Index

Note: Page numbers followed by "f" and "t" refer to figures and tables, respectively.

Α	Automatic gain control, 84
Access and Mobility Management Function	Automatic Neighbor Relations (ANR), 205
(AMF), 47	Automatic Repeat Request (ARQ), 61, 245-246
Acknowledged Mode (AM), 220-221	
Acknowledgment (ACK), 180-181, 202-203	В
Acknowledgment SN (ACK_SN), 220	Backhaul IO, 148–149
Acknowledgment/negative acknowledgment	Backhaul testing, 345
(ACK/NACK), 126	Bandwidth (BW), 22-23, 112
Active users, 249	Bandwidth adaptation (BA), 67-69
selection, 251	Bandwidth parts/partitioning (BWP), 5-6, 67-69,
Adjacent Channel Leakage Ratio (ACLR), 78, 335	320-321
Advanced Vector Extensions (AVX), 176	Bare metal/RTOS, 183
Agile development, 329	Base Station (BS), 43
All-in-one base station, 15, 15f	output power, 335
Allocation and Retention Priority (ARP), 53	scheduler algorithms, 242-248
Analog gain control, 84	combined quality of service and
Analog-to-Digital Conversion (ADC), 159-162	opportunistic schedulers, 247
Analog-to-digital converter, 77	multiuser multiple input multiple output,
"Anchored NR-U", 13-14	247-248
Announce messages, 281	opportunistic scheduler, 243-245
Antenna diversity at UE, 353	quality of Service scheduler, 245-246
Antenna Element (AE), 168	wireless scheduler algorithm
Application architecture, 210-212	active user selection, 251
Application Function (AF), 47	architectural framework for, 249-254
Application Programming Interface (API), 16	frequency allocation, 252-253
Application-specific integrated circuit (ASIC), 5,	primary user selection, 251-252
140	secondary and remainder user selection,
Arg(max) vectorization, 258-260	253-254
example of input array, $258f$	static and regular scheduling, 250, 250f
vectorized comparison to find highest value,	user database reduction, 249f
259f	Base Transceiver Station (BTS), 43
Arm, 176–177, 183, 185	Baseband to radio frequency conversion, 158-159
Artificial Intelligence (AI), 2	intermediate frequency, 160f
ASN.1, 96-97	zero-intermediate frequency, 160f
Asynchronous network, 275-276	Baseboard Management Controller (BMC), 184
Asynchronous Transfer Mode (ATM), 245	BBDEV, 194-196
Authentication and Key Agreement (AKA), 47	Beam switch process steps, 171
Authentication Server Function (AUSF), 47	Beamforming and time, 228-229

Behavior Aggregate, 99	Cellular network synchronization requirements,
Best Effort (BE), 99	290-291
Best Master Clock Algorithm, 281	frequency accuracy and stability, 290
Bit Error Rate (BER), 124	time accuracy, 291
BitIsClear, 324	Central Processing Unit (CPU), 109, 184, 215, 309,
BitIsSet, 324	331, 359
Black box testing, 340–343	cores, 140
cell performance, 342–343	loading, 319
latency, 342	Central unit (CU), 3, 30–33, 43, 48–59, 103, 254,
stability, 342	329. See also Radio Unit (RU)
throughput, 341	based small cell solution, 139
PDCP throughput test setup, 341f	blades perform CU processing, 143
Board bring-up software, 141	control plane user plane split and central unit/
Board Support Package software (BSP software),	distributed unit interface, 50–51
141, 185–186, 329	dual and multiconnectivity, 56–59
Boot process and application load, 183–185	Internet Protocol and Internet Protocol
microcontroller and microprocessor	Security, 51–52
characteristics, 184 <i>t</i>	Packet Data Convergence Protocol, 55
private key signing and public key verification,	Quality of Service and related concepts, 52–55
185 <i>f</i>	Centralized processing, 21–28
Boundary clocks, 280–281	Centralized/distributed unit use-case
Bridging functions, 93	dimensioning for throughput, 103–108
Broadband Fixed Wireless Access	elephant flows, 107–108
(BFWA), 13	traffic requirements based performance
Broadband Wireless Access (BWA), 242	analysis, 104–106
Broadcast Channel (BCH), 71	user data rate dimensioning, 106–107
Broadcast Control Channel (BCCH), 71	Certificate Transparency, 207
Buffer and memory management, 191–193	Certified Professional Installer (CPI), 12
Buffer descriptors (BD), 195	Channel coding, 74
	Channel equalization, 315
C	Channel estimation, 314
C-plane latency, 342	Channel mapping, 70–73
C-RAN, 7–8	Channel state information (CSI), 242
C-V2X, 355–357	Channelization, 78
Calibration, 336–337	China Academy of Information and
Capacity enhancement, 18	Communications Technology (CAICT), 149
Car makers, 358	China Mobile Research Institute (CMRI), 7
Cell identity (Cell ID), 88	"Clean up" function, 277
Cell performance, 342–343	Clipping, 79
Cell site integrated (CU/DU) solutions, 146–154	Clock, 276
optimized hardware, 150–154	cycles, 310
scale-out by multiple iNICs, 146f	802.1CM, 91–94
server-based solutions, 148–150	bridging functions, 93
Cell site router/gateway, 95	Fronthaul profiles, 93–94
Cell site solution, 139	traffic classes, 92–93

