

# Index

- active optical network (AON), 292
- adaptive link rate (ALR), 279
- adaptive modulation and coding (AMC), 222–3
- adaptive sectorization
  - assumptions, 107
  - azimuth antenna pattern, 104–6
  - beamwidth, 109, 110
  - blocking probability, 106, 109, 110
  - CDF, 107, 109
  - deployment, 103, 105
  - elevation pattern, 105–6
  - interest G-factor, 103
  - macro cell power model, 106, 107
  - switching off sector, 107–8, 108, 109
- additive white Gaussian noise (AWGN), 119–20
- Alliance for Telecommunication Industry Solutions (ATIS), 248–9, 392
- ALTO *see* application layer transport optimization (ALTO)
- amplify-and-forward (AF) processing, 112
- AMR *see* automatic meter reading (AMR)
- ant colony based energy-aware routing, 270–271
- application layer transport optimization (ALTO), 363
- application-specific proxy
  - EE-BitTorrent, 345–6, 346
  - Gnutella, 345
  - SIP catcher, 344–5
  - UPnP low power architecture, 344
- architecture working group 2 (SA2)
  - load redistribution, 245
  - maximum DRX cycles, 246
  - network sharing, 245
  - pooled MMEs, 244–5
  - power saving state, 246
  - scheduled communication, 245
- ATIS *see* Alliance for Telecommunication Industry Solutions (ATIS)
- automatic meter reading (AMR), 230, 230
- azimuth antenna pattern, 104–6
- backbone networks
  - CDNs, 363
  - deployment issues, 262–3
  - energy saving algorithms *see* switch-off algorithms
  - forwarding freezing approach, 261–2
  - optical network *see* wavelength division multiplexing (WDM)
  - power consumption, 258–9, 259
  - service-tailored network
    - programmability, 402
  - switch-off *vs.* energy proportionality, 259–61, 260
- base station sites (BTS)
  - backhaul connections, 25
  - baseband signal processing, 24

- base station sites (BTS) (*continued*)
  - cell size reduction, 33–5, 34
  - core network, 24
  - feeder cables, 24
  - PA and RF transceiver, 24
  - power consuming units, 25, 25–6, **26**
  - shape, size, and serving cells, 24
  - site cooling, 25
  - sleep mode, **27**, **31**, 35–6
- base stations (BSs), 86
  - adaptive (de)sectorization
    - assumptions, 107
    - azimuth antenna pattern, 104–6
    - beamwidth, 109, 110
    - blocking probability, 106, 109, 110
    - CDF, 107, 109
    - deployment, 103, 105
    - elevation pattern, 105–6
    - interest G-factor, 103
    - macro cell power model, 106, 107
    - switching off sector, 107–8, 108, 109
  - architecture evolutions
    - cloud-RAN approach, 93, 93–4
    - massive-MIMO, 93, 93–4
    - telecom industry, 92–3, 93
  - BBU, 76, 76–8
  - cellular network architecture, 74, 74–5
  - component level evolutions
    - benefits, 88
    - ETPA, 89, 89–90
    - improvements, 90
    - signal-aware power amplifiers, 90
  - energy consumption *see* energy consumption
    - consumption
  - environmental impacts, 63
  - functions, 75–6
  - initial embodied energy, 63–4
  - large and small cells, 79, 79–80
  - multiple carriers and technologies, 80, 81
  - network components, 61–2
  - number/coverage trade-off, 66–7
  - operating energy, 62, 64–5, 65
  - operation improvements
    - radio resources, 91
    - sleep modes, 92
    - smart load adaptation, 91
  - optimal cell size, 62
  - power-off strategy *see* optimal power-off strategy
  - radio head, 76, 76, 78, 78–9, 80, 81
  - sectors per site, 80, 80
  - semiconductor manufacturing, 62–3
  - simulation results, 67–9, 68–70
  - single-box architecture, 81, 81
  - single-cabinet architecture, 81, 81
  - sleeping algorithm
    - blocking probability, 169, 171
    - concept of, 144
    - DP algorithm, 164–7
    - issues, 158
    - problem formulation, 161–4
    - state distribution, 169, 170
    - switching cost, 172–4, 173, 174
    - system model, 159, 159–161
    - traffic distribution, 168, 169, 170
    - uniform pattern, 171–2, 172
  - superheterodyne architectures, 76, 79
  - traffic patterns, 62
  - two-tier cellular access network, 62
  - uplink analogue processing, 76, 79
- baseband signal processing, 24
- baseband unit (BBU), 76, 76–8, 90
- Bayesian inference techniques, 351
- BBF *see* broadband forum (BBF)
- bit error rate (BER), 301, 302
- BitTorrent, 355, 356
- blocking probability, 102, 102
- broadband access evolution
  - backhaul connection, 23
  - capacity and latency issues, 23
  - Cisco VNI, 21–2, **22**
  - load activity factor, residential area, 21–2, 22
  - macrocell network, 23
  - MNOs, 21–2
  - Moore’s law, 23
  - proactive network planning, 23–24
- broadband forum (BBF), 378, 385, 386
- BSs *see* base stations (BSs)
- BTS *see* base station sites (BTS)

