

Second edition

3G Evolution

HSPA and LTE for
Mobile Broadband

Erik Dahlman
Stefan Parkvall
Johan Sköld
Per Beming



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



AMSTERDAM • BOSTON • HEIDELBERG • LONDON • NEW YORK • OXFORD
PARIS • SAN DIEGO • SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

Academic Press is an imprint of Elsevier



Academic Press is an imprint of Elsevier
Linacre House, Jordan Hill, Oxford, OX2 8DP
30 Corporate Drive, Burlington, MA 01803

First edition 2007
Second edition 2008

Copyright © 2008. Erik Dahlman, Stefan Parkvall, Johan Sköld and Per Beming.
Published by Elsevier Ltd. All rights reserved

The right of Erik Dahlman, Stefan Parkvall, Johan Sköld and Per Beming to be
identified as the authors of this work has been asserted in accordance with the
Copyright, Designs and Patents Act 1988

No part of this publication may be reproduced, stored in a retrieval system or
transmitted in any form or by any means electronic, mechanical, photocopying,
recording or otherwise without the prior written permission of the publisher

Permission may be sought directly from Elsevier's Science & Technology Rights
Department in Oxford, UK: phone (+44) (0) 1865 843830; fax (+44) (0) 1865 853333;
email: permissions@elsevier.com. Alternatively you can submit your request online by
visiting the Elsevier website at <http://www.elsevier.com/locate/permissions>, and selecting
Obtaining permission to use Elsevier material

Notice

No responsibility is assumed by the publisher for any injury and/or damage to persons
or property as a matter of products liability, negligence or otherwise, or from any use
or operation of any methods, products, instructions or ideas contained in the material herein

British Library Cataloguing in Publication Data

3G evolution : HSPA and LTE for mobile broadband. – 2nd ed.

1. Broadband communication systems – Standards
 2. Mobile communication systems – Standards
 3. Cellular telephone systems – Standards
- I. Dahlman, Erik
621.3'8546

Library of Congress Control Number: 2008931278

ISBN: 978-0-12-374538-5

For information on all Academic Press publications visit our website at elsevierdirect.com

Typeset by Charon Tec Ltd., A Macmillan Company. (www.macmillansolutions.com)

Printed and bound in Great Britain by MPG Books Ltd, Bodmin, Cornwall

08 09 10 11 11 10 9 8 7 6 5 4 3 2 1

Working together to grow
libraries in developing countries

www.elsevier.com | www.bookaid.org | www.sabre.org

ELSEVIER

BOOK AID
International

Sabre Foundation

Contents

List of Figures	xv
List of Tables	xxvii
Preface	xxix
Acknowledgements	xxxii
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	27
3 High data rates in mobile communication	29
3.1 High data rates: Fundamental constraints	29
3.1.1 High data rates in noise-limited scenarios	31
3.1.2 Higher data rates in interference-limited scenarios	33
3.2 Higher data rates within a limited bandwidth: Higher-order modulation	34
3.2.1 Higher-order modulation in combination with channel coding	35
3.2.2 Variations in instantaneous transmit power	36
3.3 Wider bandwidth including multi-carrier transmission	37
3.3.1 Multi-carrier transmission	40
4 OFDM transmission	43
4.1 Basic principles of OFDM	43
4.2 OFDM demodulation	46
4.3 OFDM implementation using IFFT/FFT processing	46
4.4 Cyclic-prefix insertion	48
4.5 Frequency-domain model of OFDM transmission	51
4.6 Channel estimation and reference symbols	52
4.7 Frequency diversity with OFDM: Importance of channel coding	53
4.8 Selection of basic OFDM parameters	55
4.8.1 OFDM subcarrier spacing	55
4.8.2 Number of subcarriers	57
4.8.3 Cyclic-prefix length	58
4.9 Variations in instantaneous transmission power	58
4.10 OFDM as a user-multiplexing and multiple-access scheme	59
4.11 Multi-cell broadcast/multicast transmission and OFDM	61
5 Wider-band ‘single-carrier’ transmission	65
5.1 Equalization against radio-channel frequency selectivity	65
5.1.1 Time-domain linear equalization	66
5.1.2 Frequency-domain equalization	68
5.1.3 Other equalizer strategies	71
5.2 Uplink FDMA with flexible bandwidth assignment	71
5.3 DFT-spread OFDM	73
5.3.1 Basic principles	74
5.3.2 DFTS-OFDM receiver	76
5.3.3 User multiplexing with DFTS-OFDM	77
5.3.4 Distributed DFTS-OFDM	78