Cobalt, 187	Cyclic redundancy check (CRC), 63
Code analysis tools, 330	Cyclomatic Complexity, 330
Code blocks (CBs), 74, 123–124	
level CRC, 124-125	D
Coexistence methods, 12	Data breach, 207
Combined quality of service and opportunistic	Data center, 139
schedulers, 247	architecture, 142–146, 143f
Commercial grade, 186	cell site integrated (CU/DU) solutions,
Commercial-off-the-shelf (COTS), 141	146-154
Common Control Channel (CCCH), 71	iNIC solutions, 145f
Common Public Radio Interface (CPRI), 15–16	key CU interfaces, 144f
Common Vulnerabilities and Exposures (CVE),	Data converter, 133–136
210	Data locality, 354
CoMP. See Cooperative Multipoint (CoMP)	Data network (DN), 44-46
Complementary Cumulative Distribution	Data plane (DP), 48
Function, 232	Data Plane Development Kit (DPDK), 190–191,
Complex MAC (CMAC), 314	311
Complexity analysis	Data Radio Bearers (DRBs), 47, 217
eCPRI, 311-312	Data/Control (D/C), 217
physical layer complexity analysis, 313-318	Dedicated Control Channel (DCCH), 71
Congestion window, 100	Dedicated Transport Channel (DTCH), 71
Connected users, 249	Demodulation Reference Signal (DMRS), 311
Containerization (Docker), 188	Development cycle, 141–142
Control and Management (C&M), 92	development timelines for typical product, 142j
Control Element (CE), 223	Development testing, 329-332
Control PDU Type (CPT), 220	functional, 330-331
Control plane (CP), 43, 45 <i>f</i> , 46 <i>f</i> , 143	performance, 331–332
user plane split and central unit/distributed	static analysis, 329–330
unit interface, 50–51	Device under test (DUT), 331-332
Cooperative Intelligent Transport Systems (C-	Dhrystone, 177
ITS), 354	DiffServ (DS), 97–101
Cooperative Multipoint (CoMP), 28–34, 84, 94,	DiffServ code point (DSCP), 52-53
353	Digital beamforming, 77—78
processing, 25–28	Digital down conversion, 78
Coordinated Universal Time (UTC), 267–268	Digital Front End (DFE), 128, 158, 163, 172, 224,
COUNT values, 218	230-234
Crest factor (CF), 77	CFR, 231–232
Crest factor reduction (CFR), 77, 79–80, 230–232,	DPD, 232-234
231 <i>f</i>	receive side gain control, 234
feed-forward digital predistorter, 232f	signal aggregation and digital up conversion,
CU Control Plane (CU-CP), 32	230-231
CU User Plane (CU-UP), 32	Digital predistortion (DPD), 77, 80-83, 131-132,
Cycle budget, 310	162, 230, 232-234
Cycle counting, 310	Digital signal processing (DSP), 7, 66–67, 310
Cyclic prefix (CP), 69, 238—239	Digital Signal Processor, 183

Digital Unit (DU), 156	Eligible users, 249
Digital Upconversion (DUC), 78, 230–231	Embedded Linux, 183
Digital-to-Analog Conversion (DAC), 159–162	End-to-end congestion notification (ECN), 99
Digital-to-analog converter, 77	End-to-end performance tests, 341
Digital ↔ analog conversion and analog	Enhanced Common Public Radio Interface
components, 83	(eCPRI), 76, 112–115, 309
Digitally controlled oscillator (DCO), 301	complexity analysis, 311-312
Dimensioning, 103	fronthaul transport options, 223f
Direct RF, 159	fronthaul transport protocol encapsulation
Discontinuous Reception (DRX), 67, 249	options, 224f
Discontinuous Transmission (DTX), 67	processing flow
Discontinuous transmission and reception, 66–67	receive from Ethernet, 227f
Distributed antenna systems (DAS), 19	transmit to Ethernet, 227f
Distributed processing, 21–28	protocol, 86, 223–228
Distributed unit (DU), 3, 30–33, 43, 59–76, 103,	termination, 157–158
254, 314, 329	U-plane message format, 225f
based small cell solution, 139	Enhanced Mobile Broadband (eMBB), 352
blades implement Layer 2, 146	Enterprise 5G networking, 34–40
F1 termination, 59	applications, 36
interface, 86	key performance indicators, 36
internal IO, 115–117	network installation and maintenance, 34–36
Physical Layer, 70–76	RF aspects, 37–40
Radio Link Control and Medium Access	total cost of ownership, 36–37
Control, 59-70	use-case example, 37
testing, 330	users of network, 36
Double data rate (DDR), 319	Environment optimization development, 321–322
Downlink (DL), 330	Environmental and power requirements, 96
chain tests, 330	Equalization Matrix, 314
directions, 350	Ethernet, 275–276
Downlink Control Information (DCI), 63-64, 203	Evolved NB (eNB), 43
Downlink Shared Channel (DL-SCH) transport	Evolved Packet Core (EPC), 44
channel, 202–203	Extended Logical Channel ID (eLCID), 223
Dual connectivity (DC), 49, 56–59	
	F
E	F1 termination, 59
E-LSP, 101	Fast Fourier transform (FFT), 76–78, 237–238
Earliest deadline due (EDD), 246	Feature testing, 333–334
Earliest deadline first algorithm (EDF algorithm),	Federal Communications Commission (FCC),
245	346-347
Edge compute networking, 353–354	File enumeration, 207
Effective Isotropic Radiated Power (EIRP), 11, 168,	5G Core Network (5GC Network), 143
335	5G New Radio (5G NR), 143
Effective Number of Bits (ENOB), 161	5G non-Standalone (5G NSA), 332
Electromagnetic Compatibility (EMC), 96	5G QoS Identifier (5QI), 53
Elephant Flows, 107–108	5G Reduced Capabilities (5G RedCap), 360–362

