discrete-spectrum signals, FOMs for, 217-18 discrete-time environment, 3 distortion error-vector magnitude FOM, 222 dynamic carrier amplitude and phase conversion, 152-3 dynamic PA memory effects, 3 dynamic range and  $\alpha$  values in BF models, 116-17, 119-23 dynamic Volterra series. see Volterra-series-based models electronic system design automation (ESDA) tools, 249-50 envelope nonlinearity, 31 equivalent circuit models, 2, 20 error-vector magnitude (EVM) FOMs, 221, 238, 240, 241

### More Information

#### 264 Index

feedforward block-orientated approach, see three-box models; two-box models figures of merit (FOMs) amplifier characterisation, 62 and system simulation, 238-9 figures of merit, comparisons, 106, 225-30 with impulse response delay mismatch, 226 - 7with linear parameter variation, 227 with nonlinear parameter variation, 227 figures of merit, normalised, 98, 217-20 discrete-spectrum signals, 217-18 frequency-domain measurement, 217 high-linearity applications, 220 scalar spectrum-analyser measurements, 218 single-tone measurements, 219-20 time-domain measurements, 218–19 see also validation and comparison of PA models figures of merit, real-world test-signal-based, 220 - 30adjacent-channel error power ratio (ACEPR), 98, 99, 225 adjacent-channel power ratio difference  $(\Delta ACPR), 98, 99, 224$ coherence function, 223-4 error-vector magnitude (EVM) FOMs, 221, 238, 240, 241 distortion EVM, 222 normalised mean-square error (NMSE), 98, 99, 222-3, 238 power spectral density (PSD), 221-2 variance accounted for (VAF), 223 finite-impulse-response (FIR) models filter canonical forms, 5 filters, 4-5 model properties, 29 finite-time-window and finite-time-block simulations, 247 Fourier series memoryless models, 116-17Fourier-series-optimised Bessel-Fourier (FOBF) model, 123-5 algorithmic approach, 123 Gibbs effect, 123 instantaneous characteristic  $G_{\rm RF}$ , 89, 116, 123 - 4frequency-dependent Saleh model, 153-7 noise effects, 156-7 Poza-Sarkozy-Berger (PSB) model comparison, 154 scaling factors, 154-5 swept-tone measurements, 155-6 frequency-dependent two-tone intermodulation (IMD) responses, 15 frequency-domain estimation, 141-2

Fuenzalida et al. derivation, 117 Gibbs effect, 123 Hankel integral, 106 harmonic-balance (HB) simulation, 239 - 40Hermite polynomials, 131, 144-5 heterogeneous simulation, 248-50 analogue and digital-logic co-simulation, 248 - 9Hetrakul and Taylor memoryless model, 106, 125-7, 133 comparisons, 96 LDMOS characteristics, 125-7 satellite TWTA PAs, 125–6 high-electron-mobility transistors (HEMTs), distortion studies, 39 Hilbert transform, 147, 245 Ibnkahla three-box model, 15 IEEE 802.11a (WLAN) standard, 254 - 6IEEE 802.15.3a UWB (ultrawideband) standard, 257-9 IEEE 802.16 (WiMAX) standard, 256 - 7impulse response delay mismatch FOM comparisons, 226-7infinite-impulse-response (IIR) models filters, 5-6 structure models, 29 input multiplicity, 43 input-output mapping of PAs, 3 instantaneous nonlinearity, 31, 89, 100, 116, 123 - 4instantaneous quadrature model and technique, 147-8 intermodulation (IMD) 86, 94, 101, 118, asymmetries, 17 sweet spots, 37 inverse Chebyshev transform, 123 Kaye et al. and the memoryless complex BF model, 117 Kennington and the Saleh model, 106 Ku and Kenney behavioural model, 17 - 18Ku $et\ al.$  approach to memory effect modelling, 16-17 Laguerre-Volterra model, 187-9 large-signal network analyser (LSNA), 62, 76 - 9

