3G EVOLUTION: HSPA AND LTE FOR MOBILE BROADBAND
This page intentionally left blank
3G Evolution

HSPA and LTE for Mobile Broadband

Second edition

Erik Dahlman, Stefan Parkvall, Johan Sköld and Per Beming
# Contents

List of Figures .............................................. xv
List of Tables .......................................... xxvii
Preface ................................................... xxix
Acknowledgements ......................................... xxxi
List of Acronyms ............................................. xxxiii

Part I: Introduction ........................................ 1

1 Background of 3G evolution ............................... 3  
   1.1 History and background of 3G ......................... 3  
      1.1.1 Before 3G ......................................... 3  
      1.1.2 Early 3G discussions ............................ 5  
      1.1.3 Research on 3G .................................... 6  
      1.1.4 3G standardization starts ........................ 7  
   1.2 Standardization ........................................ 7  
      1.2.1 The standardization process .................... 7  
      1.2.2 3GPP ............................................... 9  
      1.2.3 IMT-2000 activities in ITU ..................... 11  
   1.3 Spectrum for 3G and systems beyond 3G ............. 13  

2 The motives behind the 3G evolution ...................... 15  
   2.1 Driving forces ........................................ 15  
      2.1.1 Technology advancements ....................... 16  
      2.1.2 Services .......................................... 17  
      2.1.3 Cost and performance ............................ 20  
   2.2 3G evolution: Two Radio Access Network approaches  
      and an evolved core network ......................... 21  
      2.2.1 Radio Access Network evolution ................ 21  
      2.2.2 An evolved core network: system architecture  
      evolution ............................................. 24
Part II: Technologies for 3G Evolution

3 High data rates in mobile communication

3.1 High data rates: Fundamental constraints

3.1.1 High data rates in noise-limited scenarios

3.1.2 High data rates in interference-limited scenarios

3.2 Higher data rates within a limited bandwidth: Higher-order modulation

3.2.1 Higher-order modulation in combination with channel coding

3.2.2 Variations in instantaneous transmit power

3.3 Wider bandwidth including multi-carrier transmission

4 OFDM transmission

4.1 Basic principles of OFDM

4.2 OFDM demodulation

4.3 OFDM implementation using IFFT/FFT processing

4.4 Cyclic-prefix insertion

4.5 Frequency-domain model of OFDM transmission

4.6 Channel estimation and reference symbols

4.7 Frequency diversity with OFDM: Importance of channel coding

4.8 Selection of basic OFDM parameters

4.8.1 OFDM subcarrier spacing

4.8.2 Number of subcarriers

4.8.3 Cyclic-prefix length

4.9 Variations in instantaneous transmission power

4.10 OFDM as a user-multiplexing and multiple-access scheme

4.11 Multi-cell broadcast/multicast transmission and OFDM

5 Wider-band ‘single-carrier’ transmission

5.1 Equalization against radio-channel frequency selectivity

5.1.1 Time-domain linear equalization

5.1.2 Frequency-domain equalization

5.1.3 Other equalizer strategies

5.2 Uplink FDMA with flexible bandwidth assignment

5.3 DFT-spread OFDM

5.3.1 Basic principles

5.3.2 DFTS-OFDM receiver

5.3.3 User multiplexing with DFTS-OFDM

5.3.4 Distributed DFTS-OFDM
9.2.1 HS-DSCH: Inclusion of features in WCDMA
   Release 5 ........................................ 144
9.2.2 MAC-hs and physical-layer processing ..................... 147
9.2.3 Scheduling ......................................... 149
9.2.4 Rate control ........................................ 150
9.2.5 Hybrid ARQ with soft combining ......................... 154
9.2.6 Data flow ............................................ 157
9.2.7 Resource control for HS-DSCH ......................... 159
9.2.8 Mobility .............................................. 160
9.2.9 UE categories ........................................ 162
9.3 Finer details of HSDPA ................................ 162
  9.3.1 Hybrid ARQ revisited: Physical-layer processing ...... 162
  9.3.2 Interleaving and constellation rearrangement .......... 167
  9.3.3 Hybrid ARQ revisited: Protocol operation ............ 168
  9.3.4 In-sequence delivery ................................ 170
  9.3.5 MAC-hs header ...................................... 172
  9.3.6 CQI and other means to assess the downlink quality ... 174
  9.3.7 Downlink control signaling: HS-SCCH ................. 177
  9.3.8 Downlink control signaling: F-DPCH ................. 180
  9.3.9 Uplink control signaling: HS-DPCCH ............... 180

10 Enhanced Uplink ........................................ 185
  10.1 Overview ........................................... 185
   10.1.1 Scheduling ....................................... 186
   10.1.2 Hybrid ARQ with soft combining .................. 188
   10.1.3 Architecture ..................................... 189
  10.2 Details of Enhanced Uplink ............................ 190
   10.2.1 MAC-e and physical layer processing ............. 193
   10.2.2 Scheduling ....................................... 195
   10.2.3 E-TFC selection .................................. 202
   10.2.4 Hybrid ARQ with soft combining ................. 203
   10.2.5 Physical channel allocation ...................... 208
   10.2.6 Power control .................................... 210
   10.2.7 Data flow ........................................ 211
   10.2.8 Resource control for E-DCH ...................... 212
   10.2.9 Mobility .......................................... 213
   10.2.10 UE categories .................................... 213
  10.3 Finer details of Enhanced Uplink ...................... 214
   10.3.1 Scheduling – the small print .................... 214
   10.3.2 Further details on hybrid ARQ operation .......... 223
   10.3.3 Control signaling ................................ 230
Contents

