Contents

Preface xiii

Acknowledgements xv

List of Abbreviations xvii

1 Introduction 1
Harri Holma and Antti Toskala
1.1 Mobile Voice Subscriber Growth 1
1.2 Mobile Data Usage Growth 2
1.3 Wireline Technologies Evolution 3
1.4 Motivation and Targets for LTE 4
1.5 Overview of LTE 5
1.6 3GPP Family of Technologies 7
1.7 Wireless Spectrum 8
1.8 New Spectrum Identified by WRC-07 10
1.9 LTE-Advanced 11

2 LTE Standardization 13
Antti Toskala
2.1 Introduction 13
2.2 Overview of 3GPP Releases and Process 13
2.3 LTE Targets 14
2.4 LTE Standardization Phases 16
2.5 Evolution Beyond Release 8 18
2.6 LTE-Advanced for IMT-Advanced 19
2.7 LTE Specifications and 3GPP Structure 21
References 22

3 System Architecture Based on 3GPP SAE 23
Atte Länsisalmi and Antti Toskala
3.1 System Architecture Evolution in 3GPP 23
3.2 Basic System Architecture Configuration with only E-UTRAN Access Network 25

References 22
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2.1</td>
<td>Overview of Basic System Architecture Configuration</td>
<td>25</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Logical Elements in Basic System Architecture Configuration</td>
<td>26</td>
</tr>
<tr>
<td>3.2.3</td>
<td>Self-configuration of S1-MME and X2 interfaces</td>
<td>34</td>
</tr>
<tr>
<td>3.2.4</td>
<td>Interfaces and Protocols in Basic System Architecture Configuration</td>
<td>35</td>
</tr>
<tr>
<td>3.2.5</td>
<td>Roaming in Basic System Architecture Configuration</td>
<td>39</td>
</tr>
<tr>
<td>3.3</td>
<td>System Architecture with E-UTRAN and Legacy 3GPP Access Networks</td>
<td>40</td>
</tr>
<tr>
<td>3.3.1</td>
<td>Overview of 3GPP Inter-working System Architecture Configuration</td>
<td>40</td>
</tr>
<tr>
<td>3.3.2</td>
<td>Additional and Updated Logical Elements in 3GPP Inter-working System Architecture Configuration</td>
<td>42</td>
</tr>
<tr>
<td>3.3.3</td>
<td>Interfaces and Protocols in 3GPP Inter-working System Architecture Configuration</td>
<td>44</td>
</tr>
<tr>
<td>3.3.4</td>
<td>Inter-working with Legacy 3GPP CS Infrastructure</td>
<td>44</td>
</tr>
<tr>
<td>3.4</td>
<td>System Architecture with E-UTRAN and Non-3GPP Access Networks</td>
<td>45</td>
</tr>
<tr>
<td>3.4.1</td>
<td>Overview of 3GPP and Non-3GPP Inter-working System Architecture Configuration</td>
<td>45</td>
</tr>
<tr>
<td>3.4.2</td>
<td>Additional and Updated Logical Elements in 3GPP Inter-working System Architecture Configuration</td>
<td>47</td>
</tr>
<tr>
<td>3.4.3</td>
<td>Interfaces and Protocols in Non-3GPP Inter-working System Architecture Configuration</td>
<td>50</td>
</tr>
<tr>
<td>3.4.4</td>
<td>Roaming in Non-3GPP Inter-working System Architecture Configuration</td>
<td>51</td>
</tr>
<tr>
<td>3.5</td>
<td>Inter-working with cdma2000® Access Networks</td>
<td>51</td>
</tr>
<tr>
<td>3.5.1</td>
<td>Architecture for cdma2000® HRPD Inter-working</td>
<td>51</td>
</tr>
<tr>
<td>3.5.2</td>
<td>Additional and Updated Logical Elements for cdma2000® HRPD Inter-working</td>
<td>54</td>
</tr>
<tr>
<td>3.5.3</td>
<td>Protocols and Interfaces in cdma2000® HRPD Inter-working</td>
<td>55</td>
</tr>
<tr>
<td>3.5.4</td>
<td>Inter-working with cdma2000® 1xRTT</td>
<td>56</td>
</tr>
<tr>
<td>3.6</td>
<td>IMS Architecture</td>
<td>56</td>
</tr>
<tr>
<td>3.6.1</td>
<td>Overview</td>
<td>56</td>
</tr>
<tr>
<td>3.6.2</td>
<td>Session Management and Routing</td>
<td>58</td>
</tr>
<tr>
<td>3.6.3</td>
<td>Databases</td>
<td>59</td>
</tr>
<tr>
<td>3.6.4</td>
<td>Services Elements</td>
<td>59</td>
</tr>
<tr>
<td>3.6.5</td>
<td>Inter-working Elements</td>
<td>59</td>
</tr>
<tr>
<td>3.7</td>
<td>PCC and QoS</td>
<td>60</td>
</tr>
<tr>
<td>3.7.1</td>
<td>PCC</td>
<td>60</td>
</tr>
<tr>
<td>3.7.2</td>
<td>QoS</td>
<td>63</td>
</tr>
<tr>
<td>4</td>
<td>Introduction to OFDMA and SC-FDMA and to MIMO in LTE</td>
<td>67</td>
</tr>
<tr>
<td>4.1</td>
<td>Introduction</td>
<td>67</td>
</tr>
<tr>
<td>4.2</td>
<td>LTE Multiple Access Background</td>
<td>67</td>
</tr>
<tr>
<td>4.3</td>
<td>OFDMA Basics</td>
<td>70</td>
</tr>
<tr>
<td>4.4</td>
<td>SC-FDMA Basics</td>
<td>76</td>
</tr>
<tr>
<td>4.5</td>
<td>MIMO Basics</td>
<td>80</td>
</tr>
<tr>
<td>4.6</td>
<td>Summary</td>
<td>82</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>82</td>
</tr>
</tbody>
</table>
5 Physical Layer  83
Antti Toskala, Timo Lunttila, Esa Tiirola, Kari Hooli and Juha Korhonen