frequency-domain measurement, FOMs for,

217

#### More Information

#### Index

laterally diffused metal oxide semiconductor (LDMOS) characteristics for PAs, 106-7, 125 - 7Legendre polynomials, 130 least-squares method with two-box models, 142 Lee-Schetzen correlation method, 142-3 linear-memory nonlinear models, see nonlinear models with linear memory linear parameter variation FOM comparisons, 227linear-time invariant (LTI) systems, 182-3 low-pass nonlinear systems, 33-4 memory effects bias-circuitry-based, 36-9 dynamic PA, 3 linear and nonlinear, 93 short and long term, 35-40, 93 memory polynomial model, 164-8 with non-uniform time-delay taps, 166-8 with unit time-delay taps, 165-6 memoryless nonlinear models, 11-12, 31, 35-6, 86 - 133accuracy, 87 applications and usefulness, 87-8 baseband-envelope-equivalent models, 90 Berman and Mahle model, 127 Bessel-Fourier (BF) models, 117-23 comparisons based on PA performance prediction, 95-9, 131-3 Berman and Mahle model, 96 Bessel-Fourier models, 96 complex power series models, 96 Hetrakul and Taylor model, 96 modified Saleh models, 96 optimised Bessel-Fourier models, 96 Saleh models, 96 complex power series models, extensible models, 132 Fourier series models, 116 Fourier-series-optimised Bessel-Fourier (FOBF) model, 123 full characterisation of PA, 94 Hetrakul and Taylor model, 127-8 linear and nonlinear memory effects, 29 mathematical description of models, 89 - 95model extraction, 87 modified Saleh models, 106-16 noise, 93 out-of-band intermodulation products (IMPs), 86, 94, 101 PA output, 91-4, 98, 100-2, 106 quasi-memoryless descriptions, 40-2 Saleh models, 103-6

solid-state PAs (SSPAs), 86, 87 system simulations, 88-9 travelling-wave tube amplifiers (TWTAs), 86 Wiener expansion, 127 zonal band, 91-3 see also Bessel-Fourier memoryless behavioural models; complex power series models; Fourier series memoryless models; Fourier-series-optimised Bessel-Fourier model; Hetrakul and Taylor memoryless model; modified Saleh models; nonlinear models with linear memory; Saleh models; Wiener series expansion microwave PAs, nonlinear dynamic properties, 9 - 10mixed frequency- and time-domain (MFTD) signal representation, 247 model validation, 47, 95-9 model-based-structure properties of behavioural models, 29-30 continuous- or discrete-time models, 29 deterministic models, 30 FIR models, 29 IIR models, 29 memoryless, linear and nonlinear memory effects, 29 multiple-input-multiple-output (MIMO) models, 29-30 parametric or nonparametric models, 29 single-input-single-output (SISO) models, 20 stochastic models, 30 time-invariant or time-varying models, 29 modelling and simulation, see system simulation modified Saleh models, 106-16 AM-AM model, 113-15 model error graphs, 114-15 model-fitting results, 114 AM-PM model, 110-13 general modified equation for, 111 modelling error, 113 optimised extraction results, 112-13 generalised form, 107-10 modelling LDMOS PAs, 106-7 quadrature models, 114-16 optimisation for the in-phase characteristic, 116 WCDMA-derived quadrature measurements, 115–16 reduction to two-parameter model, 107-8 solid-state PA (SSPA), 106 modified Volterra series, see Volterra-series-based models

## More Information

#### 266 Index

modular approach, see three-box models; two-box models multidimensional functions, 3-4 multilaver perception (MLP), 170-2 multiple-input-multiple-output (MIMO), model properties, 29-30multirate sampling, 246 multisine amplifier characterisation, 69-79 design procedures, 71-2 frequency-domain-time-domain transformations, 74 in a large-signal network analyser (LSNA) setup, 76-9 parameters, 72–5 probability density function (PDF), 69-71 algorithm summary, 71-2 estimation, 74-6 histogram presentations, 75-6 vector signal amplifier (VSA) settings, 73-4 multisine signals, 48 NARMA, see nonlinear autoregressive moving-average model non-constant-envelope modulation (NOCEM), 91 nonlinear autoregressive moving-average exogenous input (NARMAX) representation, 136-7 noise-power ratio (NPR), 238, 240 nonlinear autoregressive moving-average (NARMA) model, 174-82 description and block diagram, 175-6 PA low-pass complex-envelope example, 177 - 9AM-AM and AM-PM data dispersion, 178 - 9EVM determination, 179 stability, 175 stability test: small-gain theorem, 176-7 nonlinear dynamic properties of microwave PAs. 9-10 nonlinear dynamic systems classification (Pearson), 43–4 asymmetric response to symmetric input changes, 43 generation of harmonics, 43 generation of subharmonics, 43 input-dependent stability, 43-4 input multiplicity, 43 output multiplicity, 43 nonlinear integral model (NIM) of Filicori, 20 nonlinear memory effects, modelling of, 15-20 formal approach for complete Volterra series modelling, 19 frequency-dependent two-tone IMD responses, 15