11 MBMS: Multimedia Broadcast Multicast Services ................. 239
  11.1 Overview .................................................. 242
     11.1.1 Macro-diversity ..................................... 243
     11.1.2 Application-level coding .............................. 245
  11.2 Details of MBMS .......................................... 246
     11.2.1 MTCH .................................................. 247
     11.2.2 MCCH and MICH ...................................... 247
     11.2.3 MSCH .................................................. 249

12 HSPA Evolution ................................................. 251
  12.1 MIMO ......................................................... 251
     12.1.1 HSDPA-MIMO data transmission ..................... 252
     12.1.2 Rate control for HSDPA-MIMO ....................... 256
     12.1.3 Hybrid-ARQ with soft combining for HSDPA-MIMO . 256
     12.1.4 Control signaling for HSDPA-MIMO .................. 257
     12.1.5 UE capabilities ....................................... 259
  12.2 Higher-order modulation .................................. 259
  12.3 Continuous packet connectivity ............................ 260
     12.3.1 DTX–reducing uplink overhead ..................... 261
     12.3.2 DRX–reducing UE power consumption ................ 264
     12.3.3 HS-SCCH-less operation: downlink overhead reduction. 265
     12.3.4 Control signaling .................................... 267
  12.4 Enhanced CELL_FACH operation ........................... 267
  12.5 Layer 2 protocol enhancements ............................ 269
  12.6 Advanced receivers ....................................... 270
     12.6.1 Advanced UE receivers specified in 3GPP .......... 271
     12.6.2 Receiver diversity (type 1) ........................... 271
     12.6.3 Chip-level equalizers and similar receivers (type 2) . 272
     12.6.4 Combination with antenna diversity (type 3) ....... 273
     12.6.5 Combination with antenna diversity and interference cancellation (type 3i) ......... 274
  12.7 MBSFN operation .......................................... 275
  12.8 Conclusion ................................................ 275

Part IV: LTE and SAE ............................................. 277

13 LTE and SAE: Introduction and design targets ................. 279
  13.1 LTE design targets ....................................... 280
     13.1.1 Capabilities .......................................... 281
     13.1.2 System performance ................................. 282
<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>283</td>
</tr>
<tr>
<td>285</td>
</tr>
<tr>
<td>286</td>
</tr>
<tr>
<td>286</td>
</tr>
<tr>
<td>287</td>
</tr>
<tr>
<td>289</td>
</tr>
<tr>
<td>290</td>
</tr>
<tr>
<td>291</td>
</tr>
<tr>
<td>292</td>
</tr>
<tr>
<td>293</td>
</tr>
<tr>
<td>294</td>
</tr>
<tr>
<td>295</td>
</tr>
<tr>
<td>296</td>
</tr>
<tr>
<td>296</td>
</tr>
<tr>
<td>297</td>
</tr>
<tr>
<td>300</td>
</tr>
<tr>
<td>301</td>
</tr>
<tr>
<td>302</td>
</tr>
<tr>
<td>303</td>
</tr>
<tr>
<td>305</td>
</tr>
<tr>
<td>308</td>
</tr>
<tr>
<td>311</td>
</tr>
<tr>
<td>314</td>
</tr>
<tr>
<td>315</td>
</tr>
<tr>
<td>317</td>
</tr>
<tr>
<td>317</td>
</tr>
<tr>
<td>319</td>
</tr>
<tr>
<td>324</td>
</tr>
<tr>
<td>325</td>
</tr>
<tr>
<td>328</td>
</tr>
<tr>
<td>330</td>
</tr>
<tr>
<td>332</td>
</tr>
<tr>
<td>334</td>
</tr>
<tr>
<td>338</td>
</tr>
<tr>
<td>Section</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>16.4.4</td>
</tr>
<tr>
<td>16.4.5</td>
</tr>
<tr>
<td>16.4.6</td>
</tr>
<tr>
<td>16.4.7</td>
</tr>
<tr>
<td>16.4.8</td>
</tr>
<tr>
<td>16.5</td>
</tr>
<tr>
<td>16.5.1</td>
</tr>
<tr>
<td>16.5.2</td>
</tr>
<tr>
<td>16.5.3</td>
</tr>
<tr>
<td>16.5.4</td>
</tr>
<tr>
<td>16.5.5</td>
</tr>
<tr>
<td>16.5.6</td>
</tr>
<tr>
<td>16.5.7</td>
</tr>
<tr>
<td>16.5.8</td>
</tr>
<tr>
<td>16.6</td>
</tr>
<tr>
<td>16.6.1</td>
</tr>
<tr>
<td>16.6.2</td>
</tr>
<tr>
<td>16.6.3</td>
</tr>
<tr>
<td>16.7</td>
</tr>
<tr>
<td>17</td>
</tr>
<tr>
<td>17.1</td>
</tr>
<tr>
<td>17.2</td>
</tr>
<tr>
<td>17.2.1</td>
</tr>
<tr>
<td>17.2.2</td>
</tr>
<tr>
<td>17.3</td>
</tr>
<tr>
<td>17.3.1</td>
</tr>
<tr>
<td>17.3.2</td>
</tr>
<tr>
<td>17.4</td>
</tr>
<tr>
<td>17.5</td>
</tr>
<tr>
<td>17.5.1</td>
</tr>
<tr>
<td>17.5.2</td>
</tr>
<tr>
<td>18</td>
</tr>
<tr>
<td>18.1</td>
</tr>
<tr>
<td>18.1.1</td>
</tr>
<tr>
<td>18.1.2</td>
</tr>
<tr>
<td>18.1.3</td>
</tr>
</tbody>
</table>
18.2 System information ............................................. 425
  18.2.1 MIB and BCH transmission ............................... 426
  18.2.2 System-Information Blocks ............................... 429
18.3 Random access ............................................. 432
  18.3.1 Step 1: Random-access preamble transmission ............ 434
  18.3.2 Step 2: Random-access response .......................... 441
  18.3.3 Step 3: Terminal identification ........................ 442
  18.3.4 Step 4: Contention resolution ............................ 443
18.4 Paging .................................................. 444