combinations of abovementioned features, 362	Frequency, 265–267, 266 <i>f</i> , 274
equipment bandwidth reduction, 361	accuracy, 290
half-duplex frequency division duplexing	allocation, 252-253
operation, 361–362	domain conversion, 228-229
reduced number of Rx/Tx antennas, 361	frequency-domain scheduling, 252
relaxed maximum modulation order, 362	frequency-only systems, 298–299
relaxed maximum number of multiple-input,	filtering effect of PLL, 299f
multiple-output layers, 362	PLL, 298f
relaxed user equipment processing time, 362	synchronization, 148
5G Standalone (5G SA), 332	Frequency Division Duplexing (FDD), 352
5G	Front-End Module (FEM), 165
bandwidth examples, 112–113	Front-testing, 345
base station architectures, 17–20	Fronthaul
C-RAN, 20	bandwidth, 112-115
DAS, 19	IO, 148–149
ISC, 17–18	latency, 114–115
massive multiple-input, multiple-output,	networks, 345
19-20	profiles, 93–94
pico/micro cell, 18	switch, 142
centric data center, 142	throughput, 25
modem, 173	Fronthaul gateway (FHGW), 94
networks, 215	Full-timing support (FTS), 280, 289, 294-296
protocol, 349-350	Functional application platform interface (FAPI),
Spectrum, 8–14	201-206
allocations, 9f	functional application platform interface
CBRS spectrum options, 10f	internal API, 201 <i>f</i>
Japan Government/Enterprise 5G bands, 13f	hardware traffic bifurcation, $201f$
licensed operator spectrum, 9-10	Functional splits, 20–28
licensed private spectrum, 10-13	distributed vs. centralized processing, 21-28
unlicensed spectrum, 13-14	Functional testing, 330–331
system, 43	
5G/NR, URLLC in, 350—353	G
Fixed Wireless Access deployment, 234	G-PDU, 216
Floating-Point (FP), 176	Gain Control algorithms, 234
Flow Identifier, 226	GCC, 321
FLR. See Frame Loss Ratio (FLR)	General Authorized Access (GAA), 11
Form factor, 96	General-purpose processor (GPP), 237
Forward Error Correction (FEC), 149	Generalized Memory Polynomial, 233
4G	Global Navigation by Satellite Systems (GNSS),
bandwidth examples, 113–114	269-273
C-V2X (PC5), 356–357, 357f	constellation, 271f
FPGAs, 140, 145–146	receiver interfaces, 273f
Fractional frequency reuse, 26	Global synchronization, 101
Frame, 73	Global System for Mobile communication (GSM),
Frame Loss Ratio (FLR), 92	55

gNB, 143	High-priority fronthaul (HPF), 93
GPRS Tunneling Protocol (GTP), 3, 50–51	HPF. See High-priority fronthaul (HPF)
GTP-U, 215	Hybrid Automatic Repeat Request (HARQ), 61,
GTPv1, 215	63-65, 123-124, 250, 321, 353
GTPv1-U, 217	memory and bandwidth dimensioning,
GTPv2, 215	123-126
GTPv2-C, 215	process count dimensioning, 126-127
protocol, 215–217	
GTP-U PDU format, 216f	I
PDU session information format, 216f	I/O
GPRS Tunneling Protocol—Control (GTP-C), 53	dimensioning, 178
GPRS Tunneling Protocol—User (GTP-U), 53	termination, 331
Grandmaster, 282	IEEE 1588 standard, 280
Graphical User Interface (GUI), 186	In-band selectivity and blocking, 336
	In-channel selectivity, 336
Н	Industrial automation, 353-354
Half-duplex frequency division duplexing	Information elements (IEs), 69
operation, 361–362	Initial access, 87–91
Hardware acceleration model, 193-194	Inline Acceleration Model, 194
accelerator physical implementation, 193f	Instantaneous BandWidth (IBW), 79, 128
inline accelerator, 194f	Instruction Set Architecture (ISA), 148
parallelizing accelerator calls, 193f	Instructions Per Clock/Cycle (IPC), 319, 322
Hardware architecture choices, 139	Integrated Architectures, 153
data center architecture, 142-146	Integrated Small Cell (ISC), 17–18, 33–34, 43,
development cycle, 141-142	139, 154, 156, 172-174
ISC, 172–174	networking processor/host, 173
multicore central processing unit selection	physical layer/5G modem, 173
criteria, 174–179	radio frequency subsystem, 174
PCIe performance, 179–181	Intellectual Property Rights (IPR), 184
RU, 154–171	Inter Cell Interference Coordination (ICIC), 205
scalability, 139–141	Inter process communication, 194–196, 194f, 195f
Hardware offload, 179	Inter Processor Communication (IPC), 194-195
Hardware system dimensioning	Intermediate Frequency interface (IF interface),
centralized/distributed unit use-case	159
dimensioning for throughput, 103-108	International Electrotechnical Commission (IEC),
distributed unit internal IO, 115–117	214
eCPRI, fronthaul bandwidth and latency,	security requirements, 212-214
112-115	security algorithms for 4G/LTE, 212t
HARQ process count dimensioning, 126-127	security algorithms for 5G/NR, 213t
memory dimensioning, 117-126	Internet Protocol (IP), 43, 51–52
radio unit, 127–136	Internet Protocol Security (IPSec), 51-52, 145,
use-case dimensioning for latency, 108-110	320
users/transmission time interval, 110-111	Interoperability and Test (IoT), 1, 329
"Heisenbugs", 344–345	development testing, 329-332
High reliability, 352–353	front-, mid-, and backhaul testing, 345