- capacity-booster cell, 243
- CAPM *see* context-aware power management (CAPM)
- CDF *see* cumulative distribution function (CDF)
- CDNs *see* content delivery networks (CDNs)
- cell zooming
  - BS cooperation, 152
  - centralized algorithm, 155
  - compatibility, 153
  - coverage holes, 153
  - distributed algorithm, 155–6
  - fluctuations, 153
  - inter-cell interference, 153
  - load balancing, 152
  - performance evaluation, 156–8
  - physical adjustment, 151–2
  - planning and operations, 144, 150, 150, 151
  - power control, 153
  - relay stations, 152
  - server control, 151
  - sleeping pattern, 152
  - stages, 154, 154
- channel utilization, 203
- CHORUS *see* collaborative and harmonious open radio ubiquitous systems (CHORUS)
- Cisco Visual Networking Index (VNI), 21–2, 22
- CLI *see* convergence layer interface (CLI)
- code-of-conduct (CoC), 380–381
- cognitive radio (CR)
  - cognitive synergy, 140
  - cooperative relay system, 130–131
  - Nash equilibrium, 129
  - network elements level, 396–7
  - noncooperative game, 129
  - primary users, 128–9
  - resource allocation, 129–30
  - secondary users, 128–9
  - spectrum sharing, 129–30
- collaborative and harmonious open radio ubiquitous systems (CHORUS)
  - analysis technique, 143
  - architecture of, 141, 142
  - cognitive radio, 140
  - cognitive synergy, 140
  - collaboration, 143
  - detection process, 143
  - dynamic clustering, 145–8, 146, 147
  - reconfiguration, 143
  - ubiquitous access, 148–9, 149
- compound annual growth rate (CAGR), 44
- CONIC *see* content-oriented network with indexed caching (CONIC)
- content delivery networks (CDNs), 363–4
- content-centric networking (CCN) *see* information-centric networking (ICN)
- content-oriented network with indexed caching (CONIC), 368
- content-oriented publish/subscribe system (COPSS), 367
- context-aware power management (CAPM), 340–341, 349–51
- convergence layer interface (CLI), 332
- cooperative communication
  - LTE-advanced networks, 227
  - MIMO, 225, 226
  - principles, 225
  - relay system, 225, 225–6
  - research area, 227
  - SISO, 225, 225
- core network and terminals (CT)
  - workgroups, 246
- COST 239 network topology, 299
- co-tier interference, 193
- coverage tax, 85, 86
- CPE *see* customer premises equipment (CPE)
- CR *see* cognitive radio (CR)
- cross phase modulation (XPM), 301
- cross-tier interference, 193
- cumulative distribution function (CDF), 107, 109
- customer premises equipment (CPE), 381
- DAISIES *see* Distributed and Adaptive Interface Switch off for Internet Energy Saving (DAISIES)

- data center networks, 309, 310
  - computing and cooling, 313, 318
  - cooling infrastructure, 310–311
  - dynamic link rate adaptation, 311–12
  - energy consumption, 319, 319–20
  - energy-proportional computing, 310
  - ICT, 309
  - joint energy management solution *see*
    - joint energy management
  - link and switch sleep modes, 312
  - link bandwidth, 310
  - load balancers, 317
  - network performance, 313–14
  - network topology, 312–13, 313
  - power distribution infrastructure, 311
  - STREAMING, 318
  - switch energy model, 318, 318
  - WEB, 318
- decode-and-forward (DF) processing, 112
- delay tolerant network (DTN)
  - applications, 202
  - channel utilization, 203
  - D2D feature, 201
  - energy saving
    - alternative networks, 207–8
    - DRAM power state, 204–5, 205
    - M/M/K/L queuing system, 205–6, 206
    - spectral efficiency, 204
    - stopping decision, 205
  - 5G wireless networks, 201
  - numerical investigations
    - battery lifetime, 212–213, 213
    - delay and cost, 208–209, 209
    - maximum SU, 212, 212
    - transmission *vs.* storage cost, 209–211
  - TVWS spectrum, 203
- delay (DL) trade-off, 51
- deployment
  - base stations, 103, 105
  - cell definition, 98, 99
  - cell parameters, optimization, 100, 101–102, 102
  - vs.* energy efficiency, 51
  - propagation model and coverage, 100
- QoS, 100–101
  - spatial traffic variation model, 99–100, 100
  - traffic model, 98–9
- destination-based routing algorithm
  - ant colony based energy-aware routing, 270–271
  - ESACON, 270
  - ESIR, 269–70
  - features, 271
  - vs.* flow-based routing, 265, 265–6
  - formulation, 264–5
- device-to-device (D2D) communication
  - ad hoc networks, 228
  - delay-tolerant networking, 201
  - frequency reuse gain, 229
  - hop gain, 229
  - network-assisted, 229, 229
  - non-network-assisted, 228–9, 229
  - proximity gain, 229
  - proximity services, 229–30
- DF processing *see* decode-and-forward (DF) processing
- differentiated reliability (DiR), 303, 305
- Dinkelbach method, 125
- discontinuous reception (DRX), 220, 220–222, 221
- distributed and adaptive interface switch off
  - for internet energy saving (DAISIES), 267
- domain name system (DNS), 364
- DRX *see* discontinuous reception (DRX)
- DTN *see* delay tolerant network (DTN)
- dynamic link rate adaptation, 311–12
- dynamic programming (DP) algorithm, 164–7
- EA-RWA *see* energy-aware routing and wavelength assignment (EA-RWA)
- EASes *see* Energy-Aware States (EASes); energy-aware states (EASes)
- EAT *see* energy-aware traffic engineering (EAT)
- EC Joint Research Center (JRC), 381
- ECI *see* Energy Consumption Index (ECI); energy consumption index (ECI)