19 LTE transmission procedures .................................... 447
  19.1 RLC and hybrid-ARQ protocol operation .. ..................... 447
    19.1.1 Hybrid-ARQ with soft combining ......................... 448
    19.1.2 Radio-link control ..................................... 459
  19.2 Scheduling and rate adaptation ................................ 465
    19.2.1 Downlink scheduling .................................... 467
    19.2.2 Uplink scheduling ....................................... 470
    19.2.3 Semi-persistent scheduling .............................. 476
    19.2.4 Scheduling for half-duplex FDD .......................... 478
    19.2.5 Channel-status reporting ............................... 479
  19.3 Uplink power control ...................................... 482
    19.3.1 Power control for PUCCH ............................... 482
    19.3.2 Power control for PUSCH ................................ 485
    19.3.3 Power control for SRS .................................. 488
  19.4 Discontinuous reception (DRX) ................................ 488
  19.5 Uplink timing alignment .................................... 490
  19.6 UE categories ............................................ 495

20 Flexible bandwidth in LTE ..................................... 497
  20.1 Spectrum for LTE .......................................... 497
    20.1.1 Frequency bands for LTE ................................. 498
    20.1.2 New frequency bands ..................................... 501
  20.2 Flexible spectrum use ...................................... 502
  20.3 Flexible channel bandwidth operation ......................... 503
  20.4 Requirements to support flexible bandwidth ................... 505
    20.4.1 RF requirements for LTE ................................. 505
    20.4.2 Regional requirements ................................. 506
    20.4.3 BS transmitter requirements ............................ 507
    20.4.4 BS receiver requirements ............................... 511
    20.4.5 Terminal transmitter requirements ....................... 514
    20.4.6 Terminal receiver requirements ......................... 515
21 System Architecture Evolution ................................. 517
  21.1 Functional split between radio access network and core
      network ................................................. 518
      21.1.1 Functional split between WCDMA/HSPA radio
            access network and core network .......... 518
      21.1.2 Functional split between LTE RAN and core network .. 519
  21.2 HSPA/WCDMA and LTE radio access network ............... 520
      21.2.1 WCDMA/HSPA radio access network .......... 521
      21.2.2 LTE radio access network ................. 526
  21.3 Core network architecture ................................ 528
      21.3.1 GSM core network used for WCDMA/HSPA ....... 529
      21.3.2 The ‘SAE’ core network: The Evolved Packet Core . 533
      21.3.3 WCDMA/HSPA connected to Evolved Packet Core .. 536
      21.3.4 Non-3GPP access connected to Evolved Packet Core .. 537

22 LTE-Advanced .................................................. 539
  22.1 IMT-2000 development .................................... 539
  22.2 LTE-Advanced – The 3GPP candidate for IMT-Advanced ... 540
      22.2.1 Fundamental requirements for LTE-Advanced ...... 541
      22.2.2 Extended requirements beyond ITU requirements ... 542
  22.3 Technical components of LTE-Advanced .................... 542
      22.3.1 Wider bandwidth and carrier aggregation ........ 543
      22.3.2 Extended multi-antenna solutions ............. 544
      22.3.3 Advanced repeaters and relaying functionality .... 545
  22.4 Conclusion ............................................... 546