operator acceptance testing, 345–346	C-V2X, 356—357
performance testing, 340-345	macro cell, 223-224
regulatory approval testing, 346–347	Look-aside Acceleration Model, 193
system test setup, 332-340	Lookup Tables (LUTs), 81, 233
Interoperability testing, 338–340	Low physical layer, 158, 228–229
plug fest, 338–340	beamforming and time/frequency domain
use-case scenarios, 338	conversion, 228–229
User Equipment test pool, 338	PRACH extraction and filtering, 229
Inverse discrete Fourier transform (IDFT),	Low-priority fronthaul (LPF), 93
237-238	Lower Layer Split/CU plane (LLS-CU), 31
Inverse fast Fourier transform (IFFT), 237-238	Lower Level Split (LLS), 31
J	M
JESD, 77, 162–163	Management plane (MP), 3
	Massive multiple-input, multiple-output, 19–20
K	Master Information Block (MIB), 71
Key performance indicators (KPI), 36, 333,	Max Coupling Loss (maxCL), 351
350-351	Maximum Transfer Unit (MTU), 216
15-KHz SCS, 351	Medium Access Control (MAC), 48, 59-70, 240,
Knots Complexity, 330	312, 330
	layers, 354
L	MAC-I field, 217
L-LSP, 101	protocol, 222–223, 222f
"L1 bypass" testing, 341	Medium-priority fronthaul (MPF), 93
Latency, 112–115, 350, 354	Memory
testing, 342	dimensioning, 117–126
License-Assisted Access (LAA), 13–14	HARQ memory and bandwidth
Licensed operator spectrum, 9–10	dimensioning, 123–126
Licensed private spectrum, 10–13	life-of-a-packet memory bandwidth analysis,
in United States, 10–12	117–123
Life-of-a-packet double data rate utilization	memory sizing, 117
analysis, 320	scrubbers, 196
Life-of-a-packet memory bandwidth analysis,	sizing, 117
117-123	Memory Management Unit (MMU), 322
Limited Buffer Rate Matching (LBRM), 124	Messaging Channel, 277
Linux	"Micro kernel", 188
distribution, 186	Mid-testing, 345
kernel, 184	Mini-slot structure, 352, 352f
and processor performance tuning, 196-197	Mitigation techniques, software performance,
Log Likelihood Ratios (LLRs), 116, 315	320-321
generation process, 317	mmWave radio frequency module, 168-171, 169f
Logical Channel ID (LCID), 223	beam switch process steps, 171
Logical channels, 70–71	mmWave link budget example, 168-170
Long term support (LTS), 185–186	Mobile World Congress (MWC), 8
Long-Term Evolution (LTE), 1, 9, 43, 351	Modern Network Interface Cards, 200

Modified Largest Weighted Delay First (M-	FTS or PTS, SyncE or no SyncE, 294-296
LWDF), 251	mixed PTP profiles, 296f
Modulation Coding Scheme (MCS), 74, 221–222,	O-DU sync functions, $294t$
242	SyncE and precision time protocol, 294t
Modulation schemes, 241–242, 242f	O-RAN LLS architectures, 293f
Moore's law, 5, 186-187	Networked Femto Application Programming
MTU Discovery (MTUD), 216	Interface (nFAPI), 32–33, 203–204
Multiconnectivity, 56-59	timing window management, 204f
Multicore central processing unit selection	Networking processor/host, 148-149, 173
criteria, 174–179	Networking stacks, 197-200
Arm, 176–177	features, 197
hardware offload, 179	performance, 199–200, 200f
memory and I/O dimensioning, 178	security, 197–199
performance benchmarking, 177-178	New Radio (NR), 43, 351
SIMD, 174–176	Next-generation radio access network (NG-RAN),
x86, 176	43–48, 45 <i>f</i>
Multiple blades, 145	wired networking analogy, 48
Multiple input multiple output (MIMO), 7, 70, 76,	NF Repository function (NRF), 47
237, 246-247, 253-254, 359	NMEA-0183 standard, 273
Multiple smaller (MPS), 180	NodeB (NB), 43
Multiple-input layers, 362	Noise Figure (NF), 129, 167
Multiple-output layers, 362	Non Access Stratum (NAS), 47
Multiprotocol Label Switching support for	Non-Real-Time (non-RT), 2
DiffServ, 101	Non-Stand Alone deployments (NSA
Multiuser diversity, 243	deployments), 57
Multiuser multiple input multiple output,	NR C-V2X (PC5), 357
247-248	NR-Unlicensed (NR-U), 13-14
	Numerically Controlled Oscillator (NCO), 159, 301
N	Numerology, 73–74
Negative Acknowledgement (Nack), 63, 180-181,	3
202-203, 220	0
NETCONF protocol, 33	Occupied BandWidth (OBW), 128, 335
Network asymmetry, 287	OCXO, 304
Network Exposure function (NEF), 47	One-way protocol, 278–279
Network Interface Card (NIC), 16, 114, 148	Open Base Station Architecture Initiative (OBSAI),
Network Listening Mode, 205	15-16
Network monitor mode API, 204–206	Open Networking Foundation (ONF), 48
Network PDV, 287-288	Open Radio Access Network (O-RAN), 1, 141, 265,
Network Processor Units (NPUs), 145–146	311, 329, 349
Network reconnaissance, 208–209	5G base station architectures, 17–20
Network Slice Selection Function (NSSF), 47	5G RedCap, 360–362
Network Time Protocol (NTP), 278–279	alliance, 1–6
Network-based synchronization, 274–275	C-RAN, 7–8
network time distribution, 275 <i>f</i>	cellular network synchronization requirements,
Network-level synchronization, 292–296	290–291