- ecological footprint analysis (EFA), 59–60
- ECR *see* energy consumption rating (ECR)
- EE-BitTorrent, 345–6, 346
- EEE *see* energy-efficient Ethernet (EEE)
- EIA-RWA *see* energy and impairment aware RWA (EIA-RWA)
- elevation pattern, 105–6
- embodied energy, 69–70
  - base stations *see* base stations (BSs)
  - equipments, 59–60
  - initial construction, 57
  - LCA, 57–61
  - maintenance, 57, 60
  - operating energy, 58, 58–9, 61
  - total energy consumption model, 61
- emerging paradigm shift, 46–7
- energy and impairment aware RWA (EIA-RWA), 301, 302
- energy consumption, 4, 66, 81–2
  - component level, 82, 82–3
  - data centers, 319, 319–20
  - enterprise networks, 186–7
  - home networks, 187
  - ICT, 55–6
  - load variations, 83–5, 84, 86–87
  - metrics, 47–50
  - M2M communication, 219
  - optimal power-off strategy, 67
  - PONs, 295, 295
  - power models, 86, **87**, 88
  - telecommunication systems, 4
- energy consumption index (ECI), 114, 114–115, 399
- energy consumption rating (ECR), 26–9, **27**
- energy control and measurement function, 387
- energy expenditure, 8
- energy management function, 387
- energy metrics
  - ECR, 26–9, **27**
  - homogeneous deployment, 28
  - infrastructure development and purchases, 47–8
  - LTE RAN, 26–29, **27**
  - operating configurations, 28
  - performance trade-offs, 50–53
  - standards organizations, 48
  - taxonomy, 48–50
  - TPG, 28–9
  - types, 48
- energy profile aware routing (EPAR), 266–7
- energy proportional strategies, 259–62, 260
- energy saving, 10–13, *11*
  - assumptions, 285–7, **286**
  - delay-tolerant networks
    - alternative networks, 207–8
    - DRAM power state, 204–5, 205
    - M/M/K/L queuing system, 205–6, 206
    - optimal stopping problem, 205
    - spectral efficiency, 204
  - enterprise networks
    - challenges and limitations, 190–191
    - cluster head formation, 191–2
    - energy-efficient Ethernet, 189–90
    - hardware-level solutions, 188–9
    - heterogeneous approach, 192–3
    - interference management, 193–4
  - factors, 282
  - MTC, 253
  - PONs, 295, 296
  - power consumption, 284–5
  - SLAs, 12
  - telecommunication systems, 10–13, *11*
  - 1000BASE-T links, **283**, 283–4, **284**
  - usage patterns, 285
  - WDM technologies
    - vs.* blocking probability, 297–9, 298, **300**
    - vs.* quality of transmission, 299, 301–2, 302
    - vs.* resource utilization, 302–5, 304, 305
  - Wi-Fi, 251–3
- Energy Saving based on Algebraic Connectivity (ESACON), 270
- energy saving management (ESM), 242
- energy throughput gain (ETG), 21, 31–3, 38, 39
- energy-aware control planes, 382–4

- energy-aware routing and wavelength
  - assignment (EA-RWA), 301, 302
- energy-aware states (EASes), 332, 333
- energy-aware traffic engineering (EAT), 268
- energy-efficient Ethernet (EEE), 189–90, 378
  - ALR, 279
  - energy savings estimation *see* energy saving
  - energy star specification, 288
  - fibre channel community, 287
  - IDLE, 279
  - LLDP, 282
  - LPI, 279, 280, 280, **280**, 288, 289
  - minimum transition times, 280
  - NICs, 282
  - RTPGE, 288
  - SIEPON, 287
  - 10GBASE-T, 281, 281
  - 1000BASE-T, 281, 281
- energy-efficient networks
  - area blocking probability, 174–6
  - CHORUS
    - analysis technique, 143
    - architecture, 141, 142
    - cognitive radio, 140
    - cognitive synergy, 140
    - collaboration, 143
    - detection process, 143
    - dynamic clustering, 145–8, 146, 147
    - reconfiguration, 143
    - ubiquitous access, 148–9, 149
  - network management
    - capacity-enhancement, 137
    - collaboration techniques, 137
    - portfolio analysis, 136
    - traffic variations and, 138, 138–9
    - transmitting power, 136
    - worst-case planning, 136
  - TANGO
    - base stations, 144
    - cell zooming *see* cell zooming
    - service mechanism, 144–5
    - sleeping algorithm *see* base stations (BSs)
- energy-efficient protocol design
  - application-layer protocols, 355–6
  - application-specific proxy *see* application-specific proxy
  - CAPM, 349–51
  - NCP *see* Network Connectivity Proxy (NCP)
  - power management, edge devices, 340–341, 341
  - power management proxy server, 343, 343
  - proxy-based solutions, 344, **344**
  - remotely controlled activation and deactivation
    - Gicomp, 342
    - Magic Packet, 341
    - Polisave, 342
    - TLS, 343
    - Wake on Directed Packet, 342
    - WoL mechanism, 341, 342
  - transport protocols, 352–4, 354
- energy-saving IP routing strategy (ESIR), 269–70
- energy-saving traffic engineering (ES-TE), 260
- enterprise networks
  - bandwidth and power, 186
  - centralized management, 183
  - delay power trade-off, 186
  - dense WLAN network, 181
  - deployment and energy efficiency, 185
  - energy consumption, 186–7
  - energy saving
    - challenges and limitations, 190–191
    - cluster head formation, 191–2
    - energy-efficient Ethernet, 189–90
    - hardware-level solutions, 188–9
    - heterogeneous approach, 192–3
    - interference management, 193–4
  - extended enterprise network, 184
  - femtocells, 181
  - link utilization, 187
  - load proportionality, 187–8
  - network scenario, 181
  - spectral and energy efficiency, 186