Part V: Performance and Concluding Remarks 547

23 Performance of 3G evolution .............................. 549
  23.1 Performance assessment ................................ 549
      23.1.1 End-user perspective of performance .......... 550
      23.1.2 Operator perspective ........................... 552
  23.2 Performance in terms of peak data rates ................ 552
  23.3 Performance evaluation of 3G evolution ............... 553
      23.3.1 Models and assumptions ....................... 553
      23.3.2 Performance numbers for LTE with 5MHz FDD carriers . 555
  23.4 Evaluation of LTE in 3GPP ................................ 557
      23.4.1 LTE performance requirements ................. 557
      23.4.2 LTE performance evaluation .................. 559
      23.4.3 Performance of LTE with 20MHz FDD carrier .... 560
  23.5 Conclusion ............................................. 560
24 Other wireless communications systems .......................... 563
  24.1 UTRA TDD .......................................................... 563
  24.2 TD-SCDMA (low chip rate UTRA TDD) ................. 565
  24.3 CDMA2000 .............................................................. 566
    24.3.1 CDMA2000 1x .............................................. 567
    24.3.2 1x EV-DO Rev 0 ........................................... 567
    24.3.3 1x EV-DO Rev A .......................................... 568
    24.3.4 1x EV-DO Rev B .......................................... 569
    24.3.5 UMB (1x EV-DO Rev C) .................................. 571
  24.4 GSM/EDGE ............................................................. 573
    24.4.1 Objectives for the GSM/EDGE evolution .......... 573
    24.4.2 Dual-antenna terminals .................................. 575
    24.4.3 Multi-carrier EDGE ....................................... 575
    24.4.4 Reduced TTI and fast feedback ..................... 576
    24.4.5 Improved modulation and coding ................... 577
    24.4.6 Higher symbol rates ................................... 577
  24.5 WiMAX (IEEE 802.16) .............................................. 578
    24.5.1 Spectrum, bandwidth options and duplexing
         arrangement ..................................................... 580
    24.5.2 Scalable OFDMA ........................................... 581
    24.5.3 TDD frame structure .................................... 581
    24.5.4 Modulation, coding and Hybrid ARQ ............... 581
    24.5.5 Quality-of-service handling ....................... 582
    24.5.6 Mobility ...................................................... 583
    24.5.7 Multi-antenna technologies ......................... 584
    24.5.8 Fractional frequency reuse ............................ 584
    24.5.9 Advanced Air Interface (IEEE 802.16m) .......... 585
  24.6 Mobile Broadband Wireless Access (IEEE 802.20) .... 586
  24.7 Summary ............................................................. 588

25 Future evolution .................................................. 589
  25.1 IMT-Advanced ..................................................... 590
  25.2 The research community ....................................... 591
  25.3 Standardization bodies ....................................... 591
  25.4 Concluding remarks ........................................... 592

References ............................................................. 593

Index ....................................................................... 603
List of Figures

1.1 The standardization phases and iterative process....................... 8
1.2 3GPP organization....................................................... 9
1.3 Releases of 3GPP specifications for UTRA.......................... 11
1.4 The definition of IMT-2000 in ITU-R.............................. 12

2.1 The terminal development has been rapid the past 20 years.......... 16
2.2 The bit rate – delay service space that is important to cover when designing a new cellular system......................... 20
2.3 One HSPA and LTE deployment strategy: upgrade to HSPA Evolution, then deploy LTE as islands in the WCDMA/HSPA sea.... 25

3.1 Minimum required $E_b/N_0$ at the receiver as a function of bandwidth utilization................................................. 31
3.2 Signal constellations for (a) QPSK, (b) 16QAM and (c) 64QAM..... 35
3.3 Distribution of instantaneous power for different modulation schemes. Average power is same in all cases..................... 37
3.4 Multi-path propagation causing time dispersion and radio-channel frequency selectivity............................................ 39
3.5 Extension to wider transmission bandwidth by means of multi-carrier transmission.................................................... 40
3.6 Theoretical WCDMA spectrum. Raised-cosine shape with roll-off $\alpha = 0.22$......................................................... 41

4.1 (a) Per-subcarrier pulse shape and (b) spectrum for basic OFDM transmission......................................................... 44
4.2 OFDM subcarrier spacing.................................................. 44
4.3 OFDM modulation......................................................... 44
4.4 OFDM time–frequency grid............................................... 46
4.5 Basic principle of OFDM demodulation................................ 47
4.6 OFDM modulation by means of IFFT processing.................... 48
4.7 OFDM demodulation by means of FFT processing..................... 49
4.8 Time dispersion and corresponding received-signal timing......... 50
4.9 Cyclic-prefix insertion...................................................... 50
4.10 Frequency-domain model of OFDM transmission/reception...... 52
4.11 Frequency-domain model of OFDM transmission/reception with ‘one-tap equalization’ at the receiver......................... 52
4.12 Time-frequency grid with known reference symbols................ 53
4.13 (a) Transmission of single wideband carrier and (b) OFDM transmission over a frequency-selective channel. ................. 54
4.14 Channel coding in combination with frequency-domain interleaving to provide frequency diversity in case of OFDM transmission. .... 55
4.15 Subcarrier interference as a function of the normalized Doppler spread $f_{\text{Doppler}}/\Delta f$. ........................................ 56
4.16 Spectrum of a basic 5 MHz OFDM signal compared with WCDMA spectrum. .................................................. 57
4.17 OFDM as a user-multiplexing/multiple-access scheme: (a) downlink and (b) uplink. ................................................. 60
4.18 Distributed user multiplexing. ........................................ 61
4.19 Uplink transmission-timing control. ............................. 61
4.20 Broadcast scenario. .................................................. 62
4.21 Broadcast vs. Unicast transmission. (a) Broadcast and (b) Unicast... 62
4.22 Equivalence between simulcast transmission and multi-path propagation................................................................. 64