6	Multi-antenna techniques	81
6.1	Multi-antenna configurations	81
6.2	Benefits of multi-antenna techniques	82
6.3	Multiple receive antennas	83
6.4	Multiple transmit antennas	88
6.4.1	Transmit-antenna diversity	89
6.4.2	Transmitter-side beam-forming	93
6.5	Spatial multiplexing	96
6.5.1	Basic principles	97
6.5.2	Pre-coder-based spatial multiplexing	100
6.5.3	Non-linear receiver processing	102
7	Scheduling, link adaptation and hybrid ARQ	105
7.1	Link adaptation: Power and rate control	106
7.2	Channel-dependent scheduling	107
7.2.1	Downlink scheduling	108
7.2.2	Uplink scheduling	112
7.2.3	Link adaptation and channel-dependent scheduling in the frequency domain	115
7.2.4	Acquiring on channel-state information	116
7.2.5	Traffic behavior and scheduling	117
7.3	Advanced retransmission schemes	118
7.4	Hybrid ARQ with soft combining	120
	Part III: HSPA	125
8	WCDMA evolution: HSPA and MBMS	127
8.1	WCDMA: Brief overview	129
8.1.1	Overall architecture	129
8.1.2	Physical layer	132
8.1.3	Resource handling and packet-data session	137
9	High-Speed Downlink Packet Access	139
9.1	Overview	139
9.1.1	Shared-channel transmission	139
9.1.2	Channel-dependent scheduling	140
9.1.3	Rate control and higher-order modulation	142
9.1.4	Hybrid ARQ with soft combining	142
9.1.5	Architecture	143
9.2	Details of HSDPA	144

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

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

13.1.3	Deployment-related aspects	283
13.1.4	Architecture and migration	285
13.1.5	Radio resource management	286
13.1.6	Complexity	286
13.1.7	General aspects	286
13.2	SAE design targets	287
14	LTE radio access: An overview	289
14.1	LTE transmission schemes: Downlink OFDM and uplink DFTS-OFDM/SC-FDMA	289
14.2	Channel-dependent scheduling and rate adaptation	291
14.2.1	Downlink scheduling	292
14.2.2	Uplink scheduling	292
14.2.3	Inter-cell interference coordination	293
14.3	Hybrid ARQ with soft combining	294
14.4	Multiple antenna support	294
14.5	Multicast and broadcast support	295
14.6	Spectrum flexibility	296
14.6.1	Flexibility in duplex arrangement	296
14.6.2	Flexibility in frequency-band-of-operation	297
14.6.3	Bandwidth flexibility	297
15	LTE radio interface architecture	299
15.1	Radio link control	301
15.2	Medium access control	302
15.2.1	Logical channels and transport channels	303
15.2.2	Scheduling	305
15.2.3	Hybrid ARQ with soft combining	308
15.3	Physical layer	311
15.4	Terminal states	314
15.5	Data flow	315
16	Downlink transmission scheme	317
16.1	Overall time-domain structure and duplex alternatives	317
16.2	The downlink physical resource	319
16.3	Downlink reference signals	324
16.3.1	Cell-specific downlink reference signals	325
16.3.2	UE-specific reference signals	328
16.4	Downlink L1/L2 control signaling	330
16.4.1	Physical Control Format Indicator Channel	332
16.4.2	Physical Hybrid-ARQ Indicator Channel	334
16.4.3	Physical Downlink Control Channel	338