5.1 Introduction  83
5.2 Transport Channels and Their Mapping to the Physical Channels  83
5.3 Modulation  85
5.4 Uplink User Data Transmission  86
5.5 Downlink User Data Transmission  89
5.6 Uplink Physical Layer Signaling Transmission  93
  5.6.1 Physical Uplink Control Channel (PUCCH)  94
  5.6.2 PUCCH Configuration  97
  5.6.3 Control Signaling on PUSCH  101
  5.6.4 Uplink Reference Signals  103
5.7 PRACH Structure  109
  5.7.1 Physical Random Access Channel  109
  5.7.2 Preamble Sequence  110
5.8 Downlink Physical Layer Signaling Transmission  112
  5.8.1 Physical Control Format Indicator Channel (PCFICH)  112
  5.8.2 Physical Downlink Control Channel (PDCCH)  113
  5.8.3 Physical HARQ Indicator Channel (PHICH)  115
  5.8.4 Downlink Transmission Modes  115
  5.8.5 Physical Broadcast Channel (PBCH)  116
  5.8.6 Synchronization Signal  117
5.9 Physical Layer Procedures  117
  5.9.1 HARQ Procedure  118
  5.9.2 Timing Advance  119
  5.9.3 Power Control  119
  5.9.4 Paging  120
  5.9.5 Random Access Procedure  120
  5.9.6 Channel Feedback Reporting Procedure  123
  5.9.7 Multiple Input Multiple Output (MIMO) Antenna Technology  129
  5.9.8 Cell Search Procedure  130
  5.9.9 Half Duplex Operation  130
5.10 UE Capability Classes and Supported Features  131
5.11 Physical Layer Measurements  132
  5.11.1 eNodeB Measurements  132
  5.11.2 UE Measurements and Measurement Procedure  133
5.12 Physical Layer Parameter Configuration  133
5.13 Summary  134
References  135

6 LTE Radio Protocols  137
Antti Toskala and Woonhee Hwang

6.1 Introduction  137
6.2 Protocol Architecture  137
6.3 Medium Access Control  139
  6.3.1 Logical Channels  140
  6.3.2 Data Flow in MAC Layer  142
6.4 Radio Link Control Layer  
6.4.1 RLC Modes of Operation  
6.4.2 Data Flow in RLC Layer  
6.5 Packet Data Convergence Protocol  
6.6 Radio Resource Control (RRC)  
6.6.1 UE States and State Transitions Including Inter-RAT  
6.6.2 RRC Functions and Signaling Procedures  
6.7 X2 Interface Protocols  
6.7.1 Handover on X2 Interface  
6.7.2 Load Management  
6.8 Early UE Handling in LTE  
6.9 Summary  
References  