5.1 General time-domain linear equalization. .......................... 66
5.2 Linear equalization implemented as a time-discrete FIR filter. ... 67
5.3 Frequency-domain linear equalization. ............................ 69
5.4 Overlap-and-discard processing. ..................................... 70
5.5 Cyclic-prefix insertion in case of single-carrier transmission. .... 70
5.6 Orthogonal multiple access: (a) TDMA and (b) FDMA. ......... 72
5.7 FDMA with flexible bandwidth assignment. ........................ 73
5.8 DFTS-OFDM signal generation. ...................................... 74
5.9 PAR distribution for OFDM and DFTS-OFDM, respectively.  
   Solid curve: QPSK. Dashed curve: 16QAM. ....................... 75
5.10 Basic principle of DFTS-OFDM demodulation. .................. 76
5.11 DFTS-OFDM demodulator with frequency-domain equalization. 77
5.12 Uplink user multiplexing in case of DFTS-OFDM. (a) Equal-bandwidth assignment and (b) unequal-bandwidth assignment. 78
5.13 Localized DFTS-OFDM vs. Distributed DFTS-OFDM. ........... 78
5.14 Spectrum of localized and distributed DFTS-OFDM signals. .... 79
5.15 User multiplexing in case of localized and distributed DFTS-OFDM... 79

6.1 Linear receive-antenna combining. ............................... 83
6.2 Linear receive-antenna combining. ............................... 84
6.3 Downlink scenario with a single dominating interferer (special case of only two receive antennas) ......................... 85
6.4 Receiver scenario with one strong interfering mobile terminal: (a) Intra-cell interference and (b) Inter-cell interference. ... 86
6.5 Two-dimensional space/time linear processing (two receive antennas). 87
6.6 Two-dimensional space/frequency linear processing (two receive antennas) .......................................................... 88
6.7 Two-antenna delay diversity ......................................................... 89
6.8 Two-antenna Cyclic-Delay Diversity (CDD) ................................. 90
6.9 WCDMA Space–Time Transmit Diversity (STTD) ....................... 91
6.10 Space–Frequency Transmit Diversity assuming two transmit antennas .............................................................. 92
6.11 Classical beam-forming with high mutual antennas correlation:
    (a) antenna configuration and (b) beam-structure ................. 93
6.12 Pre-coder-based beam-forming in case of low mutual antenna correlation ......................................................... 94
6.13 Per-subcarrier pre-coding in case of OFDM (two transmit antennas) ................................................................. 96
6.14 \(2 \times 2\)-antenna configuration ............................................... 98
6.15 Linear reception/demodulation of spatially multiplexed signals .... 99
6.16 Pre-coder-based spatial multiplexing ......................................... 100
6.17 Orthogonalization of spatially multiplexed signals by means of pre-coding. \(\lambda_{ii}\) is the \(i\)th eigenvalue of the matrix \(H^TH\) 101
6.18 Single-codeword transmission (a) vs. multi-codeword transmission (b) ......................................................... 102
6.19 Demodulation/decoding of spatially multiplexed signals based on Successive Interference Cancellation .............................. 103

7.1 (a) Power control and (b) rate control ........................................ 106
7.2 Channel-dependent scheduling .................................................. 109
7.3 Example of three different scheduling behaviors for two users with different average channel quality: (a) max C/I, (b) round robin, and (c) proportional fair. The selected user is shown with bold lines 110
7.4 Illustration of the principle behavior of different scheduling strategies:
    (a) for full buffers and (b) for web browsing traffic model 119
7.5 Example of Chase combining ..................................................... 121
7.6 Example of incremental redundancy ........................................... 122

8.1 WCDMA evolution ................................................................. 128
8.2 WCDMA radio-access network architecture ................................ 130
8.3 WCDMA protocol architecture .................................................. 131
8.4 Simplified view of physical layer processing in WCDMA ............ 133
8.5 Channelization codes ............................................................... 134

