UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

SAMSUNG ELECTRONICS CO., LTD.,
Petitioner,

v.

TELEFONAKTIEBOLAGET LM ERICSSON,
Patent Owner

U.S. PATENT NO. 9,509,440

Case IPR2021-TBD

DECLARATION OF DR. JAMES L. MULLINS IN SUPPORT OF PETITION FOR *INTER PARTES* REVIEW OF U.S. PATENT NO. 9,509,440

TABLE OF CONTENTS

Page

I, Dr. James L. Mullins, do hereby declare as follows:

I. INTRODUCTION AND ENGAGEMENT

1. I have been retained in this matter by Samsung Electronics Co., Ltd ("Petitioner" or "Samsung") in the above-captioned *inter partes* review relating to U.S. Patent 9,509,440 to provide an opinion on a specific document.

2. I am presently Dean Emeritus of Libraries and Esther Ellis Norton Professor Emeritus at Purdue University. My career as a professional and academic/research spanned more than 44 years including library positions at Indiana University, Villanova University, Massachusetts Institute of Technology, and Purdue University. Appendix A is a true and correct copy of my curriculum vitae describing my background and experience.

3. In 2018, I founded the firm Prior Art Documentation Librarian Services, LLC, located at 106 Berrow, Williamsburg, VA 23188 after purchasing the intellectual property of and successor to Prior Art Documentation, LLC located at 711 South Race Street, Urbana, IL 61801. Further information about my firm, Prior Art Documentation Librarian Services, LLC (PADLS), is available at www.priorartdoclib.com.

4. I have been retained by Petitioner to offer my opinion on the authenticity and dates of public accessibility of various documents. For this service, I am being paid my usual hourly fee of $250.00. I have no stake in the outcome of this proceeding or any related litigation or administrative proceedings, and my compensation in no way depends on the substance of my testimony or the outcome of this proceeding.

II. BACKGROUND AND QUALIFICATIONS

5. I received a Bachelor of Arts degree in History, Religion and Political Science in 1972 as well as a Master of Arts degree in Library Science in 1973 from the University of Iowa. I received my Ph.D. in Academic Library Management in 1984 from Indiana University. Over the past forty-four years, I have held various positions and as a leader in the field of library and information sciences.

6. I am presently Dean Emeritus of Libraries and Esther Ellis Norton Professor Emeritus at Purdue University, and have been since January 1, 2018. I have been previously employed as follows:

- Dean of Libraries and Professor and Esther Ellis Norton Professor, Purdue University, West Lafayette, IN (2004-2017)
- Assistant/Associate Director for Administration, Massachusetts Institute of Technology (MIT) Libraries, Cambridge, MA (2000-2004)
- University Librarian and Director, Falvey Memorial Library, Villanova University, Villanova, PA (1996-2000)
- Director of Library Services, Indiana University South Bend, South Bend, IN (1978-1996)
- Part-time Instructor, School of Library and Information Science, Indiana University, Bloomington, IN (1979-1996)
- Associate Law Librarian, and associated titles, Indiana University School of Law, Bloomington, IN (1974-1978)
- Catalog Librarian, Assistant Professor, Georgia Southern College (now University), Statesboro, GA (1973-1974)

7. I am a member of the American Library Association ("ALA"), where I served as the chair of the Research Committee of the Association of College and Research Libraries ("ACRL"). My service to ALA included service on the editorial board of the most prominent library journal, *College and Research Libraries*. I also served on the Standards Committee, College Section of the Association of College and Research Libraries, where I was instrumental in developing a re-issue of the *Standards for College Libraries* in 2000.

8. I am an author of numerous publications in the field of library science, and have given presentations in library sciences at national and international conferences. During more than 44 years as an academic librarian and library science scholar, I have gained extensive experience with catalog records and online library management systems (LMS) built using Machine-Readable Cataloging ("MARC") standards. As an academic library administrator, I have had responsibility to ensure that students were educated to identify, locate, assess, and integrate information garnered from research library resources. I have also facilitated the research of faculty colleagues either directly or through the provision of and access to the requisite print and/or digital materials and services at the universities where I worked.

9. Based on my experience identified above and detailed in my curriculum vitae, which is attached hereto as Appendix A, I consider myself to be an expert in the field of library science and academic library administration. I have previously offered my opinions on the public availability and authenticity of documents in over 40 cases. I have been deposed in one case.

III. <u>BACKGROUND ON PUBLIC ACCESSIBILITY</u>

A. Scope of This Declaration

10. I am not a lawyer, and I am not rendering an opinion on the legal question of whether a particular document is, or is not, a "printed publication" under the law. I am, however, rendering my expert opinion on the authenticity of the document referenced herein and when and how this document was disseminated or otherwise made available to the extent that persons interested and ordinarily skilled in the subject matter or art, exercising reasonable diligence, could have located the document.

11. I am informed by counsel that an item is considered authentic if there is sufficient evidence to support a finding that the item is what it is claimed to be. I am also informed that authenticity can be established based on the contents of the document itself, such as the appearance, content, substance, internal patterns, or other distinctive characteristics of the item.

12. I am informed by counsel that a given reference qualifies as "publicly accessible" if it was disseminated or otherwise made available such that a person interested in and ordinarily skilled in the relevant subject matter could locate it through the exercise of ordinary diligence.

13. While I understand that the determination of public accessibility under the foregoing standard rests on a case-by-case analysis of the facts particular to an individual publication, I also understand that a printed publication is rendered "publicly accessible" if it is cataloged and indexed by a library such that a person interested in the relevant subject matter could locate it (*i.e.*, I understand that cataloging and indexing by a library is sufficient, though there are other ways that a printed publication may qualify as "publicly accessible"). One manner of sufficient indexing is indexing according to subject matter. I understand that it is not necessary to prove someone actually looked at the printed publication in order to show it was publicly accessible by virtue of a library's cataloging and indexing thereof. I understand

that cataloging and indexing by a single library of a single instance of a particular printed publication is sufficient. I understand that, even if access to a library is restricted, a printed publication that has been cataloged and indexed therein is publicly accessible so long as a presumption is raised that the portion of the public concerned with the relevant subject matter would know of the printed publication. I also understand that the cataloging and indexing of information that would guide a person interested in the relevant subject matter to the printed publication, such as the cataloging and indexing of an abstract for the printed publication, is sufficient to render the printed publication publicly accessible.

14. I understand that evidence showing the specific date when a printed publication became publicly accessible is not necessary. Rather, routine business practices, such as general library cataloging and indexing practices, can be used to establish an approximate date on which a printed publication became publicly accessible.

B. Person of Ordinary Skill in the Art

15. In forming the opinions expressed in this declaration, I have reviewed the documents and appendices referenced herein. These materials are records created in the ordinary course of business by publishers, libraries, indexing services, and others. From my years of experience, I am familiar with the process for creating many of these records, and I know that these records are created by people with knowledge of the information contained within the record. Further, these records are created with the expectation that researchers and other members of the public will use them. All materials cited in this declaration and its appendices are of a type that experts in my field would reasonably rely upon and refer to in forming their opinions.

16. I have been informed by counsel that the subject matter of this proceeding relates to the use of modulation and coding schemes in a wireless communication network.

17. I have been informed by counsel that a "person of ordinary skill in the art at the time of the inventions" (POSITA) is a hypothetical person who is presumed to be familiar with the relevant field and its literature at the time of the inventions. This hypothetical person is also a person of ordinary creativity, capable of understanding the scientific principles applicable to the pertinent field.

18. I have been informed by counsel that persons of ordinary skill in this subject matter or art would have included someone with a Master's degree in Electrical Engineering, Computer Science, Applied Mathematics, Physics or equivalent and three to five years of experience working with wireless digital communication systems including physical layer of such systems, and that additional education might compensate for less experience, and vice-versa. It is my opinion that such a person would have been actively engaged in academic research and learning through study and practice in the field, and possibly through formal instruction through the bibliographic resources relevant to his or her research. By the 2000s, such a person would have had access to a vast array of print resources, including at least the documents referenced below, as well as to a fast-changing set of online resources.

C. Library Catalog Records and Other Resources

19. Some background on MARC (Machine-Readable Cataloging) formatted records, OCLC, and *WorldCat* is helpful to understand the library catalog records discussed in this declaration. I am fully familiar with the library cataloging standard known as the MARC standard, which is an industry-wide standard method of storing and organizing library catalog

information.[1] MARC practices have been consistent since the MARC format was developed by the Library of Congress in the 1960s, and by the early 1970s became the U.S. national standard for disseminating bibliographic data. By the mid-1970s, MARC format became the international standard, and persists through the present. A MARC-compatible library is one that has a catalog consisting of individual MARC records for each of its items. The underlying MARC format (computer program) underpins the online public access catalog (OPAC) that is available to library users to locate a particular holding of a library. Today, MARC is the primary communications protocol for the transfer and storage of bibliographic metadata in libraries.[2] The MARC practices discussed below were in place during the 2000s time frame relevant to the documents referenced herein.

20. Online Computer Library Center (OCLC) is a not-for-profit worldwide consortium of libraries. Similar to MARC standards, OCLC's practices have been consistent since the 1970s through to the present. Accordingly, the OCLC practices discussed below were in place during the time frame discussed in my opinions section. OCLC was created "to establish, maintain and operate a computerized library network and to promote the evolution of library use, of libraries themselves, and of librarianship, and to provide processes and products for the

[1] The full text of the standard is available from the Library of Congress at http://www.loc.gov/marc/bibliographic/.

[2] Almost every major library in the world uses a catalog that is MARC-compatible. *See, e.g.*, Library of Congress, *MARC Frequently Asked Questions (FAQ)*, https://www.loc.gov/marc/faq.html (last visited Jan. 24, 2018) ("MARC is the acronym for MAchine-Readable Cataloging. It defines a data format that emerged from a Library of Congress-led initiative that began nearly forty years ago. It provides the mechanism by which computers exchange, use, and interpret bibliographic information, and its data elements make up the foundation of most library catalogs used today."). MARC is the ANSI/NISO Z39.2-1994 (reaffirmed 2009) standard for Information Interchange Format.

benefit of library users and libraries, including such objectives as increasing availability of library resources to individual library patrons and reducing the rate of rise of library per-unit costs, all for the fundamental public purpose of furthering ease of access to and use of the ever-expanding body of worldwide scientific, literary and educational knowledge and information."[3] Among other services, OCLC and its members are responsible for maintaining the *WorldCat* database (http://www.worldcat.org/), used by libraries throughout the world.

21. Libraries worldwide use the machine-readable MARC format for catalog records. MARC-formatted records include a variety of subject access points based on the content of the document being cataloged. A MARC record for a particular work comprises several fields, each of which contains specific data about the work. Each field is identified by a standardized, unique, three-digit code corresponding to the type of data that follows. For example, a work's title is recorded in field 245, the primary author of the work is recorded in field 100, a work's International Standard Book Number ("ISBN") is recorded in field 020, and the work's Library of Congress call number (assigned by Library of Congress) is recorded in field 050. Some fields can contain subfields, which are indicated by letters. For example, a work's publication date is recorded in field 260 under the subfield "c."

22. The MARC Field 040, subfield "a," identifies the library or other entity that created the catalog record in the MARC format. The MARC Field 008 identifies the date when this first MARC record was created. The MARC Field 005 identifies the most recent catalog

---

[3] OCLC Online Computer Library Center, Inc., *Amended Articles of Incorporation of OCLC Online Computer Library Center, Inc.*, Third Article (OCLC, Dublin, Ohio) Revised November 30, 2016, https://www.oclc.org/content/dam/oclc/membership/articles-of-incorporation.pdf.

activity including location assignment, by the holding library, that is, the library which owns the book and is identified in the OPAC.

23. MARC records also include several fields that include subject matter classification information. An overview of MARC record fields is available through the Library of Congress at http://www.loc.gov/marc/bibliographic/. For example, 6XX fields are termed "Subject Access Fields."[4] Among these, for example, is the 650 field; this is the "Subject Added Entry – Topical Term" field. *See* http://www.loc.gov/marc/bibliographic/bd650.html. The 650 field is a "[s]ubject added entry in which the entry element is a topical term." *Id.* The 650 field entries "are assigned to a bibliographic record to provide access according to generally accepted thesaurus-building rules (e.g., *Library of Congress Subject Headings* (LCSH), *Medical Subject Headings* (MeSH))." *Id.* Thus, a researcher can easily discover material relevant to a topic of interest with a search using the terms employed in the MARC Fields 6XX.

24. Further, MARC records include call numbers, which themselves include a classification number. For example, the 050 field is dedicated as the "Library of Congress Call Number"[5] as assigned by the Library of Congress. A defined portion of the Library of Congress Call Number is the classification number, and "source of the classification number is *Library of Congress Classification* and the *LC Classification-Additions and Changes*." *Id.* Thus, included in the 050 field is a subject matter classification. As an example: TK5105.59 indicates books on computer networks – security measures. When a local library assigns a classification number, most often a Library of Congress derived classification number created

---

[4] *See* http://www.loc.gov/marc/bibliographic/bd6xx.html.
[5] *See* http://www.loc.gov/marc/bibliographic/bd050.html.

by a local library cataloger or it could be a Dewey Decimal classification number for example, 005.8, computer networks – security measures, it appears in the 090 field. In either scenario, the MARC record includes a classification number in the call number field that represents a subject matter classification.

25. The 9XX fields, which are not part of the standard MARC 21 format,[6] were defined by OCLC for use by the Library of Congress, processing or holding notes for a local library, and for internal OCLC use. For example, the 955 field is reserved for use by the Library of Congress to track the progress of a new acquisition from the time it is submitted for Cataloging in Publication (CIP) review until it is published and fully cataloged and publicly available for use within the Library of Congress. Fields 901-907, 910, and 945-949 have been defined by OCLC for local use and will pass OCLC validation. Fields 905, 910, 980 etc., are often used by an individual library for internal processing purposes, for example the date of receipt or cataloging and/or the initials of the cataloger.

26. *WorldCat* is the world's largest public online catalog, maintained by the OCLC, a not-for-profit international library consortium, and built with the records created by the thousands of libraries that are members of OCLC. OCLC provides bibliographic and abstract information to the public based on MARC-compliant records through its OCLC *WorldCat* database. *WorldCat* requires no knowledge of MARC tags and code and does not require a login or password. *WorldCat* is easily accessible through the World Wide Web to all who wish to search it; there are no restrictions to be a member of a particular community, etc. The date a given catalog record was created (corresponding to the MARC Field 008) appears in some detailed *WorldCat* records as the Date of Entry but not necessarily all. *WorldCat* does not

[6] *See* https://www.oclc.org/bibformats/en/9xx.html.

provide a view of the underlying MARC format for a specific *WorldCat* record. In order to see the underlying MARC format the researcher must locate the book in a holding library listed among those shown in *WorldCat*, and search the online public catalog (OPAC) of a holding library. Whereas *WorldCat* records are widely available, the availability of library specific MARC formatted records varies from library to library. When a specific library wishes to make the underlying MARC format available there will be a link from the library's OPAC display, often identified as a MARC record or librarian/staff view.

27. When a MARC record is created by the Library of Congress or an OCLC member institution, the date of creation for that record is automatically populated in the fixed field (008), with characters 00 through 05 in year, month, day format (YYMMDD).[7] Therefore, the MARC record creation date reflects the date on which the publication associated with the record was first cataloged. Thereafter, the local library's computer system may automatically update the date in field 005 every time the library updates the MARC record (*e.g.*, to reflect that an item has been moved to a different shelving location within the library, or a reload of the bibliographic data with the introduction of a new library management system that creates and manages the OPAC).

D. Monograph Publications

28. Monograph publications are written on a single topic, presented at length and distinguished from an article and include books, dissertations, and technical reports. A library typically creates a catalog record when the monograph is acquired by the library. First, it will search OCLC to determine if a record has already been created by the Library of Congress or

[7] Some of the newer library catalog systems also include hour, minute, second (HHMMSS).

another OCLC institution. If a record is found in OCLC, the record is downloaded into the library's LMS (Library Management System) that includes typically the OPAC (online public access catalog by which researchers locate a particular library holding in a user-friendly format), acquisitions, cataloging, and circulation integrated functions. Once the item is downloaded into the library's LMS, the library adds its identifier to the OCLC database so when a search is completed on WorldCat, the library will be indicated as an owner of the title. Once a record is created in a Library's LMS, it is searchable and viewable through the library's OPAC, typically by author, title, and subject heading, at that library and from anywhere in the world through the internet by accessing that library's OPAC. The OPAC also connects with the circulation function of the library, which typically indicates whether the record is available, in circulation, etc., with its call number and location in a specific departmental/disciplinary library, if applicable. The OPAC not only provides immediate bibliographic access on-site, it also facilitates the interlibrary loan process, which is when one publication is loaned from one library to another.

29. ***O'Reilly Online Learning*** - O'Reilly learning provides individuals, teams, and businesses with expert-created and curated information covering all the areas that will shape our future—including artificial intelligence, operations, data, UX design, finance, leadership, and more. https://www.oreilly.com/online-learning/

30. ***Google Books*** - find a book, click on the "Buy this book" and "Borrow this book" links to see where it can be purchased as an e-book from the Google Play Store. https://books.google.com/googlebooks/about/index.html

31. ***Wisconsin TechSearch (WTS)*** – WTS is a set of services offered by the University of Wisconsin Libraries. WTS offers an array of article delivery and research services to any

individual or organization who requests the specialized skills of WTS staff in locating and retrieving information, regardless of whether the individual is affiliated with the University of Wisconsin. (https://wts.wisc.edu/).

IV. OPINION REGARDING AUTHENTICITY AND PUBLIC ACCESSIBILITY

Document A: Arunabha Ghosh, et al, *Fundamentals of LTE*. Prentice-Hall, 2011. 418 pages. ("Ghosh")

32. I have been asked to opine on a book authored by Arunabha Ghosh, et al, *Fundamentals of LTE* published by Prentice-Hall in 2011, "Ghosh". Ghosh contains in 418 pages, 10 Chapters, and an Index.

33. I have evaluated Exhibit 1007, the Ghosh reference several ways: (1) by assessing scans of a print copy of Ghosh owned by the University of Notre Dame Libraries, provided to me at my request by the Wisconsin TechSearch (WTS) on January 21, 2021 (Attachment 1-A); (2) by assessing a digital copy accessed through Purdue University Libraries (Attachment 1-B) from the *O'Reilly Online Learning*; (3) by purchasing a digital copy of Ghosh through Kindle (Attachment 1-C); and (4) accessing and assessing the OPAC and MARC records for Ghosh at the Library of Congress (Attachments 1-H and Attachment 1-I).

34. Attachment 1-A is the scan provided to me at my request from the University of Notre Dame Libraries by the Wisconsin Tech Search (WTS) on January 21, 2021. Attachment 1-A includes: Cover; title page; copyright page with handwritten call number that reads "Engin TK5103.48325.F86 2011; Contents, includes pages: ix-xvi.

35. All identifying characteristics, such as stamps and notations on Attachment 1-A are consistent with library practice and procedure that I have observed during my career as a professional librarian. I have no cause for concern about the authenticity or accuracy of these identifying attributes. In addition, Attachment 1-A was found within the custody of a research library, the University of Notre Dame Libraries, one of the most likely locations for an authentic publication to be located.

36. Attachment 1-B are screenshots from Ghosh that include: cover; title page; copyright page; and contents. This digital version was accessible to me from the *O'Reilly Online Learning* database through Purdue University Libraries, and was downloaded on January 27, 2021, due to license limitations it was not possible to download Ghosh in its entirety from *O'Reilly Online Learning*, hence the reason for screen shots, at this URL: https://learning.oreilly.com/library/view/fundamentals-of-lte/9780137033638/title.html

37. Attachment 1-C is screenshots from *Google Books*. I purchased a digital copy of Ghosh through *Google Books* on January 26, 2021. It was downloaded to my Kindle platform. I did call up the copy that I downloaded to compare the content of Ghosh purchased from *Google Books* and the copy I accessed through Purdue University Libraries from *O'Reilly Online Learning*.

38. The digital version of Ghosh is available to anyone for a fee through *Google books at:*

https://www.google.com/books/edition/_/HjxmKq5MABcC?hl=en&gbpv=1&pg=PT21&dq=Fundamentals+of+LTE+

39. To verify authenticity of Attachment 1-A, Attachment 1-B, and Attachment 1-C, I assessed the title page, copyright page and table of contents, from all three, they are identical.

Having located Ghosh in a research library, University of Notre Dame Libraries, and in a publisher data base, *O'Reilly Online Learning*, and a digital copy through *Google Books*, I can verify that Ghosh is an authentic document published by Prentice-Hall in 2011 in print and made available in digital format.

40. I conclude and affirm that Ghosh is an authentic document.

Public Accessibility

41. Attachment 1-D is the University of Notre Dame Library OPAC (online catalog) record that I downloaded on January 20, 2021. The document cataloged in this record is Ghosh as verified by author: Arunabha Ghosh; title: *Fundamentals of LTE;* publisher and publication date: Prentice Hall in 2011; and ISBN: 978-0-13-703311-9.

42. I also compared the LC Classification (call number): TK5103.48325.F86 2011 with that handwritten on the copyright pages of Attachment 1-A and it is the same on both, and on the OPAC record it indicates it is available in the "Lower Level Engineering Collection" also identified as a part of the call number. Ghosh could have been located by searching on the University of Notre Dame Libraries OPAC for the author: Arunabha Ghosh; title: *Fundamentals of LTE;* or by searching the subject heading: *Long-term Evolution (Telecommunications).*

43. As mentioned above the MARC Field 005 and 9XX often indicate the date of receipt and cataloging, depending upon the practice and procedure of the library. Attachment 1-E is a download I made on January 20, 2021 of the MARC record from the University of Notre Dame Libraries OPAC through the link: "Staff MARC View." It provides detailed information about the ordering/receipt/ cataloging/indexing of Ghosh.

44. In Attachment 1-E, the MARC 980 Field is: 20101018 (October 18, 2010) and the MARC 005 Field is: 20101202123027, i.e., December 2, 2010 (the remaining digits are check digits).

45. I contacted Diane Walker, University Librarian, University of Notre Dame on January 22, 2021, to ask for clarification on the MARC 005 and MARC 980 fields as used by the University of Notre Dame Libraries, specifically for the MARC record for Ghosh.

46. Attachment 1-F, is the email I received from Diane Walker, University Librarian of the University of Notre Dame on January 24, 2021. In her email she included an email to her from the head of Metadata Services of the University of Notre Dame in which she describes the policy and practice of the Metadata Department on the use of the MARC 005 and MARC 980 fields:

Here is a summary of what happened with this title:

10/18/2010: Title invoiced by vendor and item prepared to ship from vendor.

10/29/2010: Bibliographic record loaded in Aleph system and order record created automatically using the local 9XX MARC data. Shipment arrives in library Acquisitions sometime around this date. After which, the shipment is unpacked, displayed for a two-week subject librarian review, taken off display for final invoice processing, and sent to Cataloging for final processing (just prior to Thanksgiving, I would guess).

12/2/2010: Cataloging of book is completed and it is sent to Labelling and delivery to the Engineering Library. This date corresponds to the MARC 005.

47. From Attachment 1-E and verified in Attachment 1-F, the date in the MARC 005 Field is the final cataloging of Ghosh at the University of Notre Dame Libraries, December 2,

2010. Consistent with library practice and procedures I witnessed during my professional work as a librarian, Ghosh would have been available for public access within one week to ten days after it finished processing (labeling and transfer to the shelf) at the University of Notre Dame Libraries in the Engineering Collection on December 12, 2010.

48. Attachment 1-G is a download from *WorldCat* for holdings of Ghosh when searched using the geographical location of Indiana. The University of Notre Dame, Hesburgh Library was second among the 199 libraries shown as holding Ghosh worldwide.

49. Attachment 1-G shows that Ghosh is the document associated with this *WorldCat* entry, as verified by the author: Arunabha Ghosh, with the title: *Fundamentals of LTE;* and ISBN: 978-0-13-703311-9.

50. Ghosh could have been located by searching for the editors – Arunabha Ghosh; title: *Fundamentals of LTE;* or by searching the subject heading: *Long-term Evolution (Telecommunications*

51. The search discussed above could have been performed anywhere in the world by anyone who accessed *WorldCat* and its predecessor database through an OCLC member,

52. Attachment 1-H is a true and correct copy of the Library of Congress OPAC (online catalog) record and Attachment 1-I is the true and correct copy of the MARC record for Ghosh. Typically, I would have had scans of the copy of the print copy of Ghosh owned by the Library of Congress, however, due to the pandemic, the Library of Congress has been and remains closed at the time of this declaration and, hence, I am unable to obtain scans of Ghosh owned by the Library of Congress. Therefore, I will draw upon the OPAC and MARC records to verify the ownership, date of receipt and availability of Ghosh at the Library of Congress. As described above, the Library of Congress reserved the MARC 955 field to describe the receipt,

cataloging and processing of items added to the collections of the Library of Congress. The MARC record is a record created and maintained by federal employees of the Library of Congress.

53. In Attachment 1-H the document cataloged in this record is *Fundamentals of LTE* as verified by the fields listing author: Arunabha Ghosh; title: *Fundamentals of LTE*; publisher and publication date: Prentice Hall in 2011 and ISBN: 978-0-13-703311-9.

54. Ghosh could have been located in the Library of Congress OPAC by searching for the author: Arunabha Ghosh; title: *Fundamentals of LTE*; or by searching the subject heading: *Long-Term Evolution (Telecommunications).*

55. Attachment 1-I is the MARC record I downloaded from the Library of Congress OPAC. The MARC format provides information about the processing of Ghosh by the Library of Congress. As mentioned above, the 9XX field in the MARC format is allocated to local libraries to enter information specific to that library. The Library of Congress has reserved the 955 field to indicates date of receipt of the published book and cataloging.

The MARC 955 field in this record reads –

955__ |**b** rc02 2011-02-15 z-processor |**i** rc02 2011-02-15 to BCCD |**t** rf18 2011-04-14 copy 2 added.

56. The 955 record indicates the processing Ghosh began 2011-02-15 (February 15, 2011) and finished processing on 2011-02-15 (February 15, 2011). The physical copy of Ghosh at the Library of Congress, consistent with library practice and procedures I witnessed during my professional work as a librarian, Ghosh would have been available for public access within one week to ten days after it finished processing (labeling and transfer to the shelf) on

2011-02-15 (February 15, 2011), therefore, Ghosh would have been available at the Library of Congress no later than February 25, 2011.

57. Ghosh was then accessible through Library of Congress OPAC. Once Ghosh was entered into the general collection of the Library of Congress, members of the public could access the book by having it brought to either the Jefferson or Adams Reading Rooms. The collections of the Library of Congress are searchable by subject matter, author, or title such that a skilled researcher could find works in which they were interested. For example, a member of the public could have located a copy of Ghosh by searching for the authors: Arunabha Ghosh, et al; title: *Fundamentals of LTE* and for the subject field *Long-Term Evolution (Telecommunications)* in MARC field 650 in the Library of Congress OPAC. Members of the public could read, study, and make notes about a selected work in the Reading Rooms. Further, members of the public were permitted to make photocopies of portions of the works while in the Reading Rooms. Accordingly, a copy of Ghosh was accessible to the general public when it was available at the Library of Congress.

58. Attachment 1-J, a *WorldCat* entry for Ghosh. I obtained by completing a search on *WorldCat* on January 28, 2021. When I searched *WorldCat* for holdings of Ghosh in the District of Columbia, Library of Congress was second on the list among the 199 libraries shown as holding Ghosh worldwide.

59. Attachment 1-J shows that Ghosh is the document associated with this *WorldCat* entry, as verified by the authors: by Arunabha Ghosh, et al, with the title *Fundamentals of LTE* published by Prentice-Hall in 2011; and ISBN: 978-0-13-703311-9.

60. Ghosh could have been located by searching for the author – Arunabha Ghosh, et al, with the title *Fundamentals of LTE*; or by searching the subject heading: *Long-term Evolution (Telecommunications).*

61. The search discussed above could have been performed anywhere in the world by anyone who accessed *WorldCat* and its predecessor database through an OCLC member,

Conclusion

62. I conclude that Ghosh is an authentic document and would have been publicly accessible through the University of Notre Dame Libraries no later than December 12, 2010, and the Library of Congress no later than February 25, 2011.

Document B: Harri Holma and Antti Toskala, editors. *LTE for UMTS. Evolution to LTE-Advanced. 2d edition.* Wiley, 2011. Pages 543. ("Holma")

Authentication

63. I have been asked to opine on a book edited by Harri Holma and Antti Toskala titled *LTE for UMTS. Evolution to LTE-Advanced. 2d edition*, published by Wiley in 2011. Holma contains in 543 pages, 13 Chapters, and an Index.

64. I have evaluated the Holma reference several ways: (1) by assessing Holma, Exhibit 1013, provided to me by counsel; (2) by downloading Holma from the *Wiley Online Library* through the Purdue University Libraries; and (3) by accessing and reviewing the OPAC and MARC records for Holma at the Library of Congress.

65. Attachment 2-A is a download of Holma that includes the entire book. This digital version was accessible to me from the *Wiley Online Library* through Purdue University

Libraries, and was downloaded on February 5, 2021 at this URL: https://onlinelibrary-wiley-com.ezproxy.lib.purdue.edu/doi/pdf/10.1002/9781119992943

66. The digital version of Holma is available to anyone for a fee through the *Wiley Online Library* at:
https://www.google.com/books/edition/LTE_for_UMTS/X9XwEOxYnAkC?hl=en&gbpv=1
&dq=LTE+for+UMTS.+Evolution+to+LTE-Advanced.&pg=PP11&printsec=frontcover

67. Attachment 2-B is a true and correct copy of the Library of Congress OPAC (online catalog). Typically, I would have had scans of the print copy of Holma owned by the Library of Congress, however, due to the pandemic, the Library of Congress has been and remains closed at the time of this declaration and hence, I am unable to obtain scans of Holma owned by the Library of Congress. Therefore, I will draw upon the OPAC and MARC records to verify the ownership, date of receipt and availability of Holma at the Library of Congress.

68. In Attachment 2-B the document cataloged in this record is as verified *LTE for UMTS. Evolution to LTE-Advanced. 2d edition.* by the fields listing main title: *LTE for UMTS. Evolution to LTE-Advanced. 2d edition.*; publisher and publication date: John Wiley in 2011 and ISBN: 9780470660003.

69. Holma could have been located in the Library of Congress OPAC by searching for the editors: Harri Holma and Antti Toskala; title: *LTE for UMTS. Evolution to LTE-Advanced. 2d edition*; or by searching the subject headings: *Universal Mobile Telecommunication Systems; Wireless Communication Systems- Standards; Mobile Communication Systems – Standards; Global System for Mobile Communications and/or Long-Term Evolution (Telecommunications).*

70. To verify authenticity of Attachment 2-A and Attachment 2-B, I assessed the title page, copyright page and table of contents, from both, they are identical. Having located Holma in a research library, the Library of Congress, and in a publisher data base, *Wiley Online Library*, I can verify that Holma is an authentic document published by Wiley in 2011 in print and also made available in digital format.

71. I conclude and affirm that Holma is an authentic document.

i. Public Accessibility

72. Attachment 2-C is the MARC record I downloaded from the Library of Congress OPAC. The MARC format provides information about the processing of Holma by the Library of Congress. As mentioned above, the 9XX field in the MARC format is allocated to local libraries to enter information specific to that library. The Library of Congress has reserved the 955 field to indicate date of receipt of the published book and cataloging/indexing. The MARC record is a record created and maintained by Federal employees of the Library of Congress.

73. The MARC 955 field in this record reads –

74. 955__ |**b** rg11 2010-11-29 (telework) |**c** rg11 2010-11-29 ONIX (telework) to Gen Sci/Tech (STM) |**d** xh12 2010-12-29 |**w** rd11 2010-12-29 |**a** xe07 2011-06-02 1 copy rec'd., to CIP ver. |**f** rf08 2011-06-21 to BCCD

75. The 955 record indicates the processing Holma began 2010-11-29 (November 29, 2010) and finished processing on 2011-06-21 (June 21, 2011). The physical copy of Holma at the Library of Congress would have been available for public access within one week to ten days, consistent with library practice and procedures I witnessed during my professional work as a librarian, after it finished processing (labeling and transfer to the shelf) on June 21, 2011,

therefore, Holma would have been available at the Library of Congress no later than July 1, 2011.

76. Holma was then accessible through Library of Congress OPAC. Once Holma was entered into the general collection of the Library of Congress, members of the public could access the book by having it brought to either the Jefferson or Adams Reading Rooms. The collections of the Library of Congress are searchable by subject matter, author, or title such that a skilled researcher could find works in which they were interested. For example, a member of the public could have located a copy of Holma by searching for the editors: Harri Holma and Antti Toskala; title;

77. *LTE for UMTS. Evolution to LTE-Advanced*; **or** searching the subject headings: Universal Mobile Telecommunication Systems; Wireless Communication Systems- Standards; Mobile Communication Systems – Standards; Global System for Mobile Communications and/or Long-Term Evolution (Telecommunications).

75. Members of the public could read, study, and make notes about a selected work in the Reading Rooms. Further, members of the public were permitted to make photocopies of portions of the works while in the Reading Rooms. Accordingly, a copy of Holma was accessible to the general public when it was available at the Library of Congress.

76. Attachment 2-D, the WorldCat entry for Holma, I obtained by completing a search on WorldCat on February 5, 2021. Attachment 2-D shows that Holma is the document associated with this *WorldCat* entry, as verified by the editors: Harri Holma and Antti Toskala, with the title: *LTE for UMTS. Evolution to*

77. *LTE-Advanced;* and by ISBN: 9780470660003.

78. When I searched WorldCat for holdings of Holma in the District of Columbia, Library of Congress was sixth on the among the 690 libraries shown as holding Holma worldwide.

79. The search discussed above could have been performed anywhere in the world by anyone who accessed WorldCat and its predecessor database through an OCLC member,

Conclusion

80. I conclude that Holma is an authentic document and would have been publicly accessible through the Library of Congress no later than July 1, 2011.

Document C: Stefania Sesia, Issam Toufik, and Matthew Baker, editors. *LTE: The UMTS Long Term Evolution from Theory to Practice*. 2d edition. Wiley, 2011. ("Sesia")

Authentication

81. I have been asked to opine on a book edited by Stefania Sesia, Issam Toufik, and Matthew Baker titled. *LTE: The UMTS Long Term Evolution from Theory to Practice. 2d edition.* published by Wiley in 2011. Sesia contains in 752 pages, 32 Chapters, and an Index.

82. I have evaluated the Sesia reference several ways: (1) by assessing Sesia, Exhibit 1008, provided to me by counsel; (2) by downloading Sesia from the *Wiley Online Library* through the Purdue University Libraries; and (3) by accessing and reviewing the OPAC and MARC records for Sesia at the Library of Congress.

Attachment 3-A is a download of Holma that includes the entire book. This digital version was accessible to me from the *Wiley Online Library* through Purdue University Libraries, and was downloaded on February 5, 2021 at this URL: https://onlinelibrary-wiley-com.ezproxy.lib.purdue.edu/doi/pdf/10.1002/9780470978504

The digital version of Holma is available to anyone for a fee through the *Wiley Online Library* at:
https://www.google.com/books/edition/LTE_The_UMTS_Long_Term_Evolution/g0lficnQ6eUC?hl=en&gbpv=1&dq=LTE+-+the+UMTS+long+term+evolution+%5Belectronic+resource%5D+:+from+theory+to+practice&pg=PR21&printsec=frontcover

83. Attachment 3-B is a true and correct copy of the Library of Congress OPAC (online catalog). Typically, I would have had scans of the print copy of Holma owned by the Library of Congress, however, due to the pandemic, the Library of Congress has been and remains closed at the time of this declaration and hence, I am unable to obtain scans of Sesia owned by the Library of Congress. Therefore, I will draw upon the OPAC and MARC records to verify the ownership, date of receipt and availability of Sesia at the Library of Congress.

84. In Attachment 3-B the document cataloged in this record is as verified by the fields listing under personal name: Sesia, Stefania; title: *LTE: The UMTS Long Term Evolution from Theory to Practice. 2d edition.* published by Wiley in 2011 and ISBN: 9780470660256.

85. Sesia could have been located in the Library of Congress OPAC by searching for the editors: Stefania Sesia, Issam Toufik, and Matthew Baker; title:: . *LTE: The UMTS Long Term Evolution from Theory to Practice* and/or by the following subject headings*: Universal Mobile Telecommunication Systems; and/or Long-Term Evolution (Telecommunications).*

86. To verify authenticity of Attachment 3-A and Attachment 3-B, I assessed the title page, copyright page and table of contents, from both, they are identical. Having located Sesia in a research library, the Library of Congress, and in a publisher data base, *Wiley Online Library*, I can verify that Sesia is an authentic document published by Wiley in 2011 in print and also made available in digital format.

87. I conclude and affirm that Sesia is an authentic document.

Public Accessibility

88. Attachment 3-C is the MARC record I downloaded from the Library of Congress OPAC. The MARC format provides information about the processing of Sesia by the Library of Congress. As mentioned above, the 9XX field in the MARC format is allocated to local libraries to enter information specific to that library. The Library of Congress has reserved the 955 field to indicate date of receipt of the published book and cataloging/indexing. The MARC record is a record created and maintained by Federal employees of the Library of Congress.

89. The MARC 955 field in this record reads –

955__ |**b** xj12 2010-09-14 |**c** xj12 2010-09-14 ONIX (telework) to STM |**w** rd11 2010-10-19 |**a** xn02 2011-11-21 2 copies rec'd., to CIP ver. |**f** xj16 2012-04-10 copy 1 and 2 to BCCD

90. The 955 record indicates the processing Holma began 2010-09-14 (September 14, 2010) and finished cataloging/processing on 2012-04-10 (April 4, 2012). The physical copy of Sesia at the Library of Congress would have been available for public access within one week to ten days, consistent with library practice and procedures I witnessed during my professional work as a librarian, after it finished processing (labeling and transfer to the shelf)

on April 4, 2012, therefore, Sesia would have been available at the Library of Congress no later than April 14, 2012.

91. Sesia was then accessible through Library of Congress OPAC. Once Sesia was entered into the general collection of the Library of Congress, members of the public could access the book by having it brought to either the Jefferson or Adams Reading Rooms. The collections of the Library of Congress are searchable by subject matter, author, or title such that a skilled researcher could find works in which they were interested. For example, a member of the public could have located a copy of Sesia by searching for the editors: Stefania Sesia, Issam Toufik, and Matthew Baker; title: *LTE: The UMTS Long Term Evolution from Theory to Practice* and/or by the following subject headings*: Universal Mobile Telecommunication Systems; and/or Long-Term Evolution (Telecommunications).*

92. Members of the public could read, study, and make notes about a selected work in the Reading Rooms. Further, members of the public were permitted to make photocopies of portions of the works while in the Reading Rooms. Accordingly, a copy of Sesia was accessible to the general public when it was available at the Library of Congress.

93. Attachment 3-D, the WorldCat entry for Sesia, I obtained by completing a search on WorldCat on February 5, 2021. Attachment 3 -D shows that Sesia is the document associated with this *WorldCat* entry, as verified by the editors: Stefania Sesia, Issam Toufik, and Matthew Baker; title: *LTE: The UMTS Long Term Evolution from Theory to Practice* and by ISBN*:* 9780470660256

94. When I searched WorldCat for holdings of Sesia in the District of Columbia, the Library of Congress was sixth on the among the 770 libraries shown as holding Sesia worldwide.

95. The search discussed above could have been performed anywhere in the world by anyone who accessed WorldCat and its predecessor database through an OCLC member,

Conclusion

96. I conclude that Sesia is an authentic document and would have been publicly accessible through the Library of Congress no later than April 14, 2012.

AVAILABILITY FOR CROSS-EXAMINATION

97. In signing this Declaration, I recognize that this Declaration will be filed as evidence in a contested case before the Patent Trial and Appeal Board of the U.S. Patent and Trademark Office. I also recognize that I may be subject to cross-examination in the case and that cross-examination will take place within the United States. If cross-examination is required of me, I will appear for cross-examination within the United States during the time allotted for cross-examination.

V. RIGHT TO SUPPLEMENT

98. I reserve the right to supplement my opinions in the future to respond to any arguments that the Patent Owner raises and to take into account new information as it becomes available to me.

VI. SIGNATURE

99. I declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code.

100. I declare under penalty of perjury that the foregoing is true and correct.

Dated: February 5, 2021

Dr. James L. Mullins

Appendix A

JAMES L. MULLINS, PhD

Prior Art Documentation Librarian Services, LLC

106 Berrow, Williamsburg, VA 23188

jlmullins@priorartdoclib.com

ph. 765 479 4956

Prior Art Documentation Librarian Services, LLC. (PADLS). Founded January 2018. As of January, 2021, 87 declarations have been completed for 32 law firms; four depositions scheduled, three cancelled a few days prior, and one was held, and was successful for my client.

Library Experience:

2018-present **Dean Emeritus of Libraries and Esther Ellis Norton Professor Emeritus**

2011 - 2017 **Dean of Libraries & Esther Ellis Norton Professor**

2004 - 2011 **Dean of Libraries & Professor, Purdue University, West Lafayette, IN**

2000-2004 **Assistant/Associate Director for Administration, MIT Libraries, Massachusetts Institute of Technology, Cambridge, MA.**

1996-2000 **University Librarian & Director, Falvey Memorial Library. Villanova University, Villanova, PA.**

1978-1996 **Director of Library Services, Indiana University South Bend.**

1974-1978 **Associate Librarian, Indiana University Bloomington, School of Law.**

1973-1974 **Instructor/Catalog Librarian. Georgia Southern College (now University)**.

Teaching Experience:

1977-1996 **Associate Professor (part-time), School of Library and Information Science, Indiana University. Subjects taught: Cataloging, Management, and Academic Librarianship.**

Education:

The University of Iowa. Honors Bachelor of Arts in History, Religion and Political Science.

The University of Iowa. Master of Arts in Library Science.

Indiana University. Doctor of Philosophy. Concentration: Academic Library Administration. Emphasis: Law Librarianship.

Awards and Recognition:

2017 Wilmeth Active Learning Center/Library of Engineering and Science, Grand Reading Room, was announced by President Mitch Daniels, Purdue University, that it would be re-named the James L. Mullins Reading Room to honor his leadership and reputation in the academic library profession. September 2017. Portrait unveiled December 2017.

2017 Distinguished Alumnus Award by the School of Informatics and Computing, Indiana University, Bloomington. Given June 25, 2017.

2016 Hugh C. Atkinson Memorial Award, jointly sponsored by the four divisions of the American Library Association (ALA), June 27, 2016.

2015 ACRL Excellence in University Libraries Award, April 23, 2015.

Named Esther Ellis Norton Professor of Library Science by Purdue Trustees, December 11, 2011.

International Review Panel to evaluate the University of Pretoria Library, February 20 – 24, 2011. Pretoria, South Africa.

Publications: (selected)

A Purdue Icon: creation, life, and legacy, edited by James L. Mullins, Founder's Series, Purdue University Press, 138pp., August 2017.

"The policy and institutional framework." In *Research Data Management, Practical Strategies for Information Professionals,* edited by Ray, J M. Purdue University Press, pp.25-44, 2014.

"DataCite: linking research to data sets and content." In Benson, P and Silver, S. *What Editors Want: An Author's Guide to Scientific Journal Publishing*. University of Chicago Press, pp. 21-23, December 2012.

"Library Publishing Services: Strategies for Success," with R. Crow, O. Ivins, A. Mower, C. Murray-Rust, J. Ogburn, D Nesdill, M. Newton, J. Speer, C. Watkinson. *Scholarly Publishing and Academic Resources Coalition (SPARC),* version 2.0, March 2012.

"The Changing Definition and Role of Collections and Services in the University Research Library." *Indiana Libraries,* Vol 31, Number 1 (2012), pp.18-24.

"Are MLS Graduates Being Prepared for the Changing and Emerging Roles that Librarians must now assume within Research Libraries?" *Journal of Library Administration.* Volume 52, Issue 1, 2012, p. 124-132

Baykoucheva, Svetla. What Do Libraries Have to Do with e-Science?: An Interview with James L. Mullins, Dean of Purdue University Libraries. Chem. Inf. Bull. [Online] 2011, 63 (1), 45-49. http://www.acscinf.org/publications/bulletin/63-1/mullins.php (accessed Mar 16, 2011).

"The Challenges of e-Science Data-set Management and Scholarly Communication for Domain Sciences and Technology: a Role for Academic Libraries and Librarians," chapter in, *The Digital Deluge: Can Libraries Cope with e-Science?"* Deanna B. Marcum and Gerald George, editors, Libraries Unlimited/Teacher Ideas Press, 2009. (a monograph publication of the combined proceedings of the KIT/CLIR proceedings).

"Bringing Librarianship to e-Science," *College and Research Libraries.* vol. 70, no. 3, May 2009, editorial.

"The Librarian's Role in e-Science" *Joho Kanri (Journal on Information Processing and Management),* Japan Science and Technology Agency (formerly Japan Information Center of Science and Technology), Tokyo, Japan. Translated into Japanese by Taeko Kato. March 2008.

