ANSWERS TO PROBLEMS

CHAPTER 1

1.1. Operational amplifiers, active filters, comparators, voltage regulators, analog mixers, analog switches, and transistors. **1.2.** Comparators, analog switches, PGAs, AGCs, ADCs, DACs, PLLs, and switched capacitor filters. **1.3.** Programmable gain amplifier (PGA). **1.4.** Digital-to-analog converter (DAC). **1.5.** Analog-to-digital converter (ADC). **1.6.** Digital signal processor (DSP). **1.7.** Automatic gain control (AGC). **1.8.** Short between metal traces (i.e., blocked etch). Bonus answer: Can also cause a gap in the trace, if using a negative process. **1.9.** A clean room eliminates particles in the air, thus reducing the particulate defects such as those in Figure 1.8. **1.10.** Wafer probe testing, bond wire attachment into lead frames, plastic encapsulation (injection molding), lead trimming, final testing. **1.11.** Two devices do not represent a good statistical sample from which to draw conclusions. Need data from hundreds or thousands of devices. **1.12.** Mainframe, test head, user computer, system computer, DIB. **1.13.** Provides a temporary electrical interface between the ATE tester and the DUT. Also provides DUT-specific circuits such as load circuits and buffer amplifiers. **1.14.** Wafer prober. **1.15**. Requires proactive test engineering, better communications between test and design engineering, coordinated engineering effort. **1.16.** Allows design engineers and test engineers to agree upon an appropriate set of tests. Also serves as test program documentation. **1.17.** Time to market, accuracy/repeatability/correlation, electromechanical fixturing, economics of production testing (test economics). **1.18.** We have to test a total of 5,555,555 devices to get 5 million good ones since we have a 90% yield (yield = ratio of good devices to total devices tested). For the good devices, the time saved is 1.5 s times 5 million devices, or 7.5 million seconds of reduced test time per year. Multiplying this by 3 cents per second, we get a total savings of $225,000 per year in reduced testing costs for the good devices. Multiplying the 0.5-s test time reduction for the bad devices by 555,555 devices per year, we see an additional savings of 3 cents per second times 0.5 s times 555,555 devices, or $8333 per year. Thus the total test cost savings is $233,333 per year. **1.19.** The after-tax profit margin is 12.8% (20% times 100%–36%). Therefore, we would have to ship $233,333/12.8% = 1.823 million dollars worth of product to equal the extra profit offered by the reduced test time. Thus, we have to ship approximately one million extra devices to get the same incremental profit as we get from the 1.5 second test time reduction for this device. Obviously, reducing test time can have as high an impact on profits than selling and shipping millions of extra devices!

CHAPTER 2

2.1. System computers, DC sources, DC meters, relay control lines, relay matrix lines, time measurement hardware, arbitrary waveform generators, waveform digitizers, clocking and synchronization sources, and a digital subsystem for generating and evaluating digital patterns and signals. **2.2.** It improves DC measurement repeatability by removing high frequency noise from the signal under test. **2.3.** A PGA placed before the meter's ADC allows proper ranging of the instrument to minimize the effects of the ADC's quantization error. **2.4.** Using the two-measurement approach, we obtain two readings on the ±5 V-range that have errors of ±5 mV, giving a total differential error of ±10 mV. Using the meter's sample-and-difference mode, the 1-V range can be selected, giving a worst-case error of ±1 mV.Using the two-pass (normal) measurement mode, we have to set the meter to the 5-V range to accommodate the 3.5-V common-mode offset. This gives an error of 0.01% of 5 V, or 0.5 mV. The worst-case error is twice this amount, or 1 mV, since we are subtracting two measurements. Using the sample-and-difference mode, the meter range can be set to the 1-V range. The single measurement has a worst-case error of 0.01% of 1 V, or 0.1 mV. The sample-and-difference mode is much more accurate. **2.5.** Kelvin connections compensate for the *IR* voltage drops in the high force line and current return line of a DC source. **2.6.** A local relay can provide a low-noise ground to the DUT inputs. (Alternate answer: A local relay can provide local connections to load circuits, buffer amplifiers, and other sensitive DIB circuits.) **2.7.** Flyback diodes prevent inductive kickback caused by the relay coil from damaging the drive circuitry. **2.8.** A digital pattern generates digital 1/0 waveforms and high/low comparisons. A digital signal contains waveform information such as samples of a sine wave. **2.9.** Source memory stores digital signal samples and supplies them to a mixed-signal circuit such as a DAC. **2.10.** Capture memory captures and stores digital signal samples from a DUT circuit such as an ADC. **2.11.** Formatting and timing information are combined with one/zero information to reduce the amount of digital pattern memory required to produce a particular digital waveform. It also reduces the required vector (bit cell) rate for complex patterns (see Figure 2.11). Finally, it gives us better control of edge placement. **2.12.** The NRZ waveform could be produced using clocked digital logic operating at 2 MHz. The RZ waveform would require clocked digital logic operating at a period of 100 ns, or 10 MHz. If the stop time for the RZ formatted waveform had to be delayed to 901 ns, we would need digital logic operating at a clock rate of 1 GHz. **2.13.** The CW source and RMS voltmeter are only able to measure a single frequency during each measurement, leading to long test times compared to DSP-based testing. Also, the RMS voltmeter can't distinguish between the DUT's signal and its distortion and noise. **2.14.** The low-pass filter is used to reconstruct, or smooth, the stepped waveform from the AWG's DAC output. **2.15.** The PGA sets the measurement range, reducting the effects of the digitizer's ADC quantization error. **2.16.** Distributed DSP processing reduces test time by splitting the processing task among several processors that perform the mathematical operations in parallel.

CHAPTER 3

3.1. 6.1%. **3.2.** 10.8%. **3.3.** 8.75 V. **3.4.** 5.78 V. **3.5.** 540 Ω. **3.6.** 1000 Ω. **3.7.** 105 Ω. **3.8.** 200 Ω. **3.9.** Output offset = 5 V; input offset = 0.477 V. **3.10.** 0.95 V. **3.11.** 50%. **3.12.** $V_{OS,SE}{}^{+} = -0.1$ V; $V_{OS,SE}{}^{-} = 0.2$ V; $V_{OS,DE} = -0.3$ V; $V_{OS,CM} = 0.05$ V. **3.13.** 0.122 V. **3.14.** 7.56 V/V; 17.57 dB. **3.15** $V_{OUT}(2.0\text{ V}) = 8$ V; $V_{OUT}(3.0\text{ V}) = 11.5$ V; gain = 3.5 V/V = 10.88 dB. **3.16.** $V_{OUT}(2.0\text{ V}) = 5.4$ V; $V_{OUT}(1.0\text{ V}) = 2.85$ V; gain = 2.55 V/V = 8.13 dB. **3.17.** $G_{ol} = -15392.3$ V/V = 83.7 dB. **3.18.** 1.34 mV. **3.19.** 3.0 V. **3.20.** PSS = 0.04 V/V; PSSR = 0.0041 V/V. **3.21.** –85.7 dB. **3.22.** 56.2 μV. **3.23.** 2.606 V. **3.24.** 2.020 V. **3.25.** 2.590 V. **3.26.** 2.490 V. **3.27.** 6 iterations of linear search; 15 iterations of binary search. **3.28.** 9 iterations of linear search; summary of 9 iteration beginning with input of 0.0 V; 9th iteration: Input = 1.820287463, Output = 1.999961500.