9.1 Time- and code-domain structure for HS-DSCH .......................... 140
9.2 Channel-dependent scheduling for HSDPA .................................. 141
9.3 Illustration of the HSDPA architecture ........................................ 143
9.4 Dynamic power usage with HS-DSCH. .......................... 145
9.5 Channel structure with HSDPA. ................................. 147
9.6 MAC-hs and physical-layer processing. ....................... 148
9.7 Priority handling in the scheduler. ............................ 151
9.8 Transport-block sizes vs. the number of channelization codes for
QPSK and 16QAM modulation. The transport-block sizes used for
CQI reporting are also illustrated. ............................... 152
9.9 Generation of redundancy versions. ............................ 155
9.10 Multiple hybrid-ARQ process (six in this example). ......... 156
9.11 Protocol configuration when HS-DSCH is assigned. The numbers
in the rightmost part of the figure corresponds to the numbers to
the right in Figure 9.12. ............................................. 157
9.12 Data flow at UTRAN side. ...................................... 158
9.13 Measurements and resource limitations for HSDPA. ........ 160
9.14 Change of serving cell for HSPA. It is assumed that both the
source and target NodeB are part of the active set. .............. 161
9.15 The principle of two-stage rate matching. ..................... 164
9.16 An example of the generation of different redundancy versions in
the case of IR. ....................................................... 166
9.17 The channel interleaver for the HS-DSCH. ..................... 168
9.18 The priority queues in the NodeB MAC-hs (left) and the
reordering queues in the UE MAC-hs (right). ..................... 171
9.19 Illustration of the principles behind reordering queues. .... 171
9.20 The structure of the MAC-hs header. .......................... 173
9.21 Timing relation for the CQI reports. .......................... 176
9.22 HS-SCCH channel coding. ...................................... 179
9.23 Fractional DPCH (F-DPCH), introduced in Release 6. .... 180
9.24 Basic structure of uplink signaling with IQ/code-multiplexed
HS-DPCH. ......................................................... 181
9.25 Detection threshold for the ACK/NAK field of HS-DPCH. ... 183
9.26 Enhanced ACK/NAK using PRE and POST. .................. 183
10.1 Enhanced Uplink scheduling framework. ..................... 187
10.2 The architecture with E-DCH (and HS-DSCH) configured. ... 190
10.3 Separate processing of E-DCH and DCH. ..................... 191
10.4 Overall channel structure with HSDPA and Enhanced Uplink.
The new channels introduced as part of Enhanced Uplink are
shown with dashed lines. ........................................ 192
10.5 MAC-e and physical-layer processing. ........................ 194
10.6 Overview of the scheduling operation. ......................... 198
10.7 The relation between absolute grant, relative grant and serving
grant. .............................................................. 200
10.8 Illustration of relative grant usage. ........................... 200
10.9 Illustration of the E-TFC selection process. .......................... 203
10.10 Synchronous vs. asynchronous hybrid ARQ. ......................... 205
10.11 Multiple hybrid ARQ processes for Enhanced Uplink.............. 206
10.12 Retransmissions in soft handover. ...................................... 207
10.13 Code allocation in case of simultaneous E-DCH and HS-DSCH
    operation (note that the code allocation is slightly different when
    no HS-DPCCH is configured). Channels with SF > 4 are shown
    on the corresponding SF4 branch for illustrative purposes. ........ 209
10.14 Data flow. .............................................................. 211
10.15 Illustration of the resource sharing between E-DCH and DCH
    channels. ............................................................... 212
10.16 The relation between absolute grant, relative grant and serving
    grant. ........................................................................ 215
10.17 Illustration of UE monitoring of the two identities. ................. 215
10.18 Example of common and dedicated scheduling. ....................... 216
10.19 Grant table. ................................................................ 217
10.20 Example of activation of individual hybrid ARQ processes. ....... 218
10.21 E-TFC selection and hybrid ARQ profiles. ............................. 222
10.22 E-DCH rate matching and the r and s parameters. The bit
    collection procedure is identical to the QPSK bit collection
    for HS-DSCH. .............................................................. 224
10.23 Amount of puncturing as a function of the transport block
    size. ........................................................................ 225
10.24 Mapping from RSN via RV to s and r. ................................. 226
10.25 Reordering mechanism. ...................................................... 228
10.26 Structure and format of the MAC-e/es PDU. ......................... 230
10.27 E-DCH-related out-band control signaling. ......................... 231
10.28 E-HICH and E-RGCH structures (from the serving cell). ....... 232
10.29 Illustration of signature sequence hopping. ........................ 233
10.30 E-AGCH coding structure. .............................................. 234
10.31 Timing relation for downlink control channels, 10 ms TTI. ...... 236
10.32 Timing relation for downlink control channels, 2 ms TTI. ....... 237
10.33 E-DPCCH coding. ......................................................... 238
11.1 Example of MBMS services. Different services are provided in
    different areas using broadcast in cells 1–4. In cell 5, unicast is
    used as there is only single user subscribing to the MBMS
    service. ....................................................................... 240
11.2 Example of typical phases during an MBMS session. The
    dashed phases are only used in case of multicast and not for
    broadcast. .................................................................... 241
11.3 The gain with soft combining and multi-cell reception in
    terms of coverage vs. power for 64 kbit/s MBMS service
(vehicular A, 3 km/h, 80 ms TTI, single receive antenna, no transmit diversity, 1% BLER).

11.4 Illustration of the principles for (a) soft combining and (b) selection combining.

11.5 Illustration of application-level coding. Depending on their different ratio conditions, the number of coded packets required for the UEs to be able to reconstruct the original information differs.

11.6 Illustration of data flow through RLC, MAC, and L1 in the network side for different transmission scenarios.

11.7 MCCH transmission schedule. Different shades indicate (potentially) different MCCH content, e.g. different combinations of services.

12.1 HS-DSCCH processing in case of MIMO transmission.

12.2 Modulation, spreading, scrambling and pre-coding for two dual-stream MIMO.

12.3 HS-SCCH information in case of MIMO support. The gray shaded information is added compared to Release 5.

12.4 Example of type A and type B PCI/CQI reporting for a UE configured for MIMO reception.

12.5 WCDMA state model.

12.6 Example of uplink DTX.

12.7 CQI reporting in combination with uplink DTX.

12.8 Example of simultaneous use of uplink DTX and downlink DRX.

12.9 Example of retransmissions with HS-SCCH-less operation.

12.10 Median HSDPA data rate in a mildly dispersive propagation channel for UEs with 15 channelization codes (from [112]).