7 Mobility  
*Chris Callender, Harri Holma, Jarkko Koskela and Jussi Reunanen*  
7.1 Introduction  
7.2 Mobility Management in Idle State  
7.2.1 Overview of Idle Mode Mobility  
7.2.2 Cell Selection and Reselection Process  
7.2.3 Tracking Area Optimization  
7.3 Intra-LTE Handovers  
7.3.1 Procedure  
7.3.2 Signaling  
7.3.3 Handover Measurements  
7.3.4 Automatic Neighbor Relations  
7.3.5 Handover Frequency  
7.3.6 Handover Delay  
7.4 Inter-system Handovers  
7.5 Differences in E-UTRAN and UTRAN Mobility  
7.6 Summary  
References  

8 Radio Resource Management  
*Harri Holma, Troels Kolding, Daniela Laselva, Klaus Pedersen, Claudio Rosa and Ingo Viering*  
8.1 Introduction  
8.2 Overview of RRM Algorithms  
8.3 Admission Control and QoS Parameters  
8.4 Downlink Dynamic Scheduling and Link Adaptation  
8.4.1 Layer 2 Scheduling and Link Adaptation Framework  
8.4.2 Frequency Domain Packet Scheduling  
8.4.3 Combined Time and Frequency Domain Scheduling Algorithms  
8.4.4 Packet Scheduling with MIMO  
8.4.5 Downlink Packet Scheduling Illustrations  
8.5 Uplink Dynamic Scheduling and Link Adaptation  
8.5.1 Signaling to Support Uplink Link Adaptation and Packet Scheduling  

7 Mobility  
*Chris Callender, Harri Holma, Jarkko Koskela and Jussi Reunanen*  
7.1 Introduction  
7.2 Mobility Management in Idle State  
7.2.1 Overview of Idle Mode Mobility  
7.2.2 Cell Selection and Reselection Process  
7.2.3 Tracking Area Optimization  
7.3 Intra-LTE Handovers  
7.3.1 Procedure  
7.3.2 Signaling  
7.3.3 Handover Measurements  
7.3.4 Automatic Neighbor Relations  
7.3.5 Handover Frequency  
7.3.6 Handover Delay  
7.4 Inter-system Handovers  
7.5 Differences in E-UTRAN and UTRAN Mobility  
7.6 Summary  
References  

8 Radio Resource Management  
*Harri Holma, Troels Kolding, Daniela Laselva, Klaus Pedersen, Claudio Rosa and Ingo Viering*  
8.1 Introduction  
8.2 Overview of RRM Algorithms  
8.3 Admission Control and QoS Parameters  
8.4 Downlink Dynamic Scheduling and Link Adaptation  
8.4.1 Layer 2 Scheduling and Link Adaptation Framework  
8.4.2 Frequency Domain Packet Scheduling  
8.4.3 Combined Time and Frequency Domain Scheduling Algorithms  
8.4.4 Packet Scheduling with MIMO  
8.4.5 Downlink Packet Scheduling Illustrations  
8.5 Uplink Dynamic Scheduling and Link Adaptation  
8.5.1 Signaling to Support Uplink Link Adaptation and Packet Scheduling
11 Performance Requirements

Andrea Ancora, Iwajlo Angelow, Dominique Brunel, Chris Callender, Harri Holma, Peter Muszynski, Earl McCune and Laurent Noël

11.1 Introduction

11.2 Frequency Bands and Channel Arrangements
  11.2.1 Frequency Bands
  11.2.2 Channel Bandwidth
  11.2.3 Channel Arrangements

11.3 eNodeB RF Transmitter
  11.3.1 Operating Band Unwanted Emissions
  11.3.2 Coexistence with Other Systems on Adjacent Carriers Within the Same Operating Band
  11.3.3 Coexistence with Other Systems in Adjacent Operating Bands
  11.3.4 Transmitted Signal Quality