The Challenge of e-Science Data-set Management to Domain Sciences and Engineering: a Role for Academic Libraries and Librarians," KIT (Kanazawa Institute of Technology)/CLIR (Council of Library and Information Resources) International Roundtable for Library and Information Science, July 5-6, 2007. Developments in e-science status quo and the challenge, The Japan Foundation, 2007.

"An Administrative Perspective," Chapter 14, *Proven Strategies for Building an Information Literacy Program*, Susan Curzon and Lynn Lampert, editors, Neal-Schuman Publishers, Inc., New York, 2007. pp. 229-237.

Library Management and Marketing in a Multicultural World, proceedings of the IFLA Management and Marketing (M&M) Section, Shanghai, China, August 16-17, 2006, edited. K.G. Saur, Munchen, Germany, June 2007. 390 pp.

Top Ten Assumptions for the Future of Academic Libraries and Librarians: a report from the ACRL Research Committee, with Frank R. Allen and Jon R. Hufford. *College & Research Libraries,* April 2007, vol.68, no.4. pp.240-241, 246.

To Stand the Test of Time: Long-term Stewardship of Digital Data Sets in Science and Engineering. A report to the National Science Foundation from the ARL Workshop on New Collaborative Relationships: the Role of Academic Libraries in the Digital Data Universe. September 26-27, 2006, Arlington, VA. p.141. http://www.arl.org/bm~doc/digdatarpt.pdf

“Enabling Interaction and Quality in a Distributed Data DRIS,” *Enabling Interaction and Quality: Beyond the Hanseatic League*. 8th International Conference on Current Research Information Systems, with D. Scott Brandt and Michael Witt. Promoted by euro CRIS. Leuven University Press, 2006. pp.55-62. Editors: Anne Garns Steine Asserson and Eduard J. Simons.

"Standards for College Libraries, the final version approved January 2000," prepared by the ACRL College Libraries Standards Committee (member), *C&RL News*, March 2000, p.175-182.

"Standards for College Libraries: a draft," prepared by the ACRL College Libraries Section, Standards Committee (member), *C&RL News*, May 1999, p. 375-381.

"Statistical Measures of Usage of Web-based Resources," *The Serials Librarian,* vol. 36, no. 1-2 (1999) p. 207-10.

"An Opportunity: Cooperation between the Library and Computer Services," in *Building Partnerships: Computing and Library Professionals.* Edited by Anne G. Lipow and Sheila D. Creth. Berkeley and San Carlos, CA, Library Solutions Press, 1995. p. 69-70.

"Faculty Status of Librarians: A Comparative Study of Two Universities in the United Kingdom and How They Compare to the Association of College and Research Libraries Standards, " in *Academic Librarianship, Past, Present, and Future: a Festschrift in Honor of David Kaser.* Englewood, Colorado; Libraries Unlimited, 1989. p. 67-78. Review in: *College & Research Libraries,* vol. 51, no. 6. November 1990, p. 573-574.

Presentations: (Representative)

“How Long the Odyssey? Transitioning the Library and Librarians to Meet the Needs and Expectations of the 21st Century University,” David Kaser Lecture, School of Informatics & Computing, Indiana University, Bloomington, IN, November 16, 2015.

Presentation at University of Cape Town, Cape Town, South Africa, August 20, 2015.

“The Challenge of Discovering Science and Technology Information,” Moderator, International Federation of Library Associations (IFLA) Science and Technological Libraries Section Program, Cape Town, South Africa, August 18, 2015.

“An Odyssey in Data Management: Purdue University,” International Federation of Library Associations (IFLA) Research Data Management: Finding Our Role – A program of the Research Data Alliance, Cape Town, South Africa, August 17, 2015.

Presentation at University of Pretoria, Pretoria, South Africa, August 11, 2015.

Co-Convener with Sarah Thomas, Harvard University, at the Harvard Purdue Symposium on Data Management, Harvard University, Cambridge, MA, June 15-18, 2015.

"Strategic Communication," panel discussion on the Director's role and perspective on library communications at Committee on Institutional Cooperation (CIC) Center for Library Initiatives (CLI) Annual Conference, University of Illinois Urbana-Champaign, May 20, 2015.

"Issues in Data Management," panel discussion moderated by Catherine Woteki, United States Undersecretary for Research, Education & Economics at 20th Agriculture Network Information Collaborative (AgNIC) Annual Meeting in the National Agricultural Library, Beltsville, MD, May 6, 2015.

"Active learning/IMPACT & the Active Learning Center at Purdue University," Florida Institute of Technology, Melbourne, FL, February 11, 2015.

"Science+art=creativity: libraries and the new collaborative thinking," panel moderator, International Federation of Library Associations (IFLA) 80th General Conference and Assembly, Lyon, France, August 19, 2014.

"Purdue University The Active Learning Center—A new concept for a library," Association of University Architects 59th Annual National Conference, University of Notre Dame, South Bend, IN, June 23, 2014.

"Big Data & Implications for Academic Libraries," keynote speaker, Greater Western Library Alliance (GWLA) Cyber-infrastructure Conference, Kansas City, MO, May 28, 2014.

"Research Infrastructure," panel moderator, Association of Research Libraries (ARL) 164th Membership Meeting, Ohio State University, Columbus, OH, May 7, 2014.

"An Eight Year Odyssey in Data Management: Purdue University," International Association of Scientific and Technological University Libraries (IATUL) 2013 Workshop Research Data Management: Finding Our Role, University of Oxford, UK, December 2013.

"Purdue University Libraries & Press: from collaboration to integration," Ithaka Sustainable Scholarship, The Evolving Digital Landscape: New Roles and Responsibilities in Higher Education, libraries as publishers, New York, New York, October 2013.

"Tsinghua and Purdue: Research Libraries for the 21st Century," Tsinghua University, Tsinghua, China, August 2013.

"Purdue Publishing Experience in the Libraries Publishing Coalition," Association of American University Presses Annual Meeting, Press-Library Coalition Panel, Boston, Massachusetts, June 21, 2013.

"Indiana University Librarians Day: Purdue University Libraries Ready for the 21st Century," Indiana University Purdue University Indianapolis (IUPUI), June 7, 2013.

"Purdue University Libraries and Open Access; CNI Project Update," Coalition for Networked Information, San Antonio, TX, April 5, 2013.

Memorial Resolution, honoring Joseph Brannon, to the Board of the Association of College & Research Libraries, Seattle, WA, January 2013.

"An overview of sustaining e-Science collaboration in an Academic Research Library—the Purdue experience," Duraspace e-Science Institute webcast, October 17, 2012.

"The Role of Libraries in Data Curation, Access, and Preservation: an International Perspective, " Panel Moderator, 78th General Conference and Assembly, International Federation of Library Associations, Helsinki, Finland, August 15, 2012.

"21st Century Libraries," moderator of First Plenary Session, International Association of Technological University Libraries 33rd Annual Conference, Singapore, June 4, 2012.

"Planning for New Buildings on Campus," panel presenter, University of Calgary Building Symposium on Designing Libraries for the 21st Century, Calgary, Alberta, Canada, May 17, 2012.

"Data Management and e-Science, the Purdue Response." Wiley-Blackwell Executive Seminar-2012, Washington, DC, March 23, 2012.

"An overview of Sustaining e-Science Collaboration in Academic Research Libraries and the Purdue Experience." Leadership & Career Development Program Institute, Association of Research Libraries (ARL). Houston, TX, March 21, 2012.

"An overview of Data Activities at Purdue University in response to Data Management Requirements." Coalition for Academic Scientific Computation (CASC). Arlington, VA, September 8, 2011.

"Getting on Track with Tenure," Association of College and Research Libraries (ACRL) Research Program Committee. Washington, DC, June 26, 2011.

"Integration of the Press and Libraries Collaboration to Promote Scholarly Communication," Association of Library Collections & Technical Services (ALCTS) Scholarly Communication Interest Group – American Library Association, New Orleans, Louisiana, June 25, 2011.

“Cooperation for improving access to scholarly communication,” with N. Lossau (Germany), C. Mazurek (Poland), J. Stokker (Australia), panel moderator and presenter, Second Plenary Session, International Association of Scientific and Technological University Libraries (IATUL) 32nd Conference 2011, Warsaw, Poland. May 29-June 2, 2011.

“Riding the Wave of Data,” STM Annual Spring Conference 2011. Trailblazing & transforming scholarly publishing **2011**. Washington, D.C., April 28, 2011.

“Confronting old assumptions to assume new roles: physical and operational integration of the Press and Libraries at Purdue University,” keynote speaker, 2011 BioOne Publishers & Partners Meeting. Washington, D. C., April 22, 2011.

“Are MLS Graduates Being Prepared for the Changing and Emerging Roles that Librarians must now assume within Research Libraries?” University of Oklahoma Libraries Seminar, March 4, 2011, Oklahoma City, Oklahoma.

“The Future Role of University Librarians,” the University of Cape Town, South Africa, February 25, 2011.

“New Roles for Librarians: the Application of Library Science to Scientific/Technical Research – Purdue University – a case study. International Council for Science and Technology (ICSTI); Ottawa, Canada. June 9, 2009.

“Reinventing Science Librarianship: Models for the Future,” Association of Research Libraries / Coalition for Networked Information. October 16-17th, 2008, Arlington, VA. Moderator and convener of Data Curation: Issues and Challenges.

“Practical Implementation and Opportunities Created at Purdue University,” African Digital Curation Conference, Pretoria, South Africa, (live video transmission), February 12, 2008.

Keynote speaker. “*Scholarly Communication & Academe: The Winter of Our Discontent,”* XXVII Charleston Conference on Issues in Book and Serial Acquisition, Charleston, South Carolina. November 8, 2007.

Keynote speaker. “*Enabling Access to Scientific & Technical Data-sets in e-Science: a role for Library and Archival Sciences,”* Greater Western Library Alliance (GWLA), Tucson, Arizona. September 17, 2007. A meeting of library directors and vice presidents for research of member institutions.

“*The Challenge of e-Science Data-set Management to Domain Sciences and Engineering: a Role for Academic Libraries and Librarians,”* KIT (Kanazawa Institute of Technology)/CLIR (Council of

Library and Information Resources) International Roundtable for Library and Information Science, July 5-6, 2007. Invited to participate by the Deputy Librarian of Congress.

International Association of Technological University Libraries (IATUL), Stockholm, Sweden. June 8, 2007**.** Invited paper**,** *Enabling International Access to Scientific Data-sets: creation of the Distributed Data Curation Center (D2C2).*

"A New Collaboration for Librarians: The Principles of Library and Archival Sciences Applied to the Curation of Datasets," Symposium of the Libraries and the College of Engineering, University of Louisville, April 6, 2007.

"Purdue University Libraries: Through Pre-eminent Innovation and Creativity, Meeting the Challenges of the Information Age," Board of Trustees, Purdue University, February 15, 2007.

ARL Workshop on New Collaborative Relationships: The Role of Academic Libraries in the Digital Data Universe, September 26-27, 2006, Arlington, VA. Invited participant.

NARA and SDSC: A partnership. A panel before the National Science Foundation, June 27, 2006. Arlington, VA. Invited participant.

"Kaleidoscope of Scientific Literacy: fusing new connections," with Diane Rein, American Library Association, Association of College and Research Libraries, Science & Technology Section, Annual Conference, New Orleans, June 26th, 2006.

"Leadership for Learning: Building a Culture of Teaching in Academic Libraries – an administrative perspective," American Library Association, Association of College and Research Libraries, Instruction Section, Annual Conference, New Orleans, June 25th, 2006.

"Building an interdisciplinary research program in an academic library:
how the Libraries'associate dean for research makes a difference at Purdue University," International Association of Technological University Libraries (IATUL), Porto, Portugal, May 23rd, 2006.

"Enabling Interaction and Quality in a Distributed Data DRIS," *Enabling Interaction and Quality: Beyond the Hanseatic League*. 8th International Conference on Current Research Information Systems, with D. Scott Brandt and Michael Witt. Promoted by euro CRIS, Bergen, Norway, May 12th, 2006, Brandt, and Witt presented in person

"Interdisciplinary Research," with D. Scott Brandt, Coalition for Networked Information (CNI) Spring Meeting: Project Briefing, Washington, D.C., April 3rd, 2006.

"An Interview with Purdue's James Mullins," a podcast submitted by Matt Pasiewicz, on *Educause Connect,* http://connect.educause.edu/James_L_Mullins_Interview_CNI_2005

“Managing Long-Lived Digital Data-sets and their Curation: Interdisciplinary Policy Issues,” Managing Digital Assets Forum, Association of Research Libraries (ARL), Washington, D.C., October 28th, 2005.

“The Odyssey of a Librarian.” Indiana Library Federation (ILF), District 2 Meeting, South Bend, Indiana. October 4th, 2005.

"New College Library Standards," Standards Committee Presentation, ALA, Chicago, July 7, 2000.

SUNY Library Directors, Lake George, New York. “*The College Library Standards: a Tool for Assessment.”* April 5, 2000.

Tri-State College Library Association, *Finding You Have Talents You Never Knew You Had,* Penn State Great Valley, March 25, 2000.

Using Web Statistics, American Library Association, New Orleans, June 24, 1999.

Keynote speaker at the JSTOR Workshop, January 29, 30, 1999. University of Pennsylvania, Philadelphia, PA.

"The New Standards for Electronic Resources Statistics," Society of Scholarly Publishers, Washington, D.C., September 17, 1998.

"Evaluating Online Resources: Now that you've got them what do you do?," joint presenter with Chuck Hamaker, LSU, at the NASIG Conference, Boulder, Colorado. June 1998.

"What Employers Are Looking for in New Librarians?" Pennsylvania Library Association, Philadelphia. September 26, 1997.

"The Theory of Matrix Management" panel presentation of the Comparative Library Organization Committee of the Library Organization and Management Section of the Library Administration and Management Association, a division of the American Library Association, Annual Meeting, Chicago, June 24, 1990.

Professional Involvement: (summary of recent emphasis)

The focus for my professional involvement and research has moved recently toward managing massive data-sets. This has resulted in working with faculty in the sciences and technology to determine how librarians can collaborate in managing, curating, and preserving data-sets for future access and documentation. This has included various speaking opportunities as well as participation in planning with the National Science Foundation (NSF) on ways in which librarians can be integrated more completely into the funded research process. Participation in the Kanazawa Institute of Technology/Council of Library Resources Roundtable was particularly rewarding and provided new opportunities to share with international colleagues the issues surrounding data-set management. I was the champion for the creation of the Distributed Data Curation Center (D2C2) at Purdue University (http://d2c2.lib.purdue.edu/)

Throughout my career, beginning with my dissertation, I have been actively involved with assessing and evaluating libraries. In the fall of 1999, I contacted twenty-two academic library directors to determine whether the need was also felt by others. The response was overwhelmingly affirmative. This resulted in a meeting at ALA Midwinter, January 2000. A formal meeting followed at Villanova University in April 2000. As convener, I helped to form the University Libraries Group (ULG), modeled after the Oberlin Group for college libraries. The ULG is made up of university libraries that support diverse wide-ranging programs through doctoral level and have a level of support that places them in the top tier of academic institutions. A few of the member libraries, along with Villanova, are William and Mary, Wake Forest, Lehigh, Carnegie-Mellon, Tufts, Marquette, Miami of Ohio, and Southern Methodist.

In 1994 appointed to the Standards Committee, College Section, Association of College and Research Libraries. During the next six years, the Committee concentrated on changing the focus of the standards from quantitative analysis of input and output factors to emphasis on assessment of the outcome. Culmination of the work was a re-issue of the *Standards for College Libraries* in 2000. The knowledge gained through my work experience enabled me to formulate the changes needed in the standards. This work allowed for close collaboration with accrediting agencies, both professional and regional.

During this same time another focus emerged, the impact of digital resources. Through my work on the JSTOR Statistics Task Force, standards were developed on the collection of use of electronic databases. This Standard was later adopted in 1998 by the International Consortium of Library Consortia (ICOLC).

In 2002, the American Library Association appointed me to serve as the liaison to the Marketing and Management Section of the International Federation of Library Associations (IFLA).

Professional Service: (representative list)

Nominations Committee, Association of Research Libraries (ARL), 2016.

Steering Committee, Scholarly Publishing and Academic Resources Coalition (SPARC), 2016 – 2017.

"Excellence in Library Services," Chair, Review Team, University of Hong Kong, Hong Kong, August 24-27, 2015.

Chair, Management Advisory Board, 2015-2017; Member, Scientific Advisory Board, arXiv, Cornell University, 1/1/2013 – present.

Advisory Board for the Wayne State University School of Library and Information Science, July 2012 – present.

Advisory Board for Microsoft Academic Search, 2012 – 2015. Redmond, WA.

Transforming Research Libraries, a Strategic Direction Steering Committee of the Association of Research Libraries (ARL), 2012-2015.

Science and Technology section, representing ARL, International Federation of Library Associations (IFLA), Chair, 2013 – 2017; Member, 2011 to present.

Member of University of Pretoria, South Africa, Library Review Committee. August 2013.

Co-chair, Local Arrangements Planning Committee for 2013 Conference, Association of College and Research Libraries (ACRL), a division of the American Library Association (ALA).

Association of Research Libraries Leadership & Career Development Program Mentor, 2011-2017.

e-Science Task Force, Association of Research Libraries. July 2006 – present. Chair, October 2011 – October 2012.

Board of Directors, International Association of Technological University Libraries (IATUL). January 2008 – December 2014.

Midwest Collaborative for Library Services (MCLS); Board Member, October 2010 – December 2012.

Chair, Library Directors, Committee on Institutional Cooperation (CIC), July 2010 – June 2012.

Board of Directors, Association of Research Libraries (ARL); October 2008 – October 2011.

Scholarly Communication Steering Committee, Association of Research Libraries (ARL)
2008-2011.

Editorial Board, *College and Research Libraries*, Association of College and Research Libraries, American Library Association. January 2008 – December 2014.

Chair, Organizing Committee for IATUL Conference 2010, June 21-24, 2010, Purdue University, West Lafayette, Indiana/Chicago, Illinois.

Conference Planning Committee for National Conference of the Association of College and Research Libraries, 2009, Seattle, Washington.

Research Committee, Association of College and Research Libraries, ACRL, division of ALA. 2002-2007, chair, 2005-2007.

Association of Research Libraries, Search and Screen Committee, Executive Director. March – January 2008.

Center for Research Libraries, Board of Directors. April 2006 – April 2012.

Academic Libraries of Indiana, Board of Directors, 2004 – present. Vice-president, 2005-2007. President, 2007- 2009.

ALA Representative to the International Federation of Library Associations (IFLA), Marketing and Management (M&M) Section, initial term 2003-2007, re-appointed for second term, 2007-2011.
Invited to represent Research Libraries at the ACRL/3M Wonewok Retreat to assess Marketing of Academic Libraries, October 2002.
Hugh A. Atkinson Award Committee, LAMA Representative, ALA, 2001-2005.
Program Committee, Library Administrators and Management Association (LAMA), a division of ALA. 1996-2001.
ACRL, Standards and Accreditation Committee, a division of ALA. Liaison to RBMS Section of ACRL. 1997-2002.
Elected to the Executive Committee of LAMA, LOMS, a division of the American Library Association, 1998-2000. Nominated as Chair/Elect for 2003 – 2005.
Columbia University Press Advisory Committee. 1996 - 2000.
LITA/LAMA Conference Evaluation Committee, Pittsburgh, Pennsylvania, October 1996.
"New Learning Communities," Coalition for Networked Information, Indianapolis. November 19-21, 1995. Facilitator for invitational, national conference committed to developing collaborative learning and teaching techniques, involving librarians.
Planning Committee-Evaluation. LITA/LAMA 1996 Conference, Pittsburgh. This first conference, to be held jointly between two divisions of ALA, will focus on new technologies within libraries.
Indiana Cooperative Library Services Authority (InCoLSA), elected to Executive Committee, April 1991, served as President in 1993-94. InCoLSA is a statewide network of academic, public, school, and special libraries that supports library cooperation for cataloging, interlibrary loan, collection development and application of new technologies.
Governor's Conference on Libraries and Information Services. Served on Planning Committee, Academic Libraries Representative, appointed by the Governor to represent academic libraries in Indiana, Chair, Finance Committee, April 1989-July 1991.
Indiana Library Endowment Foundation Board, 1984-92. Charter Member, 1984, President, 1988-1992. 2004-2005.

University Service: (Summary)

Served on search and screen committees for senior positions including chancellor, dean, and directors; most recently I have been asked to serve on the search committee for the provost of Purdue University. At MIT service included the Library Council & appointment to the Administrative Council by President

Vest, 2001-2003 & Member of the Faculty Committee on the Library System. At Purdue appointed by the President to the Search Committee for the Provost, October 2007 to May 2008; member of the Capital Projects Committee, and IT Operational Oversight Committee as senior academic dean, 2008-2014.

Global Council, Global Policy Institute, 2012 – 2016.

Academic Program Excellence and Rankings (APER) project team, 2014.

Representative of the Academic Deans on the Re-engineering Business Operations, Purdue University, 2016 –

Academic Deans Council chaired by Provost – 2004 – 2017.

University Promotion and Tenure Committee – 2006 – 2017.

"Outstanding Team Award, Electronic Reserve Project," served as Chair, recognition awarded by the President of Villanova University to one team who made an outstanding contribution to the operations of the University, selected by a committee of administrators, faculty, and staff. Awarded September 9, 1999.

Nominated for the IUSB Lundquist Award, 1995 & 1996. The Lundquist award is given to faculty who have "exhibited excellence in teaching, scholarly or artistic achievement, and diversified relevant service..."

Attachment 1-A

PRENTICE HALL

Fundamentals of LTE

Arunabha Ghosh • Jun Zhang
Jeffrey G. Andrews • Rias Muhamed

Foreword by Rajiv Laroia

Fundamentals of LTE

Arunabha Ghosh
Jun Zhang
Jeffrey G. Andrews
Rias Muhamed

PRENTICE
HALL

Upper Saddle River, NJ • Boston • Indianapolis • San Francisco
New York • Toronto • Montreal • London • Munich • Paris • Madrid
Capetown • Sydney • Tokyo • Singapore • Mexico City

Credits and permissions appear on pages 417 and 418.

The publisher offers excellent discounts on this book when ordered in quantity for bulk purchases or special sales, which may include electronic versions and/or custom covers and content particular to your business, training goals, marketing focus, and branding interests. For more information, please contact:

U.S. Corporate and Government Sales
(800) 382-3419
corpsales@pearsontechgroup.com

For sales outside the United States please contact:

International Sales
international@pearson.com

Visit us on the Web: informit.com/ph

Library of Congress Cataloging-in-Publication Data

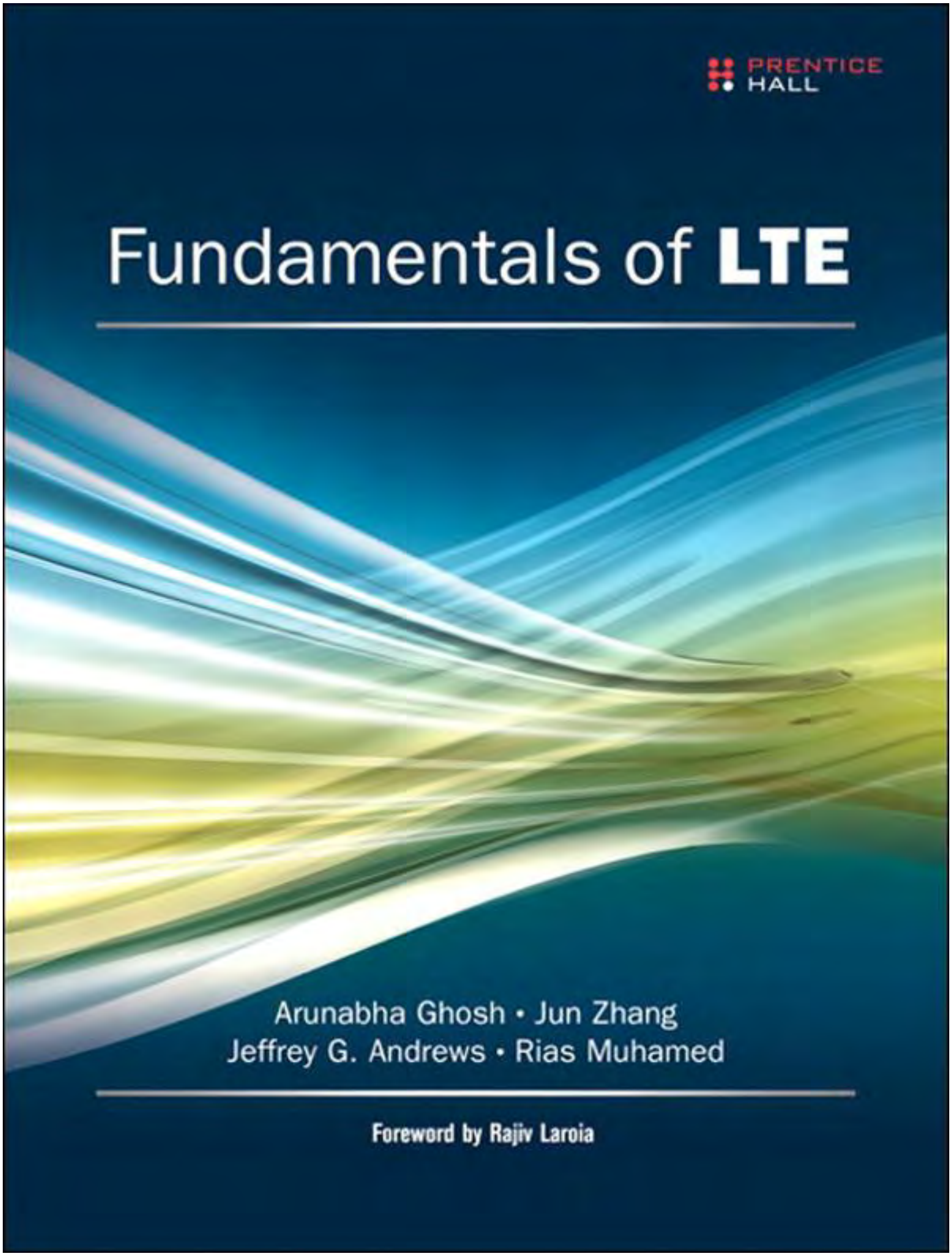
Fundamentals of LTE / Arunabha Ghosh ... [et al.].
p. cm.
Includes bibliographical references and index.
ISBN-10: 0-13-703311-7 (hardcover : alk. paper)
ISBN-13: 978-0-13-703311-9 (hardcover : alk. paper) 1. Long-Term Evolution (Telecommunications) I. Ghosh, Arunabha, 1969-
TK5103.48325.F86 2010
621.3845'6—dc22 2010021369

ISBN-13: 978-0-13-703311-9
ISBN-10: 0-13-703311-7

Text printed in the United States on recycled paper at Courier in Westford, Massachusetts.
First printing, August 2010

Contents

Attachment 1-B


PRENTICE HALL
Fundamentals of LTE
Arunabha Ghosh • Jun Zhang
Jeffrey G. Andrews • Rias Muhamed
Foreword by Rajiv Laroia

Fundamentals of LTE

ARUNABHA GHOSH
JUN ZHANG
JEFFREY G. ANDREWS
RIAS MUHAMED

PRENTICE HALL

Upper Saddle River, NJ • Boston • Indianapolis • San Francisco
New York • Toronto • Montreal • London • Munich • Paris • Madrid
Capetown • Sydney • Tokyo • Singapore • Mexico City

Credits and permissions appear on pages 417 and 418.

The publisher offers excellent discounts on this book when ordered in quantity for bulk purchases or special sales, which may include electronic versions and/or custom covers and content particular to your business, training goals, marketing focus, and branding interests. For more information, please contact:

corpsales@pearsontechgroup.com

For sales outside the United States please contact:

International Sales
international@pearson.com

Visit us on the Web: informit.com/ph

Library of Congress Cataloging-in-Publication Data

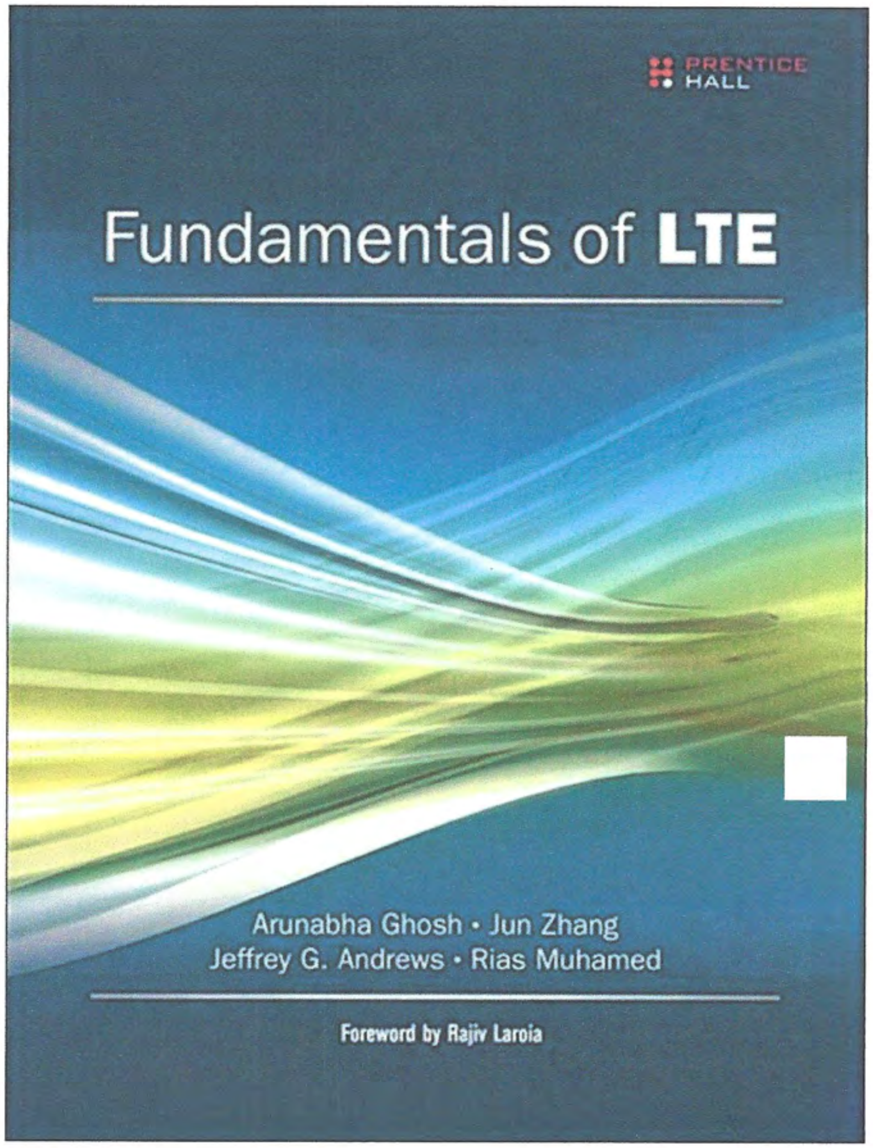
Fundamentals of LTE / Arunabha Ghosh ... [et al.].
p. cm.
Includes bibliographical references and index.
ISBN-10: 0-13-703311-7 (hardcover : alk. paper)
ISBN-13: 978-0-13-703311-9 (hardcover : alk. paper) 1. Long-Term Evolution (Telecommunications) I. Ghosh, Arunabha, 1969–
TK5103.48325.F86 2010
621.3845'6---dc22 2010021369

Contents

Attachment 1-C

Library

Search



0% · Location 1 of 10892

Library

Search

Fundamentals of LTE

Arunabha Ghosh
Jun Zhang
Jeffrey G. Andrews
Rias Muhamed

PRENTICE HALL

Upper Saddle River, NJ • Boston • Indianapolis • San Francisco
New York • Toronto • Montreal • London • Munich • Paris • Madrid
Capetown • Sydney • Tokyo • Singapore • Mexico City

Credits and permissions appear on pages 417 and 418.

The publisher offers excellent discounts on this book when ordered in quantity for bulk purchases or special sales, which may include electronic versions and/or custom covers and content particular to your business, training goals, marketing focus, and branding interests. For more information, please contact:

U.S. Corporate and Government Sales
(800) 382-3419
corpsales@pearsontechgroup.com

For sales outside the United States please contact:

International Sales
international@pearson.com

Visit us on the Web: informit.com/ph

Library of Congress Cataloging-in-Publication Data

Fundamentals of LTE / Arunabha Ghosh ... [et al.].
p. cm.

Includes bibliographical references and index.
ISBN-10: 0-13-703311-7 (hardcover : alk. paper)
ISBN-13: 978-0-13-703311-9 (hardcover : alk. paper) 1. Long-Term Evolution (Telecommunications) I. Ghosh, Arunabha, 1969–
TK5103.48325.F86 2010
621.3845'6---dc22 2010021369

Pearson Education, Inc
Rights and Contracts Department
501 Boylston Street, Suite 900
Boston, MA 02116
Fax: (617) 671-3447

ISBN-13: 978-0-13-703311-9
ISBN-10: 0-13-703311-7

Text printed in the United States on recycled paper at Courier in Westford, Massachusetts.
First printing, August 2010

Library

Search

Contents

Library

Search

Library

Search

Library

Search

1% · Location 117 of 10892

Library

Search

Library

Search

Library

Search

2% · Location 224 of 10892

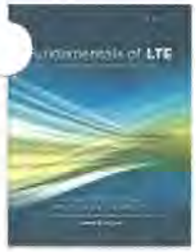
Library Search

Library

Search

Attachment 1-D

BACK TO RESULTS LIST



BOOK

Fundamentals of LTE

Arunabha Ghosh 1969-

Upper Saddle River, NJ : Prentice Hall, c2011

Export

EXPORT BIBTEX
EXPORT RIS
RW REFWORKS
MENDELEY
ENDNOTE
EASYBIB
CITATION
PERMALINK
PRINT
E-MAIL

Print Copies

LOCATIONS

Notre Dame, Hesburgh Library
Available • Lower Level Engineering Collection • TK 5103.48325 .F86 2011

Lower Level Engineering Collection TK 5103.48325 .F86 2011

Request

Request an electronic copy of an article or book chapter

Details

BACK TO RESULTS LIST

Request

Request an electronic copy of an article or book chapter

Details

Title
Fundamentals of LTE

Series
Prentice Hall communications engineering and emerging technologies series.

Contributor
Arunabha Ghosh 1969-

Published
Upper Saddle River, NJ : Prentice Hall
c2011
xxxi, 418 p. : ill. ; 24 cm..

Language
English

Subjects
Long-Term Evolution [Telecommunications]

Identifier
ISBN: 0137033117 (hardcover : alk. paper)
ISBN: 9780137033119 (hardcover : alk. paper)
OCLC : 471787103

Record ID
ndu_aleph002640010

Type
Book

Report a problem with this record

Need Help?

Chat with us now.

NO THANKS CLICK TO CHAT

More Links

Notre Dame Catalog
This item in WorldCat
This item in Google Books
Staff MARC View

Fundamentals of LTE

- **Series:** Prentice Hall communications engineering and emerging technologies series.
- **Contributor:** Arunabha Ghosh 1969-
- **Published:** Upper Saddle River, NJ : Prentice Hall
- **Published:** c2011
- **Format:** xxxi, 418 p. : ill. ; 24 cm..
- **Language:** English
- **Subjects:** Long-Term Evolution [Telecommunications]
- **Identifier:** ISBN: 0137033117 (hardcover : alk. paper); $$C ISBN
- **Record ID:** ndu_aleph002640010
- **Type:** book

Availability and location:

Hesburgh Libraries, University of Notre Dame:

- Available:
  - Notre Dame, Hesburgh Library Lower Level Engineering Collection TK 5103.48325 .F86 2011

Attachment 1-E

```
Leader 00000cam a2200301 a 4500
005    20101202123027.0
008    100609s2011    njua    b    001 0 eng
010    ##$a2010021369
015    ##$aGBB057637$2bnb
016    7#$a015545055$2Uk
020    ##$a0137033117 (hardcover : alk. paper)
020    ##$a9780137033119 (hardcover : alk. paper)
035    ##$b(ybp)40018398814
035    ##$a(OCoLC)471787103
040    ##$aDLC$cDLC$dYDX$dUKM$dBTCTA$dYDXCP$dIND
049    ##$aINDU
050    00$aTK 5103.48325$b.F86 2011
082    00$a621.3845/6$222
245    00$aFundamentals of LTE /$cArunabha Ghosh ... [et al.].
260    ##$aUpper Saddle River, NJ :$bPrentice Hall,$cc2011.
300    ##$axxxi, 418 p. :$bill. ;$c24 cm.
490    1#$aThe Prentice Hall communications engineering and
emerging technologies series
504    ##$aIncludes bibliographical references and index.
599    99$anew$d20101202
599    99$aauth$d20101202
650    #0$aLong-Term Evolution (Telecommunications)
700    1#$aGhosh, Arunabha,$d1969-
830    #0$aPrentice Hall communications engineering and emerging
technologies series.
852    00$aInNd$bENGIN$cGEN$hTK 5103.48325$i.F86 2011
980    ##$a20101018$b79.99$e65.19$f40018398814$g1$i115477
981    ##$bEDIAPRV-2011
994    ##$aC0$bIND
AVA    ##$aNDU50$bENGIN$cLower Level Engineering Collection$dTK
5103.48325 .F86 2011$eavailable$tAvailable$f1$g0$hN$i5$jGEN$k0
BAR    ##$b00000028560894
FMT    BK
LDR         cam a2200301 a 4500
SRS    ##$aCommunications engineering and emerging technologies
series
SUB    ##$a3GPP Long-Term Evolution (Telecommunications)
SUB    ##$aLTE (Telecommunications)
SUL    ##$a3GPP Long-Term Evolution (Telecommunications)
SUL    ##$aLTE (Telecommunications)
TYP    ##$aBook
XYZ    ##$a3GPP Long-Term Evolution (Telecommunications)
XYZ    ##$aLTE (Telecommunications)
```

Attachment 1-F

ND Apps

Diane Walker <dwalker6@nd.edu>

. Favor:

Laura Sill <ljenny@nd.edu>
To: Diane Walker <Diane.Parr.Walker@nd.edu>

Sun, Jan 24, 2021 at 9:03 PM

Hello, Diane,

This title was shipped as part of the North American Approval plan from YPB in 2010. Note our approval processing looked different then, i.e., two week display cycles of shipments and no shelf-ready until 2013.

Here is a summary of what happened with this title:
10/18/2010: Title invoiced by vendor and item prepared to ship from vendor.
10/29/2010: Bibliographic record loaded in Aleph system and order record created automatically using the local 9XX MARC data. Shipment arrives in library Acquisitions sometime around this date. Afterwhich, the shipment is unpacked, displayed for a two-week subject librarian review, taken off display for final invoice processing, and sent to Cataloging for final processing (just prior to Thanksgiving, I would guess).
12/2/2010: Cataloging of book is completed and it is sent to Labelling and delivery to the Engineering Library. This date corresponds to the MARC 005.

==

Here's the detail with system screen shots:
10/18/2010 = date of the invoice and date of shipping of material from vendor as recorded in YBP/GOBI system.

Title: FUNDAMENTALS OF LTE: ARUNABHA GHOSH ... ET AL.
Publisher: PRENTICE HALL
Pub Year: 2011 **ISBN:** 9780137033119
Binding: Cloth
Series Title: PRENTICE HALL COMMUNICATIONS ENGINEERING AND EMERGING TECHNOLOGIES SERIES.
Series ID: 32098
Content Level: ADV-AC
LC Class: TK5103.48325.F66 2010
Subject Headings: LONG-TERM EVOLUTION (TELECOMMUNICATIONS)
Approval Note: TEXTBOOK--ADV. UNDERGRAD.
Format: Textbook--adv.
Language: English **LCCN:** 2010-021269
US List: 79.99 USD **US Status:** Out of print. Sourced to an out-of-print supplier
Handled On Approval YBP-US: 10/13/2010
Library Note: Add...

Place of Publication: UPPER SADDLE RIVER
Country Of Origin: US
Pagination: 418 P.
Series Type: Unnumbered Series
Series Format: Print
YBP Select: Research-Recommended
OCLC: OCN471787103
NON-RETURN/NON-CANCEL YBP-US
Last Received YBP-US: 8/6/2013

shipped to library (10/18/2010)
alternate editions (1P/0E)
library activity (45 sold)
table of contents

Library History

Title: FUNDAMENTALS OF LTE: ARUNABHA GHOSH ... ET AL.
Author:
Pub Year: 2011
Series Title: PRENTICE HALL COMMUNICATIONS ENGINEERING AND EMERGING TECHNOLOGIES SERIES.
Publisher: PRENTICE HALL
Series ID: 32098

ISBN: 9780137033119
Binding: Cloth
Series Type: Unnumbered Series

Action	Date	Qty	Descriptor	Subaccount	Fund/ Other	PO#	Initials	Submitted By	Invoice#	Tracking#
Shipped	10/18/2010	1	US N AMER AP HUMAN	8087-11	ENGIN				115477	1Z05E3950368316626
Holdings			US HQ	8087-99						

library activity (45 sold)

980 bibliographic field - local MARC field/subfields used to pass vendor system data to library. Used to automatically populate the Aleph order record. We retain the 9XX fields for assessment and reference. Includes the invoice date, list and net price, vendor order key, quantity and invoice number.

```
980   ##$a20101018$b79.99$e65.19$f40018398814$g1$i115477
981   ##$bEDIAPRV-2011
```

This snipit is from our GOBI record load specifications document:

980			a	Invoice date (yyyymmdd)
980			b	List price (explicit decimal)
980			e	Net price (explicit decimal)
980			f	YBP order key
980			g	Quantity
980			i	Invoice number
981			b	Fund code (see below)
981			v	Fund code (see below)

Here is our invoice for this item (see red marked item), the 10/20/2010 date, invoice number, prices, etc.

RETURN BOOKS ONLY TO:
YBP Library Services
999 Maple St.
Contoocook, NH 03229

YBP Library Services
A Baker and Taylor Company
PO Box 277991
Atlanta, GA 30384-7991
(603) 746-3102 (800) 258-3774 FAX (603) 746-5628 FED. ID #02-0302143

T# 220

Please refer to invoice number below when writing or remitting
INVOICE NUMBER 115477
App. Date 10/20/10
PAGE 1

SOLD TO: UNIVERSITY OF NOTRE DAME
HESBURGH LIBRARY
ACQUISITIONS DEPARTMENT
NOTRE DAME, IN 46556

SHIP TO: UNIVERSITY OF NOTRE DAME
APPROVAL
120 HESBURGH LIBRARY
NOTRE DAME, IN 46556

115477

INVOICE DATE	TERMS	DUE DATE		CUSTOMER ORDER NUMBER	CUSTOMER NUMBER
10/18/10	net 30	11/17/10	N	AMERICAN APPR	8087-11

QUANTITY	PURCHASE ORDER #	AUTHOR	ISBN		VOL#	LIST PRICE	DISCOUNT	SINGLE NET	NET AMOUNT
1			1441963200	PSY	LB	129.00	18.5%	105.14	105.14
	ACTIVITY SYSTEMS ANALYSIS METHODS: UNDERSTANDI								
1		COLGAN, B	0786448873	WORLDHIS	D	38.00	.0%	38.00	38.00
	ALLIED STRAFING IN WORLD WAR II: A COCKPIT VIE								
1		AYALA, FR	0801897548	BIOS	QH	12.95	18.5%	10.55	10.55
	AM I A MONKEY?: SIX BIG QUESTIONS ABOUT EVOLUT								
1		BATESON,	0307266435	GEND	HQ	25.95	18.5%	21.15	21.15
	COMPOSING A FURTHER LIFE: THE AGE OF ACTIVE								
1		RAHIMI, S	047040745X	ENGIN	QA	135.00	18.5%	110.03	110.03
	DISTRIBUTED DATABASE MANAGEMENT SYSTEMS: A								
1			0137033117	ENGIN	TK	79.99	18.5%	65.19	65.19
	FUNDAMENTALS OF LTE; ARUNABHA GHOSH ... ET AL.								
1			0765680831	AMER	E	229.00	18.5%	186.64	186.64
	LATINO HISTORY AND CULTURE: AN ENCYCLOPEDIA; E				2 VOLS.				
1		MAGAZINER	0821419188	WORLDHIS	DT	26.95	10.0%	24.26	24.26
	LAW AND THE PROPHETS: BLACK CONSCIOUSNESS IN								
1		GROVES, D	0820336793	ENGLISH	PS	16.95	10.0%	15.26	15.26
	LOST BOYS.								
1		BOURGEAUL	1590304950	RELIG	BS	16.95	10.0%	15.26	15.26
	MEANING OF MARY MAGDALENE: DISCOVERING THE WOM								
1		BLANCHOT,	082322998X	FRENCH	PQ	28.00	10.0%	25.20	25.20
	POLITICAL WRITINGS, 1953-1993; TRANS. BY ZAKIR								
1			0470121947	CHEMPHYS	RS	99.95	18.5%	81.46	81.46
	PRACTICAL APPROACHES TO METHOD VALIDATION AND								
1		CRAGG, PE	9048125812	CHEMPHYS	QD	129.00	18.5%	105.14	105.14
	SUPRAMOLECULAR CHEMISTRY: FROM BIOLOGICAL								
1		WOOD, GEO	0813929032	AMER	E	30.00	18.5%	24.45	24.45
	YOUNG VIRGINIA BOATMAN NAVIGATES THE CIVIL WAR								

10/29/2020 = date bibliographic record was first loaded into the library Aleph system, creating the order record; Acquisitions approval display cycle starts (see detail above).