- envelope tracking power amplifier (ETPA), 89, 89–90
- EPAR *see* Energy Profile Aware Routing (EPAR)
- equipment energy efficiency ratio (EEER), 391
- ESACON *see* Energy Saving based on Algebraic Connectivity
- ESIR *see* energy-saving IP routing strategy (ESIR)
- ESM *see* energy saving management (ESM)
- ES-TE *see* energy-saving traffic engineering (ES-TE)
- ETG *see* energy throughput gain (ETG)
- Ethernet
  - auto-negotiation, 278
  - high-speed transceivers, 278
  - IEEE 802.3az standard, 278
  - LOM, 278
  - NIC cards, 278
  - PHYs, 278
  - UTP, 277
- European Telecommunications Standards Institute (ETSI), 218, 247–8
- evolved packet core (EPC), 74
- evolved universal terrestrial radio access network (eUTRAN), 74
- extended enterprise network, 184
  
- fat tree network, 315–17, 316
- femtocells, 180–181, 183
- fibre channel community, 287
- 5G wireless communication, 201
- flow-based routing algorithm
  - DAISIES algorithm, 267
  - vs.* destination-based routing, 265, 265–6
  - EAT algorithm, 268
  - EPAR algorithm, 266–7
  - features, **269**
  - formulation, 263–4
  - GBNB and GMTE, 268–9
  - GRiDA and GreenTE, 267–8
  - LFA and MPA, 266
  - L-Game, 266
- forwarding freezing approach, 261–2
- forwarding information base (FIB), 366
- 4WARD project, 367
- four wave mixing (FWM), 301
  
- GERAN *see* GSM EDGE Radio Access Network (GERAN)
- Gicomp, 342
- Gnutella, 345
- green abstraction layer (GAL), 324
  - abstraction layer, 332
  - ACPI standard, 332, 333
  - EAS, 333
  - GAL-NCP-LCP communications, 333, 333–4
  - hierarchical architecture, 334, 334–5
- Green BitTorrent, 355–6, 356
- green distributed algorithm (GRiDA), 267
- Green Information Centric Networking (GreenICN) project, 367–8
- green standard interface (GSI), 332
- Green Telnet, 355
- Green Traffic Engineering (GreenTE), 267–8
- GSM Association (GSMA), 247
- GSM EDGE Radio Access Network (GERAN), 246
  
- heterogeneous network (HetNet), 23, 36–8, **38**, 40, 45–6, 110–112, *111*
- H-GW *see* home gateway (H-GW)
- holistic energy efficient networking
  - agile networks, 401–2
  - network federation, 402
  - orchestration, 402
  - reconfigurable hardware, 402–3
  - service-tailored network
    - programmability, 402
    - splitting data and signalling, 401, *401*
- home gateway (H-GW), 179–80
- home networks
  - apartment LAN network, 184
  - bandwidth and power, 186
  - bluetooth and BANs, 180
  - delay power trade-off, 186
  - deployment and energy efficiency, 186
  - energy consumption, 187