CHAPTER 4

4.1. $\mu = 1.591$, $\sigma = 0.0493$, $\sigma^2 = 0.0024$. **4.2.** (a) 3, (b) 0.0473, (c) 0.99987, (d) 0.9502, (e) $F(x)=\begin{cases} 0, & x \le 0 \\ -e^{-3x}+1 & x > 0 \end{cases}$. **4.3.** max. error< 0.4%. **4.4.** (a) $\Phi = 0.001349$, $\Phi_{app} = 0.001347$, error

= 0.19%. (b) Φ = 0.02872, Φ_{app} = 0.028573, error = 0.49%. (c) Φ = 0.2879, Φ_{app} = 0.2843, error = 1.17%. (d) Φ = 0.4052, Φ_{app} = 0.4016, error = 0.87%. (e) Φ = 0.5, Φ_{app} = 0.5, error = 0%. (f) Φ = 0.4642, Φ_{app} = 0.4621, error = 0.431%. (g) Φ = 0.567, Φ_{app} = 0.5705, error = –0.54%. (h) Φ = 0.999, Φ_{app} = 0.9987, error = –0.00026%. (i) Φ = 0.999, Φ_{app} = 0.999, error = -1.2×10^{-8}%. (j) $\Phi = 2.86\times10^{-7}$, $\Phi_{app} = 2.86\times10^{-7}$, error = 0.044%. **4.6.** (a) 0.498650, (b) 0, (c) 1.0, (d) 0.8399, (e) 0.9331, (f) 0.2023, (g) 0.9973, (h) 0.0027. **4.7.** (a) 1.60, (b) 0.800, (c) –0.800, (d) 0.800, (e) 0.800. **4.8.** (a) 1.281, (b) –0.5244, (c) 0.5244, (d) 0.5244. **4.9.** μ = 0.0372, σ = 0.0256. **4.10.** $P(23 \le X \le 33) = 0.1$; μ = 50, σ = 28.87. **4.11.** μ = 0.0392, σ = 0.022. **4.12.** $P(X < -0.2) = 0.03881$, $P(0 < X) = 0.01551$. **4.13.** $P(X < 9.8) = 0.0569$, $P(10.0 < X < 10.5) = 0.56506$. **4.14.** $P(X < 0.70\text{e}{-4}) = 0.0507$, $P(0.70\text{e}{-4} < X < 0.140\text{e}{-3}) = 0.9044$, $P(0.140\text{e}{-3} < X) = 0.0478$. **4.15.** μ = 0.977, σ = 0.0132, $g(v) = 30.26e^{-2876.87(v-0.977)^2}$. **4.16.** μ = 0.0944, σ = 0.055, $g(v) = 7.23e^{-164.2(v-0.0944)^2}$. **4.17.** μ = 0.0944, σ = 0.055, $g(v) = \begin{cases} 5.231, & -0.00119 \le v \le 0.1899 \\ 0, & \text{otherwise} \end{cases}$.

4.20. # code hits at code 50 is 68. **4.21.** # code hits at code 50 is 22. **4.22.** μ = 0, σ = 6.06, $F(x) = \frac{1}{21}\sum_{k=-10}^{10} u(x-k)$. **4.23.** μ = 550, σ = 260.1, $F(x) = \frac{1}{901}\sum_{k=100}^{1000} u(x-k)$. **4.24.** μ = 0.533, σ = 0.221, $F(x) = \begin{cases} 0, & x \le 0 \\ 2x^2 - x^4, & x \le 1 \\ 1, & 1 < x \end{cases}$. **4.25.** 0.0374. **4.26.** 0.0022. **4.27.**

$$f(x) = \frac{625}{1296}\delta(x) + \frac{125}{324}\delta(x-1) + \frac{25}{216}\delta(x-2) + \frac{5}{324}\delta(x-3) + \frac{1}{1296}\delta(x-4)\cdot$$

4.28. μ = 10, $P(\text{Errors} = 1) = 4.5\times10^{-4}$. **4.29.** μ = 0.1, $P(\text{Errors} = 1) = 0.090$. **4.30.** $P(0 < X) = 0.9999999$; $P(2 < X) = 0.921$; $P(X < 3) = 0.671$. **4.31.** P(0 < X) = 0.503; P(2 < X) = 0.057; P(X < –3) = 0.036. **4.32.** $g(v) = 132.9e^{-55555.5(v+0.005)^2}$. **4.33.** $g(v) = 39.89e^{-0.08(500v-1)^2} + 39.89e^{-0.08(500v+1)^2}$.
4.34. No closed form. Use numerical method to evaluate.

4.35. $g(x) = \frac{1}{\sqrt{2\pi}\sqrt{\sigma_1^2 + 4\sigma_2^2}} e^{-\frac{1}{2}\frac{1}{\sigma_1^2+4\sigma_2^2}\left(4x^2 - 4x\mu_1 + \mu_1^2 + 4\mu_2^2 + 8x\mu_2 - 4\mu_1\mu_2\right)}$ **4.36.** $g(x) = 0.066e^{-0.0138(x+2.5)^2}$.

4.37. $g(x) = 0.1596e^{-0.08\left(x^2+x-0.25\right)}$.

CHAPTER 5

5.1. 400. **5.2.** 150 ppm. **5.3.** μ = 55.6, error = 0.6 mV. **5.4**. 0.003%. **5.5.** #bits = 16.6, Range setting = 125 mV. **5.6.** $-0.322\ V < \text{Measurement} < 0.324$ V. **5.7.** $66.49e^{-13888.9(x-10.1)^2}$. **5.8.** $664.9e^{-1.3888\times10^6(x-10.1)^2}$. **5.9.** $664.9e^{-1.3888\times10^6(x-0.1)^2}$. **5.10.** 0.0982 V/V < measurement error < 0.1018 V/V. **5.11.** $V_{CAL} = -0.0379 + 0.926\times VM$. **5.12.** 1.2583 V. **5.13.** Calibration factors: 0.970@1 kHz, 0.984@ 2 kHz, 0.800@3 kHz; Programmed voltage levels: 0.515@1 kHz, 0.559@2 kHz, 0.625@3 kHz. **5.14.** Gain = 1.155 V/V, Offset = –0.135 V. **5.15.** V_{CAL} = 1.961 V, Error = –0.169. **5.16.** RMS noise voltage for 10 μF = 0.5 μV; RMS Noise Voltage for 2.2 μF = 1.1 μV. **5.17.** Settling time for 10 μF = 62.1 ms; Settling time for 2.2 μF = 13.6 ms. **5.18**. Bandwidth needs to be reduced by a factor of 25; test time increases by 25 times. **5.19.** Here we see that increasing the yield through more test time has created a excess profit (Benefit = 0.06625000000 N). This benefit scale with the number of devices tested. **5.20.** Average 11 sample sets. **5.22.** 3σ: UTL = 6.35 V/V, LTL = 5.65 V/V; For 6 σ guardbands, average sample set 9 times. **5.23.** UTL = 6.69 mV, LTL = –6.69 mV. **5.24.** UTL = 9.5 mV, LTL = –9.5 mV. **5.25.** USL = 6.4 V/V, LSL = 5.9 V/V. **5.26.** If 6σ guardbands required, one must average the measurement 7 times. **5.27.** (a) 3, (b) 1, (c) 0. **5.29.** 0.0175 V. **5.30.** 1.82 %. **5.31.** 76.2 %. **5.32.** Because the C_{pk} = 0.44 is less than 1.5, the lot will not meet six-sigma quality standards.