centralized RAN architecture, 21f	unraveling standards spaghetti, 305–306
CoMP, 28–34	URLLC, 349-354
effects of timestamping location and resolution,	vehicle-to-infrastructure roadside unit
303-305	architecture and implementation, 354-360
enterprise 5G networking, 34–40	working groups, 2f
functional splits, 20–28	xRAN, 7–8
members, 4, 5f	Open Telecom IT Infrastructure (OTII), 149
network-level synchronization, 292–296	Open vRAN, 7–8
Open vRAN, 7–8	OpenFlow, 48
OpenRAN, 7–8	OpenRAN, 7–8
spectrum, 8–14	Operating band unwanted emissions (OBUE), 335
supported functional splits, 30–34	Operating System (OS), 117, 140, 183–197
synchronization, 273–290, 292	bare metal/RTOS vs. embedded Linux, 183
equipment requirements, 296–298	BBDEV and inter process communication,
solution implementation, 298–302	194-196
system components, requirements, and	boot process and application load, 183-185
interfaces, 43	buffer and memory management, 191–193
802. 1CM, 91–94	hardware acceleration model, 193–194
ASN. 1, 96–97	Linux and processor performance tuning,
cell site router/gateway, 95	196–197
central unit, 48–59	long term support, 185–186
DiffServ, 97–101	realtime and timing, 186–191
distributed unit, 59–76	roll your own <i>vs.</i> commercial grade, 186
distributed unit/radio unit interface,	Operation and Maintenance (OAM), 156, 172
Enhanced Common Public Radio Interface	Operator acceptance testing, 345–346
protocol overview, 86	Opportunistic scheduler, 243–245
FHGW, 94	Oprofile, 319
form factor, environmental and power	Optimization techniques
requirements, 96	architectural framework for base station
initial access, 87–91	wireless scheduler algorithm, 249-254
Multiprotocol Label Switching support for	base station scheduler algorithms, 242-248
DiffServ, 101	OFDM(A), 237–242
next-generation radio access network, 43-48,	subcarrier allocation, 240-241
45f	software optimization techniques, 257-260
radio unit, 76–86	system-level optimization, 254-257
telecommunications infrastructure project, 7–8	Optimized hardware, 150-154
traditional base station architectures, 14–17	deeply integrated/embedded approach, 154f
understanding frequency, time, syntonization,	disaggregated approach, 155f
and synchronization, 265-269	software defined approach, 156f
frequency, 265–267	Orbiting satellites, 270
global navigation by satellite systems,	Orthogonal frequency division multiple access
270-273	(OFDM(A)), 237–242
syntonized vs. synchronized, 269, 270f	subcarrier allocation, 240-241
time, 267-273	Orthogonal frequency division multiplexing
time and phase, 267	(OFDM), 66, 237, 330

Orthogonal frequency division multiplexing	black box testing, 340-343
(OFDM) (Continued)	white box testing, 343–345
numerologies, 351–352, 351 <i>t</i>	Phase, 267
Oscillator selection and holdover, 303-305	Phase-locked loop (PLL), 133–136, 298
Out-of-band blocking, 336	PHY API, 202-203
Output power, 167	Physical Broadcast Channel (PBCH), 73, 88, 202
dynamics, 335	Physical Cell ID (PCI), 190–191
Oversubscription, 104	Physical channels, 70–73
ratio, 106–107	ID, 226
_	mapping and modulation, 75–76
P	Physical Downlink Control Channel (PDCCH),
802.11p standard, 356	71-72
Packet Data Convergence Protocol (PDCP), 48,	Physical Downlink Shared Channel (PDSCH), 73
55, 330	Physical Layer, 70–76, 173, 354
performance, 341	channel coding, 74
protocol, 217–220	channel mapping, 70–73
PDCP PDU example, 217f	complexity analysis, 313-318
robust header compression, 219–220	L1 processing in DU, 313f
stack memory domains, 218f	numerology, 73–74
Packet Delay Variation (PDV), 285	performance proof points, 316–318
Packet processing, 331–332	QAM demodulation, 317f
Packet processing cycle budget analysis, 310–312 eCPRI complexity analysis, 311–312	physical channel mapping and modulation, 75–76
Packet time transport, 278–279	processing, 228–229
one-way protocol, 278f	Radio Network Temporary Identifier, 73
two-way protocol, 279f	stack development, 318
Paging Channel (PCH), 71	TBs, 223
Paging Control Channel (PCCH), 71	theoretical analysis, 314–316
Partial-timing support (PTS), 280, 294-296	Physical Layer Acceleration, 149
PC5 interface, 356-357	Physical Network Function (PNF), 203
PCIe performance, 179-181	Physical Random Access Channel (PRACH), 73,
example calculation, 181	85-86, 315
transaction layer packetization, 180–181	extraction and filtering, 229, 229f
Peak cancellation, 80	Physical resource block (PRB), 69
Peak to Average Power Ratio (PAPR), 78, 230	Physical Uplink Control Channel (PUCCH), 73
reduction and performance improvement	Physical Uplink Shared Channel (PUSCH), 73
techniques, 78–83	Physical-layer transport, 275–278
Peak windowing, 80	"Pico kernel", 187
Per Hop Behavior (PHB), 98	Pico/micro cell, 18
Performance, 199-200, 331-332	Platform Control Hub (PCH), 184
benchmarking, 177–178	Plug fest, 338–340, 339f
exploration, 344	Policy Control Function (PCF), 47
metrics, 309	Polling (P), 220
proof points, 316-318	Polynomial algorithm, 233
testing, 340–345	Polynomial models, 233