- home networks (*continued*)
  - energy saving
    - interference management, 193–4
    - low-power Bluetooth, 189
    - network-level solution, 190
    - traffic aggregation, 191
  - ethernet-based networks, 180–181
  - femtocells, 180
  - gateway network, 179–80
  - IEEE 802.11 standard, 180
  - link utilization, 187
  - load proportionality, 187
  - network scenario, 181
  - spectral and energy efficiency, 186
  - zero configuration, 182
- IA-RWA *see* impairment aware RWA (IA-RWA)
- ICN *see* information-centric networking (ICN)
- ICNRG *see* Information-Centric Networking Research Group (ICNRG)
- ICT *see* Information and Communication Technology (ICT)
- IDLE signal, 279
- IEEE 802.11
  - BSS Max Idle Period mechanism, 251
  - flexible multicast service, 251
  - legacy PSM, 250, 250
  - proxy-ARP, 251
  - traffic filtering service, 251
  - U-APSD, 250, 250–251
- IETF *see* Internet Engineering Task Force (IETF)
- IETF energy management (EMAN), 388–90
- impairment aware RWA (IA-RWA), 299, 301, 302
- Information and Communication Technology (ICT), 1–2, 4, 5, 13–15
  - applications, 399
  - broadband access, 136
  - data centers, 309
  - embodied energy *see* embodied energy
  - energy consumption, 55–6
  - equipments, 380
  - global carbon emissions, 20, 44–5, 217
  - IEA, 287
  - past researches problem, 56–7
- information-centric networking (ICN)
  - caching, 371–2, 372
  - CDNs, 363–4
  - CONIC, 368
  - COPSS, 367
  - DNS, 364
  - DONA, 368
  - energy efficiency, 368–9
  - 4WARD project, 367
  - GreenICN project, 367–8
  - hops reduction, 369, 369–71, 370
  - IP, 374
  - IRTF, 368
  - mobile IP protocol, 365
  - NDN, 365–6, 366
  - network operations, 372–4, 373, 374
  - peer-to-peer services, 362–3
  - PSIRP, 367
- information-centric networking research group (ICNRG), 368
- integrated communication and broadcast networks (ICBN), 148
- International Energy Agency (IEA), 287
- International Telecommunication Union Telecommunication Standardization Sector (ITU-T), 377, 379, 382, 392
- Internet Assigned Numbers Authority (IANA), 389
- Internet Business Solutions Group (IBSG), 44
- Internet Engineering Task Force (IETF), 368, 378
- Internet of Things (IoT), 217, 219, 229, 234, 396
- Internet Protocol (IP), 352, 353
- Internet Research Task Force (IRTF), 368, 378
- Internet service providers (ISPs), 48, 180, 182, 339
- IRTF *see* Internet Research Task Force (IRTF)



- ITU-T *see* International Telecommunication Union Telecommunication Standardization Sector (ITU-T)
- joint energy management  
  elastic tree, 315  
  fat tree network, 315–17, 316  
  OpenFlow, 314  
  path selection algorithm, 316–17
- key environmental performance indicators (KEPI), 59–60
- key performance indicators (KPI), 391
- LAN on motherboard (LOM), 278
- LCs *see* local control policies (LCs)
- least flow algorithm (LFA), 266
- L-Game algorithm, 266
- life cycle assessment (LCA), 57–61
- link and switch sleep modes, 312
- Link Layer Discovery Protocol (LLDP), 282, 286
- link state databases (LSDB), 384
- link utilization, 183, 184, 187, 268, 270, 285, 314
- local control policies (LCs), 327, 328
- long term evolution radio access network (LTE RAN)  
  base station sites *see* base station sites (BTS)  
  broadband access evolution, 21–4, **22**, 22  
  heterogeneous networks, **27**, 36–8, **38**  
  power and energy metrics, 26–29, **27**  
  throughput efficiency *see* throughput efficiency
- low power idle (LPI), 279, 280, **280**, 280
- LSDB *see* link state databases (LSDB)
- machine type communications (MTC), 253
- machine-to-machine (M2M)  
  communication  
  AMC mechanism, 222–3  
  automatic meter reading, 230, 230  
  automotive applications, 229, 229–30  
  complexity reduction, 223–4  
  control signaling reduction, 224  
  cooperative communication, 225, 225–7  
  data compression, 224  
  D2D communication, 227–9  
  discontinuous reception, 220, 220–222, 221  
  energy consumption, 219  
  high-level architecture, 218, 218  
  low mobility feature, 224–5  
  offloading and relaying, 223  
  research area, 233–4  
  smart city application, 232–3  
  smart grid application, 230–232, 231  
  UPC mechanism, 222–3
- macro cell power model, 106, 107
- Magic Packet, 341
- management information base (MIB), 388
- maximum conditional failure probability (MCFP), 303
- MIB *see* management information base (MIB)
- micro/cell-discontinuous transmission, 91–2
- M2M communication *see*  
  machine-to-machine (M2M)  
  communication
- mobile data traffic, 43–4
- mobile network operators (MNOs), 21–2
- Moore’s law, 23
- most power algorithm (MPA), 266
- MTC *see* machine type communications (MTC)
- multi-base station (Multi-BS) collaboration, 137
- multiple-input-multiple-output (MIMO), 225, 226
- multi-protocol label switching (MPLS), 385, 386
- multiuser communications  
  cognitive radio *see* cognitive radio (CR)  
  MIMO, 123–6  
  OFDMA, 126–8, 127
- multiuser MIMO system  
  Dinkelbach method, 125  
  power allocation, 124–5  
  quasi-concave function, 125–6