CHAPTER 6

6.2. 5.46 V**6.3.** 0 V. **6.4.** code = [–16., 2.0], [–15., 2.06], [–14., 2.13], [–13., 2.19], [–12., 2.26], [–11., 2.32], [–10., 2.39], [–9., 2.45], [–8., 2.52], [–7., 2.58], [–6., 2.64], [–5., 2.71], [–4., 2.77], [–3., 2.84], [–2., 2.90], [–1., 2.97], [0., 3.03], [1., 3.10], [2., 3.16], [3., 3.23], [4., 3.29], [5., 3.35], [6., 3.42], [7., 3.48], [8., 3.55], [9., 3.61], [10., 3.68], [11., 3.74], [12., 3.81], [13., 3.87], [14., 3.94], [15., 4.00]. **6.5.** V_{LSB} = 1.333 V; OUT = [–8, –10.], [–7, –8.66], [–6, –7.33], [–5, –6.00], [–4, –4.66], [–3, –3.335], [–2, –2.00], [–1, –0.666], [0, 0.666], [1, 2.00], [2, 3.333], [3, 4.66], [4, 6.0], [5, 7.33], [6, 8.66], [7, 10.0]. **6.6.** V_{LSB} = 0.156 V; OUT = [0, 0.], [1, .156], [2, .312], [3, .468], [4, .624], [5, .780], [6, .936], [7, 1.09], [8, 1.25], [9, 1.40], [10, 1.56], [11, 1.72], [12, 1.87], [13, 2.03], [14, 2.18], [15, 2.34], [16, 2.50], [17, 2.65], [18, 2.81], [19, 2.96], [20, 3.12], [21, 3.28], [22, 3.43], [23, 3.59], [24, 3.74], [25, 3.90], [26, 4.06], [27, 4.21], [28, 4.37], [29, 4.52], [30, 4.68], [31, 4.84]. **6.7.** (a) G_{DAC} = 0.365 V/V, offset = –1.72 mV, ΔG = –8.64%, Offset error = –1.7 mV. (b) V_{LSB} = 0.365 V. (c) Absolute error = [0., 0.127], [1., –0.203], [2., –0.227], [3., –0.438], [4., –0.192], [5., –0.493], [6., –0.630], [7., –0.658], [8., –0.904], [9., –0.712], [10., –0.986], [11., –0.959], [12., –1.12], [13., –1.34], [14., –1.37], [15., –1.37] (d) Yes the DAC is monotonic. (e) DNL = –0.236, 0.0702, –0.109, 0.334, –0.196, –0.0539, 0.0792, –0.154, 0.290, –0.186, 0.112, –0.0561, –0.143, 0.0696, 0.117. As max(|DNL|) < ½ LSB, DAC passes test. **6.8.** (a) G_{DAC} = 0.365 V/V, offset = 46.5 mV, ΔG = –9.03 %, offset error = 46.5 mV. (b) V_{LSB} = 0.364 V. (c) Absolute Error = [0., 0.128], [1., –0.203], [2., –0.228], [3., –0.440], [4., –0.192], [5., –0.494], [6., –0.632], [7., –0.659], [8., –0.907], [9., –0.714], [10., –0.989], [11., –0.962], [12., –1.13], [13., –1.35], [14., –1.37], [15., –1.37]. (d) Yes the DAC is monotonic. (e) DNL = –0.231, 0.07, –0.113, 0.35, –0.203, –0.038, 0.07, –0.148, 0.29, –0.176, 0.13, –0.066, –0.121, 0.07, 0.10. As max(|DNL|) < ½ LSB, DAC passes test. **6.9.** (a) G_{DAC} = 0.119 V/V, offset = –0.962V, ΔG = –10.5 %, Offset error = –6.8 mV. (b) V_{LSB} = 0.119 V. (c) Absolute error = [0., .807], [1., .471], [2., .975], [3., .160], [4., 1.21], [5., .118], [6., .185], [7., .151], [8., –.400], [9., .176], [10., –.261], [11., .471], [12., –.807], [13., –.504], [14., –.975], [15., –1.01], (d) Yes the DAC is monotonic. (e) DNL = –0.218, 0.62, –0.697, 1.17, –0.975, 0.18, 0.08, –0.467, 0.76, –0.345, 0.82, –1.10, 0.39, –0.378, 0.14. As max(|DNL|) > ½ LSB, DAC does not pass the test. **6.10.** (a) G_{DAC} = 0.119 V/V, offset = –0.974 V, ΔG = –10.8%, Offset Error = –0.974 V. (b) V_{LSB} = 0.119 V. (c) Absolute error = [0., 0.807], [1., 0.471], [2., 0.975], [3., 0.160], [4., 1.21], [5., 0.118], [6., 0.185], [7., 0.151], [8., –0.400], [9., 0.176], [10., –0.261], [11., 0.471], [12., –0.807], [13., –0.504], [14., –0.975], [15., –1.01]; (d) Yes the DAC is monotonic. (e) DNL = –0.218, 0.62, –0.697, 1.17, –0.975, 0.18, 0.08, –0.467, 0.76, –0.345, 0.82, –1.10, 0.39, –0.378, 0.14; As max(|DNL|) > ½ LSB, DAC does not pass the test. **6.11.** Yes the DAC passes the DNL test. **6.12.** Yes the DAC passes the DNL test. **6.14.** W_0 = 0.194, W_1 = 0.327, W_2 = 0.652, W_3 = 1.30, W_4 = 2.61. **6.15.** W_0 = 0.105, W_1 = 0.208, W_2 = 0.413, W_3 = 0.828. **6.17.** Case A: W_0 = 0.0552, W_1 = 0.1207, W_2 = 0.2414, W_3 = 0.4788; poor data fit; major carrier test does not work.Case B: W_0 = 0.0552, W_1 = 0.1207, W_2 = 0.2414, W_3 = 0.4788; good data fit; major carrier test does work. **6.18.** $t_{settling}$ = 20.65 ns, $t_{risetime}$ = 1.22 ns, OS = 59.3 %, E_{glitch} = 0.544 ns-V. **6.19.** $t_{settling}$ = 22.0 ns, $t_{risetime}$ = 1.64 ns.

CHAPTER 7

7.1. (a) $P(V < 40\text{ mV})$ = 0.5318, (b) $P(V > 10\text{ mV})$ = 0.4207, (c) $P(-10\text{ mV} < V < 40\text{ mV})$ = 0.3674. **7.2.** (a) $P(V < 40\text{ mV})$ = 0.4522, (b) $P(V > 10\text{ mV})$ = 0.5, (c) $P(-10\text{ mV} < V < 40\text{ mV})$ = 0.3812. **7.3.** 0.0507. **7.4.** P(Code = 325) = 0.2525; #Code 325 = 101.0. **7.5.** 21.28 mV RMS. **7.6.** #Code

115 = 79.33, #Code 116 = 266.4, #Code 117 = 154.3. **7.7.** V_{LSB} = 206.7 mV; Code width (V) = 0.2125, 0.1417, 0.2125, 0.2480, 0.2480, 0.1771; Code edge (V) = 0.010, 0.2226, 0.3643, 0.5768, 0.8248, 1.073, 1.250. **7.8.** V_{LSB} = 320.3 mV; Code width (V) = 0.339, 0.293, 0.270, 0.225, 0.270, 0.270, 0.315, 0.315, 0.293, 0.339, 0.429, 0.362, 0.315, 0.451; Code edge (V) = 0.075, 0.414, 0.707, 0.977, 1.202, 1.472, 1.742, 2.057, 2.372, 2.665, 3.004, 3.433, 3.795, 4.110, 4.561. **7.9.** V_{LSB} = 0.5155, measurement accuracy = ±17.7 mV. **7.10.** $T_{R,min}$ = 0.98 ms @ 6 hits per code; $T_{R,min}$ = 16.3 ms @ 100 hits per code. **7.11.** ΔV = 1.66 mV; N = 6000. **7.12.** V_{LSB} = 66.8 mV, Code width (V) = 0.0671, 0.0663, 0.0670, 0.0667, 0.0664, 0.0674, 0.0672, 0.0673, 0.0664, 0.0674, 0.0667, 0.0667, 0.0666, 0.0669; Code edge (V) = 0.014, 0.0811, 0.147, 0.214, 0.281, 0.347, 0.415, 0.482, 0.549, 0.616, 0.683, 0.750, 0.817, 0.883, 0.950.**7.13.** V_{LSB} = 708.6 mV, Code width (V) = 0.702, 0.610, 0.812, 0.608, 0.802, 0.599, 0.800, 0.604, 0.800, 0.593, 0.787, 0.587, 0.775, .803; Code edge (V) = 0.020, 0.722, 1.33, 2.14, 2.75, 3.56, 4.15, 4.95, 5.56, 6.36, 6.95, 7.74, 8.32, 9.10, 9.90. **7.14.** $V_{IN,DC}$ = 0.4924 V; $V_{IN,min}$ = –0.0315 V; $V_{IN,max}$ = 1.016 V. **7.15.** $V_{IN,DC}$ = 5.099 V; $V_{IN,min}$ = –0.4020 V; $V_{IN,max}$ = 10.60 V. **7.16.** $F_{T,min}$ = 194.28 @ 10 hits, $F_{T,min}$ = 19.42 @ 100 hits, N = 1,286,797, T_T = 51.5 ms. **7.17.** V_{RES} = 41.9 µV, N = 375,000. **7.18.** DNL = 0.061, –0.0099, –0.1513, –0.2221, –0.1513, –0.1513, –0.0099, –0.0099, –0.0806, 0.061, 0.132, 0.132, –0.0099, 0.414; INL = 0, 0.061, 0.0511, –0.1002, –0.3223, –0.4736, –0.6249, –0.6348, –0.6447, –0.7253, –0.6643, –0.5323, –0.4003, –0.4102, 0; bestfit DNL = 0.0909, 0.0199, –0.1214, –0.1922, –0.1214, –0.1214, 0.0199, 0.0200, –0.0507, 0.0909, 0.1619, 0.1618, 0.0200, 0.4401; bestfit INL: = 0.1821, 0.2730, 0.2929, 0.1715, –0.0207, –0.1421, –0.2635, –0.2436, –0.2236, –0.2743, –0.1834, –0.0215, 0.1403, 0.1603, 0.6004. **7.19.** DNL = 0.056, –0.0852, –0.1555, –0.2963, –0.1555, –0.1555, –0.0148, –0.0148, –0.0852, 0.056, 0.337, 0.126, –0.0148, 0.407; INL = 0, 0.056, –0.0292, –0.1847, –0.4810, –0.6365, –0.7920, –0.8068, –0.8216, –0.9068, –0.8508, –0.5138, –0.3878, –0.4026, 0; bestfit DNL = 0.0829, –0.0584, –0.1287, –0.2694, –0.1287, –0.1287, 0.0120, 0.0121, –0.0584, 0.0828, 0.3639, 0.1528, 0.0120, 0.4294; bestfit INL = 0.2896, 0.3725, 0.3141, 0.1854, –0.0840, –0.2127, –0.3414, –0.3294, –0.3173, –0.3757, –0.2929, 0.0710, 0.2238, 0.2358, 0.6652. **7.20.** DNL = 0.125, –0.0624, 0.125, –0.2500, 0.125, –0.0624; INL = 0, 0.125, 0.0626, 0.1876, –0.0624, 0.0626, 0.; bestfit DNL = 0.1339, –0.05349, 0.1339, –0.2411, 0.1339, –0.05368; bestfit INL = –0.07147, 0.06245, 0.00896, 0.1429, –0.09820, 0.03572, –0.01796.