16.4.4	Downlink scheduling assignment.	340
16.4.5	Uplink scheduling grants	348
16.4.6	Power-control commands.	352
16.4.7	PDCCH processing	352
16.4.8	Blind decoding of PDCCHs.	357
16.5	Downlink transport-channel processing	361
16.5.1	CRC insertion per transport block	361
16.5.2	Code-block segmentation and per-code-block CRC insertion.	362
16.5.3	Turbo coding	363
16.5.4	Rate-matching and physical-layer hybrid-ARQ functionality	365
16.5.5	Bit-level scrambling	366
16.5.6	Data modulation.	366
16.5.7	Antenna mapping	367
16.5.8	Resource-block mapping	367
16.6	Multi-antenna transmission.	371
16.6.1	Transmit diversity.	372
16.6.2	Spatial multiplexing	373
16.6.3	General beam-forming	377
16.7	MBSFN transmission and MCH.	378
17	Uplink transmission scheme	383
17.1	The uplink physical resource	383
17.2	Uplink reference signals	385
17.2.1	Uplink demodulation reference signals	385
17.2.2	Uplink sounding reference signals.	393
17.3	Uplink L1/L2 control signaling	396
17.3.1	Uplink L1/L2 control signaling on PUCCH	398
17.3.2	Uplink L1/L2 control signaling on PUSCH.	411
17.4	Uplink transport-channel processing	413
17.5	PUSCH frequency hopping.	415
17.5.1	Hopping based on cell-specific hopping/mirroring patterns	416
17.5.2	Hopping based on explicit hopping information	418
18	LTE access procedures.	421
18.1	Acquisition and cell search.	421
18.1.1	Overview of LTE cell search	421
18.1.2	PSS structure	424
18.1.3	SSS structure	424

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 5 MHz 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 20 MHz 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 $f_{Doppler}/\Delta f$	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	2×2 -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. $\lambda_{i,i}$ is the i th eigenvalue of the matrix $H^H H$	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-DPCCH.	181
9.25	Detection threshold for the ACK/NAK field of HS-DPCCH.	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).....	243
11.4	Illustration of the principles for (a) soft combining and (b) selection combining.....	243
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. . . .	246
11.6	Illustration of data flow through RLC, MAC, and L1 in the network side for different transmission scenarios.	248
11.7	MCCCH transmission schedule. Different shades indicate (potentially) different MCCCH content, e.g. different combinations of services. . . .	248
12.1	HS-DSCH processing in case of MIMO transmission.....	253
12.2	Modulation, spreading, scrambling and pre-coding for two dual-stream MIMO.....	254
12.3	HS-SCCH information in case of MIMO support. The gray shaded information is added compared to Release 5.	257
12.4	Example of type A and type B PCI/CQI reporting for a UE configured for MIMO reception.....	258
12.5	WCDMA state model.....	260
12.6	Example of uplink DTX.....	262
12.7	CQI reporting in combination with uplink DTX.	263
12.8	Example of simultaneous use of uplink DTX and downlink DRX.	264
12.9	Example of retransmissions with HS-SCCH-less operation.	267
12.10	Median HSDPA data rate in a mildly dispersive propagation channel for UEs with 15 channelization codes (from [112]).	273
13.1	LTE and HSPA Evolution.....	279
13.2	The original IMT -2000 ‘core band’ spectrum allocations at 2GHz.	285
14.1	Downlink channel-dependent scheduling in time and frequency domains.....	292
14.2	Example of inter-cell interference coordination.....	293
14.3	Frequency- and time-division duplex.....	296
15.1	LTE protocol architecture (downlink).	300
15.2	RLC segmentation and concatenation.	302
15.3	Downlink channel mapping.	305
15.4	Uplink channel mapping.....	305
15.5	Transport-format selection in (a) downlink and (b) uplink.	306
15.6	Multiple parallel hybrid-ARQ processes.	310
15.7	Simplified physical-layer processing for DL-SCH.....	311