Power	R
control, 66	Radio access network (RAN), 1
receive side, 66	performance, 354
transmit side, 66	Radio Access Network Application Part (RANAP),
efficiency, 167	53
Power Amplifier (PA), 78, 131, 155, 230	Radio Equipment (RE), 66
Precision Time Protocol (PTP), 269, 278-290	Radio frequency (RF), 154, 354
example network PDV, 286f	compliance testing, 335-338
head of line blocking, 286f	calibration, 336–337
master selection process, 282f	receiver, 336, 337 <i>f</i>
network topology, 280f	tools needed, 337–338
one-way protocol, 278f	transmitter, 335, 337 f
PTP + SyncE solution, 302, $304f$	subsystem, 162–165, 174
synchronization	analog, 163–165
message flow, 282f	JESD, 162–163
process, 284f	Radio Link Control (RLC), 48, 59-70, 249, 330
syntonization process, 283f	layers, 220-221, 354
effect of timestamping point, 287f	protocol, 220-222
two-way protocol, 279f	RLC header example, 221f
Predictive HARQ, 65	Radio Network Temporary Identifier (RNTI), 67,
PREEMPT_RT, 187	73
Primary Reference Clock, 273	Radio Resource Control (RRC), 48, 330
Primary Synchronization Signal (PSS), 88	Radio resource management (RRM), 2
Primary user selection, 251-252	Radio Unit (RU), 3, 30-33, 43, 76-86, 103,
frequency-domain scheduling challenge,	127-136, 154-171, 215, 254, 316, 329.
253f	See also Central unit (CU)
PF time-domain scheduling, 252f	analog gain control, 84
Priority Access Licensed (PAL), 10-11	baseband to radio frequency conversion,
"Processing cycle budget analysis", 310	158-159
Processor binding, 196	data converter and PLL, 133-136
Profiling, 206–208	digital beamforming and fast Fourier transform,
Program Counter (PC), 184	77-78
Proportional fair (PF), 250	digital predistortion, 131-132
Protocol, 277, 333	digital up conversion, channelization, and digital down conversion, 78
Q	digital-to-analog conversion and analog-to-
QoS Class Identifier (QCI), 55	digital conversion, 159–162
QoS Flow Identifier (QFI), 52-53, 215	digital ↔ analog conversion and analog
Quadrature amplitude modulation (QAM), 74,	components, 83
159, 241, 315, 335	eCPRI termination, 157-158
Quadrature Phase Shift Keying (QPSK), 241, 335	generalized block diagram, 76-77
Quality of Service (QoS), 44, 242	IBW, 128
flows in 5GC and NG-RAN, 52f	key components in integrated radio unit, $157f$
and related concepts, 52-55	latency and delay, 130–131
scheduler, 245–246	low physical layer and digital front end, 158