CHAPTER 8

8.1. (a) F_t = 1/32, UTP = 32, F_f = 1/32. (b) F_t = 13/64, UTP = 64, F_f = 1/64. (c) F_t = 5/64, UTP = 64, F_f = 1/64. (d) F_t = 33/64, UTP = 64, F_f = 1/64. (e) F_t = 65/128, UTP = 128, F_f = 1/128. (f) F_t = 0.078125, UTP = 32, F_f = 1/32. **8.3.** (a) F_t = =250, UTP = 0.004, F_f = 250. (b) F_t = 1625, UTP = 0.008, F_f = 125. (c) F_t = 625, UTP = 0.008, F_f = 125. (d) F_t = 4125, UTP = 0.008, F_f = 125. (e) F_t = 4062, UTP = 0.0160, F_f = 62.5. (f) F_t = 625, UTP = 0.004, F_f = 250. **8.7.** V_{LSB} = 0.723 mV, Noise = 0.2115 mV. **8.8.** 3.29 mV. **8.9.** 261.9 mV, 309.5 mV. **8.10.** 238.1 mV, 285.7 mV. **8.11.** 22.21 µV. **8.12.** 33.0 ns. **8.13.** 1.24 ps. **8.14.** 2.04 MHz. **8.15.** 5.2 bits (ADC), 2.74 bits (DAC). **8.16.** 1.8 mV. **8.17.** 25.4 mV. **8.18.** µ = 0 V and σ = 8.0 mV; µ = 0 V and σ = 2.0 mV. **8.19.** F_f = 19.53 Hz, UTP = 51.2 ms. **8.20.** M = 16; M = 15; 16 cycles are coherent in UTP. **8.21.**62, 120, 190, 250, 310, 370, 430, 500. **8.26.** frequencies (in Hz): 970, 2010, 3030, 3990; no harmonic or intermodulation collisions. **8.27.** (a) No collisions, (b) no collisions, (c) collisions. **8.28.** 195.3125 kHz. **8.29.** 2.980277714 to 51.200 GHz.

CHAPTER 9

9.1. (a) $v(t) = 6.3662\sin(2000\pi t) + 2.1221\sin(6000\pi t) + 1.2732\sin(10000\pi t)$

(b) $v(t) = -6.3662\cos(2000\pi t) + 2.1221\cos(6000\pi t) - 1.2732\cos(10000\pi t)$

(c) $v(t) = -3.1831\sin(2000\pi t) - 1.5915\sin(4000\pi t) - 1.0610\sin(6000\pi t)$
$-0.7958\sin(8000\pi t) - 0.6366\sin(10000\pi t)$

(d) $v(t) = 2.5 + 2.0264\cos(2000\pi t) + 0.22521\cos(6000\pi t) + 0.0811\cos(10000\pi t)$

9.2. $v(t) = \frac{2}{\pi}\sin(\pi t) - \frac{1}{\pi}\sin(2\pi t) + \frac{2}{3\pi}\sin(3\pi t) - \frac{1}{2\pi}\sin(4\pi t) + \frac{2}{5\pi}\sin(5\pi t)$

9.3. $v(t) = -\frac{2}{\pi}\cos\left(\pi t + \frac{1}{2}\pi\right) + \frac{1}{\pi}\cos\left(2\pi t + \frac{1}{2}\pi\right) - \frac{2}{3\pi}\cos\left(3\pi t + \frac{1}{2}\pi\right)$
$+\frac{1}{2\pi}\cos\left(4\pi t + \frac{1}{2}\pi\right) - \frac{2}{5\pi}\cos\left(5\pi t + \frac{1}{2}\pi\right)$

9.4. $v(t) = \frac{4}{\pi}\sin(\pi t) + \frac{4}{3\pi}\sin(3\pi t) + \frac{4}{5\pi}\sin(5\pi t)$

9.5. $v[n] = 0.3667 + 0.8647\cos\left(\frac{\pi}{3}n + 1.317\right) + 2.025\cos\left(\frac{2\pi}{3}n - 2.684\right) + 1.333\cos(\pi n)$

9.6. $v[n] = 1.445 + 1.419\cos\left(\frac{\pi}{3}n + 2.750\right) + 2.074\cos\left(\frac{2\pi}{3}n + 1.300\right) + 0.6875\cos(\pi n - 3.141)$

9.10. $v[n] = 0.3667 + 0.8647\cos\left(\frac{\pi}{3}n + 1.317\right) + 2.025\cos\left(\frac{2\pi}{3}n - 2.684\right) + 1.333\cos(\pi n)$

9.11. $v[n] = 2.0 + 5.2345\cos\left(\frac{\pi}{2}n - 0.8124\right) + 1.5811\cos\left(\frac{3\pi}{4}n + 0.3218\right)$

9.15. (a)

$v[n] = 0.25 + 0.5\cos\left(\frac{\pi}{5}n\right) + 0.1\sin\left(\frac{\pi}{5}n\right) + 2.1\cos\left(\frac{2\pi}{5}n\right) - 0.9\cos\left(\frac{3\pi}{5}n\right) - 0.1\sin\left(\frac{3\pi}{5}n\right)$

(c) $v[n] = 0.25 + (0.25 - j0.05)\,e^{j\pi n/5} + 1.05e^{j2\pi n/5} + (-0.45 + j0.05)\,e^{j3\pi n/5}$
$+ (-0.45 - j0.05)\,e^{j7\pi n/5} + 1.05e^{j8\pi n/5} + (0.25 + j0.05)\,e^{j9\pi n/5}$

9.16.

(a) $v[n] = 0.4\cos\left(\frac{\pi}{5}n\right) + 0.8\sin\left(\frac{\pi}{5}n\right) + 0.5\cos\left(\frac{3\pi}{5}n\right) - 0.5\sin\left(\frac{3\pi}{5}n\right)$

(c) $v[n] = (0.2 - j0.4)e^{j\pi n/5} + (0.25 + j0.25)e^{j3\pi n/5} + (0.25 - j0.25)e^{j7\pi n/5} + (0.2 + j0.4)e^{j9\pi n/5}$

9.17. $c = [985, 516, 358, 282, 240, 216, 204, 100]$
$\phi(rads) = [1.2, -1.71, -2.01, -2.25, -2.48, -2.71, -2.92, -3.14]$

9.20. Rectangular window: PG = 1.0, ε = 1.0, ENBW = 1.0; Hanning window: PG = 0.666, ε = 0.6123, ENBW = 1.5; Blackman window: PG = 0.42, ε = 0.5519, ENBW = 1.73; Kasier (β = 10) Window: PG = 0.31, ε = 0.3980, ENBW = 3.19. **9.21.** $A[N = 64,\text{rms}] = 0.707$, error = 0.27% in ±10% BW; $A[N = 512, \text{rms}] = 0.7063$, error = 1.0% in ±10% BW; $A[N = 1024,\text{rms}] = 0.7071$, error = 2.7% in ±10% BW; $A[N = 8192,\text{RMS}] = 0.7071$, error = 1.0%in ±10% BW; Increasing BW, error will decrease. **9.22.** $A[N = 64,\text{RMS}] = 0.7070$, error = 0.27% in ±10% BW; $A[N = 512,\text{RMS}]$

= 0.7063, error = 1.0% in ±10% BW; $A[N = 1024,\text{RMS}] = 0.7071$, error = 2.7% in ±10% BW; $A[N = 8192, \text{RMS}] = 0.7071$, error = 1.0% in ±10% BW; Increasing BW, error will decrease. **9.23.** Δf = 7812.5 Hz (N = 128); Δf = 122.07 Hz (N = 8192). **9.24.** Rectagular: $A[N = 8192,\text{rms}] = 0.7071$, error = 0.011% in ±10% BW; Balckman: A[N = 8192,rms] = 0.7071, error~0% in ±10% BW; **9.29.** 0.9487 V. **9.30.** 0.2372 V. **9.31.** (a) [1.9500, 1.2400, –1.6500, –0.7400, 2.7500, –0.7400, –2.0500, 1.2400];(b) [1.5800, 0.8200, 1.8000, 0.8450, 0.4170, 1.1800, 0.1980, 1.1600];(c) [0.9000, 0.1640, 0.7740, 1.3400, –0.1740, –0.9000, –0.1640, –0.7740, –1.3400, 0.1740]**.** **9.32.** same solution as 10.31. **9.33.** $v[n] = 0.00998 + 0.1069\cos\left(\frac{\pi}{8}n + 1.2566\right) + 0.00056\sin\left(\frac{5\pi}{8}n - 2.66\right)$. **9.34.** 12.2 μV.