- multiuser MIMO system (*continued*)
  - SU-MIMO, 123–4
  - user-scheduling problem, 124–5
- named data networking (NDN), 365–6, 366
- NAPS *see* non-intrusive location-aware power management scheme (NAPS)
- network connectivity proxy (NCP)
  - design analysis, 347
  - ECMA-393 standard, 349
  - performance comparison, 348
  - requirements, 347
  - SleepServer, 349
  - Somniloquy, 348–9
- network control modules (NCMs), 324
- network design and planning
  - control/data plane splitting, 115, 116
  - deployment
    - cell definition, 98, 99
    - cell parameters, optimization, 100, 101–102, 102
    - propagation model and coverage, 100
    - QoS, 100–101
    - spatial traffic variation model, 99–100, 100
    - traffic model, 98–9
  - federated network, 115–6
  - rural areas, 112–114, 113–115
  - urban areas
    - adaptive (de)sectorization *see* adaptive sectorization
    - HetNet, 110–112, 111
    - on/off strategies, network layout, 102–3, 104
- network element level, 396–7
- network functions virtualization (NFV), 324
  - flexible and dynamic resource allocation, 336
  - functional composition, 325, 326
  - network architecture, 331, 331, 332
  - network sharing and multi-tenancy, 402
- network interface controller (NIC) card, 278, 282, 341
- network management
  - data centers *see* data center networks
  - GAL *see* green abstraction layer (GAL)
  - network primitives, 328–30, 330
  - NFV *see* network functions virtualization (NFV)
  - PMPs, 326–8
  - requirements, 400
  - SDN *see* software defined networking (SDN)
  - wireline communications *see* Wireline communications
- network topology, 312–13, 313
- network-based energy conservation
  - energy-aware control planes, 382–4
  - IETF, 382
  - objectives, 381–2
  - power-aware routing and traffic engineering, 384–5
- Networking of Information (NetInf), 367
- network-wide control policies (NCPs), 327, 328
- Next Generation Mobile Networks (NGMN), 44–5, 238–9, 239
- NFV *see* network functions virtualization (NFV)
- NGBASE-T standard, 278
- NIC card *see* network interface controller (NIC) card
- non-intrusive location-aware power management scheme (NAPS), 351
- OFDMA *see* orthogonal frequency division multiple access (OFDMA)
- Open Systems Interconnection (OSI) protocol, 9
- OpenFlow, 314
- operation, administration & management (OAM), 332
- operations and maintenance (O&M), 397
- optical line terminal (OLT), 294
- optical network unit (ONU), 294
- optimal power-off strategy
  - energy consumption model, 67
  - network components, 61–2
  - operating energy, 62
  - optimal cell size, 62
  - semiconductor manufacturing, 62–3

- traffic patterns, 62
  - two-tier cellular access network, 62
- optimal stopping problem, 205
- orthogonal frequency division multiple access (OFDMA), 126–8, 127
- OSI protocol *see* Open Systems Interconnection (OSI) protocol
- passive optical networks (PONs), 292
  - dozing, 294
  - energy consumption, 295, 295
  - energy savings, 295, 296
  - high-priority packets, 295, 297
  - ONU/OLT, 294
  - packet delay, 295, 296
- path computation engine (PCE), 383
- PDU *see* power distribution unit (PDU)
- peer-to-peer (P2P) networks, 345, 362–3
- Pending Interest Table (PIT), 366
- performance trade-offs
  - bandwidth *vs.* power, 51–2
  - DE *vs.* EE, 51
  - DL *vs.* PW, 52–3
  - SE *vs.* EE, 50–51
- physical layer impairments (PLIs), 299, 301
- physical layer transceivers (PHYs), 278
- PIT *see* Pending Interest Table (PIT)
- PMPs *see* power management primitives (PMPs)
- PoE *see* Power over Ethernet (PoE)
- Polisave, 342
- PONs *see* passive optical networks (PONs)
- power amplifier (PA), 24
- power consumption, 258–9, 259
- power distribution unit (PDU), 388
- power management primitives (PMPs), 324
  - DA, 326–7
  - LCP-NCP interactions, 328, 329
  - LCP-PMP interactions, 327, 328
  - LCPs, 327, 328
  - NCPs, 327, 328
  - sleeping/standby approaches, 327
- power metrics
  - ECR, 26–9, 27
  - homogeneous deployment, 28
  - LTE RAN, 26–29, 27
  - operating configurations, 28
  - TPG, 28–9
- power minimization (PM), 303, 304
- Power over Ethernet (PoE), 390, 390–391
- power save poll (PS-Poll), 250
- power source equipment (PSE), 390
- power-aware protocols
  - application-layer protocols, 355–6
  - path selection and traffic steering, 382
  - routing and traffic engineering, 384–5
  - transport protocols, 352–4, 354
  - virtual/cache memory, 379
- Proxy Address Resolution Protocol (Proxy-ARP), 251
- Publish Subscribe Internet Routing Paradigm (PSIRP) project, 367
- quality of service (QoS)
  - blocking probability, 100–101
  - cell-edge SINR, 30
  - CHORUS, 141
  - cognitive radio, 128–9
  - definition, 12, 14–15
  - Detection step, 146
  - global optimal transmission, 123
  - multiuser communications, 123
  - On and Off Periods, 221
  - wired networks, 397
- quantitative metrics, 13–15
- radio access network (RAN)
  - capacity and coverage requirements, 23
  - cell size reduction, 31–3
  - cloud-RAN approach, 92–4, 93
  - configurations/architectures, 26–7
  - core network, 74–5
  - energy metric framework, 27–8
  - ETG, 39
  - microwave backhaul, 25
  - network design and planning *see* network design and planning
  - sleep mode, 35–6
  - traffic data, 20
  - working groups, 243–4
- radio access technology (RAT), 241–2, 242, 386
- radio component level, 396