15.8	LTE states.	314
15.9	Example of LTE data flow.	316
16.1	LTE high-level time-domain structure.	318
16.2	Uplink/downlink time/frequency structure in case of FDD and TDD.	318
16.3	Different downlink/uplink configurations in case of TDD.	320
16.4	The LTE downlink physical resource.	321
16.5	Frequency-domain structure for LTE downlink.	322
16.6	Detailed time-domain structure for LTE downlink transmission.	322
16.7	Downlink resource block assuming normal cyclic prefix (i.e. seven OFDM symbols per slot). With extended cyclic prefix there are six OFDM symbols per slot.	324
16.8	Structure of cell-specific reference signal within a pair of resource blocks (normal cyclic prefix).	325
16.9	Different reference-signal frequency shifts.	327
16.10	Cell-specific reference signals in case of multi-antenna transmission: (a) two antenna ports and (b) four antenna ports.	328
16.11	Structure of UE-specific reference signal within a pair of resource blocks (normal cyclic prefix).	329
16.12	LTE time/frequency grid illustrating the split of the subframe into (variable-sized) control and data regions.	331
16.13	Overview of the PCFICH processing.	333
16.14	Numbering of resource-element groups in the control region (assuming a size of three OFDM symbols).	334
16.15	Example of PCFICH mapping in the first OFDM symbol for three different physical-layer cell identities.	335
16.16	PHICH structure.	337
16.17	Overview of DCI formats for downlink scheduling (FDD).	341
16.18	Illustration of resource-block allocation types (cell bandwidth corresponding to 25 resource blocks used in this example).	345
16.19	Number of bits used for resource allocation signaling for allocation types 0/1 and 2.	346
16.20	Computing the transport-block size.	349
16.21	Timing relation for uplink grants in FDD and TDD configuration 0	351
16.22	Processing of L1/L2 control signaling.	353
16.23	CCE aggregation and PDCCH multiplexing.	355
16.24	Example of mapping of PCFICH, PHICH, and PDCCH.	357
16.25	Principal illustration of search spaces in two terminals.	359
16.26	LTE downlink transport-channel processing. Dashed parts are only present in case of spatial multiplexing, that is when two transport blocks are transmitted in parallel within a TTI.	362

16.27	Code-block segmentation and per-code-block CRC insertion.	363
16.28	LTE Turbo encoder.	364
16.29	Principles of QPP-based interleaving.	364
16.30	Rate-matching and hybrid-ARQ functionality.	365
16.31	VRB-to-PRB mapping in case of localized VRBs. Figure assumes a cell bandwidth corresponding to 25 resource blocks.	369
16.32	VRB-to-PRB mapping in case of distributed VRBs. Figure assumes a cell bandwidth corresponding to 25 resource blocks.	370
16.33	Two-antenna-port transmit diversity – SFBC.	372
16.34	Four-antenna-port transmit diversity – combined SFBC/FSTD.	373
16.35	The basic structure of LTE closed-loop spatial multiplexing.	374
16.36	Codeword-to-layer mapping for spatial multiplexing.	374
16.37	Open-loop spatial multiplexing (‘large-delay CDD’).	376
16.38	Resource-block structure for MBSFN subframes, assuming normal cyclic prefix for the unicast part.	379
16.39	Reference-signal structure for MBSFN subframes.	380
17.1	Basic principles of DFTS-OFDM for LTE uplink transmission.	384
17.2	Frequency-domain structure for LTE uplink.	385
17.3	Detailed time-domain structure for LTE uplink transmission.	386
17.4	Transmission of uplink reference signals within a slot in case of PUSCH transmission (normal cyclic prefix).	387
17.5	Generation of uplink reference signal from a frequency-domain reference-signal sequence.	387
17.6	Generation of uplink reference-signal sequence from linear phase rotation of a basic reference-signal sequence.	390
17.7	Grouping of reference-signal sequences into sequence groups. The number indicates the corresponding bandwidth in number of resource blocks.	392
17.8	Transmission of SRS.	394
17.9	Non-frequency-hopping (wideband) SRS versus frequency- hopping SRS.	394
17.10	Generation of SRS from a frequency-domain reference-signal sequence.	396
17.11	Multiplexing of SRS transmissions from different mobile terminals.	396
17.12	Uplink L1/L2 control signaling transmission on PUCCH.	398
17.13	PUCCH format 1 (normal cyclic prefix).	401
17.14	Example of phase rotation and cover hopping for two PUCCH resource indices in two different cells.	403
17.15	Multiplexing of scheduling request and hybrid-ARQ acknowledgement from a single terminal.	405
17.16	PUCCH format 2 (normal cyclic prefix).	406

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

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