1. Order Display | 2. General | 3. Vendor | 4. Q

Order Number:	A-101290
Additional Order No.1:	YBPAPRV
Order ISBN/ISSN:	9780137033119
Open Date:	Oct-29-2010
Order Date:	Oct-18-2010

12/2/2010: Date of completion of cataloging. December 1, 2010 we overlaid the vendor record with a more complete record from OCLC, and completed the cataloging on December 2nd. Some sort of Aleph fix routine was applied in 2016 (I can check more on this, if you wish).

Cataloger	Level	Date	Hour
OCLCxfer	00	Dec-01-2010	03:52 PM
PBALES	20	Dec-02-2010	12:30 PM
LDRFIX		Dec-31-2016	11:24 AM

MARC 005: Date/time of last record update: December 2, 2010, 12:30 p.m. - last cataloging update

005 20101202123027.0

Laura Sill (she/her/hers)
Director, Metadata Services
Interim Head, Electronic Resources & Collection Metadata Management
Hesburgh Libraries

University of Notre Dame
406 Hesburgh Library
Notre Dame, IN 46556
o: (574) 631-4036
c: (574) 303-8023
e: ljenny@nd.edu

UNIVERSITY OF NOTRE DAME | HESBURGH LIBRARIES

[Quoted text hidden]

Attachment 1-G

WorldCat®

Search WorldCat

Search

Advanced Search Find a Library

Cite/Export Print E-mail Share Permalink

Add to list Add tags Write a review Rate this item: 1 2 3 4 5

Fundamentals of LTE

Author: Arunabha Ghosh; Jun Zhang; Jeffrey G Andrews; Rias Muhamed

Publisher: Uttar Pradesh, India ; Pearson India Education Services : [2018] ©2011

Edition/Format: Print book : English View all editions and formats

Rating: (not yet rated) 0 with reviews - Be the first.

Subjects Long-Term Evolution (Telecommunications)

More like this Similar Items

Get a Copy

Find a copy in the library

AbeBooks	$10.38
Amazon	$23.91

Find a copy in the library

Enter your location: indiana Find libraries

Submit a complete postal address for best results.

Displaying libraries 1-6 out of 199 for all 18 editions (Indiana, USA) Show libraries holding **just this edition**

« First ‹ Prev 1 2 3 Next › Last »

	Library	Held formats	Distance	
1.	**Miami University Libraries** King Library Oxford, OH 45056 United States	Book	91 miles MAP IT	Library info Ask a librarian Add to favorites
2.	**University of Notre Dame** Hesburgh Library Notre Dame, IN 46556 United States	Book	99 miles MAP IT	Library info Add to favorites
3.	**Xavier University** McDonald Memorial Library Cincinnati, OH 45207 United States	Book	117 miles MAP IT	Library info Ask a librarian Add to favorites
4.	**Kirkland & Ellis LLP Library** Chicago, IL 60654 United States	Book	137 miles MAP IT	Library info Add to favorites
5.	**College of DuPage Library** Glen Ellyn, IL 60137 United States	Book	149 miles MAP IT	Library info Ask a librarian Add to favorites
6.	**Schaumburg Township District Library** Schaumburg, IL 60193 United States	Book	158 miles MAP IT	Library info Ask a librarian Add to favorites

« First ‹ Prev 1 2 3 Next › Last »

Details

Document Type: Book

All Authors / Contributors: Arunabha Ghosh; Jun Zhang; Jeffrey G Andrews; Rias Muhamed

Find more information about: Arunabha Ghosh Go

ISBN: 9789353062392 935306239X

OCLC Number: 1079367343

Notes: "Indian Subcontinent Reprint."

Description: xxxi, 418 pages : illustrations ; 23 cm

Contents:

Responsibility: Arunabha Ghosh, Jun Zhang, Jeffrey G. Andews, Rias Muhamed.

Reviews

User-contributed reviews

Add a review and share your thoughts with other readers. Be the first.

Tags

Add tags for "Fundamentals of LTE". Be the first.

Similar Items

Related Subjects: (1)

Long-Term Evolution (Telecommunications)

Linked Data

Attachment 1-H

LIBRARY | CATALOG

1 of 1

BOOK

Fundamentals of LTE

Full Record | MARC Tags

Main title

Fundamentals of LTE / Arunabha Ghosh ... [et al.].

Published/Created

Upper Saddle River, NJ : Prentice Hall, c2011.

Request this Item | LC Find It

More Information

LCCN Permalink	https://lccn.loc.gov/2010021369
Description	xxxi, 418 p. : ill. ; 24 cm.
ISBN	0137033117 (hardcover : alk. paper) 9780137033119 (hardcover : alk. paper)
LC classification	TK5103.48325 .F86 2011
Related names	Ghosh, Arunabha, 1969-
LC Subjects	Long-Term Evolution (Telecommunications)
Browse by shelf order	TK5103.48325

Notes	Includes bibliographical references and index.
Series	The Prentice Hall communications engineering and emerging technologies series Prentice Hall communications engineering and emerging technologies series.
LCCN	2010021369
Dewey class no.	621.3845/6
National bib agency no.	015545055
Other system no.	(OCoLC)ocn471787103
Type of material	Book

Item Availability

Shelf Location	FLM2016 064014
CALL NUMBER	TK5103.48325 .F86 2011 OVERFLOWJ34
Request in	Jefferson or Adams Building Reading Rooms (FLM2)
Status	Not Charged

Attachment 1-I

LIBRARY CATALOG

1 of 1

BOOK

Fundamentals of LTE

Full Record   MARC Tags

000		01267cam a22003015a 4500
001		16273896
005		20160728093048.0
008		100609s2011 njua b 001 0 eng
906	__	|**a** 7 |**b** cbc |**c** orignew |**d** 1 |**e** ecip |**f** 20 |**g** y-gencatlg
925	0_	|**a** acquire |**b** 1 shelf copy |**x** policy default
925	1_	|**a** acquire |**b** 2 shelf copies |**x** policy default |**e** claim1 2010-11-15
955	__	|**b** rc02 2011-02-15 z-processor |**i** rc02 2011-02-15 to BCCD |**t** rf18 2011-04-14 copy 2 added
010	__	|**a** 2010021369
016	7_	|**a** 015545055 |**2** Uk
020	__	|**a** 0137033117 (hardcover : alk. paper)
020	__	|**a** 9780137033119 (hardcover : alk. paper)
035	__	|**a** (OCoLC)ocn471787103
040	__	|**a** DLC |**c** DLC |**d** YDX |**d** UKM |**d** BTCTA |**d** YDXCP |**d** DLC
050	00	|**a** TK5103.48325 |**b** .F86 2011
082	00	|**a** 621.3845/6 |**2** 22
245	00	|**a** Fundamentals of LTE / |**c** Arunabha Ghosh ... [et al.].
260	__	|**a** Upper Saddle River, NJ : |**b** Prentice Hall, |**c** c2011.
300	__	|**a** xxxi, 418 p. : |**b** ill. ; |**c** 24 cm.
490	1_	|**a** The Prentice Hall communications engineering and emerging technologies series
504	__	|**a** Includes bibliographical references and index.
650	_0	|**a** Long-Term Evolution (Telecommunications)
700	1_	|**a** Ghosh, Arunabha, |**d** 1969-

830 _0 |**a** Prentice Hall communications engineering and emerging technologies series.

Request this Item | LC Find It

Item Availability

Shelf Location	FLM2016 064014
CALL NUMBER	TK5103.48325 .F86 2011 OVERFLOWJ34
Request in	Jefferson or Adams Building Reading Rooms (FLM2)
Status	Not Charged

Attachment 1-J

WorldCat®

Search WorldCat

Search
Advanced Search Find a Library

<< Return to Search Results Cite/Export Print E-mail Share Permalink

Add to list Add tags Write a review Rate this item: 1 2 3 4 5

Fundamentals of LTE

Author:	Arunabha Ghosh; Jun Zhang; Jeffrey G Andrews; Rias Muhamed
Publisher:	Uttar Pradesh, India ; Pearson India Education Services : [2018] ©2011
Edition/Format:	Print book : English View all editions and formats
Rating:	(not yet rated) 0 with reviews - Be the first.
Subjects	Long-Term Evolution (Telecommunications)
More like this	Similar Items

Get a Copy

Find a copy in the library

AbeBooks $10.38

Amazon $25.02

Find a copy in the library

Enter your location: Distri t of Columbia Find libraries
Submit a complete postal address for best results.

Displaying libraries 1-6 out of 199 for all 18 editions (Washington, DC, USA) Show libraries holding just this edition

« First ‹ Prev 1 2 3 Next › Last »

	Library	Held formats	Distance	
1.	**Consumer Financial Protection Bureau** Washington, DC 20552 United States	Book	1 mile MAP IT	Library info Add to favorites
2.	**Library of Congress** Washington, DC 20540 United States	Book	2 miles MAP IT	Library info Ask a librarian Add to favorites
3.	**Montgomery College Library** Rockville, MD 20850 United States	Book	15 miles MAP IT	Library info Ask a librarian Add to favorites
4.	**George Mason University** **Fenwick Library** Fairfax, VA 22030 United States	Book	16 miles MAP IT	Library info Add to favorites
5.	**Space Telescope Science Institute Library** **STScI Library** Baltimore, MD 21218 United States	Book	37 miles MAP IT	Library info Add to favorites
6.	**Virginia Commonwealth University** **VCU Libraries** Richmond, VA 23284 United States	Book	97 miles MAP IT	Library info Ask a librarian Add to favorites

« First ‹ Prev 1 2 3 Next › Last »

Details

Document Type:	Book
All Authors / Contributors:	Arunabha Ghosh; Jun Zhang; Jeffrey G Andrews; Rias Muhamed
	Find more information about: Arunabha Ghosh Go
ISBN:	9789353062392 935306239X
OCLC Number:	1079367343
Notes:	"Indian Subcontinent Reprint."
Description:	xxxi, 418 pages : illustrations ; 23 cm
Contents:	Evolution of cellular technologies -- Part I: LTE tutorials -- Wireless fundamentals -- Multicarrier modulation -- Frequency domain multiple access : OFDMA and SC-FDMA -- Multiple antenna transmission and reception -- Part II: The LTE standard -- Overview and channel structure of LTE -- Downlink transport channel processing -- Uplink transport channel processing -- Physical layer procedures and scheduling -- Data flow, radio resource management, and mobility management.
Responsibility:	Arunabha Ghosh, Jun Zhang, Jeffrey G. Andews, Rias Muhamed.

Reviews

User-contributed reviews

Add a review and share your thoughts with other readers. Be the first.

Tags

Add tags for "Fundamentals of LTE". Be the first.

Similar Items

Related Subjects: (1)

Long-Term Evolution (Telecommunications)

Linked Data

Attachment 2-A

LTE for UMTS – OFDMA and SC-FDMA Based Radio Access

LTE for UMTS: OFDMA and SC-FDMA Based Radio Access Edited by Harri Holma and Antti Toskala
 ISBN: 978-0-470-99401-6

LTE for UMTS –
OFDMA and SC-FDMA Based Radio Access

Edited by

Harri Holma and Antti Toskala

both of Nokia Siemens Networks, Finland

John Wiley & Sons, Ltd

This edition first published 2009

Registered office
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

Library of Congress Cataloging-in-Publication Data

LTE for UMTS-OFDMA and SC-FDMA based radio access / edited by Harri Holma, Antti Toskala.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-470-99401-6 (cloth : alk. paper) 1. Universal Mobile Telecommunications System. 2. Wireless communication systems--Standards. 3. Mobile communication systems--Standards. 4. Global system for mobile communications. I. Holma, Harri, 1970- II. Toskala, Antti.
TK5103.4883.L78 2009
621.3845'6--dc22
2008052792

A catalogue record for this book is available from the British Library.

ISBN 9780470994016 (H/B)

Set in 10/12 pt Times by Sparks, Oxford – www.sparkspublishing.com
Printed and bound in Great Britain by Antony Rowe, Chippenham, UK

Contents

Preface

The number of mobile subscribers has increased tremendously in recent years. Voice communication has become mobile in a massive way and the mobile is the preferred way for voice communication. At the same time the data usage has grown fast in those networks where 3GPP High Speed Packet Access (HSPA) was introduced indicating that the users find value in broadband wireless data. The average data consumption exceeds hundreds of Megabytes per subscriber per month. The end users expect data performance similar to the fixed lines. The operators request high data capacity with low cost of data delivery. 3GPP Long Term Evolution (LTE) is designed to meet those targets. This book presents 3GPP LTE standard in Release 8 and describes its expected performance.

The book is structured as follows. Chapter 1 presents an introduction. The standardization background and process is described in Chapter 2. The system architecture evolution (SAE) is presented in Chapter 3, and the basics of air interface modulation choices in Chapter 4. Chapter 5 describes 3GPP LTE physical layer solutions, and Chapter 6 protocol solutions. The mobility

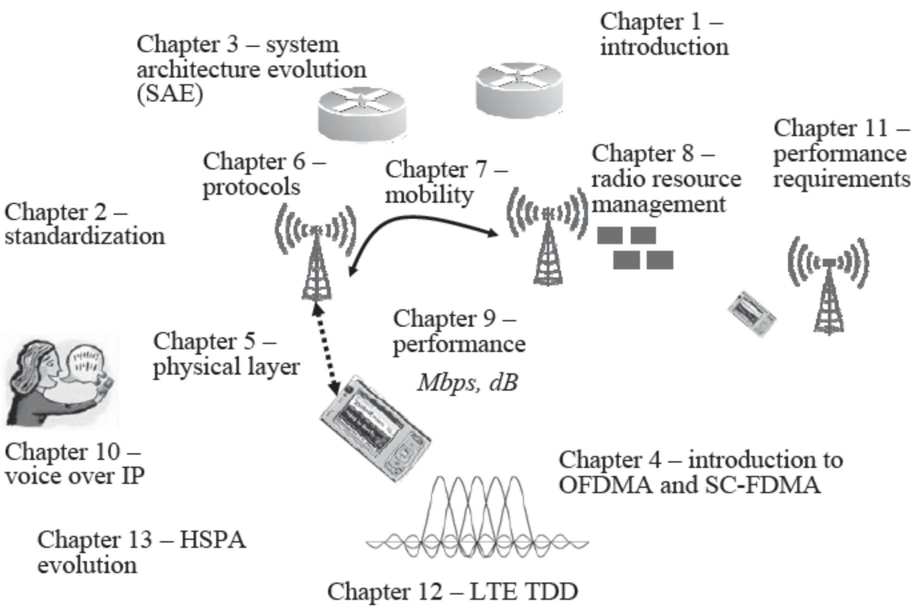


Figure 0.1 Contents of the book

aspects are addressed in Chapter 7, and the radio resource management in Chapter 8. The radio and end-to-end performance is illustrated in Chapter 9. The voice performance is presented in Chapter 10. Chapter 11 explains the 3GPP performance requirements. Chapter 12 presents the main LTE Time Division Duplex (TDD). Chapter 13 describes HSPA evolution in 3GPP Releases 7 and 8.

LTE can access a very large global market – not only GSM/UMTS operators, but also CDMA operators and potentially also fixed network service providers. The potential market can attract a large number of companies to the market place pushing the economies of scale which enable wide scale LTE adoption with lower cost. This book is particularly designed for chip set and mobile vendors, network vendors, network operators, application developers, technology managers and regulators who would like to get a deeper understanding of LTE technology and its capabilities.

Acknowledgements

The editors would like to acknowledge the hard work of the contributors from Nokia Siemens Networks, Nokia, ST-Ericsson and Nomor Research: Andrea Ancora, Iwajlo Angelow, Dominique Brunel, Chris Callender, Kari Hooli, Woonhee Hwang, Juha Kallio, Matti Kiiski, Pasi Kinnunen, Troels Kolding, Juha Korhonen, Jarkko Koskela, Istvan Kovacs, Markku Kuusela, Daniela Laselva, Earl McCune, Peter Muszynski, Petteri Lunden, Timo Lunttila, Atte Länsisalmi, Esa Malkamäki, Laurent Noel, Jussi Ojala, Kari Pajukoski, Klaus Pedersen, Karri Ranta-aho, Jussi Reunanen, Haiming Wang, Peter Skov, Esa Tiirola, Ingo Viering, Haiming Wang and Che Xiangguang.

We also would like to thank the following colleagues for their valuable comments: Asbjörn Grovlen, Jorma Kaikkonen, Michael Koonert, Peter Merz, Preben Mogensen, Sari Nielsen, Gunnar Nitsche, Miikka Poikselkä, Sabine Rössel, Benoist Sebire, Issam Toufik and Helen Waite.

The editors appreciate the fast and smooth editing process provided by Wiley and especially Sarah Tilley, Mark Hammond, Katharine Unwin, Brett Wells, Tom Fryer and Mitch Fitton.

We are grateful to our families, as well as the families of all the authors, for their patience during the late night and weekend editing sessions.

The editors and authors welcome any comments and suggestions for improvements or changes that could be implemented in forthcoming editions of this book. The feedback is welcome to editors' email addresses harri.holma@nsn.com and antti.toskala@nsn.com.

List of Abbreviations

3GPP	Third Generation Partnership Project
AAA	Authentication, Authorization and Accounting
ACF	Analog Channel Filter
ACIR	Adjacent Channel Interference Rejection
ACK	Acknowledgement
ACLR	Adjacent Channel Leakage Ratio
ACS	Adjacent Channel Selectivity
ADC	Analog-to Digital Conversion
ADSL	Asymmetric Digital Subscriber Line
AKA	Authentication and Key Agreement
AM	Acknowledged Mode
AMBR	Aggregate Maximum Bit Rate
AMD	Acknowledged Mode Data
AMR	Adaptive Multi-Rate
AMR-NB	Adaptive Multi-Rate Narrowband
AMR-WB	Adaptive Multi-Rate Wideband
ARP	Allocation Retention Priority
ASN	Abstract Syntax Notation
ASN.1	Abstract Syntax Notation One
ATM	Adaptive Transmission Bandwidth
AWGN	Additive White Gaussian Noise
AWGN	Additive White Gaussian Noise
BB	Baseband
BCCH	Broadcast Control Channel
BCH	Broadcast Channel
BE	Best Effort
BEM	Block Edge Mask
BICC	Bearer Independent Call Control Protocol
BiCMOS	Bipolar CMOS
BLER	Block Error Rate
BO	Backoff
BOM	Bill of Material
BPF	Band Pass Filter
BPSK	Binary Phase Shift Keying

BS	Base Station
BSC	Base Station Controller
BSR	Buffer Status Report
BT	Bluetooth
BTS	Base Station
BW	Bandwidth
CAZAC	Constant Amplitude Zero Autocorrelation Codes
CBR	Constant Bit Rate
CCE	Control Channel Element
CCCH	Common Control Channel
CDD	Cyclic Delay Diversity
CDF	Cumulative Density Function
CDM	Code Division Multiplexing
CDMA	Code Division Multiple Access
CIR	Carrier to Interference Ratio
CLM	Closed Loop Mode
CM	Cubic Metric
CMOS	Complementary Metal Oxide Semiconductor
CoMP	Coordinated Multiple Point
CP	Cyclic Prefix
CPE	Common Phase Error
CPICH	Common Pilot Channel
CQI	Channel Quality Information
CRC	Cyclic Redundancy Check
C-RNTI	Cell Radio Network Temporary Identifier
CS	Circuit Switched
CSCF	Call Session Control Function
CSFB	Circuit Switched Fallback
CSI	Channel State Information
CT	Core and Terminals
CTL	Control
CW	Continuous Wave
DAC	Digital to Analog Conversion
DARP	Downlink Advanced Receiver Performance
D-BCH	Dynamic Broadcast Channel
DC	Direct Current
DCCH	Dedicated Control Channel
DCH	Dedicated Channel
DC-HSDPA	Dual Cell (Dual Carrier) HSDPA
DCI	Downlink Control Information
DCR	Direct Conversion Receiver
DCXO	Digitally-Compensated Crystal Oscillator
DD	Duplex Distance
DFCA	Dynamic Frequency and Channel Allocation
DFT	Discrete Fourier Transform
DG	Duplex Gap
DL	Downlink

DL-SCH	Downlink Shared Channel
DPCCH	Dedicated Physical Control Channel
DR	Dynamic Range
DRX	Discontinuous Reception
DSP	Digital Signal Processing
DTCH	Dedicated Traffic Channel
DTM	Dual Transfer Mode
DTX	Discontinuous Transmission
DVB-H	Digital Video Broadcast – Handheld
DwPTS	Downlink Pilot Time Slot
E-DCH	Enhanced DCH
EDGE	Enhanced Data Rates for GSM Evolution
EFL	Effective Frequency Load
EFR	Enhanced Full Rate
EGPRS	Enhanced GPRS
E-HRDP	Evolved HRPD (High Rate Packet Data) network
EIRP	Equivalent Isotropic Radiated Power
EMI	Electromagnetic Interference
EPA	Extended Pedestrian A
EPC	Evolved Packet Core
EPDG	Evolved Packet Data Gateway
ETU	Extended Typical Urban
E-UTRA	Evolved Universal Terrestrial Radio Access
EVA	Extended Vehicular A
EVDO	Evolution Data Only
EVM	Error Vector Magnitude
EVS	Error Vector Spectrum
FACH	Forward Access Channel
FCC	Federal Communications Commission
FD	Frequency Domain
FDD	Frequency Division Duplex
FDE	Frequency Domain Equalizer
FDM	Frequency Division Multiplexing
FDPS	Frequency Domain Packet Scheduling
FE	Front End
FFT	Fast Fourier Transform
FM	Frequency Modulated
FNS	Frequency Non-Selective
FR	Full Rate
FRC	Fixed Reference Channel
FS	Frequency Selective
GB	Gigabyte
GBF	Guaranteed Bit Rate
GDD	Group Delay Distortion
GERAN	GSM/EDGE Radio Access Network
GF	G-Factor
GGSN	Gateway GPRS Support Node

GMSK	Gaussian Minimum Shift Keying
GP	Guard Period
GPON	Gigabit Passive Optical Network
GPRS	General packet radio service
GPS	Global Positioning System
GRE	Generic Routing Encapsulation
GSM	Global System for Mobile Communications
GTP	GPRS Tunneling Protocol
GTP-C	GPRS Tunneling Protocol, Control Plane
GUTI	Globally Unique Temporary Identity
GW	Gateway
HARQ	Hybrid Adaptive Repeat and Request
HB	High Band
HD-FDD	Half Duplex Frequency Division Duplex
HFN	Hyper Frame Number
HII	High Interference Indicator
HO	Handover
HPBW	Half Power Beam Width
HPF	High Pass Filter
HPSK	Hybrid Phase Shift Keying
HRPD	High Rate Packet Data
HSDPA	High Speed Downlink Packet Access
HS-DSCH	High Speed Downlink Shared Channel
HSGW	HRPD Serving Gateway
HSPA	High Speed Packet Access
HS-PDSCH	High Speed Physical Downlink Shared Channel
HSS	Home Subscriber Server
HS-SCCH	High Speed Shared Control Channel
HSUPA	High Speed Uplink Packet Access
IC	Integrated Circuit
IC	Interference Cancellation
ICI	Inter-carrier Interference
ICIC	Inter-cell Interference Control
ICS	IMS Centralized Service
ID	Identity
IETF	Internet Engineering Task Force
IFFT	Inverse Fast Fourier Transform
IL	Insertion Loss
iLBC	Internet Lob Bit Rate Codec
IM	Implementation Margin
IMD	Intermodulation
IMS	IP Multimedia Subsystem
IMT	International Mobile Telecommunications
IoT	Interference over Thermal
IOT	Inter-Operability Testing
IP	Internet Protocol
IR	Image Rejection

IRC	Interference Rejection Combining
ISD	Inter-site Distance
ISDN	Integrated Services Digital Network
ISI	Inter-system Interference
ISTO	Industry Standards and Technology Organization
ISUP	ISDN User Part
IWF	Interworking Funtion
LAI	Location Area Identity
LMA	Local Mobility Anchor
LB	Low Band
LCID	Logical Channel Identification
LCS	Location Services
LMMSE	Linear Mininum Mean Square Error
LNA	Low Noise Amplifier
LO	Local Oscillator
LOS	Line of Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MAP	Maximum a Posteriori
MAP	Mobile Application Part
MBMS	Multimedia Broadcast Multicast System
MBR	Maximum Bit Rate
MCH	Multicast Channel
MCL	Minimum Coupling Loss
MCS	Modulation and Coding Scheme
MGW	Media Gateway
MIB	Master Information Block
MIMO	Multiple Input Multiple Output
MIP	Mobile IP
MIPI	Mobile Industry Processor Interface
MIPS	Million Instructions Per Second
MM	Mobility Management
MME	Mobility Management Entity
MMSE	Minimum Mean Square Error
MPR	Maximum Power Reduction
MRC	Maximal Ratio Combining
MSC	Mobile Switching Center
MSC-S	Mobile Switching Center Server
MSD	Maximum Sensitivity Degradation
MU	Multiuser
NACC	Network Assisted Cell Change
NACK	Negative Acknowledgement
NAS	Non-access Stratum
NAT	Network Address Table
NB	Narrowband
NF	Noise Figure
NMO	Network Mode of Operation

NRT	Non-real Time
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OI	Overload Indicator
OLLA	Outer Loop Link Adaptation
OOB	Out of Band
OOBN	Out-of-Band Noise
O&M	Operation and Maintenance
PA	Power Amplifier
PAPR	Peak to Average Power Ratio
PAR	Peak-to-Average Ratio
PBR	Prioritized Bit Rate
PC	Personal Computer
PC	Power Control
PCC	Policy and Charging Control
PCCC	Parallel Concatenated Convolution Coding
PCCPCH	Primary Common Control Physical Channel
PCFICH	Physical Control Format Indicator Channel
PCH	Paging Channel
PCI	Physical Cell Identity
PCM	Pulse Code Modulation
PCRF	Policy and Charging Resource Function
PCS	Personal Communication Services
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
PDF	Probability Density Function
PDN	Packet Data Network
PDU	Payload Data Unit
PDSCH	Physical Downlink Shared Channel
PF	Proportional Fair
P-GW	Packet Data Network Gateway
PHICH	Physical HARQ Indicator Channel
PHR	Power Headroom Report
PHS	Personal Handyphone System
PHY	Physical Layer
PLL	Phase Locked Loop
PLMN	Public Land Mobile Network
PMI	Precoding Matrix Index
PMIP	Proxy Mobile IP
PN	Phase Noise
PRACH	Physical Random Access Channel
PRB	Physical Resource Block
PS	Packet Switched
PSD	Power Spectral Density
PSS	Primary Synchronization Signal
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel

QAM	Quadrature Amplitude Modulation
QCI	QoS Class Identifier
QD	Quasi Dynamic
QN	Quantization Noise
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RACH	Random Access Channel
RAD	Required Activity Detection
RAN	Radio Access Network
RAR	Random Access Response
RAT	Radio Access Technology
RB	Resource Block
RBG	Radio Bearer Group
RF	Radio Frequency
RI	Rank Indicator
RLC	Radio Link Control
RNC	Radio Network Controller
RNTP	Relative Narrowband Transmit Power
ROHC	Robust Header Compression
RR	Round Robin
RRC	Radio Resource Control
RRM	Radio Resource Management
RS	Reference Signal
RSCP	Received Symbol Code Power
RSRP	Reference Symbol Received Power
RSRQ	Reference Symbol Received Quality
RSSI	Received Signal Strength Indicator
RT	Real Time
RTT	Round Trip Time
RV	Redundancy Version
SA	Services and System Aspects
SAE	System Architecture Evolution
SAIC	Single Antenna Interference Cancellation
S-CCPCH	Secondary Common Control Physical Channel
SC-FDMA	Single Carrier Frequency Division Multiple Access
SCH	Synchronization Channel
SCM	Spatial Channel Model
SCTP	Stream Control Transmission Protocol
SDQNR	Signal to Distortion Quantization Noise Ratio
SDU	Service Data Unit
SE	Spectral Efficiency
SEM	Spectrum Emission Mask
SF	Spreading Factor
SFBC	Space Frequency Block Coding
SFN	System Frame Number
SGSN	Serving GPRS Support Node
S-GW	Serving Gateway

SIB	System Information Block
SID	Silence Indicator Frame
SIM	Subscriber Identity Module
SIMO	Single Input Multiple Output
SINR	Signal to Interference and Noise Ratio
SMS	Short Message Service
SNR	Signal to Noise Ratio
SON	Self Optimized Networks
SON	Self Organizing Networks
SR	Scheduling Request
S-RACH	Short Random Access Channel
SRB	Signaling Radio Bearer
S-RNC	Serving RNC
SRS	Sounding Reference Signals
SSS	Secondary Synchronization Signal
SR-VCC	Single Radio Voice Call Continuity
S-TMSI	S-Temporary Mobile Subscriber Identity
SU-MIMO	Single User Multiple Input Multiple Output
S1AP	S1 Application Protocol
TA	Tracking Area
TBS	Transport Block Size
TD	Time Domain
TDD	Time Division Duplex
TD-LTE	Time Division Long Term Evolution
TD-SCDMA	Time Division Synchronous Code Division Multiple Access
TM	Transparent Mode
TPC	Transmit Power Control
TRX	Transceiver
TSG	Technical Specification Group
TTI	Transmission Time Interval
TU	Typical Urban
UDP	Unit Data Protocol
UE	User Equipment
UHF	Ultra High Frequency
UICC	Universal Integrated Circuit Card
UL	Uplink
UL-SCH	Uplink Shared Channel
UM	Unacknowledged Mode
UMD	Unacknowledged Mode Data
UMTS	Universal Mobile Telecommunications System
UpPTS	Uplink Pilot Time Slot
USB	Universal Serial Bus
USIM	Universal Subscriber Identity Module
USSD	Unstructured Supplementary Service Data
UTRA	Universal Terrestrial Radio Access
UTRAN	Universal Terrestrial Radio Access Network
VCC	Voice Call Continuity

VCO	Voltage Controlled Oscillator
VDSL	Very High Data Rate Subscriber Line
VLR	Visitor Location Register
V-MIMO	Virtual MIMO
VoIP	Voice over IP
WCDMA	Wideband Code Division Multiple Access
WG	Working Group
WLAN	Wireless Local Area Network
WRC	World Radio Conference
X1AP	X1 Application Protocol
ZF	Zero Forcing

1

Introduction

Harri Holma and Antti Toskala

1.1 Mobile Voice Subscriber Growth

The number of mobile subscribers has increased tremendously during the last decade: the first billion landmark was exceeded in 2002, the second billion in 2005, the third billion in 2007 and the fourth billion by the end of 2008. More than 1 million new subscribers per day have been added globally, that is more than ten subscribers on average every second. This growth is illustrated in Figure 1.1. Mobile phone penetration worldwide is approaching

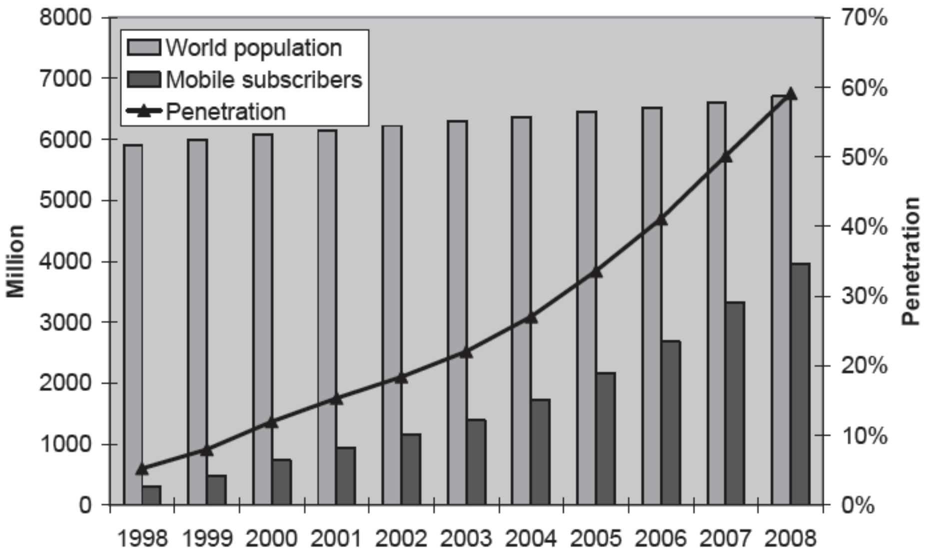


Figure 1.1 Growth of mobile subscribers

LTE for UMTS: OFDMA and SC-FDMA Based Radio Access Edited by Harri Holma and Antti Toskala
 ISBN: 978-0-470-99401-6

60%[1]. Voice communication has become mobile in a massive way. The mobile is the preferred method for voice communication, with mobile networks covering over 90% of the world's population. This voice growth has been fuelled by low cost mobile phones and efficient network coverage and capacity, which is enabled by standardized solutions and by an open ecosystem leading to the economies of scale. Mobile voice is not the privilege of the rich but also brings value for users on low incomes – because of the benefits of being connected, low income users spend a larger part of their income on mobile communications.

1.2 Mobile Data Usage Growth

The second generation mobile networks – like Global System for Mobile Communications (GSM) – were originally designed for carrying voice traffic while the data capability was added later. Data usage has increased but the traffic volume in second generation networks is clearly dominated by voice traffic. The introduction of third generation networks with High Speed Downlink Packet Access (HSDPA) has boosted data usage considerably. Example operator statistics for 12 months are shown in Figure 1.2 where the HSDPA downlink data volumes are several terabytes per day, which correspond to beyond 1 Gbps busy hour network level throughput. Such fast data growth shows that the end users find value in the wireless broadband access.

Data traffic volume has in many cases already exceeded voice traffic volume when voice traffic is converted into terabytes by assuming a voice data rate of 12 kbps. A typical case is illustrated in Figure 1.3. HSDPA data growth is advanced by high speed radio capability, flat rate pricing schemes and simple device installation. In short, the introduction of HSDPA has changed mobile networks from voice dominated to packet data dominated networks.

Data usage is advanced by a number of bandwidth hungry laptop applications including internet and intranet access, file sharing, streaming services to distribute video content and mobile

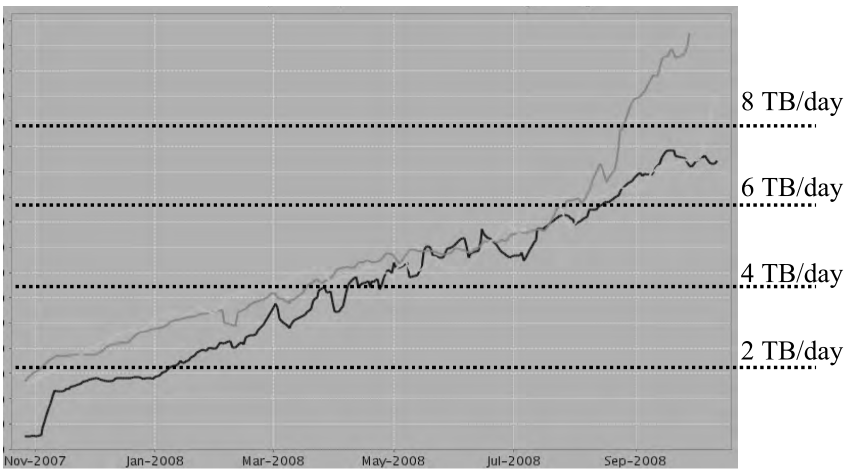


Figure 1.2 Growth of HSDPA data traffic

1 The actual user penetration can be different since some users have multiple subscriptions and some subscriptions are shared by multiple users.

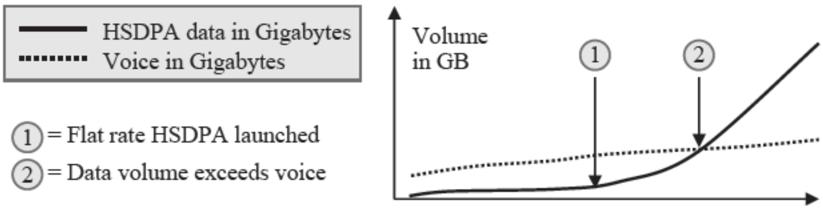


Figure 1.3 HSDPA data volume exceeds voice volume

TV and interactive gaming. In addition, service bundles of video, data and voice – known also as triple play – are entering the mobile market, also replacing the traditional fixed line voice and broadband data services with mobile services both at home and in the office.

A typical voice subscriber uses 300 minutes per month, which is equal to approximately 30 megabyte of data with a voice data rate of 12.2 kbps. A broadband data user can easily consume more than 1000 megabyte (1 gigabyte) of data. Heavy broadband data usage takes 10–100× more capacity than voice usage, which sets high requirements for the capacity and efficiency of network data.

It is expected that by 2015, 5 billion people will be connected to the internet. Broadband internet connections will be available practically anywhere in the world. Already today, the existing wireline installations can reach approximately 1 billion households and the mobile networks connect over 3 billion subscribers. These installations need to evolve into broadband internet access. Further extensive use of wireless access as well as new wireline installations with enhanced capabilities are required to offer true broadband connectivity to the 5 billion customers.

1.3 Wireline Technologies Evolution

Although wide area wireless networks have experienced a fast evolution of data rates, wireline networks still provide the highest data rates. The evolution of the peak user data rate both in wireless and wireline networks is illustrated in Figure 1.4. Interestingly, the shape of the evolution curve is similar in both domains with a relative difference of approximately 30 times. An application of Moore's law predicts that data rates double every 18 months. Currently, copper based wireline solutions with Very High Data Rate Digital Subscriber Line (VDSL2) can offer bit rates of tens of Mbps and the passive optical fibre based solution gives rates in excess of 100 Mbps. Both copper and fibre based solutions will have further data rate evolution in the near future, increasing the data rate offerings to the Gbps range.

Wireless networks must make data rates higher in order to match the user experience provided by wireline networks. When customers are used to wireline performance, they expect the wireless network to offer comparable performance. The applications designed for wireline networks advance the evolution of the wireless data rates.

Wireless technologies, on the other hand, have the huge benefit of being capable of offering personal broadband access independently of user location – in other words, mobility, for nomadic or full mobile use cases. A wireless solution can also provide low cost broadband coverage compared to new wireline installations if there is no existing wireline infrastructure. Therefore, wireless broadband access is an attractive option, especially in new growth markets in urban areas as well as in rural areas in other markets.

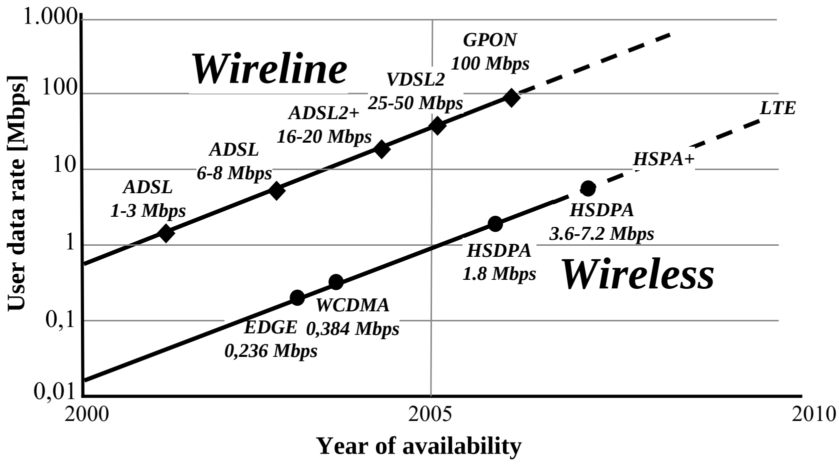


Figure 1.4 Evolution of wireless and wireline user data rates [Broadband Access for All - A Brief Technology Guide, Nokia Siemens Networks white paper (2007)]. GPON = Gigabit Passive Optical Network; VDSL = Very High Data Rate Subscriber Line; ADSL = Asymmetric Digital Subscriber Line

1.4 Motivation and Targets for LTE

The work towards 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) started in 2004 with the definition of the targets. Even though HSDPA was not yet deployed at that time, it became evident that work for the next radio system should be started. It takes more than 5 years from setting the system targets to commercial deployment using interoperable standards. Therefore, system standardization must be started early enough to be ready by the time the need is there. A few driving forces can be identified advancing LTE development: wireline capability evolution, the need for additional wireless capacity, the need for lower cost wireless data delivery and the competition of other wireless technologies. As wireline technology keeps improving, a similar evolution is required in the wireless domain to make sure that the applications also work fluently in the wireless domain. There are also other wireless technologies – including IEEE 802.16 – which promise high data capabilities. 3GPP technologies must match and exceed the competition. More capacity is a clear requirement for taking maximum advantage of the available spectrum and base station sites. These reasons are summarized in Figure 1.5.

LTE must be able to deliver superior performance compared to existing 3GPP networks based on High Speed Packet Access (HSPA) technology. The performance targets in 3GPP are defined relative to HSPA in Release 6. The peak user throughput should be minimum 100 Mbps in downlink and 50 Mbps in uplink, which is ten times more than HSPA Release 6. Also the latency must be reduced in order to improve the end user performance. The terminal power consumption must be minimized to enable more usage of the multimedia applications without recharging the battery. The main performance targets are shown in Figure 1.6 and are listed below:

- spectral efficiency two to four times more than with HSPA Release 6;
- peak rates exceed 100 Mbps in downlink and 50 Mbps in uplink;

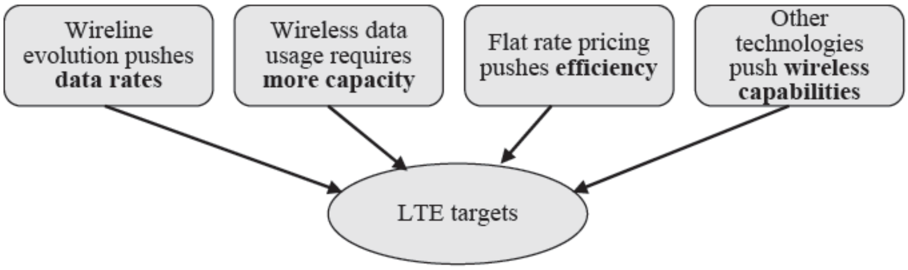


Figure 1.5 Driving forces for LTE development

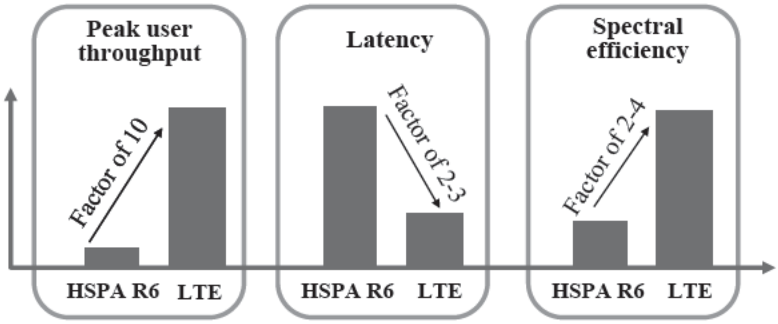


Figure 1.6 Main LTE performance targets

- enables round trip time <10 ms;
- packet switched optimized;
- high level of mobility and security;
- optimized terminal power efficiency;
- frequency flexibility with from below 1.5 MHz up to 20 MHz allocations.

1.5 Overview of LTE

The multiple access scheme in LTE downlink uses Orthogonal Frequency Division Multiple Access (OFDMA) and uplink uses Single Carrier Frequency Division Multiple Access (SC-FDMA). These multiple access solutions provide orthogonality between the users, reducing the interference and improving the network capacity. The resource allocation in the frequency domain takes place with a resolution of 180 kHz resource blocks both in uplink and in downlink. The frequency dimension in the packet scheduling is one reason for the high LTE capacity. The uplink user specific allocation is continuous to enable single carrier transmission while the downlink can use resource blocks freely from different parts of the spectrum. The uplink single carrier solution is also designed to allow efficient terminal power amplifier design, which is relevant for the terminal battery life. The LTE solution enables spectrum flexibility where the transmission bandwidth can be selected between 1.4 MHz and 20 MHz depending on the available spectrum. The 20 MHz bandwidth can provide up to 150 Mbps downlink user data rate with 2×2 MIMO, and 300 Mbps with 4×4 MIMO. The uplink peak data rate is 75 Mbps. The multiple access schemes are illustrated in Figure 1.7.

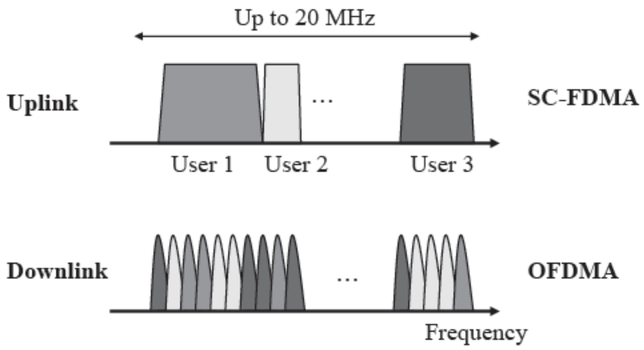


Figure 1.7 LTE multiple access schemes

The high network capacity also requires an efficient network architecture in addition to the advanced radio features. The target in 3GPP Release 8 is to improve the network scalability for traffic increase and to minimize the end-to-end latency by reducing the number of network elements. All radio protocols, mobility management, header compression and all packet retransmissions are located in the base stations called eNodeB. eNodeB includes all those algorithms that are located in Radio Network Controller (RNC) in 3GPP Release 6 architecture. Also the core network is streamlined by separating the user and the control planes. The Mobility Management Entity (MME) is just the control plane element while the user plane bypasses MME directly to System Architecture Evolution (SAE) Gateway (GW). The architecture evolution is illustrated in Figure 1.8. This Release 8 core network is also often referred to as Evolved Packet Core (EPC) while for the whole system the term Evolved Packet System (EPS) can also be used.