- radio frequency (RF) transceiver, 24
- radio link control (RLC), 75
- RAN *see* radio access network (RAN)
- RAT *see* radio access technology (RAT)
- received signal strength indicator (RSSI), 351
- reduced twisted pair Gigabit Ethernet (RTPGE), 288
- relay nodes (RNs), 112–114, 113–115
- remote radio head (RRH) architectures, 81, 81
- resource minimization (RM), 303, 304
- routing algorithm
  - ant colony based energy-aware routing, 270–271
  - DAISIES algorithm, 267
  - vs.* destination-based routing, 265, 265–6
  - EAT algorithm, 268
  - EPAR algorithm, 266–7
  - ESACON, 270
  - ESIR, 269–70
  - features, **269, 271**
  - vs.* flow-based routing, 265, 265–6
  - formulation, 263–4, 264–5
  - GBNB and GMTE, 268–9
  - GRiDA and GreenTE, 267–8
  - LFA and MPA, 266
  - L-Game, 266
- routing and wavelength assignment (RWA), 297, 301, 302
- RRH architectures *see* remote radio head (RRH) architectures
- RSSI *see* received signal strength indicator (RSSI)
- SDN *see* software defined networking (SDN)
- self-organized network (SON), 397
- service and system aspects work group 5 (SA5)
  - capacity limited network, 241
  - eNB overlaid scenario, 240–241
  - ESM procedures, 242
  - inter-and intra-RAT, 241–2, **242**
  - in/not in ES, 242
  - probing for ES, 243
  - switch-off times, 242
- service interoperability in Ethernet passive optical networks (SIEPONs), 287
- service level agreements (SLAs), 12, 267, 303, 331, 378
- session initiation protocol (SIP) catcher, 344–5
- signal-to-interference (SIR), 29–30, 35–37
- signal-to-interference-and-noise ratio (SINR), 29–30, 112, 113, 222
- signal-to-noise ratio (SNR), 29–30
- simple network management protocol (SNMP), 15, 312, 314, 388
- single-input single-output (SISO), 225, 225
- single-user communications
  - AWGN channel, 119–20
  - broadband frequency-selective channels, 122–3
  - channel impairment and issues, 120
  - flat fading channels, 121, 121–2
- single-user MIMO (SU-MIMO) system, 123–4
- SLAs *see* service level agreements (SLAs)
- SleepServer (SSR), 349
- sleep/wake-up on bluetooth, 351
- software defined networking (SDN)
  - advantages, 324
  - components, 324, 325
  - energy-efficient network architecture, 331, 331–2
  - functional composition, 325, 326
  - GAL-NCP-LCP communications, 333–4
  - NCMs, 324
  - NCPs, 330
  - Northbound-API, 324
  - Southbound-API, 324
- Somniloquy, 348–9
- SON *see* self-organized network (SON)
- spectral efficiency (SE), 44
- subnet-directed broadcast, 341–2
- switch energy model, 318, 318
- switching off sector, 107–8, 108, 109
- switch-off algorithms
  - destination-based routing, 265, 265–6

- ant colony based energy-aware routing, 270–271
- ESACON, 270
- ESIR, 269–70
- features, **271**
- formulation, 264–5
- energy minimization problem, 263
- vs. energy proportionality, 259–61, *260*
- flow-based routing, 265, 265–6
  - DAISIES algorithm, 267
  - EAT algorithm, 268
  - EPAR algorithm, 266–7
  - features, **269**
  - formulation, 263–4
  - GBNB and GMTE, 268–9
  - GRiDA and GreenTE, 267–8
  - LFA and MPA, 266
  - L-Game, 266
- synergetic cognition, 140
- system architecture level, 397
  