13.1 LTE and HSPA Evolution.

13.2 The original IMT -2000 ‘core band’ spectrum allocations at 2 GHz.

14.1 Downlink channel-dependent scheduling in time and frequency domains.

14.2 Example of inter-cell interference coordination.

14.3 Frequency- and time-division duplex.

15.1 LTE protocol architecture (downlink).

15.2 RLC segmentation and concatenation.

15.3 Downlink channel mapping.

15.4 Uplink channel mapping.

15.5 Transport-format selection in (a) downlink and (b) uplink.

15.6 Multiple parallel hybrid-ARQ processes.

15.7 Simplified physical-layer processing for DL-SCH.
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.27</td>
<td>Code-block segmentation and per-code-block CRC insertion</td>
</tr>
<tr>
<td>16.28</td>
<td>LTE Turbo encoder</td>
</tr>
<tr>
<td>16.29</td>
<td>Principles of QPP-based interleaving</td>
</tr>
<tr>
<td>16.30</td>
<td>Rate-matching and hybrid-ARQ functionality</td>
</tr>
<tr>
<td>16.31</td>
<td>VRB-to-PRB mapping in case of localized VRBs. Figure assumes a cell bandwidth corresponding to 25 resource blocks</td>
</tr>
<tr>
<td>16.32</td>
<td>VRB-to-PRB mapping in case of distributed VRBs. Figure assumes a cell bandwidth corresponding to 25 resource blocks</td>
</tr>
<tr>
<td>16.33</td>
<td>Two-antenna-port transmit diversity – SFBC</td>
</tr>
<tr>
<td>16.34</td>
<td>Four-antenna-port transmit diversity – combined SFBC/FSTD</td>
</tr>
<tr>
<td>16.35</td>
<td>The basic structure of LTE closed-loop spatial multiplexing</td>
</tr>
<tr>
<td>16.36</td>
<td>Codeword-to-layer mapping for spatial multiplexing</td>
</tr>
<tr>
<td>16.37</td>
<td>Open-loop spatial multiplexing (‘large-delay CDD’)</td>
</tr>
<tr>
<td>16.38</td>
<td>Resource-block structure for MBSFN subframes, assuming normal cyclic prefix for the unicast part</td>
</tr>
<tr>
<td>16.39</td>
<td>Reference-signal structure for MBSFN subframes</td>
</tr>
<tr>
<td>17.1</td>
<td>Basic principles of DFTS-OFDM for LTE uplink transmission</td>
</tr>
<tr>
<td>17.2</td>
<td>Frequency-domain structure for LTE uplink</td>
</tr>
<tr>
<td>17.3</td>
<td>Detailed time-domain structure for LTE uplink transmission</td>
</tr>
<tr>
<td>17.4</td>
<td>Transmission of uplink reference signals within a slot in case of PUSCH transmission (normal cyclic prefix)</td>
</tr>
<tr>
<td>17.5</td>
<td>Generation of uplink reference signal from a frequency-domain reference-signal sequence</td>
</tr>
<tr>
<td>17.6</td>
<td>Generation of uplink reference-signal sequence from linear phase rotation of a basic reference-signal sequence</td>
</tr>
<tr>
<td>17.7</td>
<td>Grouping of reference-signal sequences into sequence groups. The number indicates the corresponding bandwidth in number of resource blocks</td>
</tr>
<tr>
<td>17.8</td>
<td>Transmission of SRS</td>
</tr>
<tr>
<td>17.9</td>
<td>Non-frequency-hopping (wideband) SRS versus frequency-hopping SRS</td>
</tr>
<tr>
<td>17.10</td>
<td>Generation of SRS from a frequency-domain reference-signal sequence</td>
</tr>
<tr>
<td>17.11</td>
<td>Multiplexing of SRS transmissions from different mobile terminals</td>
</tr>
<tr>
<td>17.12</td>
<td>Uplink L1/L2 control signaling transmission on PUCCH</td>
</tr>
<tr>
<td>17.13</td>
<td>PUCCH format 1 (normal cyclic prefix)</td>
</tr>
<tr>
<td>17.14</td>
<td>Example of phase rotation and cover hopping for two PUCCH resource indices in two different cells</td>
</tr>
<tr>
<td>17.15</td>
<td>Multiplexing of scheduling request and hybrid-ARQ acknowledgement from a single terminal</td>
</tr>
<tr>
<td>17.16</td>
<td>PUCCH format 2 (normal cyclic prefix)</td>
</tr>
</tbody>
</table>
17.17 Simultaneous transmission of channel-status reports and hybrid-ARQ acknowledgements: (a) normal cyclic prefix and (b) extended cyclic prefix. 409
17.18 Allocation of resource blocks for PUCCH. 410
17.19 Multiplexing of control and data onto PUSCH. 412
17.20 Uplink transport-channel processing. 414
17.21 Definition of subbands for PUSCH hopping. A total of four subbands, each consisting of eleven resource blocks. 416
17.22 Hopping according to predefined hopping pattern. 417
17.23 Hopping/mirroring according to predefined hopping/mirroring patterns. Same hopping pattern as in Figure 17.22. 417
17.24 Frequency hopping according to explicit hopping information. 418

18.1 Time-domain positions of PSSs in case of FDD and TDD. 422
18.2 Definition and structure of PSS. 424
18.3 Definition and structure of SSS. 425
18.4 Channel coding and subframe mapping for the BCH transport channel. 427
18.5 Detailed resource mapping for the BCH transport channel. 428
18.6 Example of mapping of SIBs to SIs. 431
18.7 Transmission window for the transmission of an SI. 431
18.8 Overview of the random-access procedure. 433
18.9 Preamble subsets. 434
18.10 Principal illustration of random-access-preamble transmission. 436
18.11 Different preamble formats. 438
18.12 Random-access preamble generation. 440
18.13 Random-access preamble detection in the frequency domain. 441
18.14 DRX for paging. 445