CHAPTER 10

10.1. (a) 6.019 dBV (b) –12.8 dBm (c) –20.0 dBV (d) 0.495 V. **10.2.** 0.714 V, 8.05 degrees, 0.505 V, –5.93 dBV. **10.3.** 0.707 V, 135.0 degrees, 0.5 V, –6.02 dBV. **10.4.** (a) 0.99 V/V, (b) $2 + 0.2V_{IN} + 0.03V_{IN}^2$, (c) $a_1 + 2a_2V_{IN} + 3a_3V_{IN}^2 + \cdots + na_nV_{IN}^{n-1}$, (d) $\frac{4}{1 + V_{IN}^2}$. **10.5.** (a) 1.9125 V/V, –0.388 dB. 1.86 V/V, –0.63 dB (b) 0.622 dB, 0.370 dB, 0.194 dB, 0. dB, –0.159 dB. **10.6.** F_t = 9406.25 Hz, 2.1 V/V, 6.44 dB. **10.7.** 500, 850, 860, 8500, 8600, 12000, 16000. **10.8.** (a) 0.1 V (b) 0.0489 V. **10.9.** 0.365 V. **10.10.** Absolute gain V/V = 1.0, 0.99, 0.90, 0.96, 1.0, 0.75, 0.46, 0.23; Relative Gain dB : = 0., –0.088, –0.92, –0.36, 0., –2.4, –6.8, –13.0. **10.11.** 19,698.27 Hz. **10.12.** (a) X_{IN} (Vrms) = [0.70, 0.70, 0.70, 0.70, 0.70, 0.70, 0.70, 0.70, 0.70]; X_{OUT} (Vrms) = [0.70, 0.67, 0.66, 0.70, 0.67, 0.45e–2, 0.22e–1, 0.17e–1, 0].(b) phase_{IN} (degrees) = [16., 86., 160., 38., 130., 58., –58., –74., –140.]; phase_{OUT} (degrees) = [16., 120., –140., 140., 30., –86., 3.5, 0.15, 45.].(c)Absolute gain (V/V) = [1.0, 0.96, 0.94, 1.0, 0.96, 0.64e–2, 0.31e–1, 0.24e–1, 0].(d) Relative gain (dB) = [0., 0., –.18, 0., 0., –44., –30., –32., –360.].(e) Phase unwrapped (degrees) = [0., 30., 61., 110., 250., 220., 61., 77., 180.].(f) Group Delay (s) = [1.7×10^{-7}, 1.7×10^{-7}, 2.7×10^{-7}, 7.8×10^{-7}, -1.7×10^{-7}, -8.8×10^{-7}, 8.9×10^{-7}, 5.7×10^{-7}].Group Delay Distortion = [2.2×10^{-7}, 2.2×10^{-7}, 3.2×10^{-7}, 8.3×10^{-7}, -1.1×10^{-7}, -8.3×10^{-7}, 1.4×10^{-7}, 6.2×10^{-7}]. **10.13.** (a) 34.8 dB. (b) 54.8 dB. (c) 34.8 dB. (d) 12.9 dB. **10.14.** $\frac{S}{H_3} = \frac{4a_1 + 3a_3A^2}{a_3A^2}$. **10.15.** Second-order IM frequencies: {0, 800, 1100, 1900, 2700, 3400, 4500, 6100, 7200, 7900, 8000, 8700, 9500, 9800, 11400, 11700, 12500, 13200, 14000, 14800, 15100, 17000}; Third-order IM frequencies: {200, 500, 600, 1000, 1400, 2400, 2900, 4000, 4300, 4700, 4800, 5100, 5500, 5800, 5900, 6600, 6700, 7400, 7700, 8200, 8500, 9200, 9300, 10000, 10100, 10400, 10800, 11100, 11200, 11600, 11900, 12000, 12700, 13000, 13500, 13800, 14500, 14600, 14900, 15300, 15400, 15700, 16100, 16400, 16500, 16900, 17200, 18000, 18300, 18800, 19100, 19800, 19900, 20200, 20600, 21000, 21400, 21700, 22200, 22500, 23300, 23600, 24400, 25500}. **10.17.** 45.5 dB. **10.18.** –37.3 dB, –38.7 dB. **10.19.** PSR (dB) = [–80.00000000, –60.00000000, –57.72113296]; PSRR(dB) = [–86.02059992, –72.04119982, –69.97681008]. **10.20.** XLR (dB) = [–63.18758762, –65.12578788, –61.60396270]; XRL(dB) = [–65.12578788, –64.10273744, –59.10518798]. **10.21.** (a) 64.8 μV (b) 80.7 dB (c) 1.4 μV/sqrt(Hz). **10.22.** 8.6 μV/sqrt(Hz). **10.23.** 0.346 V**10.24.** –52.0 dBV. **10.25.** (a) –36.9 dB, relative to FS. (b) –32.0 dBm0. **10.26.** (a) –70.9 dB, relative to FS. (b) 16.0 dBmC0. **10.27.** 63.9 dB.

CHAPTER 11

11.1. N_{ADC} = 4096, N_{DAC} = 1024. **11.2.** $F_{s,DAC}$ = 17,875 Hz, $F_{s,DIG}$ = 32,832 Hz. **11.3.** $F_{s,AWG}$ = 14,658 Hz, $F_{s,ADC}$ = 14,658 Hz. **11.4.** $F_{s,AWG}$ = 64,000 Hz, N_{ADC} = 256.**11.5.** 1.886 V, CF = 1.337. **11.6.** 0.221 V (in-band), 0.158 V (first-image), 0.0651 V, 0.0582 V.**11.7.** 1.76 V (in-band), 0.00260 V (first-image). **11.8.** F_{images} = {7000, 17000, 31000, 41000, 55000, 65000, 79000} **11.9.** F_{images} = {9000, 15000, 33000, 39000, 57000, 63000, 81000}. **11.10.** first case: $F_{images \text{ of } 55 \text{ kHz}}$ = {7000, 17000, 31000, 41000, 65000}; $F_{images \text{ of } 63 \text{ kHz}}$ = {9000, 15000, 33000, 39000, 57000}; No overlap. 2nd case: $F_{images \text{ of } 65 \text{ kHz}}$ = {7000., 17000., 31000., 41000., 55000.}; Here an image of 65 kHz overlaps with the tone at 55 kHz. **11.11.** $M_{alias} = 9$ (coherent), $T_{s,eff} = 1.21 \times 10^{-11}$s. **11.12.** $M_{alias} = 80$ (coherent), $T_{s,eff} = 2.41 \times 10^{-11}$s. **11.13.** $M_{alias} = 9.6$ (noncoherent), $T_{s,eff} = 3.08 \times 10^{-11}$ s. **11.14.** 83.84 GHz. **11.15.** (a) 2 (b) 1 (c) 1.2 (d) 1009. **11.19.** 0.0191 (M = 1), 0 (M = 8). **11.20.** 0.8103 V peak. **11.21.** $G_{\text{INSTRINSIC}}$ = 1.01358 V/V. **11.22.** $G_{INSTRINSIC}$ = 1.01303 V/V. **11.23.** G_{DAC} = 17.1 mV/bit, ΔG_{DAC} = 3.28 dB. **11.24.** G_{ADC} = 203.5 bits/V, ΔG_{ADC} = –0.047 dB. **11.25.** –53.5 dB. **11.26.** 3000 Hz. **11.27.** 15th Harmonic: bin 367, 5734.375 Hz. 23rd Harmonic: bin 393, 6140.625 Hz. **11.28.** No frequency overlaps. **11.29.** G_{ADC} = 52.33 bits/V, PSSR = –32.4 dB. **11.30.** SNR = 83.0 dB, ENOB = 13.49 bits.