Radio Unit (RU) (Continued)	Roadside unit (RSU), 358–360, 359f
disaggregated approach, 159f	system architecture, 359-360
software defined approach, 158f	Robust Header Compression (RoHC), 49,
mmWave radio frequency module, 168-171	219–220, 219 <i>f</i>
OBW, 128	ROHC v1, 219
peak-to-average power ratio reduction and	Roll your own (RYO), 186
performance improvement techniques,	Round Trip Time (RTT), 100
78-83	Round-Robin algorithm (RR algorithm), 245
PRACH, 85–86	Rx DC offset, 336
radio frequency subsystem, 162-165	Rx/Tx antennas, reduced number of, 361
receiver chain analysis, 128-129	Rx/Tx IQ mismatch, 336
sub 6 GHz front end module, 165-167	
time and frequency synchronization, 84	S
Ramdisk, 184	"Safe For Network" testing, 338
RAN Intelligent Controller (RIC), 2	Scalability aspect, 139-141
Random Access Channel (RACH), 23, 71	Scalable Vector Extension (SVE), 176
Random Early Discard (RED), 98, 100	Scale-out scenarios, 140
Random-access procedure, 89–91	SCHED-FIFO (Scheduler policy), 196
Random-access response (RAR), 90	SCHED-OTHER (Scheduler policy), 196
Read Only Memory (ROM), 184	SCHED-RR (Scheduler policy), 196
Real Time (RT), 127	Scheduled users, 249
support, 186	Scheduling, static and regular, 250
and timing, 186–191	Secondary eNB (SeNB), 58-59
operating system latency for interrupt	Secondary Synchronization Signal (SSS), 88
handling, 188f	Security aspects, 206-214
time synchronization features in Linux, 189f	application architecture, 210-212
timeout array, 190f	network reconnaissance, 208-209
Receiver, 336	profiling, 206–208
chain analysis, 128–129	security updates, 209-210
dynamic range, 167	Segmentation Indicator bits (SI bits), 220
intermodulation, 336	Segmentation Offset (SO), 220
sensitivity, 167	Self-Organizing Networks (SON), 204
spurious emissions, 336	Semi-persistent scheduling (SPS), 67, 352
Reference sensitivity level, 336	Sentences, 273
Reflective Quality of Service, 55	Sequence Number (SN), 217, 220-221, 334
Regular scheduling, 250	Serial Rapid IO (sRIO), 16
Regulatory approval testing, 346-347	Server, 143
Relaxed maximum modulation order, 362	Server-based solutions, 148-150
Relaxed User Equipment processing time, 362	alternative server PCIe/offload scenario, 151,
Reliability, 350	DU acceleration blade, 147f
Remote Radio Head (RRH), 315	scale-out to multiple blades, $147f$
Resource blocks (RBs), 335	server-based cell site DU solution, 148f
Resource element (RE), 335	typical server PCIe/offload scenario, 150f
Retroactive software optimization, 331-332	Service Data Adaptation Protocol (SDAP), 48
RISC-V, 183	Service Data Unit (SDU), 218, 333, 350

Shared Channel (ULSCH), 71	Stability
Sigmoid method, 80	cellular network synchronization requirements,
Signal aggregation, 230–231, 231 f	290
Signal processing chain, 331	testing, 342
Signal-to interference and noise ratio (SINR),	Stack processing, 331–332
352-353	Standardization efforts, 224
Signal-to-interference ratio (SIR), 241–242	Static code analysis, 329-330
Signal-to-noise ratio (SNR), 28, 78, 243	Static scheduling, 250
Signaling Radio Bearers (SRBs), 49, 217	STREAM, 178
Silicon devices, 140	Sub 6 GHz front end module, 165-167
Single Frequency Network (SFN), 202	control, 166–167
Single Instruction Multiple Data (SIMD),	receive, 166
174–176, 257–258, 312	transmit, 166
Single-Rate Tri Color Marking (srTCM), 99–100	Subcarrier spacing (SCS), 351
Slot-slot structure, 352	"SubPDUS", 223
Slow start, 100	Supplementary Uplink operation (SUL operation)
Small cells, 354	69-70
"Smart Network Interface Card" (SmartNIC),	Symbol duration/subcarrier spacing (SCS), 65
148-149	Sync equipment requirements, O-RAN, 296–298
Software Defined Approach, 158	Sync solution implementation, 298-302
Software defined solution, 154	designing PTP + SyncE solution, 302
Software optimization techniques, 257–260	frequency-only systems, 298–299
arg(max) vectorization, 258–260	time-synchronization systems, 299-302
Software optimization techniques, 322–327	Synchronization, 88-89, 269
Software performance, 309	O-RAN, 265–269, 273–290, 274f, 292
central processing unit loading summary, 319	network-based synchronization, 274-275
development environment optimization,	packet time transport and precision time
321-322	protocol, 278–279
life-of-a-packet double data rate utilization	physical-layer transport and synchronous
analysis, 320	Ethernet, 275–278
mitigation techniques, 320-321	PTP, 279–289
packet processing cycle budget analysis,	putting PTP and SyncE, 289-290
310-312	process, 285
physical layer complexity analysis, 313-318	Synchronization Signal Block (SSB), 88
software optimization techniques, 322-327	Synchronization Status Messages (SSMs), 277
system-on-chip performance counters, 319	Synchronous Ethernet (SyncE), 275-278,
Software-defined networking (SDN), 1, 48, 350	289-290, 294-296
deployment options including, 353-354, 353f	asynchronous Ethernet clocking, 276f
Software-defined radio (SDR), 5	Ethernet rate mismatch, 276f
Sounding Reference Signal (SRS), 315	SyncE ESMC messaging, 277f
SPECint, 178	SyncE propagation, 277f
Spectral aspects, 355	Syntonization, O-RAN, 265-269
V2X spectrum allocation, 356f	System dimensioning, 103
Spectrum, 8–14	System information (SI), 49
Spectrum allocation system (SAS), 11–12, 11f	System integration, 343