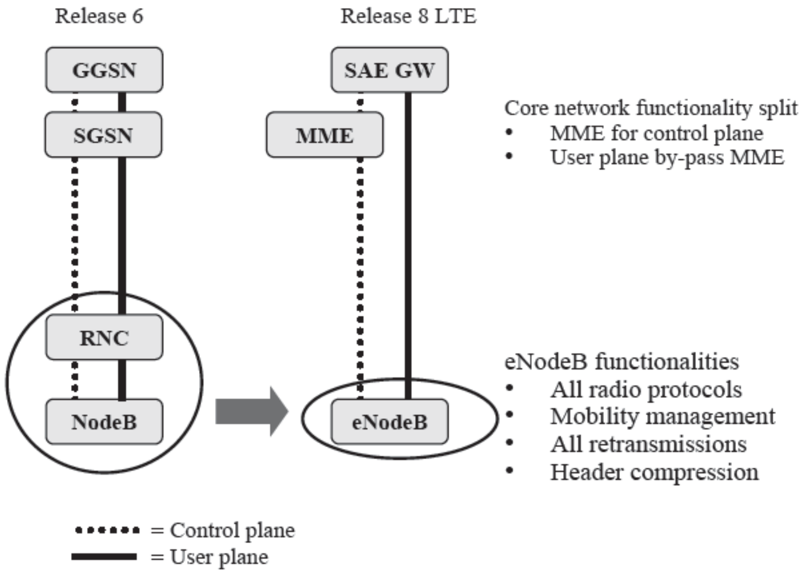


Figure 1.8 LTE network architecture

1.6 3GPP Family of Technologies

3GPP technologies – GSM/EDGE and Wideband Code Division Multiple Access (WCDMA)/HSPA – are currently serving nearly 90% of the global mobile subscribers. The market share development of 3GPP technologies is illustrated in Figure 1.9. A number of major Code Division Multiple Access (CDMA) operators have already turned or are soon turning to GSM/WCDMA for voice evolution and to HSPA/LTE for data evolution to get access to the benefits of the large and open 3GPP ecosystem and economics of scale for low cost mobile devices. The number of subscribers using 3GPP based technologies is currently more than 3.5 billion. The 3GPP LTE will be built on this large base of 3GPP technologies.

The time schedule of 3GPP specifications and the commercial deployments is illustrated in Figure 1.10. Enhanced Data rates for GSM Evolution (EDGE) was defined in 3GPP in 1997 and WCDMA at the end of 1999. Both systems had their first commercial deployments during

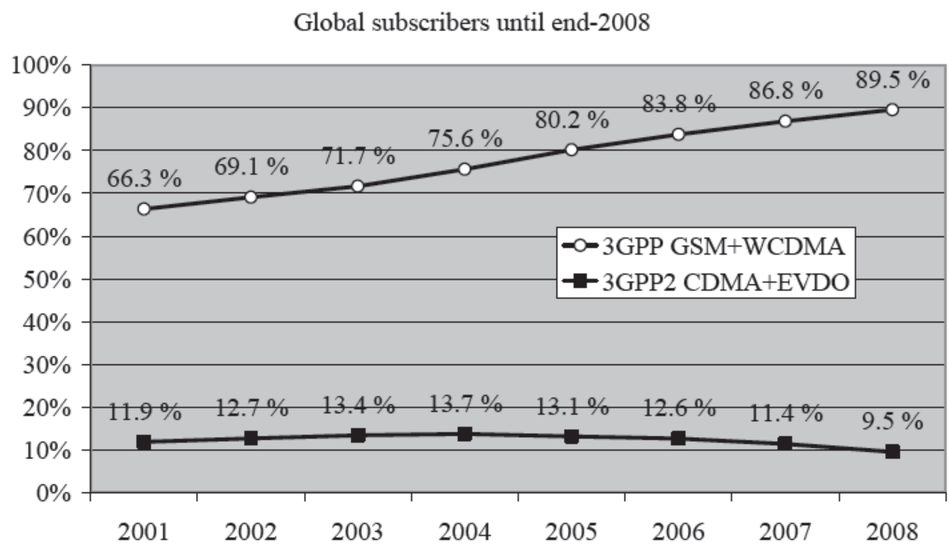


Figure 1.9 Global market share of 3GPP and 3GPP2 technologies. EVDO, evolution data only

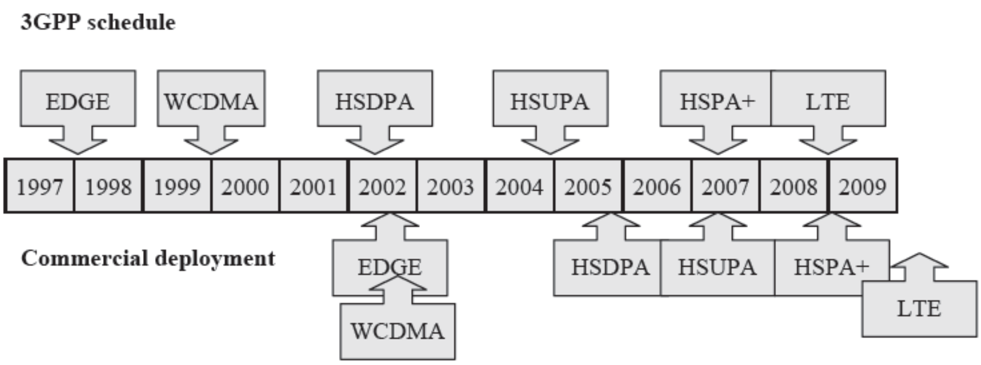


Figure 1.10 Schedule of 3GPP standard and their commercial deployments

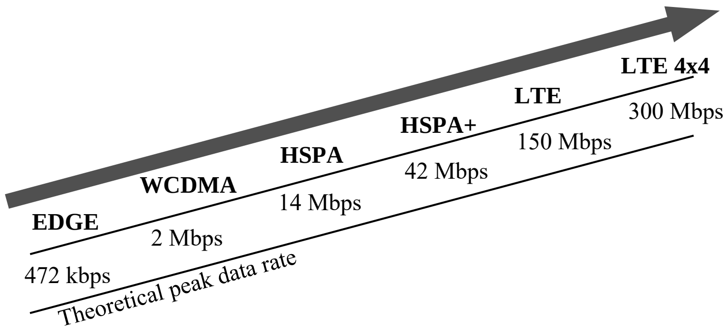


Figure 1.11 Peak data rate evolution of 3GPP technologies

2002. The HSDPA and High Speed Uplink Packet Access (HSUPA) standards were completed in March 2002 and December 2004, and the commercial deployments followed in 2005 and 2007. The first phase of HSPA evolution, also called HSPA+, was completed in June 2007 and the deployments start during 2009. The LTE standard was approved at the end of 2007, the backwards compatibility is expected to start in March 2009 and commercial deployments are expected in 2010.

The new generation of technologies pushes data rates higher. The evolution of the peak user data rates is illustrated in Figure 1.11. The first WCDMA deployments in 2002 offered 384 kbps, current HSDPA networks 7.2–14.4 Mbps, HSPA evolution 21–42 Mbps and LTE 2010 150 Mbps, that is a more than 300 times higher data rate over 8 years.

The 3GPP technologies are designed for smooth inter-working and coexistence. The LTE will support bi-directional handovers between LTE and GSM and between LTE and UMTS. GSM, UMTS and LTE can share a number of network elements including core network elements. It is also expected that some of the 3G network elements can be upgraded to support LTE and there will be single network platforms supporting both HSPA and LTE. The subscriber management and Subscriber Identity Module (SIM) based authentication will be used also in LTE; however, in LTE the system access requires the more modern and more secure Universal SIM (USIM) instead of the older 2G originated SIM card.

1.7 Wireless Spectrum

The LTE frequency bands in 3GPP specifications are shown in Figure 1.12 for paired bands and in Figure 1.13 for unpaired bands. There are 17 paired bands and 8 unpaired bands defined currently and more bands will be added during the standardization process. Some bands are currently used by other technologies and LTE can coexist with the legacy technologies. Similarly, in Europe and in Asia, WCDMA was initially deployed in the new 2100 MHz band while the refarming to the existing 900 MHz started during 2007. LTE will likely start by using the new 2600 MHz band and refarming to 900 and 1800 MHz bands. In the best case in Europe there is in total a 565 MHz spectrum available for the mobile operators when including 900 MHz, 1800 MHz, 2100 MHz Frequency Division Duplex (FDD) and Time Division Duplex (TDD) bands and the new 2600 MHz allocation all together.

Operating band	3GPP name	Total spectrum	Uplink [MHz]	Downlink [MHz]
Band 1	2100	2x60 MHz	1920-1980	2110-2170
Band 2	1900	2x60 MHz	1850-1910	1930-1990
Band 3	1800	2x75 MHz	1710-1785	1805-1880
Band 4	1700/2100	2x45 MHz	1710-1755	2110-2155
Band 5	850	2x25 MHz	824-849	869-894
Band 6	800	2x10 MHz	830-840	875-885
Band 7	2600	2x70 MHz	2500-2570	2620-2690
Band 8	900	2x35 MHz	880-915	925-960
Band 9	1700	2x35 MHz	1750-1785	1845-1880
Band 10	1700/2100	2x60 MHz	1710-1770	2110-2170
Band 11	1500	2x25 MHz	1427.9-1452.9	1475.9-1500.9
Band 12	US700	2x18 MHz	698-716	728-746
Band 13	US700	2x10 MHz	777-787	746-756
Band 14	US700	2x10 MHz	788-798	758-768
Band 17	US700	2x10 MHz	704-716	734-746
Band 18	Japan800	2x30 MHz	815-830	860-875
Band 19	Japan800	2x30 MHz	830-845	875-890

Figure 1.12 Frequency bands for paired bands in 3GPP specifications

Operating band	3GPP name	Total spectrum	Uplink and downlink [MHz]
Band 33	UMTS TDD1	1x20 MHz	1900-1920
Band 34	UMTS TDD2	1x15 MHz	2010-2025
Band 35	US1900 UL	1x60 MHz	1850-1910
Band 36	US1900 DL	1x60 MHz	1930-1990
Band 37	US1900	1x20 MHz	1910-1930
Band 38	2600	1x50 MHz	2570-2620
Band 39	UMTS TDD	1x40 MHz	1880-1920
Band 40	2300	1x50 MHz	2300-2400

Figure 1.13 Frequency bands for unpaired bands in 3GPP specifications

In the USA the WCDMA networks have been refarmed to 850 and 1900 MHz. The new frequencies at 1700/2100 are also used for 3G deployment. LTE will be deployed using 700 and 1700/2100 bands, and later refarmed to the existing bands.

In Japan the LTE deployments start using the 2100 band followed later by 800, 1500 and 1700 bands.

Flexible bandwidth is desirable to take advantage of the diverse spectrum assets: refarming typically requires a narrowband option below 5 MHz, while the new spectrum allocations could take benefit of a wideband option up to 20 MHz and higher data rates. It is also evident that both FDD and TDD modes are required to take full benefit of the available paired and unpaired spectrum. These requirements are taken into account in the LTE system specification.

1.8 New Spectrum Identified by WRC-07

The ITU-R World Radiocommunication Conference (WRC-07) worked in October and November 2007 to identify the new spectrum for International Mobile Telecommunications (IMT). The following bands were identified for IMT and are illustrated in Figure 1.14. The target was to identify both low bands for coverage and high bands for capacity.

The main additional coverage band will be in UHF frequencies 470–806/862 MHz that are currently used for terrestrial TV broadcasting. The sub-band 790–862 MHz was identified in Europe and Asia-Pacific. The availability of the band depends on the national time schedules of the analogue to digital TV switchover and it can become widely available within the 2012 to 2015 timeframe. The band allows, for example, three operators each running 10 MHz LTE FDD.

The sub-band 698–806 MHz was identified for IMT in the Americas. In the USA, part of the band has already been auctioned.

The main capacity band will be in 3.4–4.2 GHz (C-band). Total 200 MHz in the sub-band 3.4–3.8 GHz was identified for IMT in Europe and in Asia-Pacific. This spectrum can facilitate the deployment of a larger bandwidth of IMT-Advanced to provide the highest bit rates and capacities.

Additionally, the band 2.3–2.4 GHz was identified for IMT, but this band is not expected to be available in Europe or in the Americas. This band was already identified for IMT-2000 in China at the WRC-2000. The sub-band 450–470 MHz was identified for IMT globally, but it is not expected to be widely available in Europe. This spectrum will be narrow with a maximum 2 × 5 MHz deployment.

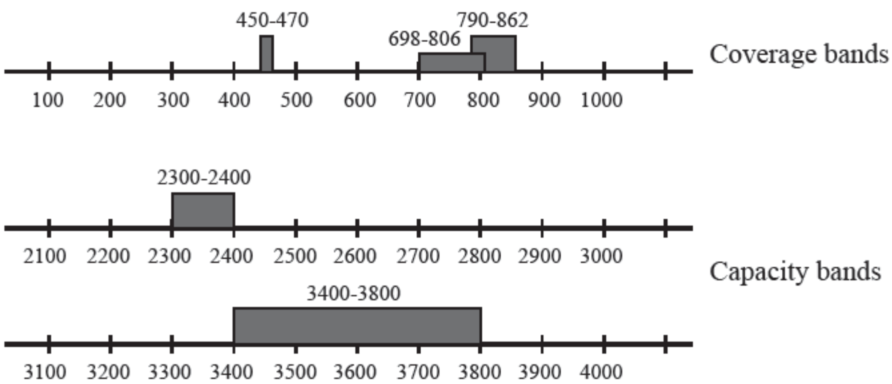


Figure 1.14 Main new frequencies identified for IMT in WRC-07

1.9 LTE-Advanced

International Mobile Telecommunications-Advanced (IMT-Advanced) is a concept for mobile systems with capabilities beyond IMT-2000. IMT-Advanced was previously known as Systems beyond IMT-2000. During 2009, there will be an open call for candidates for IMT-Advanced to be submitted to ITU, as well as the start of assessment activities of candidate technologies and systems. The radio interface submission deadline is expected by October 2009 and the final specifications by 2011.

The new capabilities of these IMT-Advanced systems are envisaged to handle a wide range of supported data rates according to economic and service demands in multi-user environments with target peak data rates of up to approximately 100 Mbps for high mobility and up to 1 Gbps for low mobility such as nomadic/local wireless access. 3GPP has started to work towards IMT-Advanced targets also for the local area radio under the name LTE-Advanced. LTE-Advanced is planned to be part of 3GPP Release 10 and the commercial deployment of IMT-Advanced will be 2013 or later. The high level evolution of 3GPP technologies to meet IMT requirements is shown in Figure 1.15.

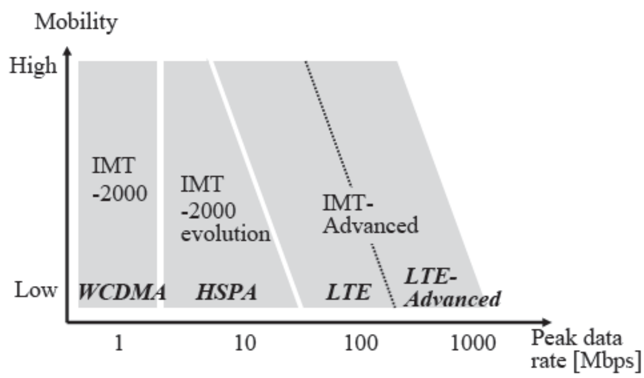


Figure 1.15 Bit rate and mobility evolution to IMT-Advanced

2

LTE Standardization

Antti Toskala

2.1 Introduction

Long Term Evolution (LTE) standardization is being carried out in the 3rd Generation Partnership Project (3GPP), as was also the case for Wideband CDMA (WCDMA), and the later phase of GSM evolution. This chapter introduces first the 3GPP LTE release schedule and the 3GPP standardization process. The requirements set for LTE by the 3GPP community are then reviewed, and the steps foreseen for later LTE Releases, including the LTE-Advanced work for the IMT-Advanced process, are covered. This chapter concludes with the introduction of LTE specifications and 3GPP structure.

2.2 Overview of 3GPP Releases and Process

The 3GPP has a background of 10 years for WCDMA development (or Universal Terrestrial Radio Access, UTRA) since the start of 3GPP in 1998. The major 3GPP releases are shown in Figure 2.1 starting from the first WCDMA release, Release 99, and covering the releases that followed. In Figure 2.1 the releases are shown with the date when the release content was finalized, not

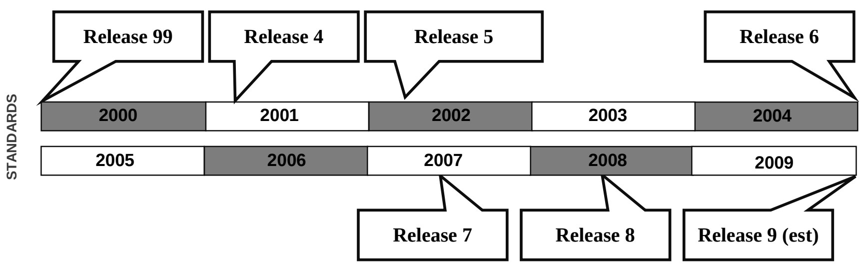


Figure 2.1 3GPP releases schedule with estimated Release 9 closure

LTE for UMTS: OFDMA and SC-FDMA Based Radio Access Edited by Harri Holma and Antti Toskala
 ISBN: 978-0-470-99401-6

the actual protocol freezing date (backwards compatibility start). The first WCDMA release – Release 99 – was published in December 1999 and contained the basic WCDMA features with theoretical data rates up to 2 Mbps, based on the different multiple access for Frequency Division Duplex (FDD) mode and Time Division Duplex (TDD) operation. After that, 3GPP abandoned the yearly release principle and thus release naming was also changed as from Release 4, completed in March 2001. Release 4 did not have many major WCDMA features, but contained the new low chip rate TDD version (TD-SCDMA) for the TDD mode of UTRA. Release 5 followed with High Speed Downlink Packet Access (HSDPA) in March 2002 and Release 6 with High Speed Uplink Packet Access (HSUPA) in December 2004 for WCDMA. Release 7 was completed in June 2007 with the introduction of several HSDPA and HSUPA enhancements. Now 3GPP has just finalized Release 8 (with a few issues pending, for March 2009), which brought along further HSDPA/HSUPA improvements (often referred to jointly as High Speed Packet Access (HSPA) evolution) as well as containing the first LTE Release. The feature content for Release 8 was completed in December 2008. A more detailed description of the WCDMA/HSPA release content can be found in Chapter 13 covering Release 8 and in [1] for the earlier releases.

The earlier 3GPP Releases have a relationship to LTE in Release 8. Several of the novel features adopted – especially with HSDPA and HSUPA – are also used in LTE, such as base station based scheduling with physical layer feedback, physical layer retransmissions and link adaptation. Also, LTE specifications reuse the WCDMA design in areas where it could be carried out without compromising performance, thus facilitating reuse of the design and platforms developed for WCDMA. The first LTE release, Release 8, supports data rates up to 300 Mbps in downlink and up to 75 Mbps in uplink with low latency and flat radio architecture. Release 8 also facilitates radio level inter-working with GSM, WCDMA and cdma2000®.

3GPP is introducing new work items and study items for Release 9, some of them related to features postponed from Release 8 and some of them for new topics raised for Release 9 with the topics introduced in December 2009. Release 9 is scheduled to be completed around the end of 2009. Release 10 is then foreseen to contain further radio capability enhancement in the form of LTE-Advanced, intended to be submitted to ITU-R IMT-Advanced process with data rate capabilities foreseen to range up to 1 Gbps. First Release 10 specifications are expected to be ready at the end of 2010.

The 3GPP process is such that more topics are started than eventually end up in the specifications. Often a study is initially carried out for more complicated issues, as was the case with LTE. Typically during a study, more alternatives are looked at than the small set of features that eventually enter a specification. Sometimes a study is completed with the finding that there is not enough gain to justify the added complexity in the system. A change requested in the work item phase could also be rejected for this same reason. The 3GPP process starting from a study item is shown in Figure 2.2.

2.3 LTE Targets

At the start of the work during the first half 2005, the 3GPP defined the requirements for LTE development. The key elements included in the target setting for the LTE feasibility study work, as defined in [2], were as follows:

- The LTE system should be packet switched domain optimized. This means that circuit switched elements are not really considered, but everything is assumed to be based on a

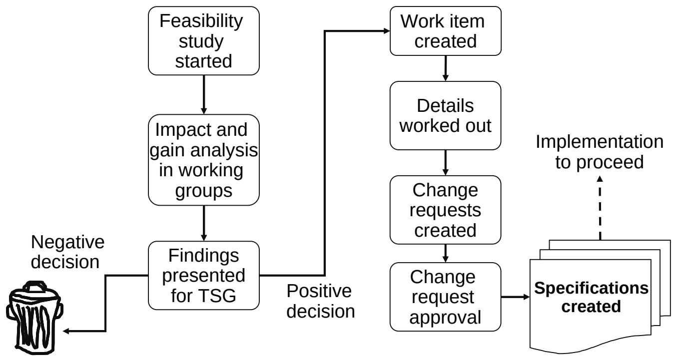


Figure 2.2. 3GPP process for moving from study towards work item and specification creation

packet type of operation. The system was required to support IP Multimedia Sub-system (IMS) and further evolved 3GPP packet core.

- As the data rates increase, latency needs to come down for the data rates to show any practical improvement. Thus the requirement for the LTE radio round trip time was set to be below 10 ms and access delay below 300 ms.
- The requirements for the data rates were defined to ensure sufficient steps in terms of data rates in contrast to HSPA. The peak rate requirements for uplink and downlink were set at 50 Mbps and 100 Mbps respectively.
- As the 3GPP community was used to a good level of security and mobility with the earlier systems – starting from GSM – it was also a natural requirement that these should be sustained. This also included inter-system mobility with GSM and WCMA, as well as cdma2000®, since there was (and is) a major interest in the cdma2000® community to evolve to LTE for next generation networks.
- With WCDMA, one of the topics that had caused challenges – especially in the beginning – was terminal power consumption, thus it was required to improve terminal power efficiency.
- In the 3GPP technology family there were both a narrowband system (GSM with 200 kHz) and a wideband system (WCDMA with 5 MHz). Thus it was now required that the new system facilitate frequency allocation flexibility with 1.25/2.5, 5, 10, 15 and 20 MHz allocations. Later during the course of work, the actual bandwidth values were slightly adjusted for the two smallest bandwidths (to use 1.4 and 3 MHz bandwidths) to give a good match for both GSM and cdma2000® refarming cases. The possibility of using LTE in a deployment with WCDMA or GSM as the system on the adjacent band was also required.
- The 'standard' requirement for any new system is also to have higher capacity. The benchmark level chosen was 3GPP Release 6, which had a stable specification and a known performance at the time. Thus Release 6 was a stable comparison level for running the LTE performance simulations during the feasibility study phase. Depending on the case, 2- to 4-times higher capacity than provided with the Release 6 HSDPA/HSUPA reference case, was required.
- One of the drivers for the work was cost, to ensure that the new system could facilitate lower investment and operating costs compared to the earlier system. This was a natural result of the flat rate charging model appearing at the time for data use and created pressure for the price vs data volume level.

It was also expected that further development of WCDMA would continue in parallel with the LTE activity, and this has been also carried out with the Release 8 HSPA improvements, as covered in Chapter 13.

2.4 LTE Standardization Phases

LTE work was started as a study in the 3GPP, with the first workshop held in November 2004 in Canada. In the workshop the first presentations were on both the expected requirements for the work and the expected technologies to be adopted. Contributions were made from both operator and vendor viewpoints.

Following the workshop, 3GPP TSG RAN approved the start of the study for LTE in December 2004, with the work first running in the RAN plenary level to define the requirements and then moving to the working groups for detailed technical discussions for multiple access, protocol solutions and architecture. The first key issues to be resolved were what the requirements are, as discussed in section 2.3, and these were mainly settled during the first half of 2005, visible in [2], with the first approved version in June 2005. Then the work focused on solving two key questions:

- What should be the LTE radio technology in terms of multiple access?
- What should be the system architecture?

The multiple access discussion was soon concluded with the finding that something new was needed instead of just extending WCDMA. This conclusion was the result of the large range of requirements for covering different bandwidths and data rates with reasonable complexity. The use of Orthogonal Frequency Division Multiple Access (OFDMA) in the downlink was obvious early on, and had already been reflected in many of the presentations in the original LTE workshop in 2004. For the uplink multiple access, the Single Carrier Frequency Division Multiple Access (SC-FDMA) soon emerged as the most favourable choice that was supported by many key vendors and operators, as could be seen, for example, in [3]. A noticeable improvement from the WCDMA was that both FDD and TDD modes had the same multiple access solution, as addressed for the FDD and TDD differences in Chapter 12. The OFDMA and SC-FDMA principles and motivational aspects are further covered in Chapter 4. The multiple access decision was officially endorsed at the end of 2005 and after that the LTE radio work focused on the chosen technologies. The LTE milestones are shown in Figure 2.3. The FDD/TDD alignment refers to the agreement on

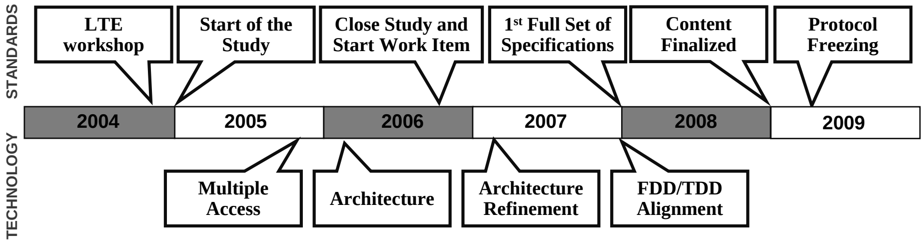


Figure 2.3 LTE milestones in 3GPP

the adjustment of the frame structure to minimize the differences between FDD and TDD modes of operation.

In the area of LTE architecture, after some debate it was decided to aim for a single node RAN, resulting in all radio related functionality being placed in the base station. This time the term used in 3GPP became eNodeB, with 'e' standing for evolved. The original architecture split, as shown in Figure 2.4, was endorsed in March 2006 with a slight adjustment carried out in early 2007 (with the Packet Data Convergence Protocol (PDCP) shifted from core network side to eNodeB). The fundamental difference to the WCDMA network was the lack of the Radio Network Controller (RNC) type of an element. The architecture is further described in Chapter 3.

The study also evaluated the resulting LTE capacity, and the studies reported in [4] and further refined studies summarized in [5] show that the requirements could be reached.

The study item was closed formally in September 2006 and detailed work items started to make the LTE part of the 3GPP Release 8 specifications.

The LTE specification work produced the first set of approved physical layer specifications in September 2007 and the first full set of approved LTE specifications in December 2007. Clearly there were open issues in the specifications at that time, especially in the protocol specifications and in the area of performance requirements. The remaining specification freezing process could be divided into three different steps:

1 Freezing the functional content of the LTE specifications in terms of what will be finalized in Release 8. This has meant leaving out some of the originally planned functionality such as support for broadcast use (point to multipoint data broadcasting). Functional freeze thus means that no new functionality can be introduced anymore but the agreed content will be finalized. In LTE the introduction of new functionality was basically over after June 2008 and during the rest of 2008 the work focused on completing the missing pieces (and correcting detected errors), especially in the protocol specifications, mainly completed for December 2008.

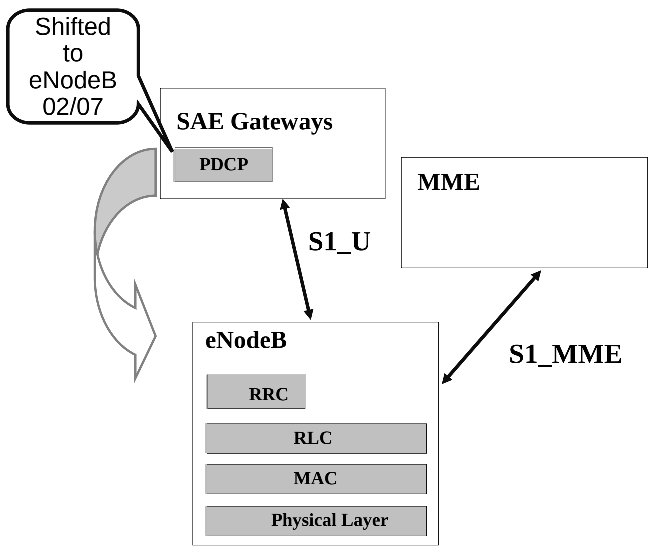


Figure 2.4 Original network architecture for LTE radio protocols

2 Once all the content is ready, the next step is to freeze the protocol specifications in terms of starting backwards compatibility. Backwards compatibility defines for a protocol the first version which can be the commercial implementation baseline. Until backwards compatibility is started, the protocol specifications are corrected by deleting any information elements that are not working as intended and replacing them with new ones. Once the start of backwards compatibility is reached, older information elements are no longer removed but extensions are used. This allows the equipment based on the older version to work based on the old information elements (though not necessarily 100% optimally), while equipment with newer software can read the improved/corrected information element after noticing the extension bit being set. Obviously, core functionality needs to work properly so that the start of backwards compatibility makes sense, as if something is totally wrong, fixing it with backwards compatible correction does not help older software versions if there is no operational functionality. It is planned to reach this step with 3GPP Release 8 protocol specifications in March 2009 when the protocol language, Abstract Syntax Notation One (ASN.1), related review for debugging all the errors is completed. With Release 7 specifications (containing HSPA improvements) this phase was reached in December 2007 following the content completion in June 2007.

3 The last phase is 'deep' freeze of the specifications, when any changes to the specifications will no longer be allowed. This is something that is valid for a release that is already rolled out in the field, such as Release 5 with HSDPA and Release 6 with HSUPA. With the devices out in the field, core functionality has been proven and tested and there is no point in any further changes to those releases, but potential improvement would need to be carried out in a later release. This kind of problem may arise when some feature has not been implemented (and thus no testing with the network has been possible) and the problem is only detected later. Then the resulting outcome could be to correct it in a later release and also recommend that the network activates it only for devices which are based on this later release. For LTE specifications, this phase is expected to be just before the actual roll-out, in a 2010 time frame, as typically some errors are detected in the implementation and trialling phase.

2.5 Evolution Beyond Release 8

The work in 3GPP during 2008 focused on Release 8 finalization, but work was started for issues beyond Release 8, including the first Release 9 topics as well as LTE-Advanced for IMT-Advanced. The following topics have been decided in 3GPP to be considered beyond Release 8:

- LTE MBMS, which is expected to cover the operation of broadcast type data both for a dedicated MBMS carrier and for a shared carrier. When synchronized properly, an OFDMA based broadcast signal can be sent in the same resource space from different base stations (with identical content) and then the signal from multiple base stations can be combined in the devices. This principle is already in use in, for example, Digital Video Broadcasting for Handhelds (DVB-H) devices in the market. DVB-H is also an OFDMA based system but only intended for broadcast use.
- Self Optimized Networks (SON) enhancements. 3GPP has worked on the self optimization/configuration aspects of LTE and that work is expected to continue in Release 9.
- Further improvements for enhanced VoIP support in LTE. In the discussions in 3GPP, it has been identified that VoIP could be further optimized to improve the maximum number

of VoIP users that could be supported simultaneously. The current capability is rather high already, as shown in Chapter 10.

- The requirements for the multi-bandwidth and multi-radio access technology base stations. The scope of this work is to define the requirements for the operation so that the same Radio Frequency (RF) part is used for transmitting, for example, LTE and GSM or LTE and WCDMA signals. Currently the requirements for the emissions on the adjacent frequencies, for example, take only a single Radio Access Technology (RAT) into account, while the requirements will now be developed for different combinations, including running multiple LTE bandwidths in parallel in addition to the multi-RAT case.

2.6 LTE-Advanced for IMT-Advanced

In parallel to the work for LTE corrections and further optimization in Release 9, the 3GPP is also targeting the creation of the input for the IMT-Advanced process in ITU-R. The ITU-R is developing the framework for next generation wireless networks. The following are the requirements from the ITU-R side for the IMT-Advanced candidate technologies, as reflected in details in the information available from ITU-R, accessible via the links given in [6]:

- support for peak data rates up to 1 Gbps for nomadic (low mobility case) and 100 Mbps for the high mobility case;
- support for larger bandwidths, and thus also 3GPP is considering specifying up to 100 MHz bandwidth support for LTE-Advanced;
- requirements for the expected spectral efficiency in different environments. In ITU-R requirements these are defined as minimum requirements and are thus different from the target type of value setting in 3GPP.

3GPP thus also has its own requirements, with the first version of the requirements approved in May 2008 as reflected in [7]. One of the 3GPP specific requirements is the backwards compatibility from the 3GPP Release 8 LTE. The requirement is defined so that a Release 8 based LTE device can operate in the LTE-Advanced system and, respectively, the Release 10 LTE Advanced device can access the Release 8 LTE networks. Obviously a Release 9 terminal would also be similarly accommodated. This could be covered, for example, with the multicarrier type of alternative as shown in Figure 2.5. The mobility between LTE-Advanced needs to work with LTE as well as GSM/EDGE, HSPA and cdma2000®.

The ITU-R process, as shown in Figure 2.6, aims for early 2011 completion of the ITU-R specifications, which requires 3GPP to submit the first full set of specifications around the end of 2010. This is one of the factors shaping the Release 10 finalization schedule, though officially the Release 10 schedule has not yet been defined in 3GPP, but will be discussed further once Release 9 work has progressed further.

3GPP has held a number of discussions on LTE-Advanced during 2008, and the technologies to be investigated include:

- Relay nodes. These are targeted for extending coverage by allowing User Equipment (UE) further away from the base station to send their data via relay nodes that can hear the eNodeB better than, for example, UE located indoors.

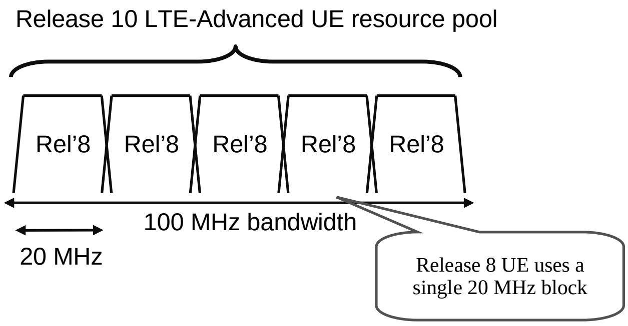


Figure 2.5 Resource sharing between LTE and LTE-Advanced

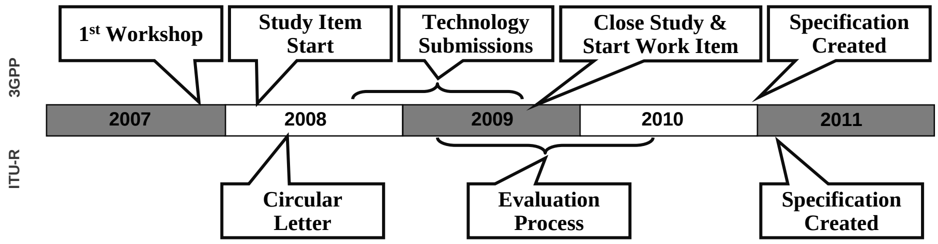


Figure 2.6 3GPP LTE-Advanced and ITU-R IMT-Advanced schedules

- UE dual transmit antenna solutions for uplink Single User MIMO (SU-MIMO) and diversity MIMO.
- Scalable system bandwidth exceeding 20 MHz, potentially up to 100 MHz. In connection with this the study has been investigating aspects related to multiple access technology with up to 100 MHz system bandwidth, and it is foreseen to be based strongly on the existing LTE solutions with extensions to larger bandwidths. How to extend the bandwidth (and how that is reflected in the multiple access) is the first topic where conclusions are expected in LTE-Advanced studies.
- Nomadic/Local Area network and mobility solutions.
- Flexible Spectrum Usage.
- Automatic and autonomous network configuration and operation.
- Coordinated Multiple Point (CoMP) transmission and reception, which is referring to MIMO transmission coordinated between different transmitters (in different sectors or even different sites in an extreme case).

It is worth noting that even though some technology is being studied, it does not necessarily mean that it will be included in the Release 10 specifications. It may be decided that some issues are already needed for Release 9 (scheduled for the end of 2009), while other issues may not be necessary at all due to low gain and/or high complexity. The 3GPP study will be completed in the second half of 2009 and then work towards the actual specifications of Release 10 will start. Some of the items from the LTE-Advanced studies are also expected to be postponed to beyond Release 10.

The process in ITU-R is open for other RAT submissions as well. Similarly, as was the case in the original IMT-2000 process, multiple RAT submissions are expected to be made available for the evaluation phase. Assuming those submissions can meet the IMT-Advanced minimum requirements, the RATs submitted are then expected to be part of the IMT-Advanced family.

2.7 LTE Specifications and 3GPP Structure

The LTE specifications mostly follow similar notation to that of the WCDMA specifications, just using the 36-series numbering. For example, when WCDMA RRC is 25.331, the corresponding LTE spec is 36.331. The LTE specifications use the term Evolved Universal Terrestrial Radio Access (E-UTRA) while the WCDMA specifications use the UTRA term (and UTRAN with N standing for Network). The terms LTE and E-UTRAN, as well as WCDMA and UTRA, are used interchangeably in the book. In the physical layer there are some differences, e.g. the specification on spreading and modulation was not needed, such as WCDMA specification 25.213. Now due to use of the same multiple access, the FDD and TDD modes are covered in the same physical layer specification series. In Figure 2.7 the specification numbers are shown for the physical layer and different protocols over the radio or internal interfaces. Note that not all the performance related specifications are shown. The following chapters will introduce the functionality in each of the interfaces shown in Figure 2.7. All the specifications listed are available from the 3GPP website [8]. When using a 3GPP specification it is always recommended that the latest version of the release in question is used. For example, version 8.0.0 is always the first approved version and versions with the number 8.4.0 (or higher) are normally more stable with fewer errors.

Inside 3GPP, the 3GPP TSG RAN is responsible for LTE specification development. The detailed specification work is covered in the Working Groups (WGs) under each TSG. TSG RAN has a total of five working groups, as shown in Figure 2.8, where working groups under other TSGs are not shown. The specifications for the Evolved Packet Core (EPC) are covered in TSA SA and in TSG CT and are also needed for an end-to-end functioning system. The TSG GERAN is responsible for the necessary Release 8 changes in GSM/EDGE specifications to facilitate the LTE-GERAN inter-working from the GERAN perspective.

From the RAN working groups the physical layer specifications 36.2 series are developed by WG1, as shown in Figure 2.8. Respectively, the Layer 2 (L2) and Layer 3 (L3) specifica-

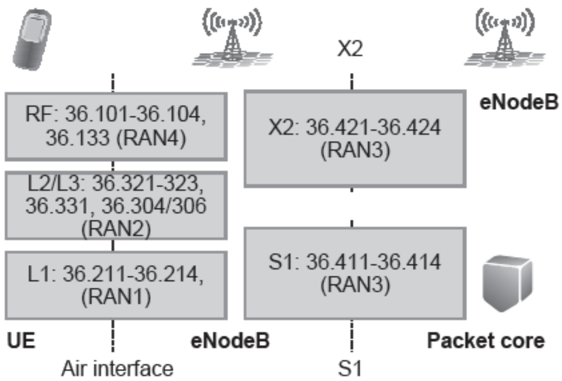


Figure 2.7. Specifications with responsible working groups for different LTE interfaces

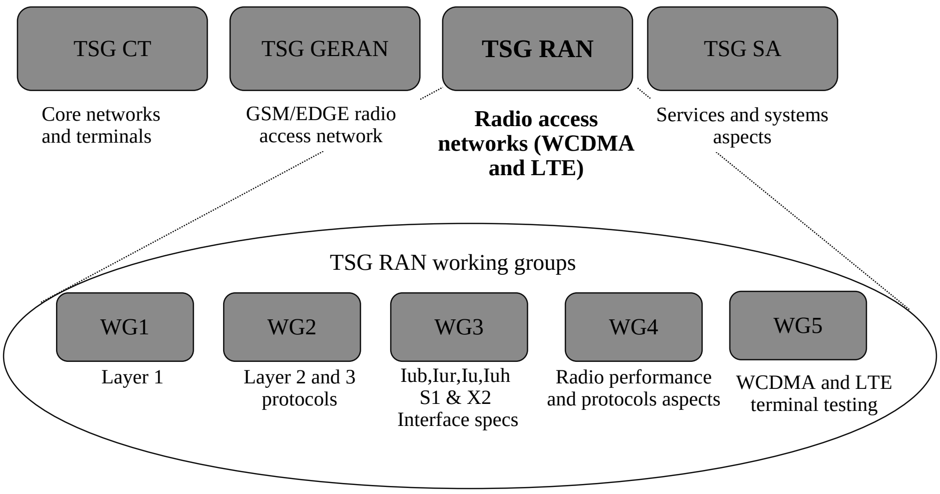


Figure 2.8 3GPP structure

tions are in the 36.3 series from WG2, internal interfaces in the 36.4 series from WG3, and radio performance requirements in the 36.1 series from WG4. Outside Figure 2.7 can be noted the LTE terminal test specifications from WG5. All groups cover the respective areas also for WCDMA/HSPA further releases as well.

References

[1] H.Holma, A.Toskala, 'WCDMA for UMTS', 4th edition, Wiley 2007.

[2] 3GPP Technical Report, TR 25.913, 'Requirements for Evolved UTRA (E-UTRA) and Evolved UTRAN (E-UTRAN)' version 7.0.0, June 2005.

[3] 3GPP Tdoc, RP-050758, LS on UTRAN LTE Multiple Access Selection, 3GPP TSG RAN WG1, November 2005.

[4] 3GPP Technical Report, TR 25.814, 'Physical layer aspects for evolved Universal Terrestrial Radio Access (UTRA)', 3GPP TSG RAN, September 2006,

[5] 3GPP Tdoc, RP-060535, LS on LTE SI Conclusions, 3GPP TSG RAN WG1, September 2006.

[6] 3GPP Tdoc, RP-080448, 'Receipt of ITU-R Circular Letter 5/LCCE/2 on IMT-Advanced', May 2008.

[7] 3GPP Technical Report, TR 36.913, 'Requirements for Further Advancements for E-UTRA (LTE-Advanced)', 3GPP TSG RAN, version 8.0.0, May 2008.

[8] www.3gpp.org

3

System Architecture Based on 3GPP SAE

Atte Länsisalmi and Antti Toskala

3.1 System Architecture Evolution in 3GPP

When the evolution of the radio interface started, it soon became clear that the system architecture would also need to be evolved. The general drive towards optimizing the system only for packet switched services is one reason that alone would have set the need for evolution, but some of the radio interface design goals – such as removal of soft handover – opened up new opportunities in the architecture design. Also, since it had been shown by High Speed Packet Access (HSPA) that all radio functionality can be efficiently co-located in the NodeB, the door was left open for discussions of flatter overall architecture.

Discussions for System Architecture Evolution (SAE) then soon followed the radio interface development, and it was agreed to schedule the completion of the work in Release 8. There had been several reasons for starting this work, and there were also many targets. The following lists some of the targets that possibly shaped the outcome the most:

- optimization for packet switched services in general, when there is no longer a need to support the circuit switched mode of operation;
- optimized support for higher throughput required for higher end user bit rates;
- improvement in the response times for activation and bearer set-up;
- improvement in the packet delivery delays;
- overall simplification of the system compared to the existing 3GPP and other cellular systems;
- optimized inter-working with other 3GPP access networks;
- optimized inter-working with other wireless access networks.

Many of the targets implied that a flat architecture would need to be developed. Flat architecture with less involved nodes reduces latencies and improves performance. Development

LTE for UMTS: OFDMA and SC-FDMA Based Radio Access Edited by Harri Holma and Antti Toskala
 ISBN: 978-0-470-99401-6

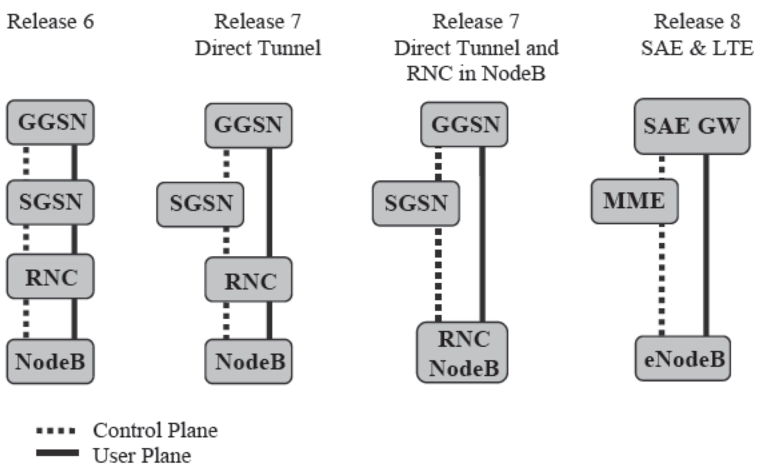


Figure 3.1 3GPP architecture evolution towards flat architecture

towards this direction had already started in Release 7 where the Direct Tunnel concept allows User Plane (UP) to bypass the SGSN, and the placement of RNC functions to HSPA NodeB was made possible. Figure 3.1 shows these evolution steps and how this aspect was captured at a high level in SAE architecture.