CHAPTER 12

12.1. WLAN (2.4–2.5GHz & 5.5GHz); WiMax (3.5 GHz), BT (2.4GHz), GPS (1.5 GHz). **12.2.** Dynamic range, power range, signals can be described more efficient with wave characteristic rather than voltage. **12.3.** –174dBm/Hz, –90dBm, 20–30dBm, 60dBm. **12.4.** A scalar measure is described by the magnitude only, a vector by magnitude and phase (or real and imaginary). **12.5** 0.316 m. **12.6.** lump equivalent; $\lambda = 0.22$ m .**12.7.** The wavelength will be shortened by $1/\sqrt{\varepsilon_{reff}}$. **12.8.** Multiple sinusoidal waves (signals) can be added for any given time to a resulting waveform (signal), but these signals can be treated as individual waves or signals. **12.9.** All circuits with an imaginary part not equal to zero (e.g. capacitive or inductive circuits). **12.10.** The power is the area under the product of voltage and time by time or

$$P = \frac{1}{nT_0} \int_0^{nTo} V_{peak} \sin\left(\frac{2\pi}{T_0} t \right) \cdot I_{peak} \sin\left(\frac{2\pi}{T_0} t + \varphi \right) dt$$

12.11. $\text{Re}[P] = 0.0313\cos(0.2\pi) + 0.0313\cos(0.2\pi)\cos(4 \times 10^{10}\pi t)$

$\text{Im}[P] = -0.0313\sin(0.2\pi)\sin(4 \times 10^{10}\pi t)$. **12.12.** 0.0253 W. **12.13.** 25 W; 43.98 dBm. **12.14.** The crest factor is a measure for the peak-to-average power ratio. While the test calculation is often done with respect to average power, the peak power must be observed and tracked as it can compress a subsystem of an RF system (e.g. the input stage of the RF-ATE) is not propertly taken into account. **12.15.** 6.34 W. **12.16.** 15.05 dB. **12.17.** Noise: 11dB; UMTS: 15dB; OFDM signals: 11dB. **12.18.** $P\big|_{\text{dBm}} = 10 \cdot \log_{10}\left(\frac{P}{1 \text{ mW}} \right)$ dBm . **12.19.** Power: 3dB; voltage: 6dB. **12.20.** $Z_S = Z_L^*$. **12.21.** $Z_S = Z_L$. **12.22.** P_L = 0.11 W, P_A = 0.13 W, P_S = 0.32 W. **12.23.** P_L = 0.21 W, P_A = 0.25 W, P_S = 0.32 W. **12.24.** The insertion loss is the ratio of power received at a load before inserting a two-port network into a system to the power received at the load after insertion of the two-port network. The insertion loss does not include loss due to source and load matching since this is a loss that is already present before the insertion of the two-port network was made.The transducer loss is the ratio of the power delivered to a load to the power produced (maximal available) by the source. It is equal to the sum of the attenuation of the two port network and the corresponding mismatch loss. **12.25.** 0.928 dB. **12.26.** 0.757 dB. **12.27.** Dissipative loss is loss caused by any reactive element in an RF system (in contrast to reflection or radiation loss). **12.28.** –141.5 dBm/Hz.**12.29.** Any test equipment with a measurement bandwidth less than 1 Hz and an appropriate noise figure.**12.30.** The system noise figure can be calculated with the Friis equation $F_{sys} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots + \frac{F_n - 1}{G_1 G_2 \cdots G_{n-1}}$, it should be obvious fromt his expression that the total system noise figure can be minimized when the first gain stage has a low noise figure and high gain. **12.31.** 33.84 dB. **12.32.** 5.42 dB. **12.33.** Phase noise in the frequency domain is equivalent to short-term random fluctuations in the phase of a waveform. It can be measured as a power ratio or as jitter in time domain. **12.34.** S_{11} is the input reflection coefficient and describes the ratio of the power reflected from a port to the power of the incident wave. It is a measure for the efficiency of the input match. S_{22} is the output reflection coefficient and describes the ratio of the power reflected from the output port to the power of the incident wave. It is a measure for the efficiency of the output match. S_{21} is the forward transmission gain and describes the power transmitted through a network compared to the input power. S_{12} is the reverse transmission gain or isolation. It describes the power ratio of the power transmitted from the output to the input of a two port to the input power at the output. **12.35.** S_{21} and S_{12} are equal for passive reciprocal networks. **12.36.** The VSWR or voltage standing wave ratio is the ratio of the amplitude of a partial standing wave at an maximum node to the amplitude at the minimum node in an RF transmission line caused by reflections. The reflection coefficient describes the amplitude of a reflected wave relative to the incident wave. The reflection coefficient is a complex number. The return loss is the loss of signal power resulting from the reflections caused by impedance mismatch A high return loss is desirable as it results in a lower insertion loss. The insertion loss is the loss of signal power resulting from reflections, radiation and resistive losses when connecting a load to source with an two-port network (e.g., a transmission line with matching components). The mismatch loss is the amount of power that will not be available to the output due to impedance mismatches and reflections. With an ideal impedance match, the mismatch loss is the amount on power which can be gained. **12.37.** $\Gamma = 0.0086e^{j0.9817}, RL = 41.3$ dB, $ML = 0.0003$ dB. **12.38.** $\rho = 0.184, RL = 14.7$ dB. **12.39.** The mismatch uncertainty is caused by the scalar description of the reflections and is the estimation of the maximal mismatch loss. The mismatch uncertainty is a measure of the power range a system can receive when the matching conditions are only known as scalar values at impedance mismatches. Mismatch uncertainty is caused by standing waves on lines and the associated variance on voltage across the line. The mismatch uncertainty is often the most significant measurement error. **12.40.** $0.016\text{ dB} \le ML \le 0.251\text{ dB}; MU = 0.234$ dB. **12.41.** 0.67 dB. **12.42.** 0.255 dB. **12.43.** $RL_{IN} = 21.2$ dB; $RL_{OUT} = 18.0$ dB; $RL_{METER} = 21.0$ dB, $0.007\text{ dB} \le ML_{IN} \le 0.197\text{ dB}; MU_{IN} = 0.19\text{ dB}, 0.006\text{ dB} \le ML_{OUT} \le 0.20\text{ dB}; MU_{OUT} = 0.19$ dB.

12.44. –3.0 dB. **12.45.** 0.125.

12.46. $IL = 3.9\text{ dB}, \rho_{IN} = 0.3, \rho_{OUT} = 0.9, Z_{IN} = 27.5 - j6.2\ \Omega, Z_{OUT} = 5.25 - j49.7\ \Omega$.

12.47. The information of a frequency modulated signal is in the frequency, while the amplitude can be constant. Noise only impacts the amplitude. **12.48.** The information of an AM or FM signal is in one single sideband of the transmitted signal. By removing the carrier and other sidebands, all transmitted signal power can be used for one sideband containing all information. However, for demodulation the carrier will need to be recreated. **12.49.** GFSK is a filtered FSK, which limits the required bandwidth.

CHAPTER 13

13.1. See Figure 13.1; mixer, tracking filter, detector, local oscillator, sweep oscillator, display. **13.2.** Amplifier, mixer, local oscillator, filter, ADC. **13.3.** The spectrum analyzer is using a tracking filter to limit the measurement bandwidth which lowers the minimum detectable power. **13.4.** The amplifiers or ADC are working above their compression point in the non-linear range, harmonics will be generated in the ATE system. In addition the calibration of the ATE is valid only for the linear range, so the displayed power level will also be off. **13.5.** The noise in the measurement path will increase, thus limiting the minimal detectable power. **13.6.** The signal spectrum will spread as shown in Figure 13.4 adding noise components to the natural phase noise of the signal. **13.7.** 18.115 MHz. **13.8.** 2.482568 GHz. **13.9.** 23.4 dB. **13.10.** 11.9 dB $\leq G_A \leq$ 14.2 dB. **13.11.** 0.273 dB. **13.12.** 109.6 –j13.0 Ω. **13.13.** 4.48 dB. **13.14.** 17.0 –j37.2 Ω. **13.15.** G_A = 19.7 dB, Z_{IN} = 28.3– j5.8 Ω. **13.16.** The IP3 is a measure for the nonlinearity of the system. As higher the IP3 value is as higher power can be measured without adding harmonic signals to the measurement signal. **13.17.** 2nd order response has the slope of 2; third-order response has a slope of 3. The slope is caused by the trigonometric identities used when multiplying the signals. **13.18.** 24 dBm. **13.19.** G = 14 dB, IIP_3 = 3 dBm, OIP_3 = 17 dBm. **13.20.** Binary search, interpolation method, and modulation methods with step function and continuous power sweep. **13.21.** The modulation methods capture the output signal for various input power level with a single capture, which is faster and has a better accuracy than measuring multiple individual power settings. **13.22.** Both results are quite close. P1dB = –2.32 dBm using the linear approximation and P1dBm = –2.35 dBm using the polynomial fit approach. **13.23.** 0.8652 dBm. **13.24.** Failed 1dB compression test. **13.25.** Y-factor and cold noise method. **13.26.** The noise source is terminating the DUT. Any change in the source impedance will change the mismatch loss, and thus the noise power injected into the DUT. **13.27.** 3.1 dB. **13.28.** 5.03. **13.29.** –81.4 dBm. **13.30.** $\pounds(f) = \dfrac{2.51}{2.51^2\pi^2 + f^2} \quad \mathrm{rad}^2/\mathrm{Hz}$