System mapping, 103	interference management, 353
System software	orthogonal frequency division multiplexing
3GPP and IEC security requirements, 212–214	numerologies, 351–352
functional application platform interface,	slot/mini-slot structure, 352
201–206	uplink grant-free transmission, 352
network monitor mode API, 204-206	systems, 189
nFAPI, 203–204	Throughput, 320–321
PHY API, 202–203	testing, 341
networking stacks, 197–200	Time, 267–273
operating system, 183–197	accuracy, 291
security aspects, 206–214	and frequency synchronization, 84
application architecture, 210–212	holdover, 305
network reconnaissance, 208–209	O-RAN, 265–269
profiling, 206–208	relationship of TAI to UTC, 268f
security updates, 209–210	synchronization, 148
System tests, 329	time-domain scheduling, 250
consumer application hardening, 340	time-frequency offset estimation, 314
feature testing, 333–334	Time-Division Duplex (TDD), 63, 311
example of feature compliance matrix, 334f	Time-Sensitive Networking (TSN), 33, 349
interoperability testing, 338-340	Time-synchronization systems, 299-302
RF compliance testing, 335-338	PTP + SyncE solution flow, $302f$
SA/NSA, 332 <i>f</i>	servo performance comparison, 301f
setup, 332-340	timestamping points, 300f
System Validation Test (SVT), 329	Timestamping location and resolution, effects of,
System-level optimization, 254–257	303-305
high-level view of an O-RAN CU/DU/RU	oscillator selection and holdover, 303-305
system implementation, $255f$	Timing, 143
system-level scheduling challenge, 255f	Tool Command Language (TCL) scripting, 330
System-on-Chip (SoC), 117-119, 309	Top of Rack (TOR), 142
performance counters, 319	Traditional base station architectures, 14–17 3G/4G/5G macro cell, 15–17
Т	all-in-one base station, 15
TCXO, 304	Traffic classes, 92–93
Telecommunications Infrastructure Project (TIP),	Traffic generators, 333
7-8	Traffic requirements based performance analysis
3G networks, 215	104-106
3G/4G/5G macro cell, 15-17	Transaction layer packetization, 180-181
3GPP, 212-214, 320	PCIe per-lane performance, $179t$
5G standards, 357	Transmission Time Interval (TTI), 65, 110
I/Q transport, 223–224	Transmit ON/OFF power, 335
Layer-2 protocol stack and interfaces, 49f, 60f	Transmit operation, 126
protocol, 187-188	Transmit Power Control (TPC), 66
split and terminology, 44f	Transmit/reception point (TRP), 28, 255
standards, 32, 333, 350-353	Transmitted signal quality, 335
high reliability, 352–353	Transmitter, 335

intermodulation, 335	test pool, 338
spurious emissions, 335	User Equipment bandwidth reduction, 361
Transparent Mode (TM), 220–221	User Plane (UP), 31, 43, 45f, 46f, 143
Transport Blocks (TBs), 59, 123-124, 223	application components
level CRC, 124-125	DFE, 230-234
Transport channels, 70–71	eCPRI protocol, 223–228
Tunnel Endpoint Identifier (TEID), 53, 215	GTP protocol, 215–217
"Turbo" frequency, 140	low physical layer, 228–229
Two-way protocol, 279	MAC protocol, 222–223
2G networks, 215	PDCP protocol, 217–220
Tx droop correction, 337	RLC protocol, 220-222
Tx gain/phase error, 337	User selection
Tx LO leakage correction, 336	active, 251
Type of Service (ToS), 98	primary, 251–252
	Users/transmission time interval, 110-111
U	UTC. See Coordinated Universal Time (UTC)
U-plane latency, 342	Utility function, 251
Ubuntu, 186	
Ultra-reliable low-latency communication	V
(URLLC), 5-6, 349-354	Vector-Length Agnostic programming model
3GPP standards, 350-353	(VLA programming model), 176
in 5G/NR, 350–353	Vehicle-to-anything standards and deployment
deployment options including edge compute	timeline, 355–358
and software-defined networking, 353-354	4G C-V2X (PC5), 356–357
use cases and requirements, 350t	802.11p, 356
UMTS Terrestrial Radio Access Network	deployment timeline, 358
(UTRAN), 53	NR C-V2X (PC5), 357
Unacknowledged Mode (UM), 220–221	standards summary, 357-358
Unified Data Management (UDM), 47	different wireless protocol stacks, 357–358
Unit testing, 330, 333	V2X protocol stacks, 358f
Unlicensed spectrum, 13–14	Vehicle-to-infrastructure (V2I), 355, 355f
Unmanned arial vehicle (UAV), 338	roadside unit architecture and implementation,
UP function (UPF), 44–47	354-360
Uplink (UL), 330	RSU, 358-360
chain tests, 330	spectral aspects, 355
directions, 350	vehicle-to-anything standards and
grant-free transmission, 352	deployment timeline, 355–358
Urban canyons, 271	Vehicle-to-Network (V2N), 355, 355f
Use-case	Vehicle-to-Pedestrian (V2P), 355, 355f
dimensioning for latency, 108-110	Vehicle-to-Vehicle (V2V), 355, 355f
scenarios, 338	Vendor lock-in, 6
User count, 103	"Vendor-independent API" concept, 33
User data rate dimensioning, 106–107	Virtual local area networks (VLAN), 209
User Equipment (UE), 11–12, 202, 251, 332–333,	Virtual Network Function (VNF), 203
352	Virtual private network (VPN), 208

Virtualization (KVM), 188	Wideband Code Division Multiple Access
VoIP, 219	(WCDMA), 86
W	X
Weighted RED (WRED), 100	x86, 176, 183
White box	xRAN, 7–8
hardware system, 141	Forum, 8
systems, 35	
testing, 343-345	Z
DU L2 stack unit test benchmarking	Zadoff-Chu sequence, 85-86
platform, 345f	Zero-Intermediate Frequency (Zero IF), 159
system lifecycle performance tracking, 343f	