11.4 eNodeB RF Receiver
  11.4.1 Reference Sensitivity Level
  11.4.2 Dynamic Range
  11.4.3 In-channel Selectivity
  11.4.4 Adjacent Channel Selectivity (ACS) and Narrow-band Blocking
  11.4.5 Blocking
  11.4.6 Receiver Spurious Emissions
  11.4.7 Receiver Intermodulation

11.5 eNodeB Demodulation Performance
  11.5.1 PUSCH
  11.5.2 PUCCH
  11.5.3 PRACH

11.6 UE Design Principles and Challenges
  11.6.1 Introduction
  11.6.2 RF Subsystem Design Challenges
  11.6.3 RF–Baseband Interface Design Challenges
  11.6.4 LTE vs HSDPA Baseband Design Complexity

11.7 UE RF Transmitter
  11.7.1 LTE UE Transmitter Requirement
  11.7.2 LTE Transmit Modulation Accuracy, EVM
  11.7.3 Desensitization for Band and Bandwidth Combinations (Desense)
  11.7.4 Transmitter Architecture

11.8 UE RF Receiver Requirements
  11.8.1 Reference Sensitivity Level
  11.8.2 Introduction to UE Self-desensitization Contributors in FDD UEs
11.8.3 ACS, Narrowband Blockers and ADC Design Challenges 341
11.8.4 EVM Contributors: A Comparison Between LTE and WCDMA Receivers 348

11.9 UE Demodulation Performance
11.9.1 Transmission Modes 352
11.9.2 Channel Modeling and Estimation 354
11.9.3 Demodulation Performance 356

11.10 Requirements for Radio Resource Management
11.10.1 Idle State Mobility 360
11.10.2 Connected State Mobility when DRX is Not Active 360
11.10.3 Connected State Mobility when DRX is Active 362
11.10.4 Handover Execution Performance Requirements 363

11.11 Summary 364
References 364

12 LTE TDD Mode 367
Che Xiangguang, Troels Kolding, Peter Skov, Wang Haiming and Antti Toskala

12.1 Introduction 367
12.2 LTE TDD Fundamentals
12.2.1 LTE TDD Frame Structure 369
12.2.2 Asymmetric Uplink/Downlink Capacity Allocation 371
12.2.3 Co-existence with TD-SCDMA 371
12.2.4 Channel Reciprocity 372
12.2.5 Multiple Access Schemes 373

12.3 TDD Control Design
12.3.1 Common Control Channels 374
12.3.2 Sounding Reference Signal 376
12.3.3 HARQ Process and Timing 376
12.3.4 HARQ Design for UL TTI Bundling 379
12.3.5 UL HARQ-ACK/NACK Transmission 380
12.3.6 DL HARQ-ACK/NACK Transmission 380
12.3.7 DL HARQ-ACK/NACK Transmission with SRI and/or CQI over PUCCH 381

12.4 Semi-persistent Scheduling 381
12.5 MIMO and Dedicated Reference Signals 383
12.6 LTE TDD Performance
12.6.1 Link Performance 385
12.6.2 Link Budget and Coverage for TDD System 386
12.6.3 System Level Performance 389
12.6.4 Evolution of LTE TDD 396

12.7 Summary 396
References 397
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.3 Circuit Switched Voice on HSPA</td>
<td>401</td>
</tr>
<tr>
<td>13.4 Enhanced FACH and RACH</td>
<td>404</td>
</tr>
<tr>
<td>13.5 Downlink MIMO and 64QAM</td>
<td>405</td>
</tr>
<tr>
<td>13.6 Dual Carrier HSDPA</td>
<td>407</td>
</tr>
<tr>
<td>13.7 Uplink 16QAM</td>
<td>409</td>
</tr>
<tr>
<td>13.8 Layer 2 Optimization</td>
<td>410</td>
</tr>
<tr>
<td>13.9 Single Frequency Network (SFN) MBMS</td>
<td>411</td>
</tr>
<tr>
<td>13.10 Architecture Evolution</td>
<td>412</td>
</tr>
<tr>
<td>13.11 Summary</td>
<td>414</td>
</tr>
<tr>
<td>References</td>
<td>415</td>
</tr>
</tbody>
</table>

**Index**

417