Some of the targets seem to drive the architecture development in completely different directions. For example, optimized inter-working with several wireless access networks (ANs) indicates the need to introduce a set of new functions and maybe even new interfaces to support specific protocols separately for each one of them. This works against the target of keeping the architecture simple. Therefore, since it is likely that that none of the actual deployments of the architecture would need to support all of the potential inter-working scenarios, the 3GPP architecture specifications were split into two tracks:

- GPRS enhancements for E-UTRAN access [1]: This document describes the architecture and its functions in its native 3GPP environment with E-UTRAN and all the other 3GPP ANs, and defines the inter-working procedures between them. The common nominator for these ANs is the use of GTP (GPRS Tunnelling Protocol) as the network mobility protocol.
- Architecture enhancements for non-3GPP accesses [2]: This document describes the architecture and functions when inter-working with non-3GPP ANs, such as cdma2000® High Rate Packet Data (HRPD), is needed. The mobility functionality in this document is based on IETF protocols, such as MIP (Mobile Internet Protocol) and PMIP (Proxy MIP), and the document also describes E-UTRAN in that protocol environment.

This chapter further describes the 3GPP system architecture in some likely deployment scenarios: basic scenario with only E-UTRAN, legacy 3GPP operator scenario with existing 3GPP ANs and E-UTRAN, and finally E-UTRAN with non-3GPP ANs, where inter-working with cdma2000® is shown as a specific example.

3.2 Basic System Architecture Configuration with only E-UTRAN Access Network

3.2.1 Overview of Basic System Architecture Configuration

Figure 3.2 describes the architecture and network elements in the architecture configuration where only the E-UTRAN AN is involved. The logical nodes and connections shown in this figure represent the basic system architecture configuration. These elements and functions are needed in all cases when E-UTRAN is involved. The other system architecture configurations described in the next sections also include some additional functions.

This figure also shows the division of the architecture into four main high level domains: User Equipment (UE), Evolved UTRAN (E-UTRAN), Evolved Packet Core Network (EPC), and the Services domain.

The high level architectural domains are functionally equivalent to those in the existing 3GPP systems. The new architectural development is limited to Radio Access and Core Networks, the E-UTRAN and the EPC respectively. UE and Services domains remain architecturally intact, but functional evolution has also continued in those areas.

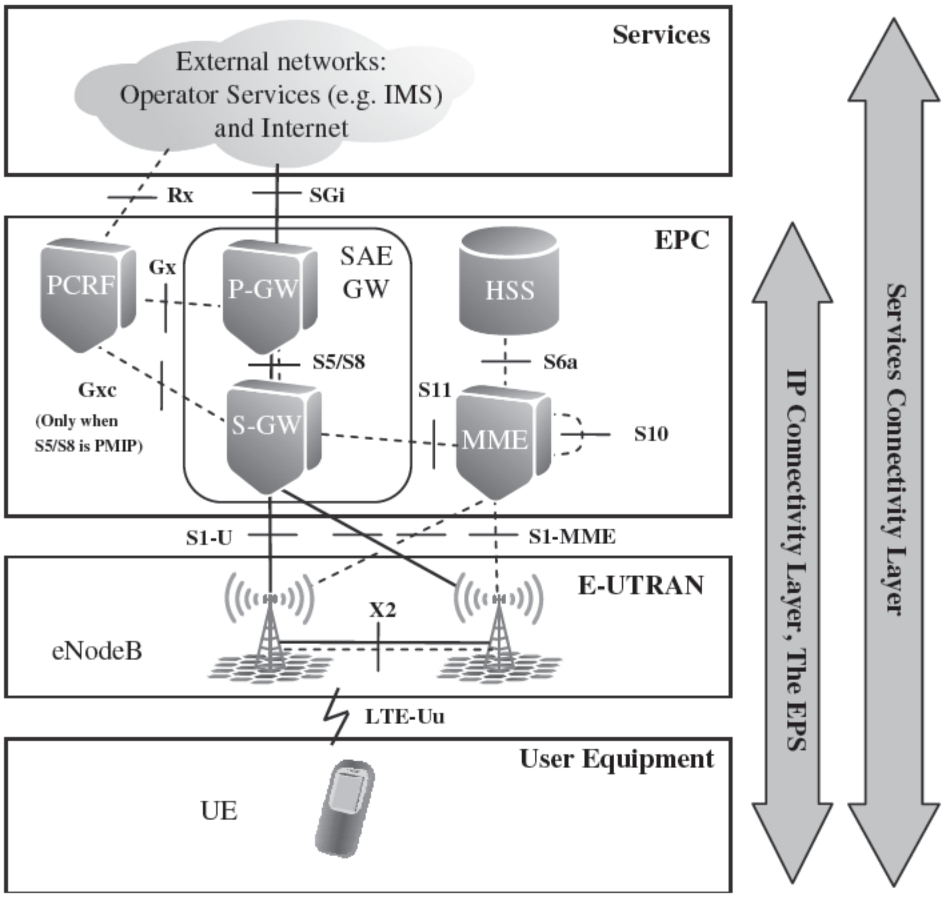


Figure 3.2 System architecture for E-UTRAN only network

UE, E-UTRAN and EPC together represent the Internet Protocol (IP) Connectivity Layer. This part of the system is also called the Evolved Packet System (EPS). The main function of this layer is to provide IP based connectivity, and it is highly optimized for that purpose only. All services will be offered on top of IP, and circuit switched nodes and interfaces seen in earlier 3GPP architectures are not present in E-UTRAN and EPC at all. IP technologies are also dominant in the transport, where everything is designed to be operated on top of IP transport.

The IP Multimedia Sub-System (IMS) [3] is a good example of service machinery that can be used in the Services Connectivity Layer to provide services on top of the IP connectivity provided by the lower layers. For example, to support the voice service, IMS can provide Voice over IP (VoIP) and interconnectivity to legacy circuit switched networks PSTN and ISDN through Media Gateways it controls.

The development in E-UTRAN is concentrated on one node, the evolved Node B (eNodeB). All radio functionality is collapsed there, i.e. the eNodeB is the termination point for all radio related protocols. As a network, E-UTRAN is simply a mesh of eNodeBs connected to neighbouring eNodeBs with the X2 interface.

One of the big architectural changes in the core network area is that the EPC does not contain a circuit switched domain, and no direct connectivity to traditional circuit switched networks such as ISDN or PSTN is needed in this layer. Functionally the EPC is equivalent to the packet switched domain of the existing 3GPP networks. There are, however, significant changes in the arrangement of functions and most nodes and the architecture in this part should be considered to be completely new.

Both Figure 3.1 and Figure 3.2 show an element called SAE GW. As the latter figure indicates, this represents the combination of the two gateways, Serving Gateway (S-GW) and Packet Data Network Gateway (P-GW) defined for the UP handling in EPC. Implementing them together as the SAE GW represents one possible deployment scenario, but the standards define the interface between them, and all operations have also been specified for when they are separate. The same approach is followed in this chapter of the book.

The Basic System Architecture Configuration and its functionality are documented in 3GPP TS 23.401 [1]. This document shows the operation when the S5/S8 interface uses the GTP protocol. However, when the S5/S8 interface uses PMIP, the functionality for these interfaces is slightly different, and the Gxc interface also is needed between the Policy and Charging Resource Function (PCRF) and S-GW. The appropriate places are clearly marked in [1] and the additional functions are described in detail in 3GPP TS 23.402 [2]. In the following sections the functions are described together for all cases that involve E-UTRAN.

3.2.2 Logical Elements in Basic System Architecture Configuration

This section introduces the logical network elements for the Basic System Architecture configuration.

3.2.2.1 User Equipment (UE)

UE is the device that the end user uses for communication. Typically it is a hand held device such as a smart phone or a data card such as those used currently in 2G and 3G, or it could be embedded, e.g. to a laptop. UE also contains the Universal Subscriber Identity Module (USIM) that is a separate module from the rest of the UE, which is often called the Terminal Equipment (TE). USIM is an application placed into a removable smart card called the Universal Integrated Circuit Card (UICC). USIM is used to identify and authenticate the user and to derive security keys for protecting the radio interface transmission.

Functionally the UE is a platform for communication applications, which signal with the network for setting up, maintaining and removing the communication links the end user needs. This includes mobility management functions such as handovers and reporting the terminals location, and in these the UE performs as instructed by the network. Maybe most importantly, the UE provides the user interface to the end user so that applications such as a VoIP client can be used to set up a voice call.

3.2.2.2 E-UTRAN Node B (eNodeB)

The only node in the E-UTRAN is the E-UTRAN Node B (eNodeB). Simply put, the eNodeB is a radio base station that is in control of all radio related functions in the fixed part of the system. Base stations such as eNodeB are typically distributed throughout the networks coverage area, each eNodeB residing near the actual radio antennas.

Functionally eNodeB acts as a layer 2 bridge between UE and the EPC, by being the termination point of all the radio protocols towards the UE, and relaying data between the radio connection and the corresponding IP based connectivity towards the EPC. In this role, the eNodeB performs ciphering/deciphering of the UP data, and also IP header compression/decompression, which means avoiding repeatedly sending the same or sequential data in IP header.

The eNodeB is also responsible for many Control Plane (CP) functions. The eNodeB is responsible for the Radio Resource Management (RRM), i.e. controlling the usage of the radio interface, which includes, for example, allocating resources based on requests, prioritizing and scheduling traffic according to required Quality of Service (QoS), and constant monitoring of the resource usage situation.

In addition, the eNodeB has an important role in Mobility Management (MM). The eNodeB controls and analyses radio signal level measurements carried out by the UE, makes similar measurements itself, and based on those makes decisions to handover UEs between cells. This includes exchanging handover signalling between other eNodeBs and the MME. When a new UE activates under eNodeB and requests connection to the network, the eNodeB is also responsible for routing this request to the MME that previously served that UE, or selecting a new MME, if a route to the previous MME is not available or routing information is absent.

Details of these and other E-UTRAN radio interface functions are described extensively elsewhere in this book. The eNodeB has a central role in many of these functions.

Figure 3.3 shows the connections that eNodeB has to the surrounding logical nodes, and summarizes the main functions in these interfaces. In all the connections the eNodeB may be in a one-to-many or a many-to-many relationship. The eNodeB may be serving multiple UEs at its coverage area, but each UE is connected to only one eNodeB at a time. The eNodeB will need to be connected to those of its neighbouring eNodeBs with which a handover may need to be made.

Both MMEs and S-GWs may be pooled, which means that a set of those nodes is assigned to serve a particular set of eNodeBs. From a single eNodeB perspective this means that it may need to connect to many MMEs and S-GWs. However, each UE will be served by only one MME and S-GW at a time, and the eNodeB has to keep track of this association. This associa-

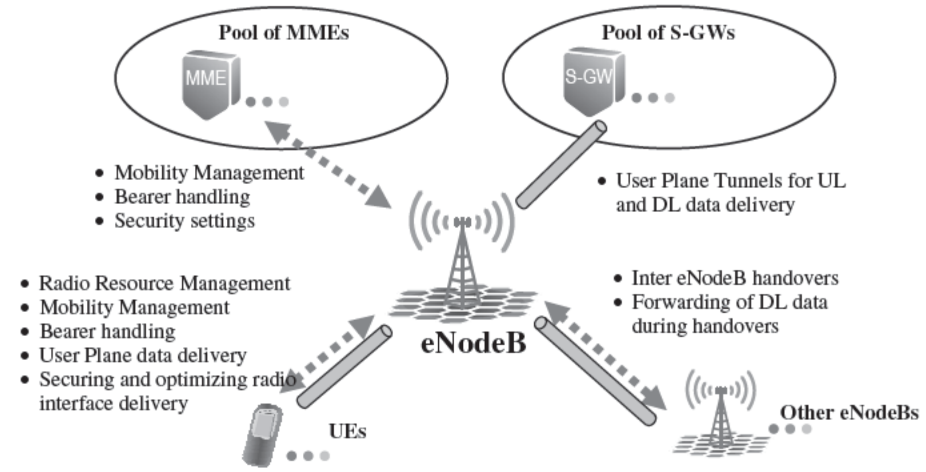


Figure 3.3 eNodeB connections to other logical nodes and main functions

tion will never change from a single eNodeB point of view, because MME or S-GW can only change in association with inter-eNodeB handover.

3.2.2.3 Mobility Management Entity (MME)

Mobility Management Entity (MME) is the main control element in the EPC. Typically the MME would be a server in a secure location in the operator's premises. It operates only in the CP, and is not involved in the path of UP data.

In addition to interfaces that terminate to MME in the architecture as shown in Figure 3.2, the MME also has a logically direct CP connection to the UE, and this connection is used as the primary control channel between the UE and the network. The following lists the main MME functions in the basic System Architecture Configuration:

- Authentication and Security: When a UE registers to the network for the first time, the MME initiates the authentication, by performing the following: it finds out the UE's permanent identity either from the previously visited network or the UE itself; requests from the Home Subscription Server (HSS) in UE's home network the authentication vectors which contain the authentication challenge – response parameter pairs; sends the challenge to the UE; and compares the response received from the UE to the one received from the home network. This function is needed to assure that the UE is who it claims to be. The details of EPS-AKA authentication are defined in [4]. The MME may repeat authentication when needed or periodically. The MME will calculate UEs ciphering and integrity protection keys from the master key received in the authentication vector from the home network, and it controls the related settings in E-UTRAN for UP and CP separately. These functions are used to protect the communication from eavesdropping and from alteration by unauthorized third parties respectively. To protect the UE privacy, MME also allocates each UE a temporary identity called the Globally Unique Temporary Identity (GUTI), so that the need to send the permanent UE identity – International Mobile Subscriber Identity (IMSI) – over the radio interface is minimized. The GUTI may be re-allocated, e.g. periodically to prevent unauthorized UE tracking.

- Mobility Management: The MME keeps track of the location of all UEs in its service area. When a UE makes its first registration to the network, the MME will create an entry for the UE, and signal the location to the HSS in the UE's home network. The MME requests the appropriate resources to be set up in the eNodeB, as well as in the S-GW which it selects for the UE. The MME will then keep tracking the UE's location either on the level of eNodeB, if the UE remains connected, i.e. is in active communication, or at the level of Tracking Area (TA), which is a group of eNodeBs in case the UE goes to idle mode, and maintaining a through connected data path is not needed. The MME controls the setting up and releasing of resources based on the UE's activity mode changes. The MME also participates in control signalling for handover of an active mode UE between eNodeBs, S-GWs or MMEs. MME is involved in every eNodeB change, since there is no separate Radio Network Controller to hide most of these events. An idle UE will report its location either periodically, or when it moves to another Tracking Area. If data are received from the external networks for an idle UE, the MME will be notified, and it requests the eNodeBs in the TA that is stored for the UE to page the UE.
- Managing Subscription Profile and Service Connectivity: At the time of a UE registering to the network, the MME will be responsible for retrieving its subscription profile from the home network. The MME will store this information for the duration it is serving the UE. This profile determines what Packet Data Network connections should be allocated to the UE at network attachment. The MME will automatically set up the default bearer, which gives the UE the basic IP connectivity. This includes CP signalling with the eNodeB, and the S-GW. At any point later on, the MME may need to be involved in setting up dedicated bearers for services that benefit from higher treatment. The MME may receive the request to set up a dedicated bearer either from the S-GW if the request originates from the operator service domain, or directly from the UE, if the UE requires a connection for a service that is not known by the operator service domain, and therefore cannot be initiated from there.

Figure 3.4 shows the connections MME has to the surrounding logical nodes, and summarizes the main functions in these interfaces. In principle the MME may be connected to any other MME in the system, but typically the connectivity is limited to one operator network only. The remote connectivity between MMEs may be used when a UE that has travelled far away while powered down registers to a new MME, which then retrieves the UE's permanent identity, the International Mobile Subscriber Identity (IMSI), from the previously visited MME. The inter-MME connection with neighbouring MMEs is used in handovers.

Connectivity to a number of HSSs will also need to be supported. The HSS is located in each user's home network, and a route to that can be found based on the IMSI. Each MME will be configured to control a set of S-GWs and eNodeBs. Both the S-GWs and eNodeBs may also be connected to other MMEs. The MME may serve a number of UEs at the same time, while each UE will only connect to one MME at a time.

3.2.2.4 Serving Gateway (S-GW)

In the Basic System Architecture configuration, the high level function of S-GW is UP tunnel management and switching. The S-GW is part of the network infrastructure maintained centrally in operation premises.

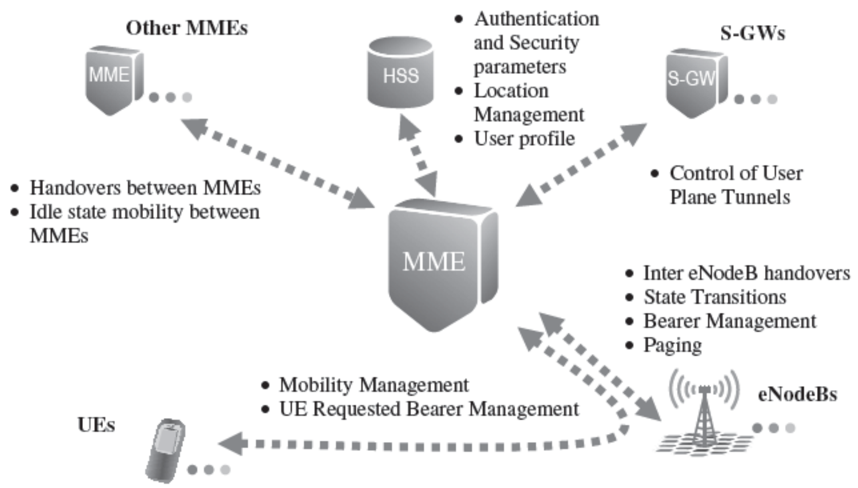


Figure 3.4 MME connections to other logical nodes and main functions

When the S5/S8 interface is based on GTP, the S-GW will have GTP tunnels on all its UP interfaces. Mapping between IP service flows and GTP tunnels is done in P-GW, and the S-GW does not need to be connected to PCRF. All control is related to the GTP tunnels, and comes from either MME or P-GW. When the S5/S8 interface uses PMIP, the S-GW will perform the mapping between IP service flows in S5/S8 and GTP tunnels in S1-U interfaces, and will connect to PCRF to receive the mapping information.

The S-GW has a very minor role in control functions. It is only responsible for its own resources, and it allocates them based on requests from MME, P-GW or PCRF, which in turn are acting on the need to set up, modify or clear bearers for the UE. If the request was received from P-GW or PCRF, the S-GW will also relay the command on to the MME so that it can control the tunnel to eNodeB. Similarly, when the MME initiated the request, the S-GW will signal on to either the P-GW or the PCRF, depending on whether S5/S8 is based on GTP or PMIP respectively. If the S5/S8 interface is based on PMIP, the data in that interface will be IP flows in one GRE tunnel for each UE, whereas in the GTP based S5/S8 interface each bearer will have its own GTP tunnel. Therefore S-GW supporting PMIP S5/S8 is responsible for bearer binding, i.e. mapping the IP flows in S5/S8 interface to bearers in the S1 interface. This function in S-GW is called Bearer Binding and Event Reporting Function (BBERF). Irrespective of where the bearer signalling started, the BBERF always receives the bearer binding information from PCRF.

During mobility between eNodeBs, the S-GW acts as the local mobility anchor. The MME commands the S-GW to switch the tunnel from one eNodeB to another. The MME may also request the S-GW to provide tunnelling resources for data forwarding, when there is a need to forward data from source eNodeB to target eNodeB during the time UE makes the radio handover. The mobility scenarios also include changing from one S-GW to another, and the MME controls this change accordingly, by removing tunnels in the old S-GW and setting them up in a new S-GW.

For all data flows belonging to a UE in connected mode, the S-GW relays the data between eNodeB and P-GW. However, when a UE is in idle mode, the resources in eNodeB are released, and the data path terminates in the S-GW. If S-GW receives data packets from P-GW on any such

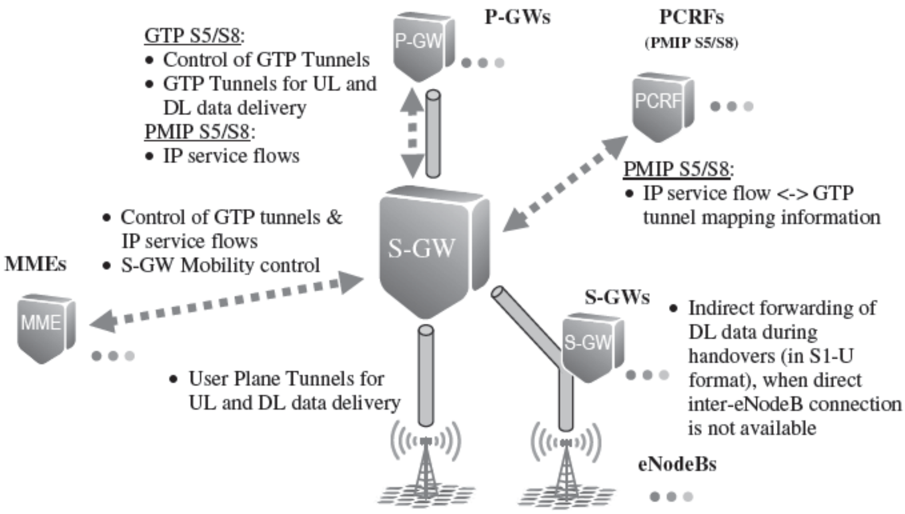


Figure 3.5 S-GW connections to other logical nodes and main functions

tunnel, it will buffer the packets, and request the MME to initiate paging of the UE. Paging will cause the UE to re-connect, and when the tunnels are re-connected, the buffered packets will be sent on. The S-GW will monitor data in the tunnels, and may also collect data needed for accounting and user charging. The S-GW also includes functionality for Lawful Interception, which means the capability to deliver the monitored user's data to authorities for further inspection.

Figure 3.5 shows how the S-GW is connected to other logical nodes, and lists the main functions in these interfaces. All interfaces have to be configured in a one-to-many fashion from the S-GW point of view. One S-GW may be serving only a particular geographical area with a limited set of eNodeBs, and likewise there may be a limited set of MMEs that control that area. The S-GW should be able to connect to any P-GW in the whole network, because P-GW will not change during mobility, while the S-GW may be relocated, when the UE moves. For connections related to one UE, the S-GW will always signal with only one MME, and the UP points to one eNodeB at a time (indirect data forwarding is the exception, see next paragraph). If one UE is allowed to connect to multiple PDNs through different P-GWs, then the S-GW needs to connect to those separately. If the S5/S8 interface is based on PMIP, the S-GW connects to one PCRF for each separate P-GW the UE is using.

Figure 3.5 also shows the indirect data forwarding case where UP data is forwarded between eNodeBs through the S-GWs. There is no specific interface name associated to the interface between S-GWs, since the format is exactly the same as in the S1-U interface, and the involved S-GWs may consider that they are communicating directly with an eNodeB. This would be the case if indirect data forwarding takes place via only one S-GW, i.e. both eNodeBs can be connected to the same S-GW.

3.2.2.5 Packet Data Network Gateway (P-GW)

Packet Data Network Gateway (P-GW, also often abbreviated as PDN-GW) is the edge router between the EPS and external packet data networks. It is the highest level mobility anchor in the system, and usually it acts as the IP point of attachment for the UE. It performs traffic gating and filtering functions as required by the service in question. Similarly to the S-GW, the P-GWs are maintained in operator premises in a centralized location.

Typically the P-GW allocates the IP address to the UE, and the UE uses that to communicate with other IP hosts in external networks, e.g. the internet. It is also possible that the external PDN to which the UE is connected allocates the address that is to be used by the UE, and the P-GW tunnels all traffic to that network. The IP address is always allocated when the UE requests a PDN connection, which happens at least when the UE attaches to the network, and it may happen subsequently when a new PDN connectivity is needed. The P-GW performs the required Dynamic Host Configuration Protocol (DHCP) functionality, or queries an external DHCP server, and delivers the address to the UE. Also dynamic auto-configuration is supported by the standards. Only IPv4, only IPv6 or both addresses may be allocated depending on the need, and the UE may signal whether it wants to receive the address(es) in the Attach signalling, or if it wishes to perform address configuration after the link layer is connected.

The P-GW includes the PCEF, which means that it performs gating and filtering functions as required by the policies set for the UE and the service in question, and it collects and reports the related charging information.

The UP traffic between P-GW and external networks is in the form of IP packets that belong to various IP service flows. If the S5/S8 interface towards S-GW is based on GTP, the P-GW performs the mapping between the IP data flows to GTP tunnels, which represent the bearers. The P-GW sets up bearers based on request either through the PCRF or from the S-GW, which relays information from the MME. In the latter case, the P-GW may also need to interact with the PCRF to receive the appropriate policy control information, if that is not configured in the P-GW locally. If the S5/S8 interface is based on PMIP, the P-GW maps all the IP Service flows from external networks that belong to one UE to a single GRE tunnel, and all control information is exchanged with PCRF only. The P-GW also has functionality for monitoring the data flow for accounting purposes, as well as for Lawful Interception.

P-GW is the highest level mobility anchor in the system. When a UE moves from one S-GW to another, the bearers have to be switched in the P-GW. The P-GW will receive an indication to switch the flows from the new S-GW.

Figure 3.6 shows the connections P-GW has to the surrounding logical nodes, and lists the main functions in these interfaces. Each P-GW may be connected to one or more PCRF, S-GW and external network. For a given UE that is associated with the P-GW, there is only one S-GW, but connections to many external networks and respectively to many PCRFs may need to be supported, if connectivity to multiple PDNs is supported through one P-GW.

3.2.2.6 Policy and Charging Resource Function (PCRF)

Policy and Charging Resource Function (PCRF) is the network element that is responsible for Policy and Charging Control (PCC). It makes decisions on how to handle the services in terms of QoS, and provides information to the PCEF located in the P-GW, and if applicable also to the BBERF located in the S-GW, so that appropriate bearers and policing can be set up. PCRF is part of the PCC framework defined in [5]. PCRF is a server usually located with other CN elements in operator switching centres.

The information the PCRF provides to the PCEF is called the PCC rules. The PCRF will send the PCC rules whenever a new bearer is to be set up. Bearer set-up is required, for exam-

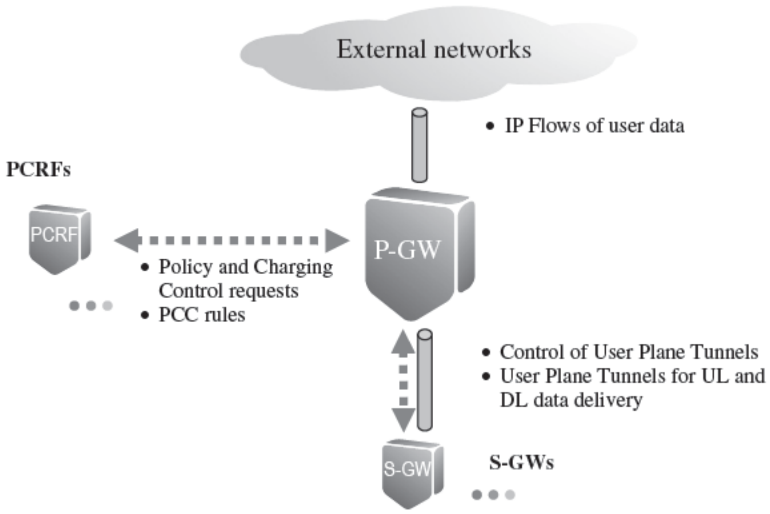


Figure 3.6 P-GW connections to other logical nodes and main functions

ple, when the UE initially attaches to the network and the default bearer will be set up, and subsequently when one or more dedicated bearers are set up. The PCRF will be able to provide PCC rules based on request either from the P-GW and also the S-GW in PMIP case, like in the attach case, and also based on request from the Application Function (AF) that resides in the Services Domain. In this scenario the UE has signalled directly with the Services Domain, e.g. with the IMS, and the AF pushes the service QoS information to PCRF, which makes a PCC decision, and pushes the PCC rules to the P-GW, and bearer mapping information to S-GW in PMIP S5/S8 case. The EPC bearers are then set up based on those.

The connections between the PCRF and the other nodes are shown in Figure 3.7. Each PCRF may be associated with one or more AF, P-GW and S-GW. There is only one PCRF associated with each PDN connection that a single UE has.

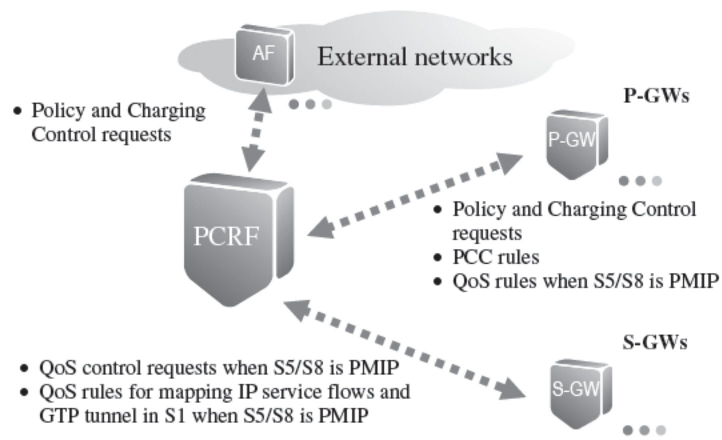


Figure 3.7 PCRF connections to other logical nodes and main functions

3.2.2.7 Home Subscription Server (HSS)

Home Subscription Server (HSS) is the subscription data repository for all permanent user data. It also records the location of the user in the level of visited network control node, such as MME. It is a database server maintained centrally in the home operator's premises.

The HSS stores the master copy of the subscriber profile, which contains information about the services that are applicable to the user, including information about the allowed PDN connections, and whether roaming to a particular visited network is allowed or not. For supporting mobility between non-3GPP ANs, the HSS also stores the Identities of those P-GWs that are in use. The permanent key, which is used to calculate the authentication vectors that are sent to a visited network for user authentication and deriving subsequent keys for encryption and integrity protection, is stored in the Authentication Center (AuC), which is typically part of the HSS. In all signalling related to these functions, the HSS interacts with the MME. The HSS will need to be able to connect with every MME in the whole network, where its UEs are allowed to move. For each UE, the HSS records will point to one serving MME at a time, and as soon as a new MME reports that it is serving the UE, the HSS will cancel the location from the previous MME.

3.2.2.8 Services Domain

The Services domain may include various sub-systems, which in turn may contain several logical nodes. The following is a categorization of the types of services that will be made available, and a short description of what kind of infrastructure would be needed to provide them:

- IMS based operator services: The IP Multimedia Sub-system (IMS) is service machinery that the operator may use to provide services using the Session Initiation Protocol (SIP). IMS has 3GPP defined architecture of its own, and is described in section 3.6, and more thoroughly, e.g. in [3].
- Non-IMS based operator services: The architecture for non-IMS based operator services is not defined in the standards. The operator may simply place a server into their network, and the UEs connect to that via some agreed protocol that is supported by an application in the UE. A video streaming service provided from a streaming server is one such example.
- Other services not provided by the mobile network operator, e.g. services provided through the internet: This architecture is not addressed by the 3GPP standards, and the architecture depends on the service in question. The typical configuration would be that the UE connects to a server in the internet, e.g. to a web-server for web browsing services, or to a SIP server for internet telephony service (i.e. VoIP).

3.2.3 Self-configuration of S1-MME and X2 interfaces

In 3GPP Release 8 development it has been agreed to define the support for self-configuration of the S1-MME and X2 interfaces. The basic process is as presented in Figure 3.8, where the eNodeB once turned on (and given that the IP connection exists) will connect to the O&M (based on the known IP address) to obtain then further parameters in terms of which other network elements to connect (and also for eNodeB software download) as well as initial parameters for the operation, such as in which part of the frequency band to operate and what kind of parameters to include for the broadcast channels.

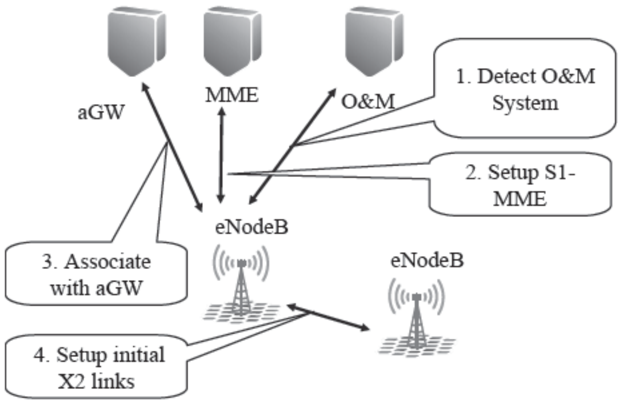


Figure 3.8 eNodeB self-configuration steps

This is expected to include setting the S1-MME connection by first setting up the SCTP association with at least one MME, and once that is connected to continue with application level information exchange to make S1-MME interface operational. Once the link to MME exists, there needs to be then association with S-GW created for UP data transfer.

To enable functionalities such as mobility and inter-cell interference control, the X2 interface configuration follows similar principles to the S1-MME interface. The difference here is that initially the eNodeB will set up the X2 connection for those eNodeBs indicated from the O&M and it may then later adapt more to the environment based on the Automatic Neighbour Relationship (ANR) functionality – as covered in Chapter 7 – to further optimize the X2 connectivity domain based on actual handover needs. The parameters that are exchanged over the X2 interface include:

- global eNodeB ID;
- information of the cell specific parameters such as Physical Cell ID (PCI), uplink/downlink frequency used, bandwidth in use;
- MMEs connected (MME Pool).

For the PCI there is also support for auto-configuration in the Release 8 specifications as covered in Chapter 5, other parameters then coming from the O&M direction with procedures that can be automated to limit the need for on-site configuration by installation personnel.

3.2.4 Interfaces and Protocols in Basic System Architecture Configuration

Figure 3.9 shows the CP protocols related to a UE's connection to a PDN. The interfaces from a single MME are shown in two parts, the one on top showing protocols towards the E-UTRAN and UE, and the bottom one showing protocols towards the gateways. Those protocols that are shown in white background are developed by 3GPP, while the protocols with light grey background are developed in IETF, and represent standard internet technologies that are used for transport in EPS. 3GPP has only defined the specific ways of how these protocols are used.

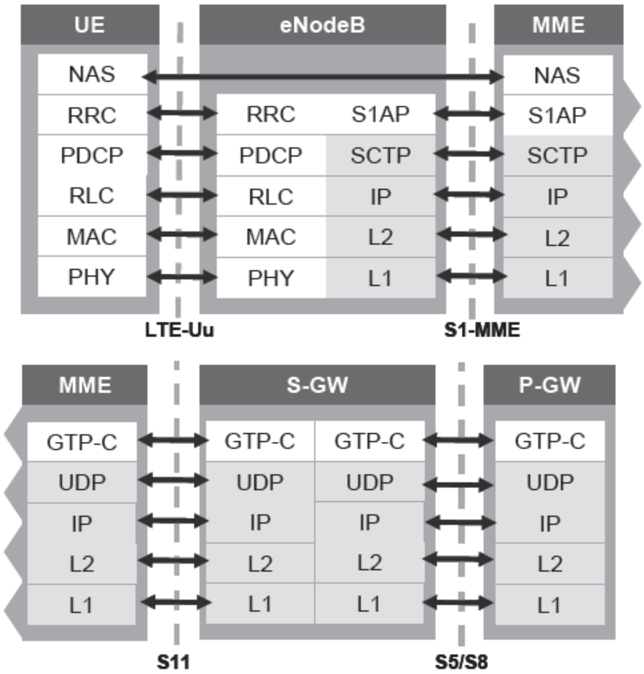


Figure 3.9 Control plane protocol stack in EPS

The topmost layer in the CP is the Non-Access Stratum (NAS), which consists of two separate protocols that are carried on direct signalling transport between the UE and the MME. The content of the NAS layer protocols is not visible to the eNodeB, and the eNodeB is not involved in these transactions by any other means, besides transporting the messages, and providing some additional transport layer indications along with the messages in some cases. The NAS layer protocols are:

- EPS Mobility Management (EMM): The EMM protocol is responsible for handling the UE mobility within the system. It includes functions for attaching to and detaching from the network, and performing location updating in between. This is called Tracking Area Updating (TAU), and it happens in idle mode. Note that the handovers in connected mode are handled by the lower layer protocols, but the EMM layer does include functions for re-activating the UE from idle mode. The UE initiated case is called Service Request, while Paging represents the network initiated case. Authentication and protecting the UE identity, i.e. allocating the temporary identity GUTI to the UE are also part of the EMM layer, as well as the control of NAS layer security functions, encryption and integrity protection.
- EPS Session Management (ESM): This protocol may be used to handle the bearer management between the UE and MME, and it is used in addition for E-UTRAN bearer management procedures. Note that the intention is not to use the ESM procedures if the bearer contexts are already available in the network and E-UTRAN procedures can be run immediately. This would be the case, for example, when the UE has already signalled with an operator affiliated Application Function in the network, and the relevant information has been made available through the PCRF.

The radio interface protocols are (only short descriptions are included here, since these functions are described extensively in other sections of this book):

- Radio Resource Control (RRC): This protocol is in control of the radio resource usage. It manages UE's signalling and data connections, and includes functions for handover.
- Packet Data Convergence Protocol (PDCP): The main functions of PDCP are IP header compression (UP), encryption and integrity protection (CP only).
- Radio Link Control (RLC): The RLC protocol is responsible for segmenting and concatenation of the PDCP-PDUs for radio interface transmission. It also performs error correction with the Automatic Repeat Request (ARQ) method.
- Medium Access Control (MAC): The MAC layer is responsible for scheduling the data according to priorities, and multiplexing data to Layer 1 transport blocks. The MAC layer also provides error correction with Hybrid ARQ.
- Physical Layer (PHY): This is the Layer 1 of LTE-Uu radio interface that takes care of DS-CDMA Layer functions.

The S1 interface connects the E-UTRAN to the EPC, and involves the following protocols:

- S1 Application Protocol (S1AP): S1AP handles the UE's CP and UP connections between the E-UTRAN and EPC, including participating in the handover when EPC is involved.
- SCTP/IP signalling transport: The Stream Control Transmission Protocol (SCTP) and Internet Protocol (IP) represent standard IP transport suitable for signalling messages. SCTP provides the reliable transport and sequenced delivery functions. IP itself can be run on a variety of data link and physical layer technologies (L2 and L1), which may be selected based on availability.

In the EPC, there are two alternative protocols for the S5/S8 interface. The following protocols are involved, when GTP is used in S5/S8:

- GPRS Tunnelling Protocol, Control Plane (GTP-C): It manages the UP connections in the EPC. This includes signalling the QoS and other parameters. If GTP is used in the S5/S8 interface it also manages the GTP-U tunnels. GTP-C also performs the mobility management functions within the EPC, e.g. when the GTP-U tunnels of a UE need to be switched from one node to the other.
- UDP/IP transport. The Unit Data Protocol (UDP) and IP are used as the standard and basic IP transport. UDP is used instead of Transmission Control Protocol (TCP) because the higher layers already provide reliable transport with error recovery and re-transmission. IP packets in EPC may be transported on top of a variety of L2 and L1 technologies. Ethernet and ATM are some examples.

The following protocols are used, when S5/S8 is based on PMIP:

- Proxy Mobile IP (PMIP): PMIP is the alternative protocol for the S5/S8 interface. It takes care of mobility management, but does not include bearer management functions as such. All traffic belonging to a UE's connection to a particular PDN is handled together.
- IP: PMIP runs directly on top of IP, and it is used as the standard IP transport.

Figure 3.10 illustrates the UP protocol structure for UE connecting to P-GW.

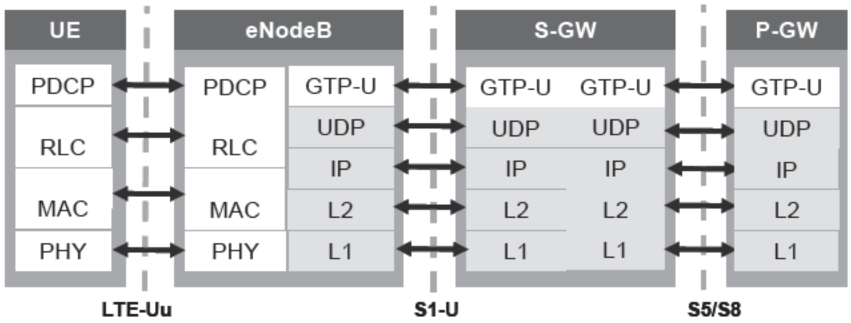


Figure 3.10 User plane protocol stack in EPS

The UP shown in Figure 3.10 includes the layers below the end user IP, i.e. these protocols form the Layer 2 used for carrying the end user IP packets. The protocol structure is very similar to the CP. This highlights the fact that the whole system is designed for generic packet data transport, and both CP signalling and UP data are ultimately packet data. Only the volumes are different. Most of the protocols have been introduced already above, with the exception of the following two that follow the selection of protocol suite in S5/S8 interface:

- GPRS Tunnelling Protocol, User Plane (GTP-U): GTP-U is used when S5/S8 is GTP based. GTP-U forms the GTP-U tunnel that is used to send End user IP packets belonging to one EPS bearer. It is used in S1-U interface, and is used in S5/S8 if the CP uses GTP-C.
- Generic Routing Encapsulation (GRE): GRE is used in the S5/S8 interface in conjunction with PMIP. GRE forms an IP in IP tunnel for transporting all data belonging to one UE's connection to a particular PDN. GRE is directly on top of IP, and UDP is not used.

Figure 3.11 illustrates the X2 interface protocol structure, which resembles that of the S1 interface. Only the CP Application Protocol is different. X2 interface is used in mobility between the eNodeBs, and the X2AP includes functions for handover preparation, and overall maintenance of the relation between neighbouring eNodeBs. The UP in the X2 interface is used for forwarding data in a transient state during handover, when the radio interface is already

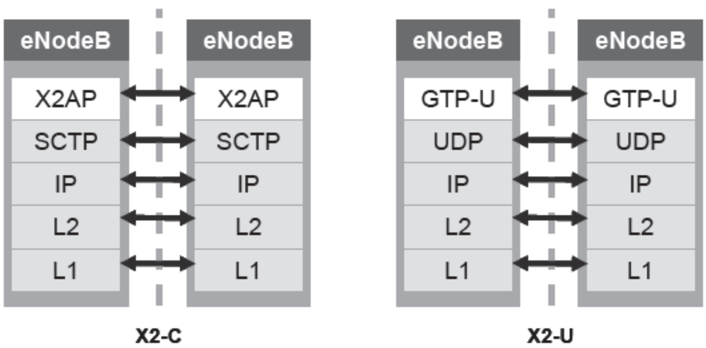


Figure 3.11 Control and user plane protocol stacks for X2 interface

Table 3.1 Summary of interfaces and protocols in Basic System Architecture configuration

Interface	Protocols	Specification
LTE-Uu	CP: RRC/PDCP/RLC/MAC/PHY UP: PDCP/RLC/MAC/PHY	36.300 [6] (stage 2)
X2	CP: X2AP/SCTP/IP UP: GTP-U/UDP/IP	36.423 [7] 29.274 [8]
S1-MME	S1AP/SCTP/UDP/IP	36.413 [9]
S1-U	GTP-U/UDP/IP	29.274 [8]
S10	GTP-C/UDP/IP	29.274 [8]
S11	GTP-C/UDP/IP	29.274 [8]
S5/S8 (GTP)	GTP/UDP/IP	29.274 [8]
S5/S8 (PMIP)	CP: PMIP/IP UP: GRE/IP	29.275 [10]
SGi	IP (also Diameter & Radius)	29.061 [11]
S6a	Diameter/SCTP/IP	29.272 [12]
Gx	Diameter/SCTP/IP	29.212 [13]
Gxc	Diameter/SCTP/IP	29.212 [13]
Rx	Diameter/SCTP/IP	29.214 [14]
UE – MME	EMM, ESM	24.301 [15]

disconnected on the source side, and has not yet resumed on the target side. Data forwarding is done for the DL data, since the UL data can be throttled effectively by the UE.

Table 3.1 summarizes the protocols and interfaces in Basic System Architecture configuration.

3.2.5 Roaming in Basic System Architecture Configuration

Roaming is an important functionality, where operators share their networks with each other's subscribers. Typically roaming happens between operators serving different areas, such as different countries, since this does not cause conflicts in the competition between the operators, and the combined larger service area benefits them as well as the subscribers. The words *home* and *visited* are used as prefixes to many other architectural terms to describe where the subscriber originates from and where it roams to respectively.