13.31. –78.9 dBc/Hc. **13.32.** The ATE should source a reference frequency of 89.8437500 MHz for a sampling frequency of 10.00084926 GHz. The offset frequency will appear at 1.2208 MHz. **13.33.** –110.6 dBc/Hz. **13.34.** As shown in Figure 13.23, the measurement path of a vector signal analyzer consists of a mixer with local oscillator, gain and attenuator stages, and filter providing a low frequency captured signal to the analysis block, which can be built as DSP, or implemented with software. The hardware is identical to the ATE shown in Figure 13.2. **13.35.** All major parameters of a transceiver impact the EVM value, especially noise, phase noise, nonlinarity, phase in-balance.

13.36. $$M(t) = \sqrt{\sin^2\left(\pi 10^{10}\cdot t + \frac{\pi}{12}\right) + \sin^2\left(\pi 10^{10}\cdot t + \frac{2\pi}{5}\right)},\ \phi(t) = \tan^{-1}\left[\frac{\sin\left(\pi 10^{10}\cdot t + \frac{2\pi}{5}\right)}{\sin\left(\pi 10^{10}\cdot t + \frac{\pi}{12}\right)}\right]$$

and phase angle difference = –57 degrees.

13.37. $$M(t) = \left[-\cos\left(1.8\times 10^9\pi t + \frac{5\pi}{14}\right) - \sin\left(1.8\times 10^9\pi t\right)\right] + j\left[\cos\left(1.8\times 10^9\pi t + \frac{\pi}{8}\right) - \cos\left(1.8\times 10^9\pi t\right)\right]$$

CHAPTER 14

14.1. $\mu = 0.0015$, $\sigma = 0.000353$, pp = 0.001.

14.2. $$J_{PER}[n] = 0.001\sin\left(\frac{7\pi}{512}n\right) - 0.001\sin\left[\frac{7\pi}{512}(n-1)\right]$$

$$J_{CYC}[n] = 0.001\sin\left(\frac{7\pi}{512}n\right) - 0.002\sin\left[\frac{7\pi}{512}(n-1)\right] + 0.001\sin\left[\frac{7\pi}{512}(n-2)\right]$$

14.6. 17.1 V/sqrt(Hz). **14.7.** 2.42 mV. **14.8.** –117.0 dBc/Hz. **14.9.** –117.0 dBc/Hz

14.10. $$S_p(f) = \frac{2.5\times 10^{-26}}{\pi^2\left(10^6 + f^2\right)}\ \frac{\text{s}}{\text{Hz}} \qquad S_p(f) = \frac{2.5\times 10^{-6}}{\pi^2\left(10^6 + f^2\right)}\ \frac{UI}{\text{Hz}}$$

14.13. (a) $\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{1}{2}\frac{(t-a)^2}{\sigma^2}}$ (b) $\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{1}{2}\frac{(t-a-\mu)^2}{\sigma^2}}$

(c) $\frac{1}{4}\delta(t-b+a)+\frac{1}{4}\delta(t-b-a)+\frac{1}{4}\delta(t+b+a)+\frac{1}{4}\delta(t+b-a)$

(d) $$\frac{1}{8}\delta(t-b+a)+\frac{1}{8}\delta(t-b-a)+\frac{1}{8}\delta(t+b+2a)+\frac{1}{8}\delta(t-b-2a)+\frac{1}{8}\delta(t+b+a)$$
$$+\frac{1}{8}\delta(t+b-a)+\frac{1}{8}\delta(t+b+2a)+\frac{1}{8}\delta(t+b-2a)$$

14.14. $1.994\times 10^8 e^{-5\times 10^{17}t^2} + 1.994\times 10^8 e^{-50(10^8 t-1)^2}$

14.15. $9.97\times 10^7 e^{-0.5(10^9 t-11)^2} + 9.97\times 10^7 e^{-0.5(10^9 t-9)^2} + 9.97\times 10^7 e^{-0.5(10^9 t-1)^2} + 9.97\times 10^7 e^{-0.5(10^9 t+1)^2}$

14.17. $P_e(V_{TH} = 0.6) = 9.865\times 10^{-10}$, $P_e(V_{TH} = 0.75) = 1.2\times 10^{-6}$. **14.18.** $P_e(V_{TH} = 0.0) = 31.6\times 10^{-6}$.

14.19. $P_e(t_{TH} = 2.5\times 10^{-10}) = 2.86\times 10^{-7}$; $P_e(t_{TH} = 4\times 10^{-10}) = 0.0113$; **14.20.** $\frac{2}{3}\delta(t)+\frac{1}{3}\delta\left(t-10^{-9}\right)$

14.21. 7.17×10^{-8}. **14.22.** 3.29×10^{-7}. **14.23.** $2.701\times 10^{-10} \le \text{BER} \le 5.498\times 10^{-10}$; TestTime=166.67 s. **14.24.** 10. **14.25.** NE = 1, 0.499×10^{-3}; NE = 2, 0.276×10^{-2}; NE = 10, 0.5830×10^{-2}. **14.27.** 1.8×10^{13}, 2.002 days. **14.28.** $N_{T,min} = 2.01\times 10^{12}$; $N_{T,max} = 4.77\times 10^{11}$; $T_{T,min} = 2014.4$ s' $T_{T,max} = 477.1$ s. **14.30.** 31. **14.32.** 4095, seed = 0000,0000,0000,0001; yes periodic. **14.33.** #1: 11$\underline{0010111}$001011100101; #2: 1011$\underline{10010111}$001011100; same pattern just time shifted with respect to one another. **14.34.** $V_{\text{logic0}} = -0.5819$ V; $V_{\text{logic1}} = 0.5819$ V; noise0 = 0.0803 V; Noise1 = 0.0803 V. BER(V_{TH} = 10 mV) = 3.18×10^{-13}. **14.35.** V_{TH}(BER = 10^{-6}) = 0.9300 V; V_{TH}(BER = 10^{-8}) = 1.088 V; test time = 0.469 s. **14.36.** 2.41×10^{-8}. **14.37.** 1.026×10^{-10}. **14.38.** $2.33\times 10^{-10} <$ BER $< 10^{-16}$. **14.39.** 3.11×10^{-12}. **14.40.** 2.44×10^{-11}. **14.42.** 1.44×10^{-9}. **14.43.** 1.56×10^{-9}. **14.44.** 1.33×10^{-11}. **14.45.** 2.56×10^{-11}. **14.46.** DJ = 0, RJ = 4×10^{-12}, TJ = 5.39×10^{-11}. **14.47.** DJ = 2.2×10^{-11}, RJ = 5×10^{-11}, TJ = 8.96×10^{-10}. **14.48.** DJ = 2.3×10^{-11}, RJ = 6×10^{-12}, TJ = 1.03×10^{-10}. **14.50.** BER = 1.2×10^{-13}; yes the system performs with a BER less than 10^{-12}. **14.52.** Bins, 0, 33, 66, 99, . . . , 33k, ..., 495. RMS level ranges from –17 dB to –24 dB. **14.53.** PJ = 0.379, DDJ = 0.1544 , BUJ = 0.103.

14.54. $pdf_G = \frac{1.0\times 10^{11}\sqrt{2}}{\sqrt{\pi}} e^{-2\times 10^{22} t^2}$

$$pdf_{SJ} = \begin{cases} \frac{1}{\pi\sqrt{\left(1.0\times 10^{-22}\right)^2 - t^2}}, & |t| \le 1.0\times 10^{-11} \\ 0, & \text{otherwise} \end{cases}$$

$$pdf_{DCD} = \frac{1}{2}\delta\left(t+1.5\times 10^{-12}\right)+\frac{1}{2}\delta\left(t-1.5\times 10^{-12}\right)$$

$$pdf_{ISI} = \frac{1}{2}\delta\left(t+3.0\times 10^{-12}\right)+\frac{1}{2}\delta\left(t-3.0\times 10^{-12}\right)$$

14.55. $1.995\times 10^{10} e^{-0.005(2x10^{12}t-9)^2} + 1.995\times 10^{10} e^{-0.005(2x10^{12}t-3)^2} + 1.995\times 10^{10} e^{-0.005(2x10^{12}t+3)^2} + 1.995\times 10^{10} e^{-0.005(2x10^{12}t+9)^2}$

14.56. $M_J = 3$, $M_C = 8\times 10^5$, $N = 5\times 10^6$.