- table lookup bypass (TLB), 271–4, 272, 273
- TANGO *see* Traffic-Aware Network planning and Green Operation (TANGO)
- target wake time (TWT), 253
- TCAM *see* ternary content addressable memory (TCAM)
- TCP *see* transmission control protocol (TCP)
- telecommunication systems
  - access networks, 7–8
  - aggregation network, 7
  - backbone network, 7–8
  - backhaul network, 7
  - cell capacity, 30
  - cell size reduction, 25, **27**, **31**, 31–3, 32
    - see also* base station sites (BTS)
  - cellular and portable communications, 3
  - climate change and energy crisis, 1
  - core networks, 7–9
  - data link, 9
  - economic and environmental matters, 3
  - embodied energy, 8–9
  - end-user terminals, 8
  - energy consumption, 4
  - energy expenditure, 8
  - energy problem, 4–5
  - energy saving, 10–13, *11*, 391
  - ETSI, 238
  - greenhouse emissions, 2–3, 3
  - GreenTouch innovation, 4, 6, 6
  - ICT, 1–2, 4, 5, 13–15
  - metro network, 7, 9
  - multiuser communications *see* multiuser communications
  - network layer, 8–9
  - networks architecture, 6–7, 7
  - OSI protocol, 9
  - performance metrics, 29–30
  - residential and enterprise networks, 7
  - single-user communications *see* single-user communications
  - SIR and SNR, 29–30
  - system lifetime, 3–4
  - technology parameters, 30–31, **31**
  - traffic projections, 2, **2**
  - upper bound power limits, 4
  - wired networks, 8–9
- telecommunications energy efficiency ratio (TEER), 392
- ternary content addressable memory (TCAM), 384
- 3rd Generation Partnership Project (3GPP), 239, 239
  - architecture working group
    - load redistribution, 245
    - maximum DRX cycles, 246
    - network sharing, 245
    - pooled MMEs, 244–5
    - power saving state, 246
    - scheduled communication, 245
  - CT1 working group, 246
  - ES-related activities, 239, **240**
  - GERAN working group, 246
  - radio access network, 243–4
  - service and system aspects workgroups
    - capacity limited network, 241
    - eNB overlaid scenario, 240–241
    - ESM procedures, 242
    - inter-and intra-RAT, 241–2, **242**

- 3rd Generation Partnership Project (3GPP)
  - (*continued*)
  - in/not in ES, 242
  - probing for ES, 243
  - switch-off times, 242
  - technical reports, 239–40
- throughput efficiency
  - cell capacity, 30
  - cell size reduction, 25, **27**, **31**, 31–3, 32
    - see also* base station sites (BTS)
  - performance metrics, 29–30
  - SIR and SNR, 29–30
  - technology parameters, 30–31, **31**
- Throughput Gain (TPG), 28–9
- TLB *see* table lookup bypass (TLB)
- TLS *see* transport layer security (TLS)
- traffic-aware network planning and green operation (TANGO)
  - BS sleeping algorithm
    - blocking probability, 169, 171
    - concept of, 144
    - DP algorithm, 164–7
    - issues with, 158
    - problem formulation, 161–4
    - state distribution, 169, 170
    - switching cost, 172–4, 173, 174
    - system model, 159, 159–61
    - traffic distribution, 168, 169, 170
    - uniform pattern, 171–2, 172
  - cell zooming
    - centralized algorithm, 155
    - compatibility, 153
    - concept of, 144, 150, 150, 151
    - cooperation, 152
    - coverageholes, 153
    - distributed algorithm, 155–6
    - fluctuations, 153
    - inter-cell interference, 153
    - load balancing, 152
    - performance evaluation, 156–8
    - physical adjustment, 151–2
    - power control, 153
    - relay stations, 152
    - server control, 151
    - sleeping pattern, 152
    - stages of, 154, 154
  - service mechanism, 144–5
  - transmission control protocol (TCP), 352–4, 354
  - transport layer security (TLS), 343
  - two-hop relay protocol, 253
  - two-tier cellular access network, 62
  - TWT *see* target wake time (TWT)
- ubiquitous connectivity, 43
- ubiquitous mobility, 43
- ultra-wideband (UWB) radio system, 350
- unicast wake-up packets, 341–2
- uniform BS sleeping approach, 171–2, 172
- universal mobile telecommunications system (UMTS), 22
- universal plug and play (UPnP), 344
- unshielded twisted pair (UTP), 277
- uplink analogue processing, 76, 79
- uplink power control (UPC), 222–3
- user equipment (UE), 74–6
- user-scheduling problem, 124–5
- UTP *see* unshielded twisted pair (UTP)
- UWB radio system *see* ultra-wideband (UWB) radio system
- video streaming, 318
- voice over IP (VOIP) phones, 284
- wake on directed packet, 342
- wake-on-LAN (WoL) mechanism, 341, 342
- wavelength division multiplexing (WDM), 292
  - energy saving
    - vs.* blocking probability, 297–9, 298, **300**
    - vs.* quality of transmission, 299, 301–2, 302
    - vs.* resource utilization, 302–5, 304, 305
  - PONs *see* passive optical networks (PONs)
  - power consumption, 292–3, **293**
- web serving, 318
- weighted power-aware optical routing (WPA-OR), 299
- Wi-Fi Direct (WFD) technology, 251–3, 252

- wireless networks
  - network element level, 396
  - radio component level, 396
  - system architecture level, 397
- wireline communications
  - CDN, 399
  - core networks and edge devices, 398
  - EC CoC, 380–381
  - energy-aware routing algorithms, 398
  - energy-efficiency metrics, measurements
    - and testing, 391–2
  - green Ethernet, 398
  - IEEE PoE, **390**, 390–391
  - IETF EMAN, 388–90
  - ITU-T energy control framework,
    - 387–8, 388
  - network design and planning, 385–6,
    - 386, 397
  - network-based energy conservation *see*
    - network-based energy conservation
  - optical networks, 398
  - power modes/power saving states,
    - 379–80
- WPA-OR *see* weighted power-aware optical routing (WPA-OR)
- XPM *see* cross phase modulation (XPM)