3GPP SAE specifications define which interfaces can be used between operators, and what additional considerations are needed if an operator boundary is crossed. In addition to the connectivity between the networks, roaming requires that the operators agree on many things at the service level, e.g. what services are available, how they are realized, and how accounting and charging is handled. This agreement is called the *Roaming Agreement*, and it can be made directly between the operators, or through a broker. The 3GPP specifications do not cover these items, and operators using 3GPP technologies discuss roaming related general questions in a private forum called the GSM Association, which has published recommendations to cover these additional requirements.

Roaming defined for SAE follows quite similar principles to the earlier 3GPP architectures. The E-UTRAN is always locally in the visited network, but the data may be routed either to the home network, or can break out to external networks directly from the visited network. This aspect differentiates the two roaming models supported for SAE, which are defined as follows:

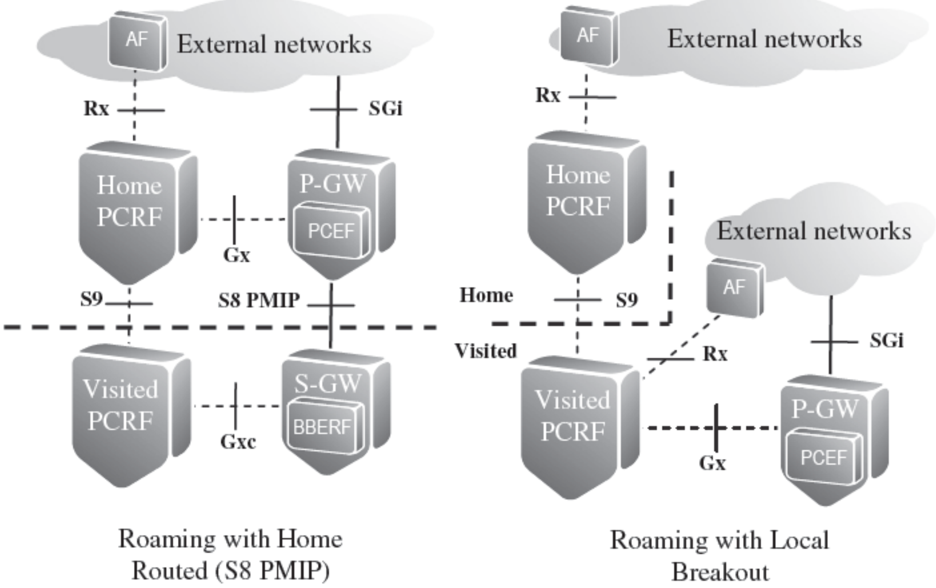


Figure 3.12 Home routed and local breakout roaming

- Home Routed model: The P-GW, HSS and PCRF reside in the home operator network, and the S-GW, MME and the radio networks reside in the visited operator network. In this roaming configuration the interface between P-GW and S-GW is called S8, whereas the same interface is called S5 when S-GW and P-GW are in the same operator's network. S5 and S8 are technically equivalent. When the S8 interface is based in GTP, the roaming architecture is as shown in Figure 3.2 (Gxa does not apply with GTP). When the S8 interface uses PMIP, the PCRF will also be divided into home and visited nodes with the S9 interface between them. This is the scenario shown in Figure 3.12 on the left, and is explained with more detail in section 3.7.1. The Home Routed roaming model applies to legacy 3GPP ANs in the same way, the additional detail being that the SGSN introduced in the next chapter and shown in Figure 3.12 resides in the visited network.
- Local Breakout model: In this model, shown in the right side of Figure 3.12, the P-GW will be located in the visited network, and the HSS is in the home network. If dynamic policy control is used, there will again be two PCRFs involved, one in the home network, and the other in the visited network. Depending on which operator's services are used, the PCRF in that operator's network is also connected to the AF. Also this scenario is explained with more detail in section 3.7.1. With these constraints the Local Breakout model also works with the legacy 3GPP ANs.

3.3 System Architecture with E-UTRAN and Legacy 3GPP Access Networks

3.3.1 Overview of 3GPP Inter-working System Architecture Configuration

Figure 3.13 describes the architecture and network elements in the architecture configuration where all 3GPP defined ANs, E-UTRAN, UTRAN and GERAN, are connected to the EPC.

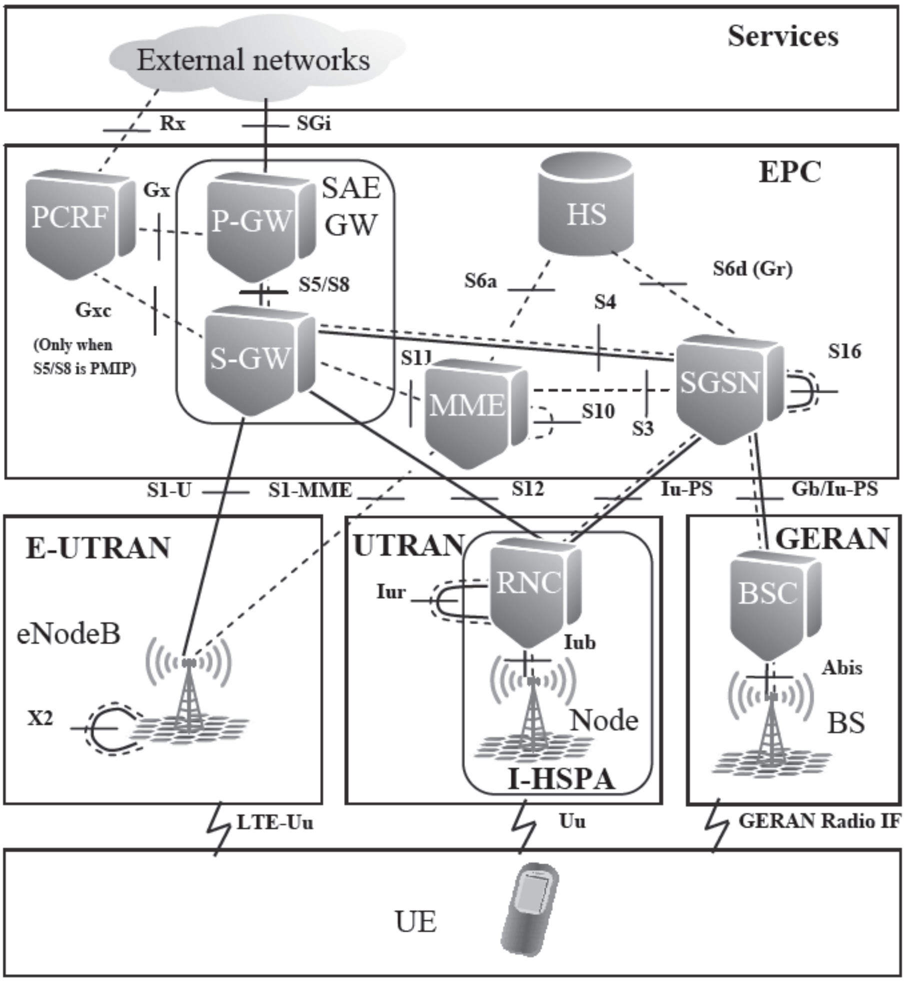


Figure 3.13 System architecture for 3GPP access networks

This is called here the 3GPP Inter-working System Architecture Configuration, and it allows optimized inter-working between the mentioned accesses.

Functionally the E-UTRAN, UTRAN and GERAN all provide very similar connectivity services, especially when looking at the situation from the end user point of view, where the only difference may be the different data rates and improved performance, but architecturally these ANs are quite different, and many things are carried out differently. There are, for example, big differences in how the bearers are managed in the EPS compared to the existing networks with UTRAN or GERAN access. However, when UTRAN or GERAN is connected to EPC, they may still operate as before from this perspective, and for this purpose the S-GW simply assumes the role of the Gateway GPRS Support Node (GGSN). Also in optimized inter-working with the E-UTRAN, the GERAN and UTRAN ANs behave almost the same way as they behave when inter-working between themselves. The differences become more visible in the EPC, because what used to be the fixed GGSN is now the S-GW that may be changed along with the SGSN change during UE mobility.

All nodes and functions described in the previous section for the Basic System Architecture Configuration are needed here also. The EPC needs the addition of a few new interfaces and functions to connect and inter-work with UTRAN and GERAN. The corresponding functions will also be required from GERAN and UTRAN. The new interfaces are S3, S4 and S12 as shown in Figure 3.12. The interface from SGSN to HSS can also be updated to Diameter based S6d, but the use of the legacy MAP based Gr is also possible.

Keeping E-UTRAN, i.e. the eNodeB design as focused to, and as optimized for the requirements of the new OFDMA radio interface, and as clean of inter-working functionality as possible, was an important guideline for the inter-working design. Consequently, the eNodeB does not interface directly with the other 3GPP ANs, and the interaction towards the EPC is the same as in other mobility cases that involve EPC. However, optimized inter-working means that the network is in control of mobility events, such as handovers, and provides functionality to hand the communication over with minimum interruption to services. This means that an eNodeB must be able to coordinate UE measuring UTRAN and GERAN cells, and perform handover decisions based on measurement results, and thus E-UTRAN radio interface protocols have been appended to support the corresponding new functions. Similar additions will be required from UTRAN and GERAN to support handover to E-UTRAN.

3.3.2 Additional and Updated Logical Elements in 3GPP Inter-working System Architecture Configuration

3.3.2.1 User Equipment

From the UE point of view, inter-working means that it needs to support the radio technologies in question, and the mobility operations defined for moving between them. The optimized inter-working means that the network controls the usage of radio transmitter and receiver in the UE in a way that only one set of them needs to be operating at the same time. This is called single radio operation, and allows UE implementations where only one pair of physical radio transmitter and receiver is implemented.

The standard does not preclude implementing multiple radio transmitters and receivers, and operating them simultaneously in dual radio operation. However, single radio operation is an important mode, because the different ANs often operate in frequencies that are so close to each other that dual radio operation would cause too much interference within the terminal. That, together with the additional power consumption, will decrease the overall performance.

3.3.2.2 E-UTRAN

The only addition to E-UTRAN eNodeB compared to the Basic System Architecture Configuration is the mobility to and from other 3GPP ANs. From the eNodeB perspective the functions are very similar irrespective of whether the other 3GPP AN is UTRAN or GERAN.

For the purpose of handover from E-UTRAN to UTRAN or GERAN, the neighbouring cells from those networks need to be configured into the eNodeB. The eNodeB may then consider handover for those UEs that indicate corresponding radio capability. The eNodeB requests the UE to measure the signal level of the UTRAN or GERAN cells, and analyses the measurement reports. If the eNodeB decides to start the handover, it signals the need to the MME in the same way that it would signal inter-eNodeB handover when the X2 interface is not available. Subsequently, the eNodeB will receive the information needed for the Handover Command from the target Access System via the MME. The eNodeB will send the Handover Command to the UE without the need for interpreting the content of this information.

In the case of handover from UTRAN or GERAN to E-UTRAN, the eNodeB does not need to make any specific preparations compared to other handovers where the handover preparation request comes through the MME. The eNodeB will allocate the requested resources, and prepare the information for handover command, which it sends to the MME, from where it is delivered to the UE through the other 3GPP Access System that originated the handover.

3.3.2.3 UTRAN

In UTRAN, the radio control functionality is handled by the Radio Network Controller (RNC), and under its control the Node B performs Layer 2 bridging between the Uu and Iub interfaces. UTRAN functionality is described extensively in [16].

UTRAN has evolved from its initial introduction in Release 99 in many ways, including the evolution of architectural aspects. The first such item is Iu flex, where the RNC may be connected to many Serving GPRS Support Nodes (SGSNs) instead of just one. Another such concept is I-HSPA, where the essential set of packet data related RNC functions is included with the Node B, and that connects to Iu-PS as a single node. Figure 3.13 also shows the direct UP connection from RNC to S-GW, which is introduced to 3G CN by the Direct Tunnel concept, where the SGSN is bypassed in UP.

Inter-working with E-UTRAN requires that UTRAN performs the same measurement control and analysis functions as well as the transparent handover information delivery in Handover Command that were described for eNodeB in the earlier section. Also the UTRAN performs similar logic that it already uses with Relocation between RNCs, when the Iur interface is not used.

3.3.2.4 GERAN

GSM EDGE Radio AN (GERAN) is the evolved version of GSM AN, which can also be connected to 3G Core Network. It consists of the Base Station Controller (BSC) and the Base Station (BS), and the radio interface functionalities are divided between them. An overview of GERAN functionality and the whole GSM system can be found in [17].

The GERAN is always connected to the SGSN in both Control and UPs, and this connection is used for all the inter-working functionality. Also the GERAN uses logic similar to that described above for E-UTRAN and UTRAN for inter-working handover.

3.3.2.5 EPC

The EPC has a central role for the inter-working system architecture by anchoring the ANs together. In addition to what has been described earlier, the MME and S-GW will support connectivity and functions for inter-working. Also the SGSN, which supports the UTRAN and GERAN access networks, will need to support these functions, and when these additions are supported, it can be considered to belong to the EPC.

The S-GW is the mobility anchor for all 3GPP access systems. In the basic bearer operations and mobility between SGSNs, it behaves like a GGSN towards the SGSN, and also towards the RNC if UP tunnels are set up in Direct Tunnel fashion bypassing the SGSN. Many of the GGSN functions are actually performed in the P-GW, but this is not visible to the SGSN. The S-GW retains its role as a UP Gateway, which is controlled by either the MME or the SGSN depending on which AN the UE is being served by.

To support the inter-working mobility, the MME will need to signal with the SGSN. These operations are essentially the same as between those two MMEs, and have been described earlier in section 3.2. An additional aspect of the MME is that it may need to combine the change of S-GW and the inter-working mobility with SGSN.

The SGSN maintains its role as the controlling node in core network for both UTRAN and GERAN. These functions are defined in [18]. The SGSN has a role very similar to that of the MME. The SGSN needs to be updated to support for S-GW change during mobility between SGSNs or RNCs, because from the legacy SGSN point of view this case looks like GGSN changing, which is not supported. As discussed earlier, the SGSN may direct the UP to be routed directly between the S-GW and UTRAN RNC, or it may remain involved in the UP handling. From the S-GW point of view this does not really make a difference, since it does not need to know which type of node terminates the far end of the UP tunnel.

3.3.3 Interfaces and Protocols in 3GPP Inter-working System Architecture Configuration

Table 3.2 summarizes the interfaces in the 3GPP Inter-working System Architecture Configuration and the protocols used in them. Interfaces and protocols in legacy 3GPP networks are not listed. Interfaces and protocols listed for Basic System Architecture Configuration are needed in addition to these.

3.3.4 Inter-working with Legacy 3GPP CS Infrastructure

While the EPS is purely a Packet Switched (PS) only system without a specific Circuit Switched (CS) domain with support for VoIP, the legacy 3GPP systems treat CS services such as voice calls with a specific CS infrastructure. IMS VoIP may not be ubiquitously available, and therefore the SAE design includes two special solutions that address inter-working with circuit switched voice. A description of how inter-working between E-UTRAN and the legacy 3GPP CS domain can be

Table 3.2 Summary of additional interfaces and protocols in 3GPP Inter-working System Architecture configuration

Interface	Protocols	Specification
S3	GTP-C/UDP/IP	29.274 [8]
S4	GTP/UDP/IP	29.274 [8]
S12	GTP-U/UDP/IP	29.274 [8]
S16	GTP/UDP/IP	29.274 [8]
S6d	Diameter/SCTP/IP	29.272 [12]

Table 3.3 Summary of additional interfaces and protocols for inter-working with legacy 3GPP CS infrastructure

Interface	Protocols	Specification
SGs	SGsAP/SCTP/IP	29.118 [21]
Sv	GTP-C(subset)/UDP/IP	29.280 [22]

arranged is given in Chapter 10 on VoIP. Two specific functions have been defined for that purpose, Circuit Switched Fall Back (CSFB) and Single Radio Voice Call Continuity (SR-VCC).

CSFB [19] is a solution for networks that do not have support for IMS VoIP. Instead, the voice calls are handled by the CS domain, and the UE is handed over there at the time of a voice call. The SGs interface between the MME and MSC Server is used for related control signalling, as shown with more detail in Chapter 10.

SR-VCC [20] is a solution for converting and handing over an IMS VoIP call to a CS voice call in the legacy CS domain. This functionality would be needed when the coverage of an IMS VoIP capable network is smaller than that of the legacy CS networks. SR-VCC allows a UE entering the edge of the VoIP coverage area with an ongoing VoIP call to be handed over to the CS network without interrupting the call. SR-VCC is a one way handover from the PS network with VoIP to the CS network. If E-UTRAN coverage becomes available again, the UE may return there when the call ends and the UE becomes idle. The solution relies on running only one radio at a time, i.e. the UE does not need to communicate simultaneously with both systems. In this solution the MME is connected to the MSC Server in the CS domain via a Sv interface, which is used for control signalling in the SR-VCC handover. The details of the solution are presented in Chapter 10. A summary of additional interfaces and protocols for inter-working with legacy 3GPP CS infrastructure is given in Table 3.3.

3.4 System Architecture with E-UTRAN and Non-3GPP Access Networks

3.4.1 Overview of 3GPP and Non-3GPP Inter-working System Architecture Configuration

Inter-working with non-3GPP ANs was one of the key design goals for SAE, and to support it, a completely separate architecture specification [2] was developed in 3GPP. The non-3GPP Inter-working System Architecture includes a set of solutions in two categories. The first category contains a set of generic and loose inter-working solutions that can be used with any other non-3GPP AN. Mobility solutions defined in this category are also called Handovers without Optimizations, and the same procedures are applicable in both connected and idle mode. The second category includes a specific and tighter inter-working solution with one selected AN, the cdma2000® HRPD. This solution category is also called Handovers with Optimizations, and it specifies separate procedures for connected and idle mode.

The generic non-3GPP Inter-working System Architecture is shown in Figure 3.14. The specific application of the architecture for cdma2000® HRPD inter-working and the required additional interfaces are described with more detail in section 3.5.

Figure 3.14 describes the generic inter-working solution that relies only on loose coupling with generic interfacing means, and without AN level interfaces. Since there are so many different kinds of ANs, they have been categorized to two groups, the trusted and un-trusted non-3GPP ANs, depending on whether it can be safely assumed that 3GPP defined authentication can be run by the network, which makes it trusted, or if authentication has to be done in overlay fashion and the AN is un-trusted. The P-GW will maintain the role of mobility anchor, and the non-3GPP ANs are connected to it either via the S2a or the S2b interface, depending on whether the non-3GPP AN functions as a Trusted or Un-trusted non-3GPP AN. Both use network controlled IP layer mobility with the PMIP protocol. For networks that do not support PMIP, Client MIPv4 Foreign Agent mode is available as an option in S2a. In addition to mobility functions, the architecture includes interfaces for authenticating the UE within and through the non-3GPP ANs, and also allows PCC functionality in them via the Gxa and Gxb interfaces. Note that the detailed functions and protocols for Gxb are not specified in Release 8.

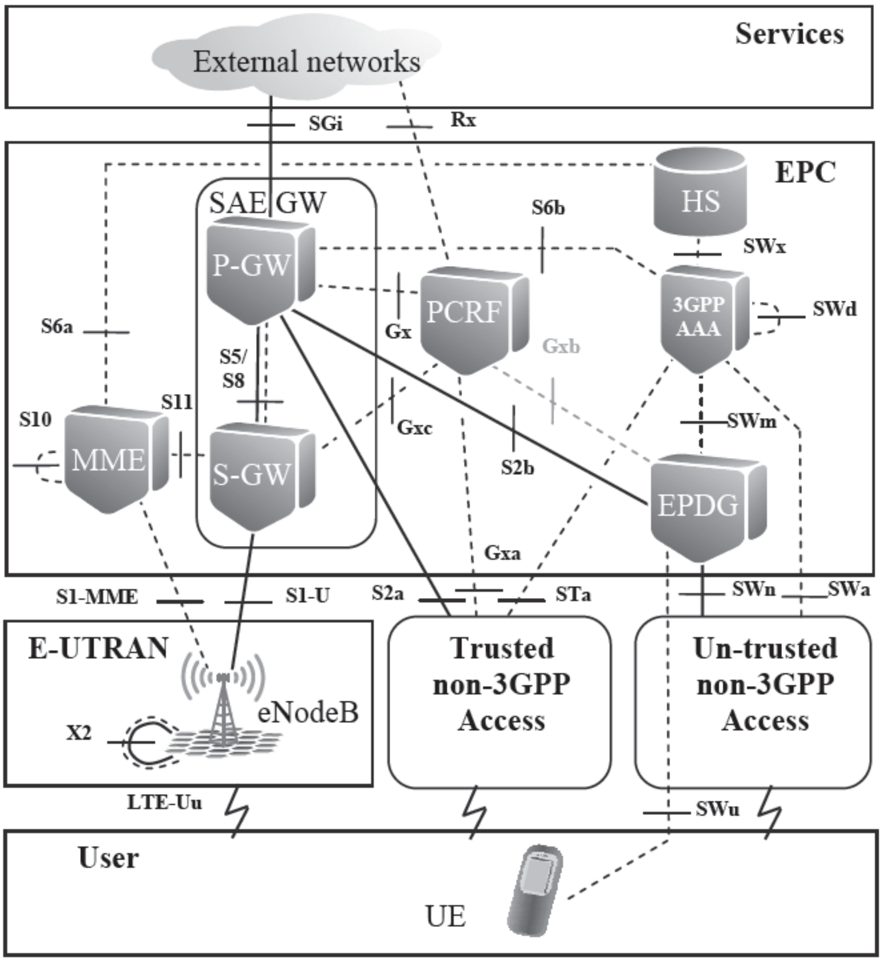


Figure 3.14 System architecture for 3GPP and non-3GPP access networks

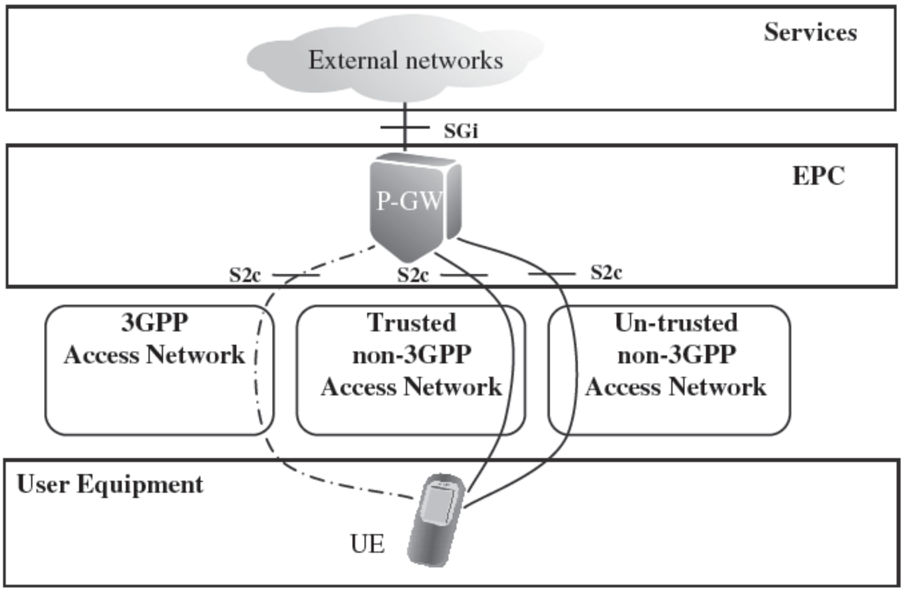


Figure 3.15 Simplified system architecture showing only S2c

In addition to the network controlled mobility solutions, a completely UE centric solution with DSMIPv6 is also included in the inter-working solutions. This scenario is depicted in Figure 3.15.

In this configuration the UE may register in any non-3GPP AN, receive an IP address from there, and register that to the Home Agent in P-GW. This solution addresses the mobility as an overlay function. While the UE is served by one of the 3GPP ANs, the UE is considered to be in home link, and thus the overhead caused by additional MIP headers is avoided.

Another inter-working scenario that brings additional flexibility is called the chained S8 and S2a/S2b scenario. In that scenario the non-3GPP AN is connected to S-GW in the visited Public Land Mobile Network (PLMN) through the S2a or S2b interface, while the P-GW is in the home PLMN. This enables the visited network to offer a roaming subscriber the use of non-3GPP ANs that might not be associated with the home operator at all, even in the case where P-GW is in the home PLMN. This scenario requires that S-GW performs functions that normally belong to P-GW in order to behave as the termination point for the S2a or S2b interfaces. In Release 8, this scenario does not support dynamic policies through the PCC infrastructure, i.e. the Gxc interface will not be used. Also, chaining with GTP based S5/S8 is not supported. All other interfaces related to non-3GPP ANs are used normally as shown in Figure 3.14.

3.4.2 Additional and Updated Logical Elements in 3GPP Inter-working System Architecture Configuration

3.4.2.1 User Equipment

Inter-working between the non-3GPP ANs requires that the UE supports the corresponding radio technologies, and the specified mobility procedures. The mobility procedures and required radio capabilities vary depending on whether optimizations are in place or not. The procedures defined for Handovers without Optimizations do not make any assumption about the UE's capability to use the radio transmitters and receivers simultaneously, and both single radio and dual radio configurations can use the procedures. However, the handover gap time is expected to be shorter, if preparing the connections towards the target side can start already while data are still flowing through the source side. This is caused by the fact that Handovers without Optimizations do not have procedures in the network side to assist in handover preparations, and the procedures follow the principle where UE registers to the target network according to the method defined for that network, and then the network switches the flow to the target network. This may be time consuming, since it normally includes procedures such as authentication. Also, the decision to make these handovers is the responsibility of the UE.

The Handovers with Optimizations, i.e. inter-working with cdma2000® HRPD, assume that they do include network control for connected mode, so the handovers are decided by the network, while the idle mode mobility relies on UE decision making, which may use cdma2000® HRPD related information in the LTE-Uu broadcast. Furthermore, the procedures are designed with the assumption that single radio configuration is enough for the UE.

3.4.2.2 Trusted Non-3GPP Access Networks

The term trusted non-3GPP AN refers to networks that can be trusted to run 3GPP defined authentication. 3GPP Release 8 security architecture specification for non-3GPP ANs [23] mandates that the Improved Extensible Authentication Protocol Method for 3rd Generation Authentication and Key Agreement (EAP-AKA') [24] is performed. The related procedures are performed over the STa interface.

The trusted non-3GPP ANs are typically other mobile networks, such as the cdma2000® HRPD. The STa interface supports also delivery of subscription profile information from Authentication, Authorization and Accounting (AAA)/HSS to the AN, and charging information from the AN to AAA Server, which are typical functions needed in mobile networks. It can also be assumed that such ANs may benefit from connecting to the PCC infrastructure, and therefore the Gxc interface may be used to exchange related information with the PCRF.

The trusted non-3GPP AN connects to the P-GW with the S2a interface, with either PMIP or MIPv4 Foreign Agent mode. The switching of UP flows in P-GW is therefore the responsibility of the trusted non-3GPP AN when UE moves into the AN's service area.

3.4.2.3 Un-trusted Non-3GPP Access Networks

To a large extent, the architectural concepts that apply for un-trusted non-3GPP ANs are inherited from the Wireless Local Area Network Inter-Working (WLAN IW) defined originally in Release 6 [25]. The Release 8 functionality for connecting un-trusted non-3GPP ANs to EPC is specified fully in [2] with references to the earlier WLAN IW specifications when applicable.

The main principle is that the AN is not assumed to perform any other functions besides delivery of packets. A secure tunnel is established between UE and a special node called the Enhanced Packet Data Gateway (EPDG) via the SWu interface, and the data delivery takes place through that tunnel. Furthermore, the P-GW has a trust relationship with the EPDG connected to it via the S2b interface, and neither node needs to have secure association with the un-trusted non-3GPP AN itself.

As an optional feature, the un-trusted non-3GPP AN may be connected to the AAA Server with the SWa interface, and this interface may be used to authenticate the UE already in the non-3GPP AN level. This can be done only in addition to authentication and authorization with the EPDG.

3.4.2.4 EPC

The EPC includes quite a few additional functions for the support of non-3GPP ANs, when compared to the previously introduced architecture configurations. The main changes are in the P-GW, PCRF and HSS, and also in S-GW for the chained S8 and S2a/S2b scenario. In addition, completely new elements, such as the EPDG (Evolved Packet Data Gateway) and the AAA are introduced. The AAA infrastructure contains the AAA Server, and it may also contain separate AAA proxies in roaming situations. Figure 3.16 highlights the AAA connections and functions for non-3GPP ANs.

The P-GW is the mobility anchor for the non-3GPP ANs. For PMIP based S2a and S2b interfaces, the P-GW hosts the Local Mobility Anchor (LMA) function in a manner similar to that for the S5/S8 PMIP interfaces. Also the Home Agent (HA) function for the Client MIPv4 Foreign Agent mode in S2a is located in P-GW. The relation between P-GWs and non-3GPP ANs is many to many. The P-GW will also interface with the AAA Server, which subsequently connects to HSS. This interface is used for reporting the selected P-GW to the HSS so that it is available in mobility between non-3GPP ANs, and to authenticate and authorize users connecting with S2c mode. Each P-GW may connect to more than one AAA server.

The PCRF supports PCC interfaces for non-3GPP ANs. The Gxa is used towards trusted non-3GPP ANs, and Gxb towards un-trusted non-3GPP ANs. Only Gxa is specified in detail level

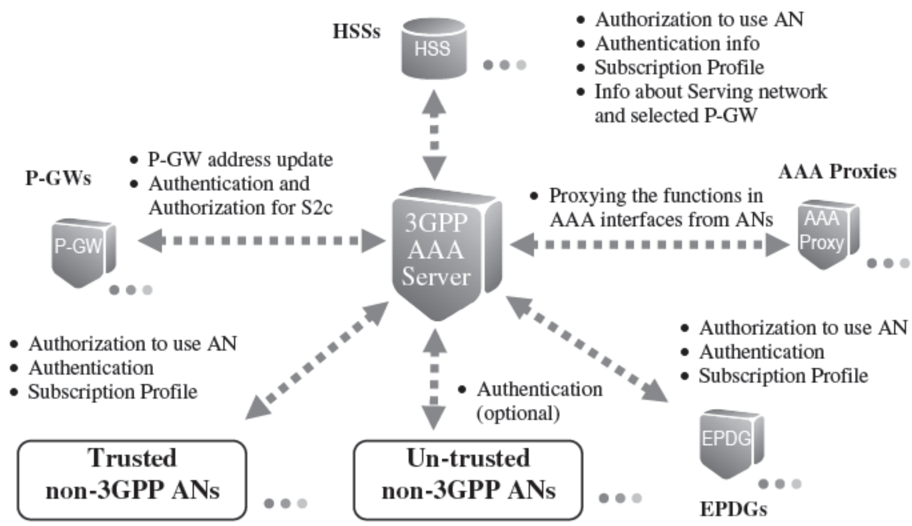


Figure 3.16 3GPP AAA server interfaces and main functions

in Release 8. The Gxa interface functions in a fashion similar to that of the Gxc interface. In this case the BBERF function will be in the non-3GPP AN, and it will receive instructions from the PCRF on how to handle the bearer level functions for the IP flows in the S2a interface. The further bearer functions internal to non-3GPP ANs are not addressed in 3GPP specifications.

The EPDG is a dedicated node for controlling the UE and inter-network connection, when an un-trusted non-3GPP AN is connected to EPC. Since the AN is not trusted, the main function is to secure the connection, as defined in [23]. The EPDG establishes an IPsec tunnel to the UE through the un-trusted non-3GPP AN with IKEv2 signalling [26] over the SWu interface. During the same signalling transaction the EAP-AKA authentication is run, and for that the EPDG signals with the AAA Server through the SWm interface. While the SWm interface is logically between UE and the EPDG, the SWn interface represents the interface on a lower layer between the EPDG and the un-trusted non-3GPP AN. The Release 8 specifications do not assume that EPDG would signal with PCRF for any PCC functions, but the architecture already contains the Gxb interface for that purpose.

The 3GPP AAA Server, and possibly a AAA Proxy in the visited network, performs a 3GPP defined set of AAA functions. These functions are a subset of what the standard IETF defined AAA infrastructure includes, and do not necessarily map with the way other networks use AAA infrastructure. The AAA Server acts between the ANs and the HSS, and in doing so it creates a context for the UEs it serves, and may store some of their information for further use. Thus, the 3GPP AAA Server consolidates the signalling from different types of ANs into a single SWx interface towards the HSS, and terminates the access specific interfaces S6b, STa, SWm and SWa. Most importantly the AAA Server performs as the authenticator for the EAP-AKA authentication through the non-3GPP ANs. It checks the authenticity of the user, and informs the AN about the outcome. The authorization to use the AN in question will also be performed during this step. Depending on the AN type in question, the AAA Server may also relay subscription profile information to the AN, which the AN may further use to better serve the UE. When the UE is no longer served by a given non-3GPP AN, the AAA Server participates in removing the UE's association from the HSS. Figure 3.16 summarizes the AAA Server main functions in relation to other nodes.

The HSS performs functions similar to those for the 3GPP ANs. It stores the main copy of the subscription profile as well as the secret security key in the AuC portion of it, and when requested, it provides the profile data and authentication vectors to be used in UEs connecting through non-3GPP ANs. One addition compared to 3GPP ANs is that since the non-3GPP ANs do not interface on the AN level, the selected P-GW needs to be stored in the HSS, and retrieved from there when the UE mobility involves a non-3GPP AN. The variety of different AN types are mostly hidden from the HSS, since the AAA Server terminates the interfaces that are specific to them, and HSS only sees a single SWx interface. On the other hand, the subscription profile stored in the HSS must reflect the needs of all the different types of ANs that are valid for that operator.

3.4.3 Interfaces and Protocols in Non-3GPP Inter-working System Architecture Configuration

Connecting the non-3GPP ANs to EPC and operating them with it requires additional interfaces to those introduced in earlier sections. Table 3.4 lists the new interfaces.

Table 3.4 Summary of additional interfaces and protocols in non-3GPP Inter-working System Architecture configuration

Interface	Protocols	Specification
S2a	PMIP/IP, or MIPv4/UDP/IP	29.275 [10]
S2b	PMIP/IP	29.275 [10]
S2c	DSMIPv6, IKEv2	24.303 [27]
S6b	Diameter/SCTP/IP	29.273 [28]
Gxa	Diameter/SCTP/IP	29.212 [13]
Gxb	*Not defined in Release 8*	*N.A.*
STa	Diameter/SCTP/IP	29.273 [28]
SWa	Diameter/SCTP/IP	29.273 [28]
SWd	Diameter/SCTP/IP	29.273 [28]
SWm	Diameter/SCTP/IP	29.273 [28]
SWn	PMIP	29.275 [10]
SWu	IKEv2, MOBIKE	24.302 [29]
SWx	Diameter/SCTP/IP	29.273 [28]
UE – foreign agent in trusted non-3GPP Access	MIPv4	24.304 [30]
UE – Trusted or Un-trusted non-3GPP access	EAP-AKA	24.302 [29]

3.4.4 Roaming in Non-3GPP Inter-working System Architecture Configuration

The principles for roaming with non-3GPP accesses are equivalent to those described in section 3.2.4 for 3GPP ANs. Both home routed and local breakout scenarios are supported and the main variations in the architecture relate to the PCC arrangement, which depends on where the services are consumed. This aspect is highlighted more in section 3.7.1.

The additional consideration that non-3GPP ANs bring to roaming is related to the case where the user is roaming to a visited 3GPP network in Home Routed model, and it would be beneficial to use a local non-3GPP AN that is affiliated with the visited network, but there is no association between that network and the home operator. For this scenario, the 3GPP Release 8 includes a so-called *chained case*, where the S-GW may behave as the anchor for the non-3GPP ANs also, i.e. it terminates the S2a or S2b interface, and routes the traffic via the S8 interface to the P-GW in the home network.

3.5 Inter-working with cdma2000® Access Networks

3.5.1 Architecture for cdma2000® HRPD Inter-working

The best inter-working performance in terms of handover gap time is achieved by specifying the networks to inter-operate very tightly to exchange critical information. This creates a specific solution that is valid for only the ANs in question. With the limited time and resources available for specification work, the number of such solutions in 3GPP Release 8 could only be limited. A tight inter-working solution also requires changes in the other ANs, and by definition the development of non-3GPP ANs is not within the control of 3GPP. Achieving a well designed solution requires special attention to coordination between the developments in different standardization bodies. With these difficulties at hand, 3GPP Release 8 only includes an optimized inter-working solution with cdma2000® HRPD AN.

Figure 3.17 highlights the architecture for cdma2000® HRPD inter-working. It shows the Evolved HRPD (E-HRPD) network, where a number of modifications have been applied to make it suitable for connecting to the EPC. Due to these modifications it will be called E-HRPD in this chapter to distinguish it from legacy HRPD systems that do not support these functions. The radio interface and the Radio Access Network have been kept as similar as possible, but the HRPD Serving Gateway (HSGW) is a completely new node inheriting many of its functions from S-GW.

The E-HRPD is generally treated as a trusted non-3GPP AN, and it is therefore connected to the EPC via S2a, Gxa and STa interfaces. These interfaces operate as described earlier. Since the inter-working solution is optimized, and does not rely on UE performing the attach

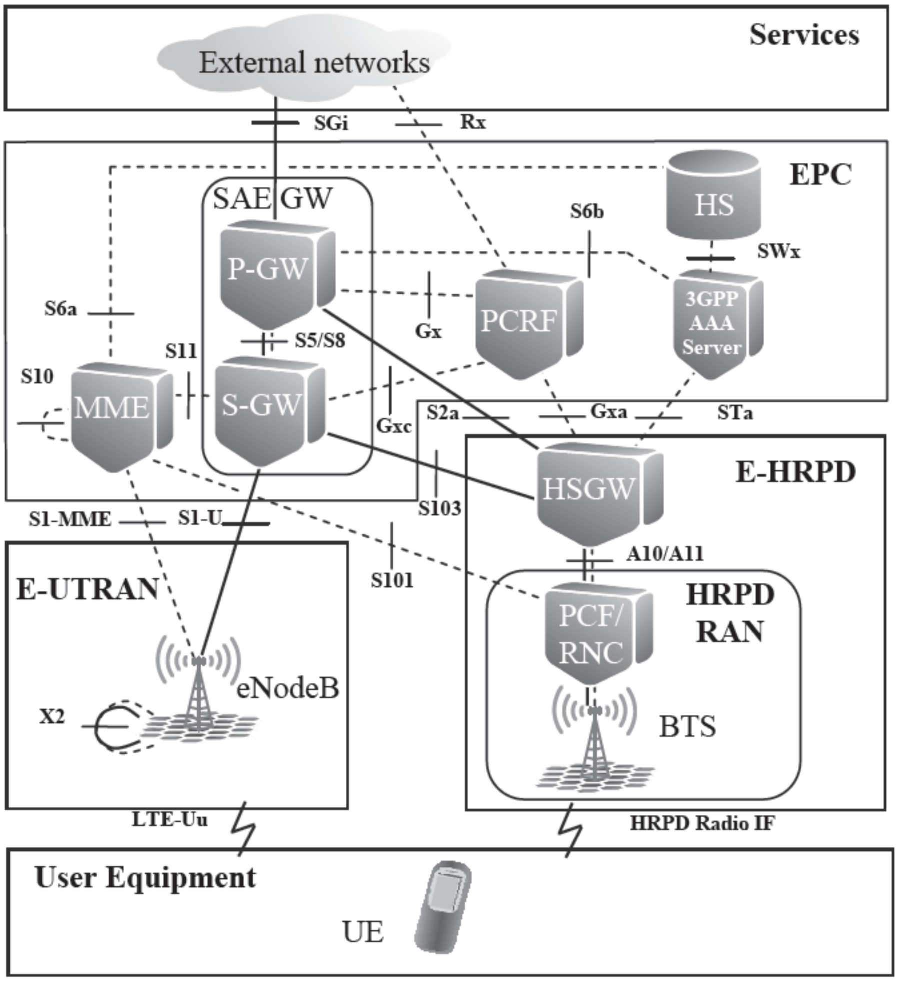


Figure 3.17 System architecture for 3GPP and cdma2000® HRPD inter-working

procedure directly to the target network, two new interfaces, S101 and S103, were defined for the CP and UP interactions respectively.

3GPP ANs and the 3GPP2-defined cdma2000® ANs share many things in common, but many things are also different. Both systems use a prepared handover, where the source system signals to the target system to give it essential parameters to be able to serve the terminal there, and the target system gives the source system parameters that can be further given to the terminal to guide it to make the access to the target radio. While there are similarities in these methods, the parameters themselves do not match well at all, and this method could not be used by applying a simple protocol conversion. To ease up on the need to align every information element that would need to be exchanged in handover, it was decided to use a transparent signalling transport method.

Figure 3.18 shows how the transparent tunnel is used in mobility from E-UTRAN to E-HRPD on the left, and the opposite direction is shown on the right. The thick black arrow indicates the signalling which is carried transparently through the source access system and over the S101 interface to the target system. In this method the source access system gives guidance to the UE to register to the target system through the tunnel. This creates the UE context in the target system without the source system having to convert its information to the target system format. This is called pre-registration, and the purpose is to take the time consuming registration/attach function away from the time critical path of handover. The transparent tunnel may also be used to build the bearer context in the target system so that when the time to make the handover is at hand, everything will be ready and waiting at the target side. The actual handover is decided based on radio interface conditions, and this solution requires that both systems are able to handle measurements from the other system. The following inter-working scenarios are supported between E-UTRAN and E-HRPD:

- E-UTRAN → E-HRPD handover: The pre-registration may be performed well before the actual handover takes place, and also all bearers are set up in the E-HRPD side. The UE remains in a dormant state (equal to idle mode) from the E-HRPD system point of view before handover, and this state may be long lived. When the radio conditions indicate the need for handover, the eNodeB commands the UE to start requesting traffic channel from E-HRPD. This takes place through the transparent tunnel, and once it is completed, the eNodeB commands the UE to make the actual handover. The S103 interface is used only

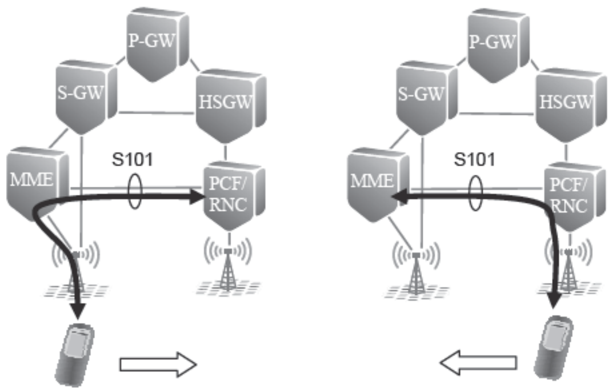


Figure 3.18 Tunnelled pre-registration to eHRPD and to E-UTRAN

in this handover scenario to forward DL data during the time when the UE is making the switch between the radios.

- E-UTRAN → E-HRPD idle mode mobility: The pre-registration state works as described above for the handover. The UE is in idle mode in the E-UTRAN also, and it moves within the system, selecting the cells on its own, and when it selects an E-HRPD cell, it briefly connects to the E-HRPD network to get the mobility pointers updated to the E-HRPD side.
- E-HRPD → E-UTRAN handover: The E-HRPD AN will request the UE to make tunnelled pre-registration (attach) only at the time the handover is needed, and the UE will immediately proceed to requesting connection directly from the E-UTRAN cell after the registration is complete. The bearers are set up in embedded fashion with the registration and connection request procedures.
- E-HRPD → E-UTRAN idle mode mobility: The idle mode procedure follows the same guidelines as the handover for the tunnelled registration (attach), but the UE accesses the E-UTRAN radio only by reporting its new location (Tracking Area), since there is no need to set up bearers in E-UTRAN for UE in idle mode.

3.5.2 Additional and Updated Logical Elements for cdma2000® HRPD Inter-working

Inter-working with eHRPD in an optimized manner brings a lot of new features in the basic SAE network elements, and introduces few totally new elements in the HRPD side. The UE, eNodeB, MME and S-GW will all be modified to support new functions, and MME and S-GW will also deal with new interfaces. The eHRPD is a new network of its own, and it consists of elements such as Base Station, Radio Network Controller (RNC), Packet Control Function (PCF) and HRPD Serving Gateway (HSGW).

The UE will need to support both radio interfaces. The design of the procedure assumes that UE is capable of single mode operation only. On the other hand, the integration is kept loose enough so that it would be possible to implement terminal with separate chip sets for E-UTRAN and E-HRPD. This means that the UE is not required to make measurements of cells in the other technology in as tightly a timewise controlled manner as is normally seen within a single radio technology. The UE will also need to support the tunnelled signalling operation. The tunnelled signalling itself is the same signalling as the UE would use directly with the other system.

The main new requirement for the eNodeB is that it also needs to be able to control mobility towards the eHRPD access. From the radio interface perspective it does this much in the same manner as with the other 3GPP accesses, by instructing the UE to make measurements of the neighbouring eHRPD cells, and making the handover decision based on this information. On the other hand, the eNodeB does not signal the handover preparation towards the eHRPD, like it would for other handovers in S1 interface. Instead the handover preparation works so that the UE sends traffic channel requests to the eHRPD AN through the transparent tunnel, and the eNodeB is only responsible for marking the uplink messages with appropriate routing information, so that the MME can select the right node in the eHRPD AN, and noting the progress of the handover from the headers of the S1 messages carrying the eHRPD signalling.