Ku and Kenney behavioural model, 17–18 Ku et al. approach, 16-17 power supply variation effects, 16 self-heating effects, 16 Zhu et al. approach, 19 see also nonlinear models with nonlinear memory nonlinear models with linear memory, 136-61, see also parallel-cascade models; three-box models; two-box models nonlinear models with nonlinear memory. 163–211, see also memory polynomial model; nonlinear autoregressive moving-average model; parallel-cascade Wiener model; state-space-based model; time-delay neural network model: Volterra-series-based models nonlinear parameter variation FOM comparison, 227 nonlinear system identification, 2-9 artificial neural networks (ANNs), 4, 6-9 branch memoryless nonlinearities, 8 direct form of the system operator, 3-5 discrete-time environment, 3 FIR filters, 4-5 IIR filters, 5–6 input-output mapping, 3 memory effects and dynamic PAs, 3 microwave PA feedback structure, 9-10 nonlinear dynamic properties of microwave PAs, 9-10 recursive form of function  $f_{\rm R}$ , 3–5 system memory span, 3-4 nonlinear vector network analyser (NVNA), 62normalised mean-square error (NMSE) FOM, 96, 98-9, 222-3 O'Droma derivation, 117 ordinary differential equations (ODEs), solving with behavioural models, 30-1 orthogonal frequency-division multiplexing (OFDM), 86, 88, 100, 105, 132, 236, 240, 254out-of-band intermodulation products (IMPs), 86 output multiplicity, 43 parallel FIR model, 185-7 parallel-cascade models, 157-60 Abuelma'atti model, 157-61 parallel-cascade Wiener model, 179-83 AM-AM and AM-PM curves extraction, 179 - 80linear time-invariant (LTI) systems, 182-3

Volterra series model comparison, 183

#### More Information

## Index

267

parametric or nonparametric models, 29 parsimony models, 47 peak-to-average power ratio (PAPR), 54, 58, 96, 132, 225, 236, 238 percentage linearisation (PL), 238 persistent excitation, 46 physical communications system simulation, see system simulation physical models and empirical models, 2 polyharmonic distortion model, 22 polynomial activation functions, 198-9 polynomial filters, 4-5 polyspectral PA models addressing linear memory, 14-15 arbitrary memoryless nonlinearity concept, 14 Ibnkahla three-box model, 15 solid-state PAs (SSPAs), 14–15 travelling-wave tube amplifiers (TWTAs), 14 - 15power amplifier (PA) modelling basics, 1-10 equivalent circuits, 2 nonlinear dynamic properties, 9-10 physical models, 2 system simulation with PAs, 238-9 see also circuit-level PA models; nonlinear system identification; system-level PA models power spectral density (PSD) FOM, 221–2 power supply variation effects, 16 Poza-Sarkozy-Berger (PSB) model, 148-53 basic concept, 148-9 dynamic carrier amplitude and phase conversion, 152-3 error identification, 151-2 identification procedure, 149--50structure of complete model, 150-1 swept-tone measurements, 150-2 synthesis procedure for AM-PM portion, 150 - 1probability density function (PDF) and multisine amplifier characterisation, 69-71 pseudo-inverse technique, 143 Ptolemy, 250 quadrature models, 92, 93, 96, 241 modified Saleh models, 114-16 Saleh models, 105-6 quasi-memoryless descriptions of PAs, 40-2, 132radio-frequency (RF) signals, with modulation, 10-11 real-valued time-delay neural network (TDNN) model, 172-4 recursive form of the system operator, 3-5

Saleh models, 11, 103-6 comparisons, 96 decomposed model, 106 general equation, 103–5 quadrature models, 96, 105-6, 114-16 travelling-wave tube amplifier (TWTA) modelling, 106-8 two-parameter model, 105 see also modified Saleh models sampling, multirate, 246 sampling rate, 245-6 satellite TWTA PAs, 125-6 scalar spectrum-analyser measurements, FOMs for, 218 self-heating effects, 16 self-heating mechanisms, 39-40 Shimbo's expression, 94, 106 sigmoid function, 171 simulation, see analogue-signal simulators; circuit-level simulation; system simulation simultaneous common nonlinear power amplification, 86 single-input-single-output (SISO), model properties, 29 single-tone measurement characterisation setups, 57-62models extracted, 63 single-tone measurements, FOMs for, 219 - 20single-unmodulated-carrier behaviour, 51, 118 - 23small-gain theorem, 176-7 solid-state PAs (SSPAs), 9, 14-15, 86, 87, 106 Spice circuit simulator, 239 state-space-based model, 199-211 model description, 200-3 data collection, 201 function fitting, 201-2 independent variables determination, 201 linear memory formulation, 200–2 microwave devices, 200-1 nonlinear memory formulation, 202-3 stochastic-behavioural-model properties, 30 symbol error rate (SER), 238, 248 system identification for amplifier characterisation, 45-7 theory, 2-3 system memory span, 3–4 system simulation, 88, 233-50 analogue and digital-logic co-simulation, 248 - 9commercial systems, 233-4 communication-network simulation, 234 complete-system simulation, 249-50 digital-logic simulation, 244