CHAPTER 15

15.1. 446.3 mΩ, HF = LF = ILoad = 0.56 A, HS = LS = 0 A, V_{drop} = 249 mV per line, V_{OUT} = 3.3V + 2 × 249 mV = 3.80 V. **15.2.** 201 nH/m, 15.4 nH total, –0.001%; 150 nH/m, 11.5 nH total, 0.00004%. **15.3.** 83 pF/m, 2.5 pF total; 120 pF/m, 3.6 pF total.

15.4. $\left|H(f)\right| = \left[\frac{1}{\sqrt{1+\left(\frac{f}{F_C}\right)^2}}\right]$ V/V and $\angle H(f) = -\frac{180}{\pi}\tan^{-1}\left(\frac{f}{F_C}\right)$ degrees

where $F_C = \frac{1}{2\pi RC}$ Hz $= \frac{1}{2\pi\times 50\times 10^3\times 3.6\times 10^{-12}}$.

15.5. 45 pF/m, 9.2 pF total; 50 pF/m, 10.3 pF total. **15.6.** 50 pF/m, 14.7 pF + 35 pF = 49.7 pF total, gain = 0.141 = –17.02 dB, buffer amplifier is needed. Using refined estimate: 110 pF/m, 32.4 pF + 35 pF = 67.4 pF total, gain = 0.104 = –19.63 dB, buffer amplifier is needed. **15.7.** 110 pF/m, 400 nH/m, Z_o = 60Ω; To lower the characteristic impedance, we would make the spacing smaller or widen the trace. Changing the length has no effect on characteristic impedance in an ideal transmission line. **15.8.** v_{signal} = 1.5× 10^8 m/s = 0.5c, T_d = 1.3 ns, 22.5 pF. **15.9.** L = 7.53 m, or 294 in., much longer than the stripline length. We can use a lumped element model for this line. **15.10.** 100 % (cable length = one wavelength), 16.7 pF, 360 degrees. **15.11.** F_c = 12.7 MHz. Max. attenuation is 0.00005 dB; We should not need a buffer amplifier unless the output becomes unstable when loaded with 125 pF. **15.12.** The LC network will consist of a shunt C of 1.43 pF and a series L of 56.5 nH.**15.13.** The values of the shunt-serces C network is 0.38 pF and 0.69 pF. **15.14.** Two possible solutions: (a) Θ_d = 143.6 degrees, Θ_{OS} = 57.7 degrees, $Y_{in,stub}$ = j 0.03169 S; (b) Θ_d = 91.9 degrees, Θ_{OS} = 122.3 degrees, $Y_{in,stub}$ = –j 0.03169 S. **15.15.** Θ_d = 87.3 degrees, Θ_{OS} = 20.7 degrees, $Y_{in,stub}$ = –j 2.64. **15.16.** 60.2 MHz. **15.17.** 106. **15.18.** 0.38 degrees; We can reduce this error using a pair of buffer amplifiers placed near the DUT to isolate the DUT outputs from the tester capacitance. Of course we need to calibrate the phase mismatch between the DIB buffer amplifiers.

15.19. $v(t) = 5.0\text{ V} - \dfrac{100\text{ mV}}{2} \times \dfrac{4.7\text{ k}\Omega}{1\text{ k}\Omega} \sin(2\pi ft) = 5.0\text{ V} - 235\text{ mV} \times \sin(2\pi \times 2400\, t)$

15.20. $v(t) = -235\text{ mV} \times \sin(2\pi \times 2400\, t)$. **15.21.** Power dissipation is caused by a resistive component associated with the line impedance—for example, the ohmic resistance of the copper trace forming a microstrip line. To reduce the power dissipation, the ohmic resistance needs to be minimized (use a wide and thick trace).

CHAPTER 16

16.1. Lower cost of test, increased fault coverage/improved process control, diagnostics and characterization, ease of test program development, and system-level diagnostics. **16.2.** Robust circuits can tolerate more measurement error without failing test limits. Since measurement accuracy generally comes at the expense of longer test time (averaging, for example), robust circuits with wide design margins can be tested more economically. **16.3.** Delayed time to market results in lower unit prices due to more competition. Lower unit prices lead to smaller profit margins. **16.4.** The IEEE Std. 1149.1 test interface is primarily designed for board-level, chip-to-chip interconnect testing. The TAP controller provides a standard, consistent interface to the scan circuits of the 1149.1 boundary scan circuits. Hold TMS at logic 1 while clocking TCK. No more than five TCK clock cycles are required. **16.5.** Test time will increase due to the tester's match mode search process. Test development time will likely increase due to match mode code development. **16.6.** Only four lines are required: TMS, TCK, TDI, and TDO **16.7.** 325 flip flops (all flip flops are in the scan chain). 10 MHz/(325 + 1). (we need one clock cycle to capture circuit response between parallel vectors). Multiple scan chains allow parallel testing, which will reduce the time require to scan data in and out. **16.8.** IDDQ testing. **16.9.** Using Eq. (6.38), $t_s = \ln(1\text{ mV}/1.5\text{ V}) \times 2\text{ k}\Omega \times 1\mu\text{F} = 15\text{ ms}$. After precharging, R increases to 50 kΩ (two 100 kΩ resistors in parallel). To recover from the worst-case op-amp offset of 10 mV takes an additional settling time of $t_s = \ln(1\text{ mV} / 10\text{ mV}) \times 50\text{ k}\Omega \times 1\mu\text{F} = 115\text{ ms}$, for a total settling time of 130 ms. (Notice that the op-amp's offset causes most of the settling time.) Without DfT, the circuit would normally take $t_s = \ln(1\text{ mV}/1.5\text{ V}) \times 50\text{ k}\Omega \times 1\mu\text{F} = 366\text{ ms}$. **16.13.** Force 1 V at the AB1 line and connect DUT 1's signal pin to the AB1 line. Connect DUT2's signal line to the internal ground connection through the ABM ground switch. Measure the voltages at the two signal pins using AB2 and subtract to get V_{drop}. Measure the current, I, supplied into AB1. Use $V_{drop} = IR$ to calculate the value of R. This method would not catch shorts to ground, but repeating the process from DUT 2 to DUT 1 will catch shorts. **16.14.** A reference multitone at a known amplitude at 1, 5, 9, and 13 kHz is applied to the input of the ADC. The DSP measures the ADC signal level and calculates the ADC gain. Then the test mux is switched to connect the DAC output to the ADC. The DAC is set to produce a multitone at the same frequencies. Its output is measured using the ADC. The ADC gain error at each frequency is removed through an on-chip calibration routine. This gives the DAC gain at each frequency. **16.15.** Place the first switch network into the "Force input" mode and apply a reference voltage to the DAC using the TESTIN analog bus. **16.16.** No, the circuit has a very long divide time. Also, it can only be clocked through a coupling capacitor. To improve the design, provide a bypass mode around the divider to allow observation of the oscillator output frequency in it's normal mode of operation. Also, provide a bypass path to clock the digital divider directly so it can be driven without the timing shift produced by the capacitor. Finally, use partitioning to split the divider into subcircuits that will count faster, or better yet, use a full-scan methodology for the divider to allow very fast testing. **16.17.** The voltage range includes the subthreshold, linear, and saturation to activate the active circuits in multiple conditions (see Figure 18.41). **16.18.** For the learning cycle a test cell with RF instrumentation as well as the test stimulus for correlation based test is needed for a subset of units. This will require a different setup than the production setup if the goal is to run production on the cheapest (with the minimum set of instrumentation) ATE. Additional cycles are required starting a lot in production when first establishing the correlation. **16.19.** There are two advantages, one of which is that a digital channel of the ATE is cheaper and more digital channels are typically available per tester. In addition, well-established BIST techniques like scan can be utilized to implement an efficient test. A more practical advantage is that, in general, digital tests are more robust in production when considering the impact of contact resistance on the test result, mismatch uncertainty due to discontinuities, calibration, and so on. (see also Chapters 12 and 13).