The MME implements the new S101 interface towards the eHRPD RAN. For UE originated messages, it needs to be able to route them to the right eHRPD RAN node based on a reference given by the eNodeB. In the reverse direction the messages are identified by the IMSI of the UE, and the basis that the MME can route them to the right S1 signalling connection. The MME does not need to interpret the eHRPD signalling message contents, but the status of the HO progress is indicated along with those messages that require special action from the MME. For example, at a given point during E-UTRAN → E-HRPD handover, the MME will set up the data forwarding tunnels in the S-GW. The MME also needs to memorize the identity of the E-HRPD AN node that a UE has been signalling with, so that if MME change takes place, the MME can update the S101 context in the HRPD AN node.

The S-GW supports the new S103 interface, which is used for forwarding DL data during the time in handover, when the radio link cannot be used. The forwarding function is similar to the function S-GW has for the E-UTRAN handovers. The difference is that S103 is based on a GRE tunnel, and there will be only one tunnel for each UE in handover, so the S-GW needs to map all GTP tunnels from the S1-U interface to a single GRE tunnel in the S103 interface.

The E-HRPD network is a completely new way to use the existing HRPD radio technology with the SAE, by connecting it to the EPC. Compared to the original HRPD, many changes are caused by the inter-working, and connecting to the EPD requires some new functions, e.g. the support of EAP-AKA authentication. The HSGW is taking the S-GW role for E-HRPD access, and performs much like a S-GW towards the P-GW. The HSGW also includes many CP functions. Towards the eHRPD AN, it behaves like the Packet Data Serving Node (PDSN) in a legacy HRPD network. It also signals with the 3GPP AAA Server to authenticate the UE, and to receive its service profile. The CN aspects of the E-HRPD are specified in [31] and the evolved RAN is documented in [32].

3.5.3 Protocols and Interfaces in cdma2000® HRPD Inter-working

The optimized inter-working introduces two new interfaces – S101 and S103 – to the architecture (see Table 3.5**)**. The S2a, Gxc and STa are as described earlier. The following summarizes the new interfaces:

- S101 is a CP interface that in principle forms a signalling tunnel for the eHRPD messages. The CP protocol is S101AP, which is specified in [33]. The S101AP uses the same message structure and coding as the newest version of GTP. The main function is to carry the signalling messages, with the IMSI as a reference and with an additional handover status parameter that is set by either the UE or either one of the networks it signals with. In addition, when the data forwarding tunnel needs to be set up, the address information is also included in S101AP. S101AP also includes a procedure to switch the interface from one MME to another if handover in E-UTRAN causes MME change.
- S103 is a simple GRE tunnel for UP data forwarding in handover. It is only used for DL data in handover from E-UTRAN to E-HRPD. S103 is a UP interface only, and all control information to set up the GRE tunnel is carried in other interfaces. It is specified with S101AP in [33].

Table 3.5 Additional interfaces and protocols for inter-working with cdma2000® eHRPD

Interface	Protocols	Specification
S101	S101AP/UDP/IP	29.276 [33]
S103	GRE/IP	29.276 [33]

Table 3.6 Additional interfaces and protocols for inter-working with cdma2000® 1xRTT

Interface	Protocols	Specification
S102	S102 protocol	29.277 [34]
A21	A21 protocol	A.S0008-C [35]

3.5.4 Inter-working with cdma2000® 1xRTT

The cdma2000® 1xRTT is a system supporting CS bearers, and is primarily used for voice calls. In this respect it is functionally equivalent to the legacy 3GPP CS infrastructure such as the MSC and the CS bearer capabilities of GERAN and UTRAN. As described in Chapter 10, the 3GPP standard includes two functions to support inter-working between the E-UTRAN and the legacy CS infrastructure. These are the CSFB [19] and SR-VCC [20]. These functions have been extended to cover inter-working with cdma2000® 1xRTT also, and at a high level they work in the same way as described in Chapter 10. In the 1xRTT case, the interface between MME and the cdma2000® 1xRTT infrastructure is called S102. S102 carries a protocol specified in 3GPP2 for the A21 interface, which is used in cdma2000® systems for voice call continuity (see Table 3.6).

3.6 IMS Architecture

3.6.1 Overview

The IP Multimedia Services Sub-System (IMS) is the preferred service machinery for LTE/SAE. IMS was first introduced in Release 5, and with the well defined inter-working with existing networks and services that have been introduced since, the Rel-8 IMS can now be used to provide services over fixed and wireless accesses alike. The IMS architecture is defined in [36], and the functionality is defined in [37]. A comprehensive description of IMS can also be found in [3]. For the purpose of this book, the functional architecture of IMS is presented in Figure 3.19, and a short description of the main functions follows below.

IMS is an overlay service layer on top of the IP connectivity layer that the EPS provides. Figure 3.19 shows a thick grey line from UE to P-GW that represents the UE's IP connectivity to IMS and other external networks through the RAN and EPC. The signalling interfaces Gm and Ut run on top of this connection, which typically use the default bearer a UE will always have in LTE/SAE. The services may further require that dedicated bearers are set up through EPC, and the service data flows may need to be handled by one of the Inter-working or Services Elements.

In principle the IMS is independent of the connectivity layer, which requires its own registration and session management procedures, but it has also been specifically designed to operate over the 3GPP-defined ANs, and it works seamlessly with the PCC described in section 3.7. IMS uses SIP protocol for registration and for controlling the service sessions. SIP is used both between the terminal and the IMS (Gm Interface) and between various IMS nodes (ISC, Mw, Mg, Mr, Mi, Mj, Mx, Mk and Mm Interfaces). The SIP usage in IMS is defined in [38]. Diameter (Cx, Dx, Dh and Sh Interfaces) and H.248 (Mp) are the other protocols used in IMS.

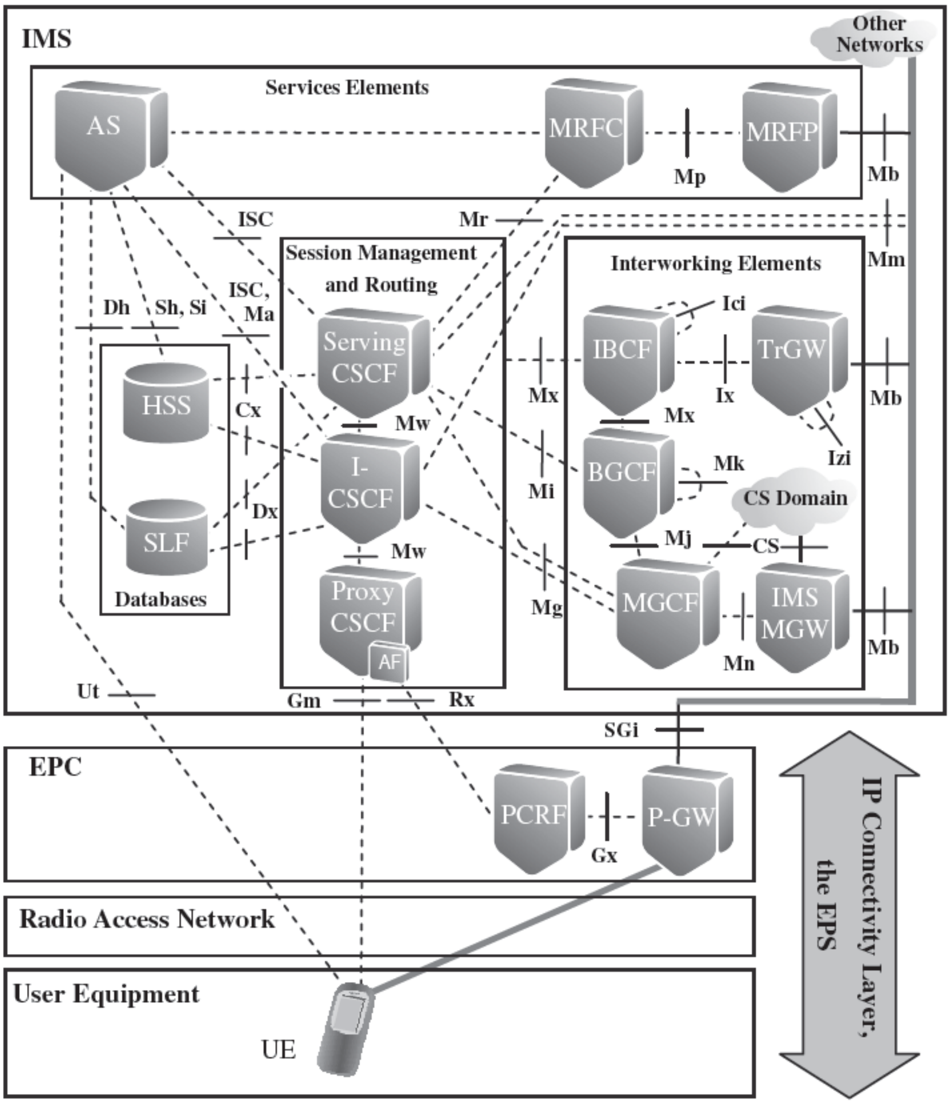


Figure 3.19 IMS architecture

The UE primarily signals with the CSCFs for the services it wishes to use, and in addition some service specific signalling may be run directly with the Application Servers. The signalling may also be network originated for terminating services. The *Session Management and Routing* functions are handled by the CSCFs that are in control of the UE's registration in IMS. For that purpose they signal with the *Databases* to get the appropriate information. The CSCFs are also in control of the UE's service sessions in IMS, and for that purpose they may need to signal with one or more of the *Services Elements* to know what kind of connectivity is needed for the service in question, and then with the connectivity layer through the Rx interface to make corresponding requests to bearer resources. Finally, the CSCFs may need to signal with one or more of the *Inter-working Elements* to control the interconnection between networks. Whenever the UP flow is routed through one of the IMS elements, it is done through the Mb interface that connects IMS to IP networks. The following sections introduce the main functions in the functional groups highlighted in Figure 3.19.

Most IMS elements responsible for session management and routing or inter-working are involved in collecting charging information. Rf and Ro interfaces are the main IMS charging interfaces (see section 3.7.1). For simplicity, charging related nodes and interfaces are not shown in Figure 3.19.

3.6.2 Session Management and Routing

The Call State Control Function (CSCF) is the central element in SIP signalling between the UE and the IMS, and it takes care of the UE's registration to the IMS, and service session management. The registration includes authentication. The primary authentication method is IMS-AKA [39], but other methods such as http digest [40] may also be used. CSCF is defined to have three different roles that may reside in the same node, or separate nodes connected through the Mw interface, and all are involved in the UE-related SIP signalling transactions:

- The Serving CSCF (S-CSCF) locates in the user's home network, and it will maintain the user's registration and session state. At registration, it interfaces with the HSS to receive the subscription profile, including authentication information, and it will authenticate the UE. For the service sessions, the S-CSCF signals with the UE through the other CSCFs, and may also interact with the Application Servers (ASs) or the MRFCs for setting up the service session properly. It also carries the main responsibility for controlling the Inter-working Elements. The S-CSCF may also need to interact with MGCF for inter-working with CS networks, or with other multimedia networks for UE requested services.
- The Interrogating CSCF (I-SCSF) is located at the border of the home network, and it is responsible for finding out the UE's registration status, and either assigning a new S-CSCF or routing to the right existing S-CSCF. The request may come from Proxy CSCF (P-CSCF), from other multimedia networks, or from CS networks through the Media Gateway Control Function (MGCF). Also I-CSCF may need to interact with the ASs for service handling. The Ma interface is used for this when Public Service Identity (PSI) is used to identify the service, and the I-CSCF can route the request directly to the proper AS.
- The (P-CSCF) is the closest IMS node the UE interacts with, and it is responsible for all functions related to controlling the IP connectivity layer, i.e. the EPS. For this purpose the P-CSCF contains the Application Function (AF) that is a logical element for the PCC concept, which is described in section 3.7.1. The P-CSCF is typically located in the same network as the EPS, but the Rel-8 includes a so-called Local Breakout concept that allows P-CSCF to remain in the home network, while PCRF in the visited network may still be used.

In addition to the above-mentioned three CSCF roles, a fourth role, the Emergency CSCF (E-CSCF), has been defined. As the name indicates, the E-CSCF is dedicated to handling the emergency call service in IMS. The E-CSCF connects to the P-CSCF via the Mw interface, and these nodes must always be in the same network. In addition, the E-CSCF is also connected to a Location Retrieval Function (LRF) through the Mi Interface. The LRF can provide the location of the UE, and routing information to route the emergency call appropriately. The E-CSCF and LRF are not shown in Figure 3.19 for simplicity

The CSCFs are connected to each other with the Mw interface, and to other multimedia networks through the Mm interface. Interconnection between CSCFs in different operators' networks may be routed through a common point called the Interconnection Border Control Function (IBCF). See section 3.6.5.

3.6.3 Databases

The Home Subscriber Server (HSS) is the main database used by the IMS. The HSS contains the master copy of subscription data, and it is used in much the same way as with the IP connectivity layer. It provides the location and authentication information based on requests from the I- or S-CSCF, or the AS. The interface between the HSS and the Services Elements will be either Sh or Si depending on the type of services elements. The Sh interface is used in case of SIP or OSA service capability server and the Si when CAMEL based AS is in question.

When there is more than one addressable HSS, another database called the Subscription Locator Function (SLF) may be used to find the right HSS.

3.6.4 Services Elements

The actual service logic is located in the Application Servers (AS). A variety of different services may be provided with different ASs, and the standards do not aim to cover all possible services. Some of the main services are covered in order to facilitate easier inter-working with operators in roaming, and to provide for consistent user experience. One example of a standardized AS is the Telephony Application Server (TAS), which may be used to provide the IMS VoIP service.

The media component of the service can be handled by the Multimedia Resource Function (MRF), which is defined as a separate controller (MRFC) and processor (MRFP). The UP may be routed through MRFP for playing announcements as well as for conferencing and transcoding. For coordination purposes, the MRFC may also be connected to the related AS.

3.6.5 Inter-working Elements

The Inter-working Elements are needed when the IMS interoperates with other networks, such as other IMS networks, or CS networks. The following are the main functions of the standardized inter-working elements:

- The Breakout Gateway Control Function (BGCF) is used when inter-working with CS networks is needed, and it is responsible for selecting where the interconnection will take place. It may select the Media Gateway Control Function (MGCF) if the breakout is to happen in the same network, or it may forward the request to another BGCF in another network. This interaction may be routed through the Interconnection Border Control Function (IBCF).
- The Interconnection Border Control Function (IBCF) is used when interconnection between operators is desired to be routed through defined points, which hide the topology inside the network. The IBCF may be used in interconnection between CSCFs or BGCFs and it is in control of Transition Gateway (TrGW), which is used for the same function in the UP.

Note that the IBCF–TrGW interface is not fully specified in Release 8. The IBCFs and the TrGWs in different operators' networks may be interconnected to each other via the Ici and Izi interfaces respectively, and together they comprise the Inter IMS Network to Network Interface (II-NNI).

- The Media Gateway Control Function (MGCF) and IMS-Media Gateway (IMS-MGW) are the CP and UP nodes for inter-working with the CS networks such as the legacy 3GPP networks with CS domain for GERAN or UTRAN, or for PSTN/ISDN. Both incoming and outgoing IMS VoIP calls are supported with the required signalling inter-working and transcoding between different voice coding schemes. The MGCF works in the control of either the CSCF or BGCF.

3.7 PCC and QoS

3.7.1 PCC

Policy and Charging Control (PCC) has a key role in the way users' services are handled in the Release 8 LTE/SAE system. It provides a way to manage the service related connections in a consistent and controlled way. It determines how bearer resources are allocated for a given service, including how the service flows are partitioned to bearers, what QoS characteristics those bearers will have, and finally, what kind of accounting and charging will be applied. If an operator uses only a very simple QoS model, then a static configuration of these parameters may be sufficient, but Release 8 PCC allows the operator to set these parameters dynamically for each service and even each user separately.

The PCC functions are defined in [5] and the PCC signalling transactions as well as the QoS parameter mapping are defined in [41]. Figure 3.20 shows the PCC functions and interfaces in the basic configuration when PCC is applied in one operator's network.

The primary way to set up service flows in Release 8 is one where the UE first signals the request for the service in the Service Layer, and the Application Function (AF) residing in that layer contacts the Policy and Charging Resource Function (PCRF) for appropriate bearer

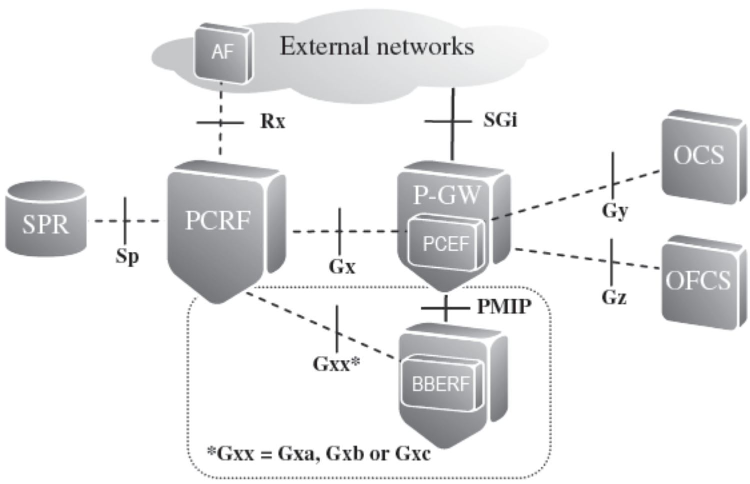


Figure 3.20 Basic PCC functions

resources. The PCRF is in charge for making the decisions on what PCC to use for the service in question. If subscriber specific policies are used, then the PCRF may enquire subscription related policies from the Subscription Profile Repository (SPR). Further details about SPR structure and, for example, its relation to HSS, and the Sp interface are not specified in Release 8. Based on the decision, the PCRF creates the appropriate PCC rules that determine the handling in the EPS.

If the interface from P-GW to the S-GW is based on GTP, the PCRF pushes the PCC rules to the Policy and Charging Enforcement Function (PCEF) residing in the P-GW, and it alone will be responsible for enforcing the PCC rules, e.g. setting up the corresponding dedicated bearers, or modifying the existing bearers so that the new IP service flows can be mapped to them, and by ensuring that only authorized service flows are allowed and QoS limits are not exceeded. In this case the Gxx interface shown in Figure 3.20 does not apply.

If the interface from P-GW towards the AN is based on PMIP, i.e. if it is S5 PMIP, S2a or S2b, there is no means to signal the bearer level information onwards from the P-GW, and the PCRF will create a separate set of QoS rules, and those are first sent to the BBERF, which will handle the mapping between IP service flows and bearers over the AN. Depending on the AN type, the BBERF may reside in S-GW (S5 PMIP), trusted non-3GPP AN, e.g. in HSGW (S2a), or in the EPDG (S2b) for the un-trusted non-3GPP AN (S2b is not supported in Release 8). Also in this case the PCC rules are also sent to PCEF in the P-GW, and it performs the service flow and QoS enforcement.

Release 8 also supports UE initiated bearer activation within the EPS, which is applicable to the case when there is no defined service that both the UE and the serving network could address. In this case the UE signals with the AN and the BBERF requests the service resources from the PCRF. The PCRF makes the PCC decision, and the logic then continues as described above.

The PCC standard [5] defines two charging interfaces, Gy and Gz, which are used for online and offline charging respectively. The Gy interface connects the PCEF to the Online Charging System (OCS), which is used for flow based charging information transfer and control in an online fashion. The Gz interface is used between the P-GW and the Offline Charging System (OFCS), and it is applied when charging records are consolidated in an offline fashion. The charging specifications [42] and [43] further define that the Gy interface is functionally equivalent to the Ro interface that uses Diameter Credit-Control Application as defined in [44]. The Gz interface may be based on either the Rf interface, which relies on the mentioned Diameter Credit-Control Application, or the Ga interface, which uses the 3GPP defined GTP protocol. The Ro and Rf interfaces are also used for charging in IMS, and were originally specified for that purpose.

The PCRF in control of the PCEF/P-GW and the BBERF typically reside in the same operator's network. In the case of roaming, they may reside in different networks, and the S9 interface between PCRFs is used to enable the use of a local PCRF. The S9 interface is defined in [9], and it re-uses the applicable parts from Rx, Gx and Gxx interfaces to convey the information between the PCRFs.

There are two different cases when the S9 interface is used. The first case, which is shown in Figure 3.21, applies when the roaming interface is based on PMIP, and the PCEF and BBERF are in different networks. In this scenario traffic is routed to the home network. In the second case, shown in Figure 3.22, the Local Breakout model is applied, and the P-GW resides in the visited network. The AF and Rx interface will be used from the same network that provides the service in question. The OCS will reside in the home network. As described

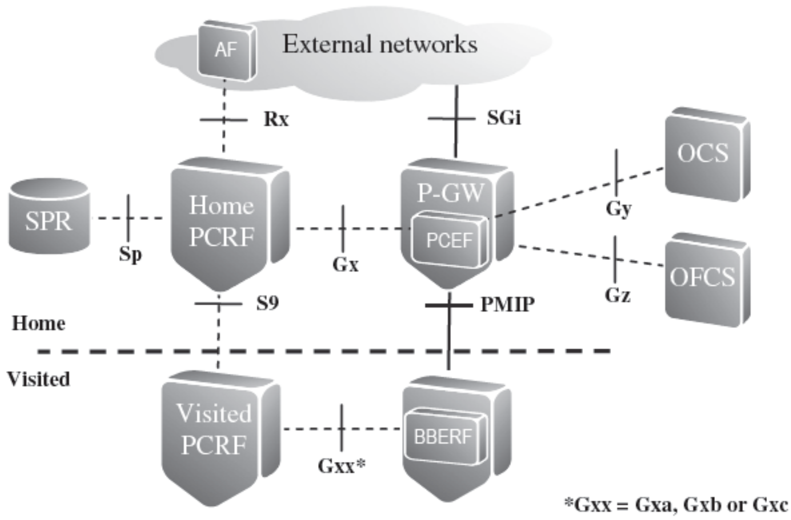


Figure 3.21 PCC functions in roaming with PMIP, home routed model

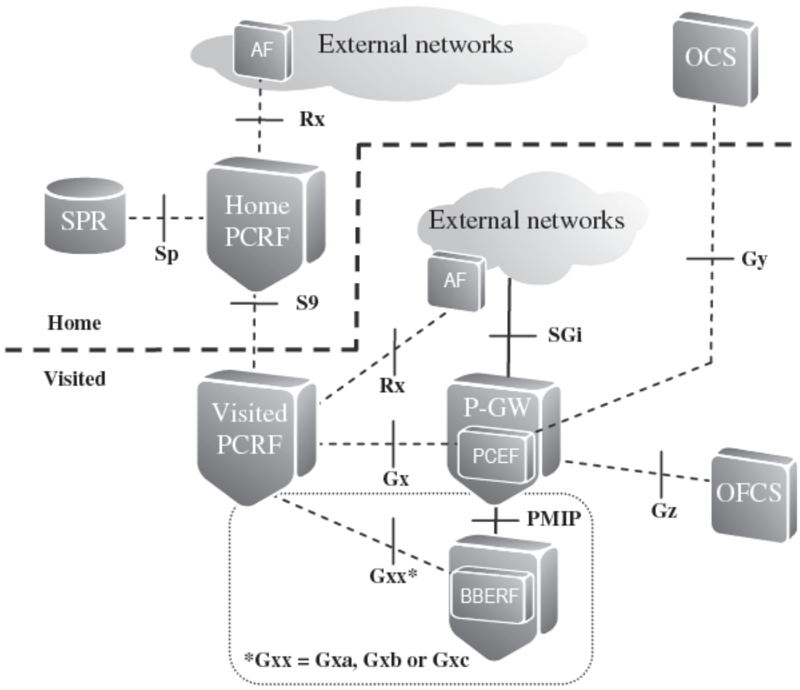


Figure 3.22 PCC functions in roaming, local breakout model

above, the separate BBERF and Gxx interfaces apply only if PMIP is used from the P-GW in the visited network.

Table 3.7 lists the PCC related interfaces and the protocols, and the standards where they are specified.

Table 3.7 Summary of PCC interfaces

Interface	Protocols	Specification
Gx	Diameter/SCTP/IP	29.212 [13]
Gxx (Gxa or Gxc)	Diameter/SCTP/IP	29.212 [13]
Rx	Diameter/SCTP/IP	29.214 [14]
S9	Diameter/SCTP/IP	29.215 [45]
Sp	*Not defined in Release 8*	*N.A.*
Gy =		32.240 [42]
Ro	Diameter/SCTP/IP	32.299 [46]
Gz =		32.251 [43]
Rf or	Diameter/SCTP/IP or	32.295 [47] or
Ga	GTP'/UDP or TCP/IP	32.299 [46]

3.7.2 QoS

The development of the SAE bearer model and the QoS concept started with the assumption that improvements compared to the existing 3GPP systems with, e.g. UTRAN access, should be made, and the existing model should not be taken for granted. Some potential areas had already been identified. It had not been easy for the operators to use QoS in the legacy 3GPP systems. An extensive set of QoS attributes was available, but it was to some extent disconnected from the application layer, and thus it had not been easy to configure the attributes in the correct way. This problem was emphasized by the fact that the UE was responsible for setting the QoS attributes for a bearer. Also, the bearer model had many layers, each signalling just about the same information. It was therefore agreed that for SAE, only a reduced set of QoS parameters and standardized characteristics would be specified. Also it was decided to turn the bearer set-up logic so that the network resource management is solely network controlled, and the network decides how the parameters are set, and the main bearer set-up logic consists of only one signalling transaction from the network to the UE and all interim network elements.

The resulting SAE bearer model is shown in Figure 3.23. The bearer model itself is very similar to the GPRS bearer model, but it has fewer layers. EPS supports the always-on concept.

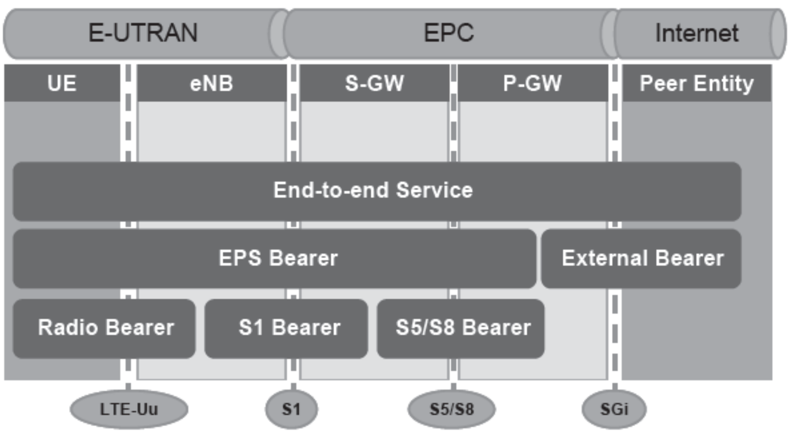


Figure 3.23 SAE Bearer model

Each UE that is registered to the system has at least one bearer called the default bearer available, so that continuous IP connectivity is provided. The default bearer may have quite basic QoS capabilities, but additional bearers may be set up on demand for services that need more stringent QoS. These are called dedicated bearers. The network may also map several IP flows that have matching QoS characteristics to the same EPS bearer.

The bearer set-up logic works so that the UE first signals on the application layer, on top of the default bearer, to an Application Server (AS) in the operator service cloud, e.g. with IMS, to set up the End-to-end Service. This signalling may include QoS parameters, or simply indication to a known service. The AS will then request the set-up of the corresponding EPS bearer through the PCC infrastructure. There is no separate signalling transaction for the EPS bearer layer, but the EPS bearer is set up together with the signalling for the lower layers, i.e. S5/S8 bearer, S1 Bearer and Radio Bearer. Furthermore, since the eNodeB is responsible for controlling the radio interface transmission in the uplink as well, the UE can operate based on very basic QoS information. The overall goal for network orientation in bearer set-up is to minimize the need for QoS knowledge and configuration in the UE.

Also the QoS parameters were optimized for SAE. Only a limited set of signalled QoS parameters are included in the specifications. They are:

- QoS Class Identifier (QCI): It is an index that identifies a set of locally configured values for three QoS attributes: Priority, Delay and Loss Rate. QCI is signalled instead of the values of these parameters. Ten pre-configured classes have been specified in two categories of bearers, Guaranteed Bit Rate (GBR) and Non-Guaranteed Bit-Rate (Non-GBR) bearers. In addition operators can create their own classes that apply within their network. The standard QCI classes and the values for the parameters within the class are shown in Table 3.8.
- Allocation and Retention Priority (ARP): Indicates the priority of the bearer compared to other bearers. This provides the basis for admission control in bearer set-up, and further in a congestion situation if bearers need to be dropped.
- Maximum Bit Rate (MBR): Identifies the maximum bit rate for the bearer. Note that a Release 8 network is not required to support differentiation between the MBR and GBR, and the MBR value is always set to equal to the GBR.
- Guaranteed Bit Rate (GBR): Identifies the bit rate that will be guaranteed to the bearer.
- Aggregate Maximum Bit Rate (AMBR): Many IP flows may be mapped to the same bearer, and this parameter indicates the total maximum bit rate a UE may have for all bearers in the same PDN connection.

Table 3.8 QoS parameters for QCI

QCI	Resource type	Priority	Delay budget	Loss rate	Example application
1	GBR	2	100 ms	1e-2	VoIP
2	GBR	4	150 ms	1e-3	Video call
3	GBR	5	300 ms	1e-6	Streaming
4	GBR	3	50 ms	1e-3	Real time gaming
5	Non-GBR	1	100 ms	1e-6	IMS signalling
6	Non-GBR	7	100 ms	1e-3	Interactive gaming
7	Non-GBR	6	300 ms	1e-6	Application with TCP:
8	Non-GBR	8			browsing, email, file
9	Non-GBR	9			download, etc.

Table 3.8 shows the QoS parameters that are part of the QCI class, and the nine standardized classes. The QoS parameters are:

- Resource Type: Indicates which classes will have GBR associated to them.
- Priority: Used to define the priority for the packet scheduling of the radio interface.
- Delay Budget: Helps the packet scheduler to maintain sufficient scheduling rate to meet the delay requirements for the bearer.
- Loss Rate: Helps to use appropriate RLC settings, e.g. number of re-transmissions.

References

[1] 3GPP TS 23.401, 'General Packet Radio Service (GPRS) enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) access (Release 8)'.
[2] 3GPP TS 23.402, 'Architecture enhancements for non-3GPP accesses (Release 8)'.
[3] M. Poikselkä et al., 'The IMS: IP Multimedia Concepts and Services', 2nd edition, Wiley, 2006.
[4] 3GPP TS 33.401, 'Security Architecture (Release 8)'.
[5] 3GPP TS 23.203, 'Policy and charging control architecture (Release 8)'.
[6] 3GPP TS 36.413, 'Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description (Release 8)'.
[7] 3GPP TS 36.423, 'Evolved Universal Terrestrial Radio Access Network (E-UTRAN); X2 Application Protocol (X2AP) (Release 8)'.
[8] 3GPP TS 29.274, 'Evolved GPRS Tunnelling Protocol (eGTP) for EPS (Release 8)'.
[9] 3GPP TS 36.413, 'Evolved Universal Terrestrial Radio Access (E-UTRA); S1 Application Protocol (S1AP) (Release 8)'.
[10] 3GPP TS 29.275, 'PMIP based Mobility and Tunnelling protocols (Release 8)'.
[11] 3GPP TS 29.061, 'Inter-working between the Public Land Mobile Network (PLMN) supporting packet based services and Packet Data Networks (PDN) (Release 8)'.
[12] 3GPP TS 29.272, 'MME Related Interfaces Based on Diameter Protocol (Release 8)'.
[13] 3GPP TS 29.212, 'Policy and charging control over Gx reference point (Release 8)'.
[14] 3GPP TS 29.214, 'Policy and charging control over Rx reference point (Release 8)'.
[15] 3GPP TS 24.301, 'Non-Access-Stratum (NAS) protocol for Evolved Packet System (EPS) (Release 8)'.
[16] H. Holma, A. Toskala, 'WCDMA for UMTS – HSPA Evolution and LTE', 4th edition, Wiley, 2007.
[17] T. Halonen, J. Romero, J. Melero, 'GSM, GPRS and EDGE Performance: Evolution Towards 3G/UMTS', 2nd edition, Wiley, 2003.
[18] 3GPP TS 23.060, 'General Packet Radio Service (GPRS); Service description; Stage 2 (Release 8)'.
[19] 3GPP TS 23.272, 'Circuit Switched (CS) fallback in Evolved Packet System (EPS); Stage 2 (Release 8)'.
[20] 3GPP TS 23.216, 'Single Radio Voice Call Continuity (SRVCC); Stage 2 (Release 8)'.
[21] 3GPP TS 29.118, 'Mobility Management Entity (MME) – Visitor Location Register (VLR) SGs interface specification (Release 8)'.
[22] 3GPP TS 29.280, '3GPP EPS Sv interface (MME to MSC) for SRVCC (Release 8)'.
[23] 3GPP TS 33.402, 'Security aspects of non-3GPP accesses (Release 8)'.
[24] IETF Internet-Draft, draft-arkko-eap-aka-kdf, 'Improved Extensible Authentication Protocol Method for 3rd Generation Authentication and Key Agreement (EAP-AKA)'. (J. Arkko,V. Lehtovirta, P. Eronen) 2008.
[25] 3GPP TS 23.234, '3GPP system to Wireless Local Area Network (WLAN) interworking; System description (Release 7)'.
[26] IETF RFC 4306, 'Internet Key Exchange (IKEv2) Protocol.' C. Kaufman, Editor, 2005.
[27] 3GPP TS 24.303, 'Mobility management based on Dual-Stack Mobile IPv6 (Release 8)'.
[28] 3GPP TS 29.273, 'Evolved Packet System (EPS); 3GPP EPS AAA interfaces (Release 8)'.
[29] 3GPP TS 24.302, 'Access to the Evolved Packet Core (EPC) via non-3GPP access networks (Release 8)'.
[30] 3GPP TS 24.304, 'Mobility management based on Mobile IPv4; User Equipment (UE) – foreign agent interface (Release 8)'.
[31] 3GPP2 Specification X.P0057, 'E-UTRAN – HRPD Connectivity and Interworking: Core Network Aspects (2008)'.

[32] 3GPP2 Specification X.P0022, 'E-UTRAN – HRPD Connectivity and Interworking: Access Network Aspects (E-UTRAN – HRPD IOS) (2008)'.
[33] 3GPP TS 29.276, 'Optimized Handover Procedures and Protocols between EUTRAN Access and cdma2000 HRPD Access (Release 8)'.
[34] 3GPP TS 29.277, 'Optimized Handover Procedures and Protocols between EUTRAN Access and 1xRTT Access (Release 8)'.
[35] 3GPP2 Specification A.S0008-C, 'Interoperability Specification (IOS) for High Rate Packet Data (HRPD) Radio Access Network Interfaces with Session Control in the Access Network (2007)'.
[36] 3GPP TS 23.002, 'Network architecture (Release 8)'.
[37] 3GPP TS 23.228, 'IP Multimedia Subsystem (IMS); Stage 2 (Release 8)'.
[38] 3GPP TS 24.229, 'IP multimedia call control protocol based on Session Initiation Protocol (SIP) and Session Description Protocol (SDP); Stage 3 (Release 8)'.
[39] 3GPP TS 33.203, '3G security; Access security for IP-based services (Release 8)'.
[40] IETF RFC 2617, 'HTTP Authentication: Basic and Digest Access Authentication', J. Franks, P. Hallam-Baker, J. Hostetler, S. Lawrence, P. Leach, A. Luotonen, L. Stewart (1999).
[41] 3GPP TS 29.213, 'Policy and Charging Control signalling flows and QoS parameter mapping (Release 8)'.
[42] 3GPP TS 32.240, 'Telecommunication management; Charging management; Charging architecture and principles (Release 8)'.
[43] 3GPP TS 32.251, 'Telecommunication management; Charging management; Packet Switched (PS) domain charging (Release 8)'.
[44] IETF RFC 4006, 'Diameter Credit-Control Application', H. Hakala, L. Mattila, J.-P. Koskinen, M. Stura, J. Loughney (2005).
[45] 3GPP TS 29.215, 'Policy and Charging Control (PCC) over S9 reference point (Release 8)'.
[46] 3GPP TS 32.299, 'Telecommunication management; Charging management; Diameter charging applications (Release 8)'.
[47] 3GPP TS 32.295, 'Telecommunication management; Charging management; Charging Data Record (CDR) transfer (Release 8)'.

4

Introduction to OFDMA and SC-FDMA and to MIMO in LTE

Antti Toskala and Timo Lunttila

4.1 Introduction

As discussed in Chapter 1, LTE multiple access is different to that of WCDMA. In LTE the downlink multiple access is based on the Orthogonal Frequency Division Multiple Access (OFDMA) and the uplink multiple access is based on the Single Carrier Frequency Division Multiple Access (SC-FDMA). This chapter will introduce the selection background and the basis for both SC-FDMA and OFDMA operation. The basic principles behind the multi-antenna transmission in LTE, using Multiple Input Multiple Output (MIMO) technology, is also introduced. The intention of this chapter is to illustrate the multiple access principles in a descriptive way without too much mathematics. For those interested in the detailed mathematical notation, two selected references are given that provide a mathematical treatment of the different multiple access technologies, covering both OFDMA and SC-FDMA.

4.2 LTE Multiple Access Background

A Single Carrier (SC) transmission means that information is modulated only to one carrier, adjusting the phase or amplitude of the carrier or both. Frequency could also be adjusted, but in LTE this is not effected. The higher the data rate, the higher the symbol rate in a digital system and thus the bandwidth is higher. With the use of simple Quadrature Amplitude Modulation (QAM), with the principles explained, for example in [1], the transmitter adjusts the signal to carry the desired number of bits per modulation symbol. The resulting spectrum waveform is a single carrier spectrum, as shown in Figure 4.1, with the spectrum mask influenced (after filtering) by the pulse shape used.

With the Frequency Division Multiple Access (FDMA) principle, different users would then be using different carriers or sub-carriers, as shown in Figure 4.2, to access the system simultaneously having their data modulation around a different center frequency. Care must be now

LTE for UMTS: OFDMA and SC-FDMA Based Radio Access Edited by Harri Holma and Antti Toskala
 ISBN: 978-0-470-99401-6

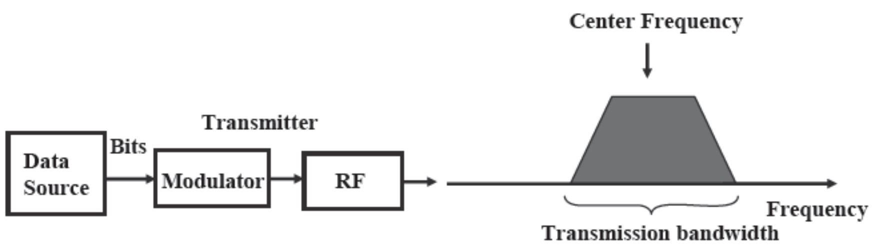


Figure 4.1 Single carrier transmitter

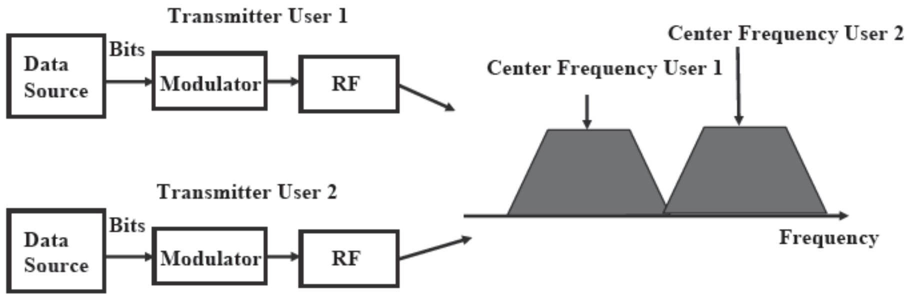


Figure 4.2 FDMA principle

taken to create the waveform in such a way that there is no excessive interference between the carriers, nor should one be required to use extensive guard bands between users.

The use of the multi-carrier principle is shown in Figure 4.3, where data are divided on the different sub-carriers of one transmitter. The example in Figure 4.3 has a filter bank which for practical solutions (such as the ones presented later) is usually replaced with Inverse Fast Fourier Transform (IFFT) for applications where the number of sub-carriers is high. There is a constant spacing between neighboring sub-carriers. One of the approaches to multi-carrier is also the dual carrier WCDMA (dual cell HSDPA, as covered in Chapter 13), which sends two WCDMA next to each other but does not use the principles explained later in this section for high spectrum utilization.

To address the resulting inefficiency from the possible guard band requirements, the approach is to choose the system parameters in such a way as to achieve orthogonality between the dif-

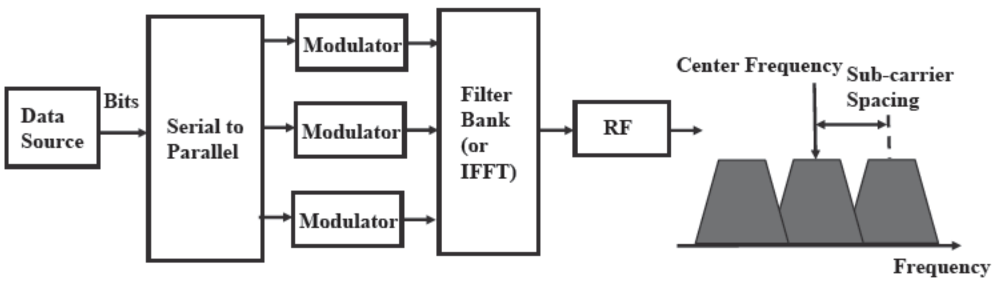


Figure 4.3 Multi-carrier principle

ferent transmissions, and to create the sub-carriers so that they do not interfere with each other but their spectrums could still overlap in the frequency domain. This is what is achieved with the Orthogonal Frequency Division Multiplexing (OFDMA) principle, where each of the center frequencies for the sub-carriers is selected from the set that has such a difference in the frequency domain that the neighboring sub-carriers have zero value at the sampling instant of the desired sub-carrier, as shown in Figure 4.4. For LTE, the constant frequency difference between the sub-carriers has been chosen to be 15 kHz in Release 8 (an alternative of 7.5 kHz is planned to be supported in later releases in connection with broadcast applications such as mobile TV).

The basic principle of OFDMA was already known in the 1950s, at a time when systems were using analog technology, and making the sub-carriers stay orthogonal as a function of component variations and temperature ranges was not a trivial issue. Since the widespread use of digital technology for communications, OFDMA also became more feasible and affordable for consumer use. During recent years OFDMA technology has been widely adopted in many areas such as in digital TV (DVB-T and DVB-H) as well as in Wireless Local Area Network (WLAN) applications.

OFDMA principles have been used in the uplink part of LTE multiple access just as the SC-FDMA uses many of the OFDMA principles in the uplink direction to achieve high spectral efficiency, as described in the next section. The SC-FDMA in the current form, covered in a later section of this chapter, is more novel technology with publications from the late 1990s, such as those presented in [2] and the references therein.

The overall motivation for OFDMA in LTE and in other systems has been due to the following properties:

- good performance in frequency selective fading channels;
- low complexity of base-band receiver;
- good spectral properties and handling of multiple bandwidths;
- link adaptation and frequency domain scheduling;
- compatibility with advanced receiver and antenna technologies.

Many of these benefits (with more explanation provided in the following sections) could only be achieved following the recent developments in the radio access network architecture, meaning setting the radio related control in the base station (or NodeB in 3GPP terms for

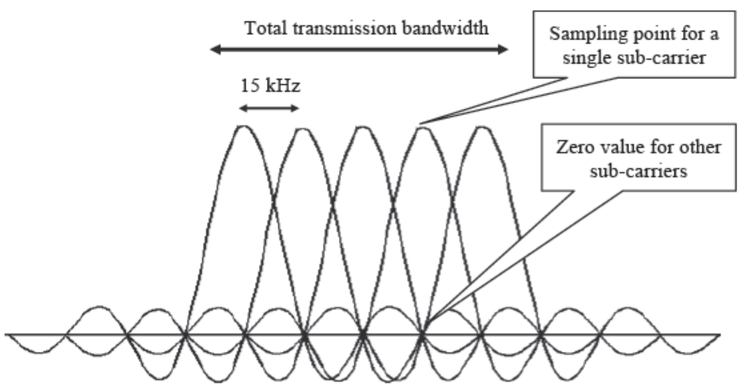


Figure 4.4 Maintaining the sub-carriers' orthogonality

WCDMA), and as the system bandwidths are getting larger, beyond 5 MHz, receiver complexity also becomes more of an issue.

The OFDMA also has challenges, such as:

- Tolerance to frequency offset. This was tackled in LTE design by choosing a sub-carrier spacing of 15 kHz, which gives a large enough tolerance for Doppler shift due to velocity and implementation imperfections.
- The high Peak-to-Average Ratio (PAR) of the transmitted signal, which requires high linearity in the transmitter. The linear amplifiers have a low power conversion efficiency and therefore are not ideal for mobile uplinks. In LTE this was solved by using the SC-FDMA, which enables better power amplifier efficiency.