19.1 Multiple parallel hybrid-ARQ processes. 449
19.2 Non-adaptive and adaptive hybrid-ARQ operation. 454
19.3 Timing relation between downlink data in subframe \( n \) and uplink hybrid-ARQ acknowledgement in subframe \( n + 4 \) for FDD. 456
19.4 Example of timing relation between downlink data and uplink hybrid-ARQ acknowledgement for TDD (configuration 2). 459
19.5 MAC and RLC structure (single-terminal view). 460
19.6 Generation of RLC PDUs from RLC SDUs. 461
19.7 In-sequence delivery. 464
19.8 Retransmission of missing PDUs. 464
19.9 Transport format selection in downlink (left) and uplink (right). 466
19.10 MAC header and SDU multiplexing ............................. 469
19.11 Prioritization of two logical channels for three different uplink grants .................................................. 472
19.12 Scheduling request transmission ........................................ 473
19.13 Buffer status and power headroom reports ...................... 474
19.14 Example of uplink inter-cell interference coordination ........ 476
19.15 Example of semi-persistent scheduling ............................. 477
19.16 Example of half-duplex FDD terminal operation ................. 478
19.17 Full vs. partial path-loss compensation. Solid curve, Full compensation ($\alpha = 1$); Dashed curve: Partial compensation ($\alpha = 0.8$) ..................................................... 488
19.18 Illustration of DRX operation ....................................... 489
19.19 Uplink timing advance .............................................. 491
19.20 Timing relation for TDD operation .................................. 493
19.21 Coexistence between TD-SCDMA and LTE ...................... 494

20.1 Operating bands specified in 3GPP above 1 GHz and the corresponding ITU allocation ....................... 500
20.2 Operating bands specified in 3GPP below 1 GHz and the corresponding ITU allocation .................... 500
20.3 Example of how LTE can be migrated step-by-step into a spectrum allocation with an original GSM deployment .......................................................... 503
20.4 The channel bandwidth for one RF carrier and the corresponding transmission bandwidth configuration ................................................. 505
20.5 Defined frequency ranges for spurious emissions and operating band unwanted emissions ......................... 509
20.6 Definitions of ACLR and ACS, using example characteristics of an ‘aggressor’ interfering and a ‘victim’ wanted signal ........................................... 510
20.7 Requirements for receiver susceptibility to interfering signals in terms of blocking, ACS, narrowband blocking, and in-channel selectivity (ICS) ......................... 513

21.1 Radio access network and core network ....................... 517
21.2 Transport network topology influencing functional allocation .................................................. 521
21.3 WCDMA/HSPA radio access network: nodes and interfaces .................................................. 522
21.4 Roles of the RNC .................................................... 524
21.5 LTE radio access network: nodes and interfaces .................. 527
21.6 Overview of GSM and WCDMA/HSPA core network – somewhat simplified figure ..................................... 529
21.7 Roaming in GSM and WCDMA/HSPA .................................................................................. 532
21.8 Overview of SAE core network – simplified figure .................................................. 533
21.9 Roaming in LTE/EPC .................................................. 535
List of Figures

21.10 WCDMA/HSPA connected to LTE/SAE ........................................ 536
21.11 CDMA/HRPD connected to LTE/SAE........................................ 538

22.1 Current time schedule for IMT-Advanced within ITU .................. 540
22.2 3GPP time schedule for LTE-Advanced in relation to ITU time schedule on IMT-Advanced ......................................................... 541
22.3 LTE carrier aggregation for extension to wider overall transmission bandwidth ............................................................... 543
22.4 Carrier aggregation as a tool for spectrum aggregation and efficient utilization of fragmented spectrum ................................. 544
22.5 Coordinated multi-point transmission ......................................... 545
22.6 Relaying as a tool to improve the coverage of high data rates in a cell .................................................................................. 546

23.1 Definitions of data rates for performance ................................... 551
23.2 Mean and cell-edge downlink user throughput vs. served traffic, Typical Urban propagation ......................................................... 556
23.3 Mean and cell-edge downlink user throughput vs. served traffic, Pedestrian A propagation ......................................................... 557
23.4 Mean and cell-edge uplink user throughput vs. served traffic, Typical Urban propagation .......................................................... 557
23.5 Mean and cell-edge uplink user throughput vs. served traffic, Pedestrian A propagation ............................................................ 558
23.6 Mean downlink user throughput vs. spectral efficiency for 5 and 20 MHz LTE carriers ............................................................... 561

24.1 The wireless technologies discussed in this book ....................... 564
24.2 The evolution from IS-95 to CDMA2000 1x and 1x EV-DO ............ 566
24.3 In 1x EV-DO Rev B, multi-carrier operation can occur on multiple independent BS channel cards to allow a simple upgrade of existing base stations .................................................. 570
24.4 UMB enables multiplexing of OFDMA and CDMA traffic on the uplink ................................................................................. 572
24.5 GSM/EDGE network structure ................................................... 574
24.6 Existing and new modulation schemes for GSM/EDGE ............... 576
24.7 Example OFDMA frame structure for WiMAX (TDD) ............... 582
24.8 Fractional frequency reuse ......................................................... 585

25.1 Illustration of capabilities of IMT-2000 and systems beyond IMT-2000, based on the framework described in ITU -R Recommendation a M.1645 [47] ......................................................... 590