## More Information

#### 268 Index

system simulation (cont.) figures of merit (FOMs), 238-9 and quality objectives, 238-9 heterogeneous simulation, 248-50 system-level techniques, 242-4 nonlinear system problems, 244 probing, 242 result accuracy, 242-3 terminology, 234–5 see also analogue-signal sampling and processing; analogue-signal simulators for wireless communication; circuit-level simulation system-level PA models, 10-20, 86-133 memoryless PA models, 11-13, 86-133 nonlinear integral model (NIM) of Filicori, 20PA models for linear memory, 12-13, 136-62 PA models for nonlinear memory, 15–20, 163 - 211polyspectral PA models for linear memory, 14 - 15RF signals with modulation, 10-11, 90, 96, 98.115 see also nonlinear memory effects, modelling of three-box models, 145-57broadband time-domain measurements, 146 - 7frequency-dependent Saleh model, 153-7 Hilbert transform, 147 Ibnkahla adaptive identification, 147 instantaneous quadrature model, 147-8 of Ibnkahla, 15 Poza–Sarkozy–Berger (PSB) model, 148–53 structure, 145-6 Volterra series relationship, 146 Wiener-Hammerstein model, 13 time-delay neural network (TDNN) model, 168 - 74artificial neural networks (ANNs), 168-72 dynamic AM-AM and AM-PM nonlinear characteristics prediction, 173-4MOSFET amplifier example, 174 real-valued TDNN model, 172-4 simulation-based example, 174-5 Volterra-series-based models, 196-9 time-domain measurements, FOMs for, 218 - 19time-domain mode sampling, 246 time-driven simulation, 246 time-invariant or time-varying models, 29 trapping, trap-related memory effects, 39-40 travelling-wave tube amplifiers (TWTAs), 9, 14-15, 86, 103-6, 125, 127

and Hetrakul and Taylor model, 125-6 and Saleh model, 106-8 two-box models, 136-45 estimation methods, 139-41 finite NARMAX representation, 136-7 Hammerstein model, 13, 137-8 linear block estimation methods, 140-3 frequency-domain estimation, 141-2 least-squares method, 142 Lee-Schetzen correlation method, 142-3 pseudo-inverse technique, 143 memory estimation, 139-40 nonlinear block estimation methods, 144-5 Chebyshev polynomials, 144 Hermite polynomials, 144-5 Volterra kernels relationship, 138-9 Wiener cascade identification, 145 Wiener model, 13, 137-8 two-slice Walker model, 22 two-tone measurement characterisation setups, 62 - 5disadvantages, 64 models extracted from. 66 two-tone PA response, 51, 101, 238 ultrawideband (UWB) technology, 256 validation and comparison of PA models, 215 - 30general-purpose metric, 215-20 model definition. 216-17 see also figures of merit (FOMs) van Heijningen et al. methodology, 241 variance accounted for (VAF) FOM, 223 vector network analyser (VNA) nonlinear VNA (NVNA), 62 single-tone amplifier characterisation, 57-62 Volterra input-output map (VIOMAP), 21 Volterra kernels and two-box models, 138-9 estimation methods, 185 Volterra nonlinear transfer functions, 9-10 Volterra-series-based models, 100, 184–99 complexity, 186-7 extraction of behavioural model parameters, 186 - 7frequency-domain form, 185 Laguerre-Volterra model, 187-9 modified or dynamic Volterra series, 190-6 alternative model description (Ngoya and Soury), 195-6 AM-AM and AM-PM plots, 193 black-box modelling, 193 description, 190-3 frequency-domain aproach, 194-5 model identification, 193-5

# More Information

# Index

269

parallel FIR model, 185–7	uniformly distribut
pruning algorithm, 186	weighting function,
time-delay neural network model, 196–9	Wiener kernels ext
polynomial activation functions, 198–9	wireless communicati
time-domain structure, 193–4	simulators for wi
truncation error, 191	wireless personal area
	technology, 256
wideband code-division multiple access	wireless standards, 25
(WCDMA) derived quadrature	IEEE $802.11a$ WL
measurements, 91, 96, 98, 115-16	allowable EVM (
Wiener cascade identification, two-box model,	IEEE 802.15.3a UV
145	256-8
Wiener-Hammerstein three-box model, 13	WPAN technolog
Wiener model, see parallel-cascade Wiener	IEEE 802.16 (WiM
model	orthogonal frequen
Wiener series, 4–5	(OFDM), 253
two-box Wiener model structure, 13	
Wiener series expansion, 127–31	zonal-band output, 3
Gaussian-distributed signals, 131	118, 132
truncated-Wiener-polynomial expansion, 128	zonal filtering, 31, 33

mly distributed signals, 130 ing function, 129 er kernels extraction, 129 communications, see analogue-signal ulators for wireless communication personal area networking (WPAN) nology, 256 standards, 253-8 802.11a WLAN, 253-5 wable EVM (dB) values, 255 802.15.3a UWB (ultrawideband), -8 AN technology, 256 802.16 (WiMAX), 255-6 onal frequency-division multiplexing DM), 253 nd output, 33–4, 51–2, 91–3, 101–2,