When looking back, the technology selections carried out for the 3rd generation system in the late 1990s, the lack of a sensible uplink solution, the need for advanced antenna solutions (with more than a single antenna) and having radio resource control centralized in the Radio Network Controller (RNC) were the key factors not to justify the use of OFDMA technology earlier. There were studies to look at the OFDMA together with CDMA in connection with the 3rd generation radio access studies, such as are covered in [3]. The key enabling technologies that make OFDMA work better, such as base station based scheduling (Release 5 and 6) and Multiple Input Multiple Output (MIMO) (Release 7), have been introduced only in the later phase of WCDMA evolution. These enhancements, which were introduced in WCDMA between 2002 and 2007, allowed the OFDMA technology to be better used than would have been the case for the simple use of OFDMA only as a modulation method based on a traditional 2nd generation cellular network without advanced features.

4.3 OFDMA Basics

The practical implementation of an OFDMA system is based on digital technology and more specifically on the use of Discrete Fourier Transform (DFT) and the inverse operation (IDFT) to move between time and frequency domain representation. The resulting signal feeding a sinusoidal wave to the Fast Fourier Transform (FFT) block is illustrated in Figure 4.5. The

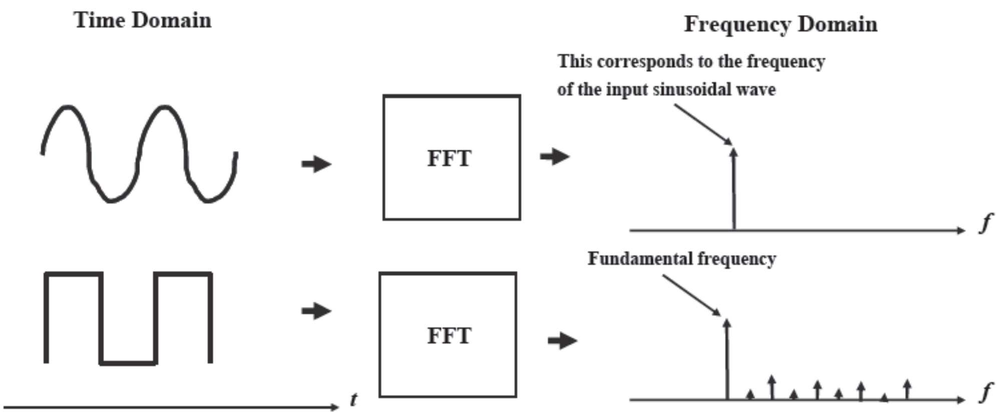


Figure 4.5 Results of the FFT operation with different inputs

practical implementations use the FFT. The FFT operation moves the signal from time domain representation to frequency domain representation. The Inverse Fast Fourier Transform (IFFT) does the operation in the opposite direction. For the sinusoidal wave, the FFT operation's output will have a peak at the corresponding frequency and zero output elsewhere. If the input is a square wave, then the frequency domain output contains peaks at multiple frequencies as such a wave contains several frequencies covered by the FFT operation. An impulse as an input to FFT would have a peak on all frequencies. As the square wave has a regular interval T, there is a bigger peak at the frequency $1/T$ representing the fundamental frequency of the waveform, and a smaller peak at odd harmonics of the fundamental frequency. The FFT operation can be carried out back and forth without losing any of the original information, assuming that the classical requirements for digital signal processing in terms of minimum sampling rates and word lengths (for the numerics) are fulfilled.

The implementation of the FFT is well researched and optimized (low amount of multiplications) when one can stay with power of lengths. Thus for LTE the necessary FFT lengths also tend to be powers of two, such as 512, 1024, etc. From the implementation point of view it is better to have, for example, a FFT size of 1024 even if only 600 outputs are used (see later the discussion on sub-carriers), than try to have another length for FFT between 600 and 1024.

The transmitter principle in any OFDMA system is to use narrow, mutually orthogonal sub-carriers. In LTE the sub-carrier spacing is 15 kHz regardless of the total transmission bandwidth. Different sub-carriers are orthogonal to each other, as at the sampling instant of a single sub-carrier the other sub-carriers have a zero value, as was shown in Figure 4.4. The transmitter of an OFDMA system uses IFFT block to create the signal. The data source feeds to the serial-to-parallel conversion and further to the IFFT block. Each input for the IFFT block corresponds to the input representing a particular sub-carrier (or particular frequency component of the time domain signal) and can be modulated independently of the other sub-carriers. The IFFT block is followed by adding the cyclic extension (cyclix prefix), as shown in Figure 4.6.

The motivation for adding the cyclic extension is to avoid inter-symbol interference. When the transmitter adds a cyclic extension longer than the channel impulse response, the effect of the previous symbol can be avoided by ignoring (removing) the cyclic extension at the receiver.

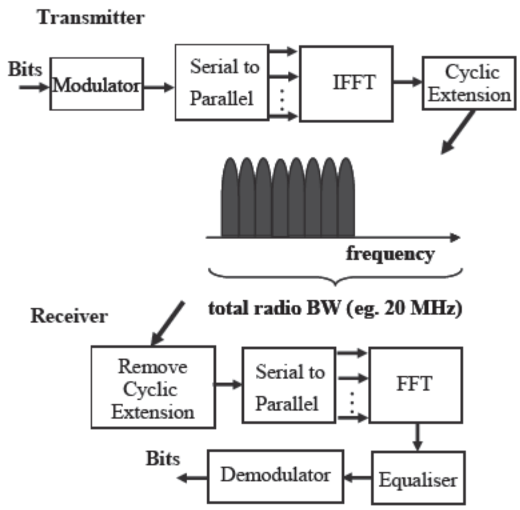


Figure 4.6 OFDMA transmitter and receiver

The cyclic prefix is added by copying part of the symbol at the end and attaching it to the beginning of the symbol, as shown in Figure 4.7. The use of cyclic extension is preferable to simply a break in the transmission (guard interval) as the OFDM symbol then seems to be periodic. When the OFDMA symbol now appears as periodic due to cyclic extension, the impact of the channel ends up corresponding to a multiplication by a scalar, assuming that the cyclic extension is sufficiently long. The periodic nature of the signals also allows for a discrete Fourier spectrum enabling the use of DFT and IDFT in the receiver and transmitter respectively.

Typically the guard interval is designed to be such that it exceeds the delay spread in the environment where the system is intended to be operated. In addition to the channel delay spread, the impact of transmitter and receiver filtering needs to be accounted for in the guard interval design. The OFDMA receiver sees the OFDMA symbol coming as through a FIR filter, without separating individual frequency components like the RAKE receiver as described in [4]. Thus, similar to the channel delay spread, the length of the filter applied to the signal in the receiver and transmitter side will also make this overall 'filtering' effect longer than just the delay spread.

While the receiver does not deal with the inter-symbol interference, it still has to deal with the channel impact for the individual sub-carriers that have experienced frequency dependent phase and amplitude changes. This channel estimation is facilitated by having part of the symbols as known reference or pilot symbols. With the proper placement of these symbols in both the time and frequency domains, the receiver can interpolate the effect of the channel to the different sub-carriers from this time and frequency domain reference symbol 'grid'. An example is shown in Figure 4.8.

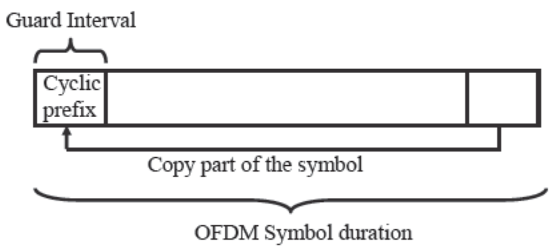


Figure 4.7 Creation of the guard interval for the OFDM symbol

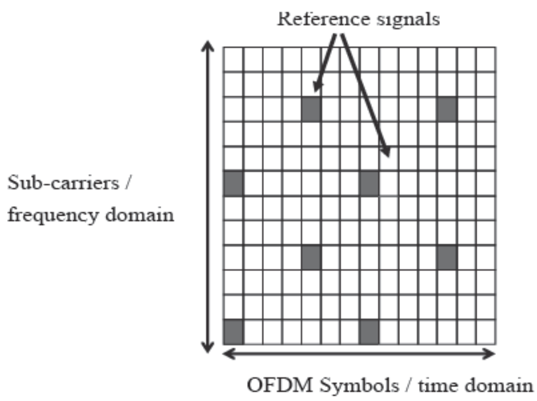


Figure 4.8 Reference symbols spread over OFDMA sub-carriers and symbols

A typical type of receiver solution is the frequency domain equalizer, which basically reverts the channel impact for each sub-carrier. The frequency domain equalizer in OFDMA simply multiplies each sub-carrier (with the complex-valued multiplication) based on the estimated channel frequency response (the phase and amplitude adjustment each sub-carrier has experienced) of the channel. This is clearly a simpler operation compared with WCDMA and is not dependent on channel length (length of multipath in chips) as is the WCDMA equalizer. For WCDMA the challenge would be also to increase the chip rate from the current value of 3.84 Mcps, as then the amount of multi-path components separated would increase (depending on the environment) resulting in the need for more RAKE fingers and contributing heavily to equalizer complexity.

In WCDMA the channel estimation in the downlink is based on the Common Pilot Channel (CPICH) and then on pilot symbols on the Dedicated Channel (DCH), which are transmitted with the spread over the whole transmission bandwidth, and different cells separated by different spreading codes. As in the OFDMA system there is no spreading available, other means must be used to separate the reference symbols between cells or between different antennas. In the multi-antenna transmission, as discussed in further detail later in this chapter, the pilot symbols have different positions. A particular position used for a pilot symbol for one antenna is left unused for other antenna in the same cell. Between different cells this blanking is not used, but different pilot symbol patterns and symbol locations can be used.

The additional tasks that the OFDMA receiver needs to cover are time and frequency synchronization. Synchronization allows the correct frame and OFDMA symbol timing to be obtained so that the correct part of the received signal is dropped (cyclic prefix removal). Time synchronization is typically obtained by correlation with known data samples – based on, for example, the reference symbols – and the actual received data. The frequency synchronization estimates the frequency offset between the transmitter and the receiver and with a good estimate of the frequency offset between the device and base station, the impact can be then compensated both for receiver and transmitter parts. The device locks to the frequency obtained from the base station, as the device oscillator is not as accurate (and expensive) as the one in the base station. The related 3GPP requirements for frequency accuracy are covered in Chapter 11.

Even if in theory the OFDMA transmission has rather good spectral properties, the real transmitter will cause some spreading of the spectrum due to imperfections such as the clipping in the transmitter. Thus the actual OFDMA transmitter needs to have filtering similar to the pulse shape filtering in WCDMA. In the literature this filtering is often referred as windowing, as in the example transmitter shown in Figure 4.9.

An important aspect of the use of OFDMA in a base station transmitter is that users can be allocated basically to any of the sub-carriers in the frequency domain. This is an additional element to the HSDPA scheduler operation, where the allocations were only in the time domain

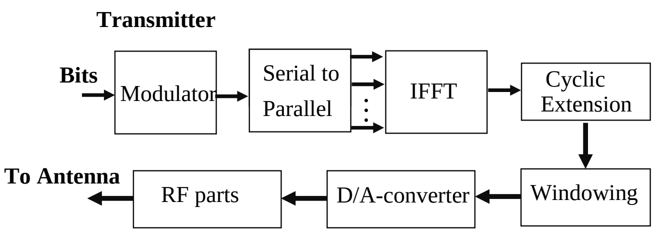


Figure 4.9 OFDMA transmitter with windowing for shaping the spectral mask

and code domain but always occupied the full bandwidth. The possibility of having different sub-carriers to allocated users enables the scheduler to benefit from the diversity in the frequency domain, this diversity being due to the momentary interference and fading differences in different parts of the system bandwidth. The practical limitation is that the signaling resolution due to the resulting overhead has meant that allocation is not done on an individual sub-carrier basis but is based on resource blocks, each consisting of 12 sub-carriers, thus resulting in the minimum bandwidth allocation being 180 kHz. When the respective allocation resolution in the time domain is 1 ms, the downlink transmission resource allocation thus means filling the resource pool with 180 kHz blocks at 1 ms resolution, as shown in Figure 4.10. Note that the resource block in the specifications refers to the 0.5 ms slot, but the resource allocation is done anyway with the 1 ms resolution in the time domain. This element of allocating resources dynamically in the frequency domain is often referred to as frequency domain scheduling or frequency domain diversity. Different sub-carriers could ideally have different modulations if one could adapt the channel without restrictions. For practical reasons it would be far too inefficient to try either to obtain feedback with 15 kHz sub-carrier resolution or to signal the modulation applied on a individual sub-carrier basis. Thus parameters such as modulation are fixed on the resource block basis.

The OFDMA transmission in the frequency domain thus consists of several parallel sub-carriers, which in the time domain correspond to multiple sinusoidal waves with different frequencies filling the system bandwidth with steps of 15 kHz. This causes the signal envelope to vary strongly, as shown in Figure 4.11, compared to a normal QAM modulator, which is only sending one symbol at a time (in the time domain). The momentary sum of sinusoids leads to the Gaussian distribution of different peak amplitude values.

This causes some challenges to the amplifier design as, in a cellular system, one should aim for maximum power amplifier efficiency to achieve minimum power consumption. Figure 4.12 illustrates how a signal with a higher envelope variation (such as the OFDMA signal in the time domain in Figure 4.11) requires the amplifier to use additional back-off compared to a regular single carrier signal. The amplifier must stay in the linear area with the use of extra power back-off in order to prevent problems to the output signal and spectrum mask. The use of additional back-off leads to a reduced amplifier power efficiency or a smaller output power. This either causes the uplink range to be shorter or, when the same average output power level

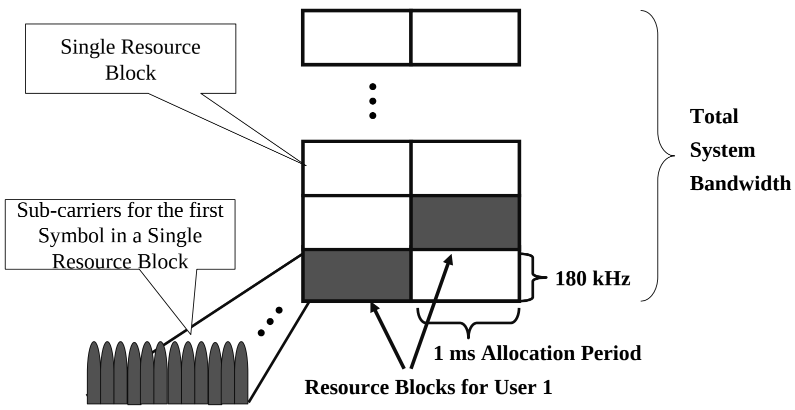


Figure 4.10 OFDMA resource allocation in LTE

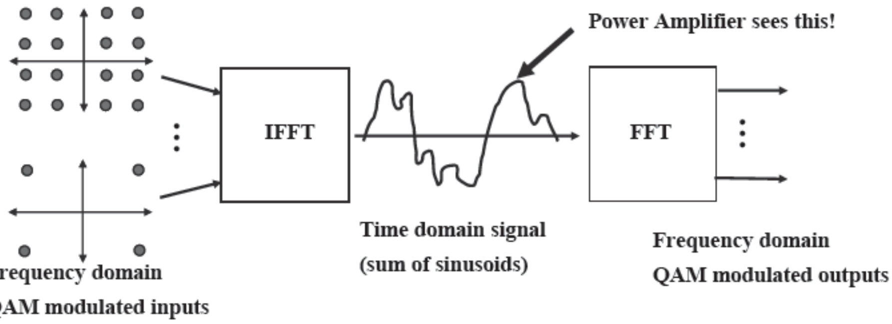


Figure 4.11 OFDMA signal envelope characteristics

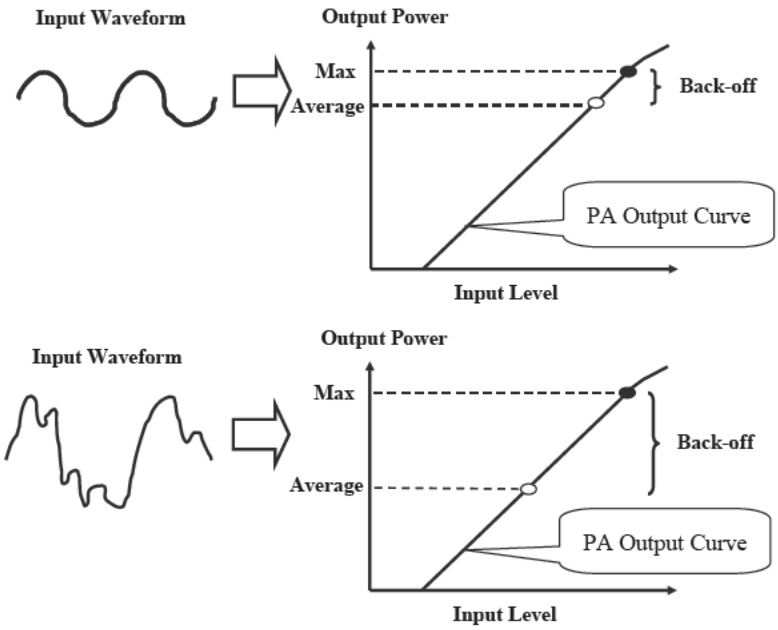


Figure 4.12 Power amplifier back-off requirements for different input waveforms

is maintained, the battery energy is consumed faster due to higher amplifier power consumption. The latter is not considered a problem in fixed applications where the device has a large volume and is connected to the mains, but for small mobile devices running on their own batteries it creates more challenges.

This was the key reason why 3GPP decided to use OFDMA in the downlink direction but to use the power efficient SC-FDMA in the uplink direction. Further principles of SC-FDMA are presented in the next section. From the research several methods are known to reduce the PAR, but of more significance – particularly for the amplifier – is the Cubic Metric (CM), which was introduced in 3GPP to better describe the impact to the amplifier. The exact definition of CM can be found from [5].

An OFDMA system is also sensitive to frequency errors as previously mentioned in section 4.2 . The basic LTE sub-carrier spacing of 15 kHz facilitates enough tolerance for the effects of implementation errors and Doppler effect without too much degradation in the sub-carrier orthogonality. 3GPP has agreed that for broadcast only (on a dedicated carrier) an optional 7.5 kHz sub-carrier spacing can also be used, but full support of the broadcast only carrier is not part of the LTE Release 8. The physical layer details for the 7.5 kHz case principles can already be found in the 36.2 series specifications of Release 8, but details – especially for the higher layer operation – are only to be completed for releases after Release 8.

4.4 SC-FDMA Basics

In the uplink direction 3GPP uses SC-FDMA for multiple access, valid for both FDD and TDD modes of operation. The basic form of SC-FDMA could be seen as equal to the QAM modulation, where each symbol is sent one at a time similarly to Time Division Multiple Access (TDMA) systems such as GSM. Frequency domain generation of the signal, as shown in Figure 4.13, adds the OFDMA property of good spectral waveform in contrast to time domain signal generation with a regular QAM modulator. Thus the need for guard bands between different users can be avoided, similar to the downlink OFDMA principle. As in an OFDMA system, a cyclic prefix is also added periodically – but not after each symbol as the symbol rate is faster in the time domain than in OFDMA – to the transmission to prevent inter-symbol interference and to simplify the receiver design. The receiver still needs to deal with inter-symbol interference as the cyclic prefix now prevents inter-symbol interference between a block of symbols, and thus there will still be inter-symbol interference between the cyclic prefixes. The receiver will thus run the equalizer for a block of symbols until reaching the cyclic prefix that prevents further propagation of the inter-symbol interference.

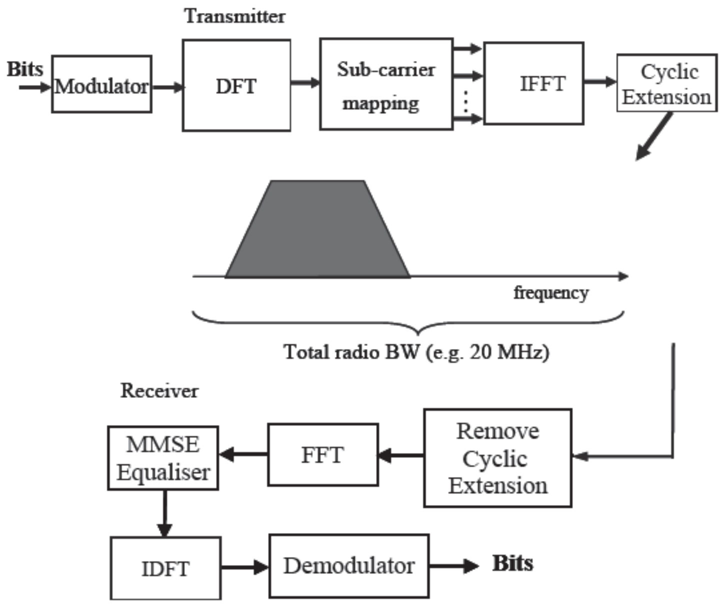


Figure 4.13 SC-FDMA transmitter and receiver with frequency domain signal generation

The transmission occupies the continuous part of the spectrum allocated to the user, and for LTE the system facilitates a 1 ms resolution allocation rate. When the resource allocation in the frequency domain is doubled, so is the data rate, assuming the same level of overhead. The individual transmission (with modulation) is now shorter in time but wider in the frequency domain, as shown in Figure 4.14. The example in Figure 4.14 assumes that in the new resource allocation the existing frequency resource is retained and the same amount of additional transmission spectrum is allocated, thus doubling the transmission capacity. In reality the allocations do not need to have frequency domain continuity, but can take any set of continuous allocation of frequency domain resources. The practical signaling constraints define the allowed amount of 180 kHz resource blocks that can be allocated. The maximum allocated bandwidth depends on the system bandwidth used, which can be up to 20 MHz. The resulting maximum allocation bandwidth is somewhat smaller as the system bandwidth definition includes a guard towards the neighboring operator. For example, with a 10 MHz system channel bandwidth the maximum resource allocation is equal to 50 resource blocks thus having a transmission bandwidth of 9 MHz. The relationship between the *Channel bandwidth* ($BW_{Channel}$) and *Transmission bandwidth configuration* (N_{RB}) is covered in more detail in Chapter 11.

The SC-FDMA resource block for frequency domain signal generation is defined using the same values used in the OFDMA downlink, based on the 15 kHz sub-carrier spacing. Thus even if the actual transmission by name is a single carrier, the signal generation phase uses a sub-carrier term. In the simplest form the minimum resource allocated uses 12 sub-carriers, and is thus equal to 180 kHz. The complex valued modulation symbols with data are allocated to the resource elements not needed for reference symbols (or control information) in the resource block, as shown in Figure 4.15. After the resource mapping has been done the signal is fed to the time domain signal generation that creates the SC-FDMA signal, including the selected length of the cyclic prefix. The example in Figure 4.15 assumes a particular length of cyclic prefix with the two different options introduced in Chapter 5.

As shown in Figure 4.15, reference symbols are located in the middle of the slot. These are used by the receiver to perform the channel estimation. There are different options for the reference symbols to be used; sometimes a reference symbol hopping pattern is also used, as covered in more detail in Chapter 5. Also specifically covered further in Chapter 5 are the sounding reference signals, which are momentarily sent over a larger bandwidth than needed,

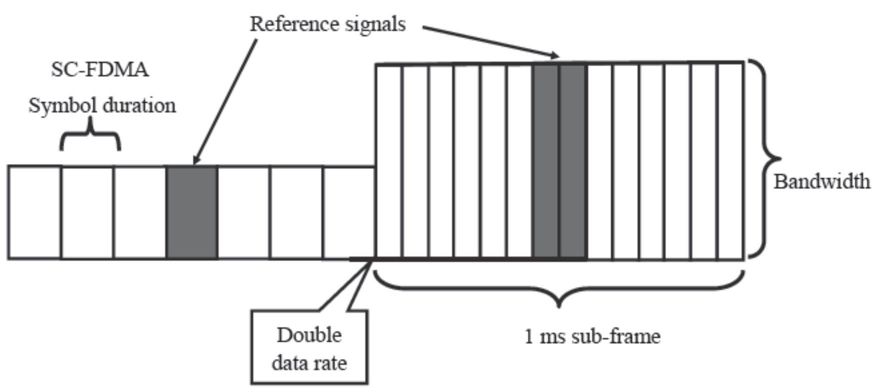


Figure 4.14 Adjusting data rate in a SC-FDMA system

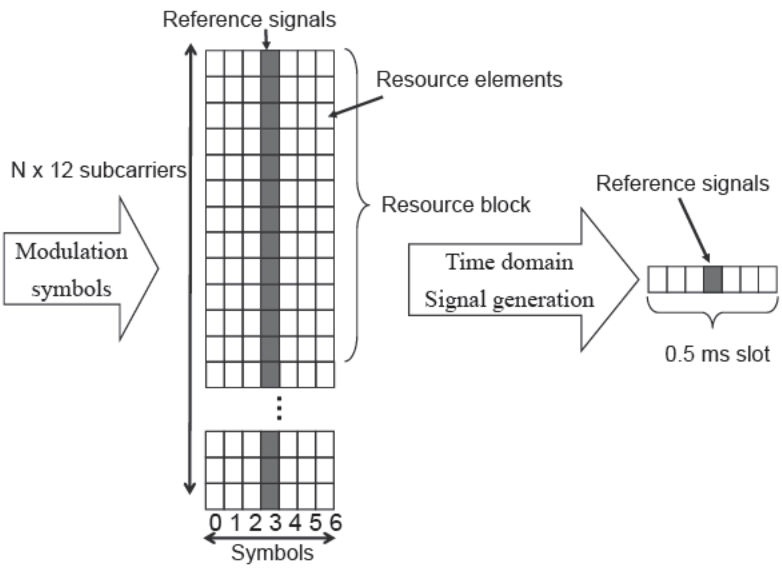


Figure 4.15 Resource mapping in SC-FDMA

for the data to give the base station receiver information of a larger portion of the frequency spectrum to facilitate frequency domain scheduling in the uplink direction.

Different users are thus sharing the resources in the time as well as in the frequency domain. In the time domain the allocation granularity is 1 ms and in the frequency domain it is 180 kHz. The base station needs to control each transmission so that they do not overlap in the resources. Also to avoid lengthy guard times, timing advance needs to be used, as presented in Chapter 5. By modifying the IFFT inputs, the transmitter can place the transmission in the desired part of the frequency, as shown in Figure 4.16. The base station receiver can detect the

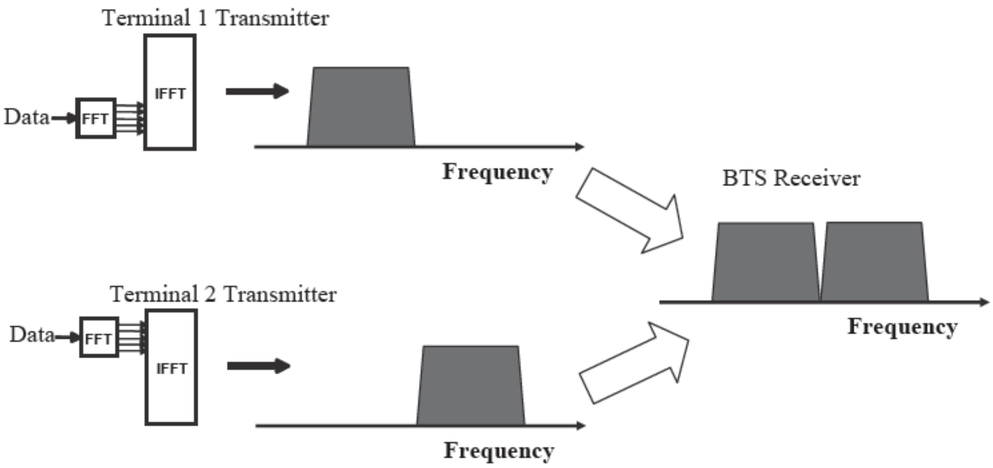


Figure 4.16 Multiple access with resource sharing in the frequency domain with SC-FDMA and frequency domain signal generation

transmission from the correct frequency/time resource. As all the uplink utilization is based on the base station scheduling, with the exception of the random access channel, the base station always knows which user to expect in which resource.

Since we are now transmitting in the time domain only a single modulation symbol at a time, the system retains its good envelope properties and the waveform characteristics are now dominated by the modulation method applied. This allows the SC-FDMA to reach a very low signal PAR or, even more importantly, CM facilitating efficient power amplifiers in the devices. The value of CM as a function modulation applied is shown in Figure 4.17. The use of a low CM modulation method such as Quadrature Phase Shift Keying (QPSK) allows a low CM value and thus the amplifier can operate close to the maximum power level with minimum back-off (Figure 4.17). This allows a good power conversion efficiency of the power amplifier and thus lowers the device power consumption. Note that the pi/2-Binary Phase Shift Keying (BPSK) was originally considered in 3GPP, but as 3GPP performance requirements are such that the full (23 dBm) power level needs to be reached with QPSK, there are no extra benefits for the use of pi/2-BPSK; thus, this was eventually not included in the specifications for user data. The modulation methods in LTE vary depending on whether the symbols are for physical layer control information or for higher layer data (user data or higher layer control signaling) transmission purposes (details in Chapter 5).

The base station receiver for SC-FDMA is slightly more complicated than the corresponding ODFMA receiver on the device side, especially when considering receivers (equalizers) that can reach a performance corresponding to that of an OFDMA receiver. This is the obvious consequence of the receiver having to deal with the inter-symbol interference that is terminated only after a block of symbols and not after every (long) symbol as in OFDMA. This increased need for processing power is, however, not foreseen to be an issue in the base station when compared to the device design constraints and was clearly considered to be outweighed by the benefits of the uplink range and device battery life with SC-FDMA. The benefits of a dynamic resource usage with a 1 ms resolution is also that there is no base-band receiver per UE on standby

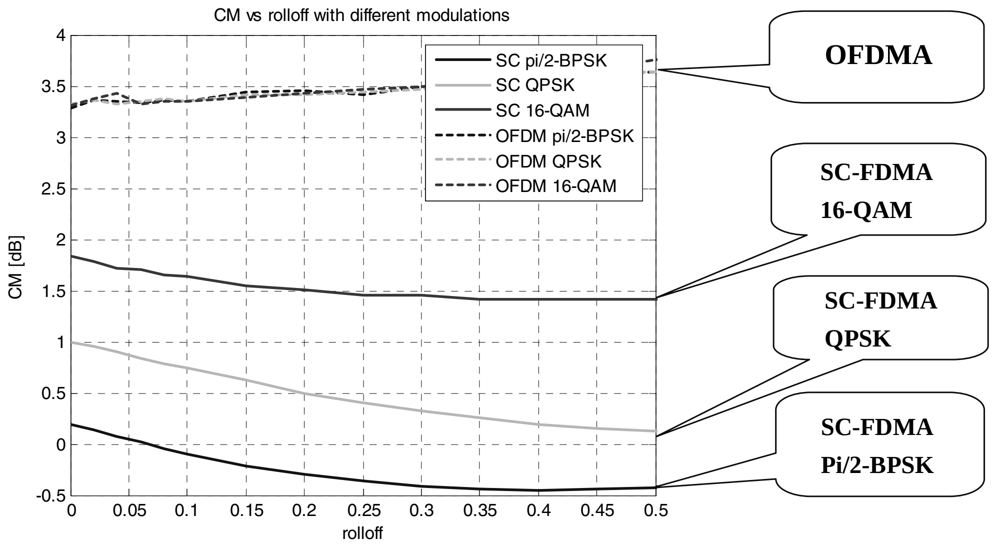


Figure 4.17 CM with OFDMA and SC-FDMA [6]. © 2006 IEEE

but the base station receiver is dynamically used for those users that have data to transmit. In any case the most resource consuming part both in uplink and downlink receiver chains is the channel decoding (turbo decoding) with the increased data rates.

4.5 MIMO Basics

One of the fundamental technologies introduced together with the first LTE Release is the Multiple Input Multiple Output (MIMO) operation including spatial multiplexing as well as pre-coding and transmit diversity. The basic principle in spatial multiplexing is sending signals from two or more different antennas with different data streams and by signal processing means in the receiver separating the data streams, hence increasing the peak data rates by a factor of 2 (or 4 with 4-by-4 antenna configuration). In pre-coding the signals transmitted from the different antennas are weighted in order to maximize the received Signal to Noise Ratio (SNR). Transmit diversity relies on sending the same signal from multiple antennas with some coding in order to exploit the gains from independent fading between the antennas. The use of MIMO has been included earlier in WCDMA specifications as covered in [4], but operating slightly differently than in LTE as a spreading operation is involved. The OFDMA nature is well suited for MIMO operation. As the successful MIMO operation requires reasonably high SNR, with an OFDMA system it can benefit from the locally (in the frequency/time domain) high SNR that is achievable. The basic principle of MIMO is presented in Figure 4.18, where the different data streams are fed to the pre-coding operation and then onwards to signal mapping and OFDMA signal generation.

The reference symbols enable the receiver to separate different antennas from each other. To avoid transmission from another antenna corrupting the channel estimation needed for separating the MIMO streams, one needs to have each reference symbol resource used by a single transmit antenna only. This principle is illustrated in Figure 4.19, where the reference symbols and empty resource elements are mapped to alternate between antennas. This principle can also be extended to cover more than two antennas, with the first LTE Release covering up to four antennas. As the number of antennas increases, the required SNR also increases the resulting transmitter/receiver complexity and the reference symbol overhead.

Even LTE uplink supports the use of MIMO technology. While the device is using only one transmit antenna, the single user data rate cannot be increased with MIMO. The cell level maximum data rate can be doubled, however, by the allocation of two devices with orthogonal reference signals. Thus the transmission in the base station is treated like a MIMO transmission, as shown in Figure 4.20, and the data stream separated with MIMO receiver processing. This

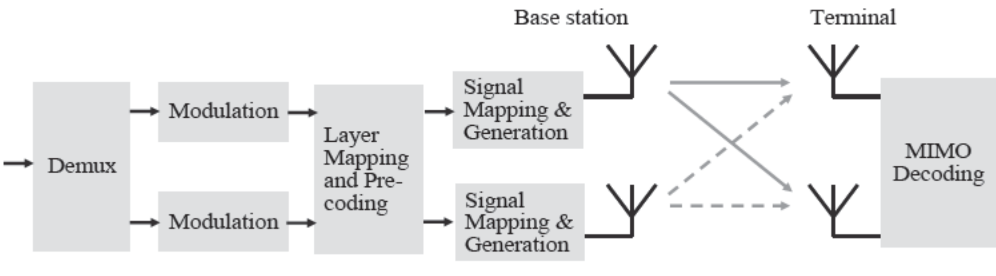


Figure 4.18 MIMO principle with two-by-two antenna configuration

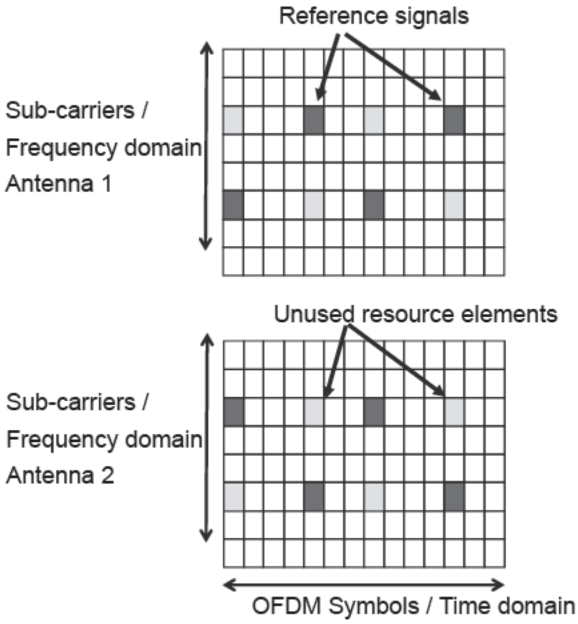


Figure 4.19 OFDMA reference symbols to support two eNodeB transmit antennas

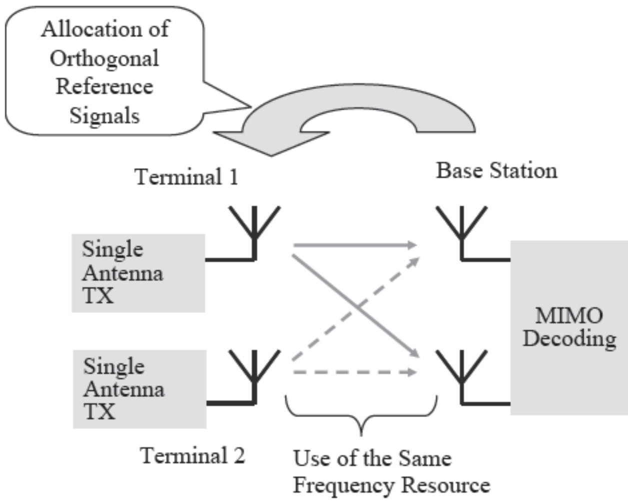


Figure 4.20 Multi-user MIMO principle with single transmit antenna devices

kind of 'virtual' or 'Multi-user' MIMO is supported in LTE Release 8 and does not represent any major implementation complexity from the device perspective as only the reference signal sequence is modified. From the network side, additional processing is needed to separate the users from each other. The use of 'classical' two antenna MIMO transmission is not particularly attractive due to the resulting device impacts, thus discussions on the device support of multi-antenna device transmission are expected to take place for later 3GPP Releases. The SC-FDMA is well-suited for MIMO use as users are orthogonal (inside the cell) and thus the local SNR may be very high for users close to the base station.

4.6 Summary

Both OFDMA and SC-FDMA are very much related in terms of technical implementation and rely on the use of FFT/IFFT in the transmitter and receiver chain implementation. The SC-FDMA is used to optimize the range and power consumption in the uplink while the OFDMA is used in the downlink direction to minimize receiver complexity, especially with large bandwidths, and to enable frequency domain scheduling with flexibility in resource allocation. Multiple antenna operation with spatial multiplexing has been a fundamental technology of LTE from the outset, and is well suited for LTE multiple access solutions. The mathematical principles of OFDMA and SC-FDMA were not included in this chapter, but can be found from different text books, some of which are included in the references, e.g. [7] for OFDMA and [8] for SC-FDMA.

References

[1] Proakis, J.G., 'Digital Communications', 3rd edition, McGraw-Hill Book Co., 1995.
[2] Czylwik, A., 'Comparison between adaptive OFDM and single carrier modulation with frequency domain equalisation', IEEE Vehicular Technology Conference 1997, VTC-97, Phoenix, USA, pp. 863–869.
[3] Toskala, A., Castro, J., Chalard, L., Hämäläinen, S., Kalliojärvi, K., 'Cellular OFDM/CDMA Downlink Performance in the link and system level', IEE Vehicular Technology Conference 1997, VTC-97, Phoenix, USA, pp. 855–859.
[4] Holma, H., Toskala, A., 'WCDMA for UMTS', 4th edition, Wiley, 2007.
[5] Holma, H., Toskala, A., 'HSDPA/HSUPA for UMTS', Wiley, 2006.
[6] Toskala, A, Holma, H., Pajukoski, K., Tiirola, E., 'UTRAN Long Term Evolution in 3GPP'. The 17th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC '06), in Proceedings, 2006, Helsinki, Finland.
[7] Schulze, H., Luders, C., 'Theory and Applications of OFDMA and CDMA', Wiley, 2005.
[8] Myung, H.G., Goodman, D.J., 'Single Carrier FDMA: A New Air Interface for Long Term Evolution', Wiley, 2008.

5

Physical Layer

Antti Toskala, Timo Lunttila, Esa Tiirola, Kari Hooli and Juha Korhonen

5.1 Introduction

In this chapter the physical layer of LTE is described, based on the use of OFDMA and SC-FDMA principles as covered in Chapter 4. The LTE physical layer is characterized by the design principle of resource usage based solely on dynamically allocated shared resources rather than having dedicated resources reserved for a single user. This has an analogy with the resource usage in the internet, which is packet based without user specific resource allocation. The physical layer of a radio access system has a key role in defining the resulting capacity and becomes a focal point when comparing different systems for expected performance. Of course a competitive system requires an efficient protocol layer to ensure good performance through to both the application layer and the end user. The flat architecture adopted, as covered in Chapter 3, also enables the dynamic nature of the radio interface because all radio resource control is located close to the radio in the base station site. The 3GPP term for the base station used in this chapter is eNodeB (different to the WCDMA BTS term, which is Node B; e stands for 'evolved'). This chapter first covers the physical channel structures and then introduces the channel coding and physical layer procedures. It concludes with a description of physical layer measurements and device capabilities as well as a brief look at aspects of the parameter configuration of the physical layer. In 3GPP specifications the physical layer was covered in 36.2 series, with the four key physical layer specifications being [1–4]. Many of the issues in this chapter are valid to both FDD and TDD, but in some areas TDD has special solutions because the frame is divided between uplink and downlink. The resulting differences needed for a TDD implementation are covered in Chapter 12.

5.2 Transport Channels and Their Mapping to the Physical Channels

By the nature of the design already discussed, the LTE contains only common transport channels; a dedicated transport channel (Dedicated Channel, DCH, as in WCDMA) does not exist. The transport channels are the 'interface' between the Medium Access Control (MAC) layer

LTE for UMTS: OFDMA and SC-FDMA Based Radio Access Edited by Harri Holma and Antti Toskala
 ISBN: 978-0-470-99401-6

and the physical layer. Each transport channel is characterized by the related physical layer processing applied to the corresponding physical channels used to carry the transport channel in question. The physical layer needs to be able to provide dynamic resource assignment both for data rate variance and for resource division between different users. This section presents the transport channels and their mapping to the physical channels.

- Broadcast Channel (BCH) is a downlink broadcast channel that is used to broadcast the necessary system parameters to enable devices accessing the system (and to identify the operator). Such parameters include, for example, random access related parameters that inform the device about which resource elements are reserved for random access operation.
- Downlink Shared Channel (DL-SCH) carries the user data for point-to-point connections in the downlink direction. All the information (either user data or higher layer control information) intended for only one user or UE is transmitted on the DL-SCH, assuming the UE is already in the RRC_CONNECTED state. As in LTE, however, the role of BCH is mainly for informing the device of the scheduling of the system information; control information intended for multiple devices is carried on DL-SCH as well. In case data on DL-SCH are intended for a single UE only, then dynamic link adaptation and physical layer retransmissions can be used.
- Paging Channel (PCH) is used for carrying the paging information for the device in the downlink direction to move the device from a RRC_IDLE state to a RRC_CONNECTED state.
- Multicast Channel (MCH) is used to transfer multicast service content to the UE in the downlink direction. 3GPP has decided to postpone the full support beyond Release 8.
- Uplink Shared Channel (uplink-SCH) carries the user data as well as device originated control information in the uplink direction in the RRC_CONNECTED state. Similar to the DL-SCH, dynamic link adaptation and retransmissions are available.
- Random Access Channel (RACH) is used in the uplink to respond to the paging message or to initiate the move from/to the RRC_CONNECTED state according to UE data transmission needs. There is no higher layer data or user data transmitted on RACH (such as can be done with WCDMA) but it is used just to enable uplink-SCH transmission where, for example, actual connection set-up with authentication, etc. will take place.

In the uplink direction the uplink-SCH is carried by the Physical Uplink Shared Channel (PUSCH). Correspondingly, the RACH is carried by the Physical Random Access Channel (PRACH). An additional physical channel exists but it is used only for physical layer control information transfer (as covered in connection with section 5.6 on control information). Uplink transport channel mapping to physical channels is illustrated in Figure 5.1.

In the downlink direction the PCH is mapped to the Physical Downlink Shared Channel (PDSCH). The BCH is mapped to Physical Broadcast Channel (PBCH), but as shown in Chapter 6 for the mapping of logical channels to transport channels, only part of the broadcasted param-

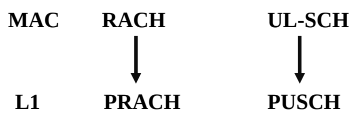


Figure 5.1 Mapping of the uplink transport channels to the physical channels

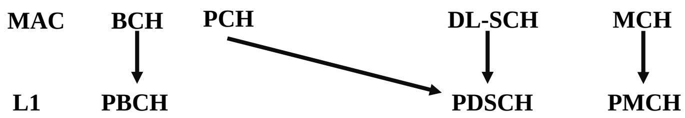


Figure 5.2 Mapping of the downlink transport channels to the physical channels

eters are on BCH while the actual System Information Blocks (SIBs) are then on DL-SCH. The DL-SCH is mapped to the PDSCH and MCH is mapped to the Physical Multicast Channel, as shown in Figure 5.2.

5.3 Modulation

In the uplink direction the modulation is the more traditional Quadrature Amplitude Modulation (QAM) modulator, as was explained in Chapter 4. The modulation methods available (for user data) are Quadrature Phase Shift Keying (QPSK), 16QAM and 64QAM. The first two are available in all devices while the support for 64QAM in the uplink direction is a UE capability, as covered in section 5.10. The different constellations are shown in Figure 5.3.

The PRACH modulation is phase modulation as the sequences used are generated from Zadoff–Chu sequences with phase differences between different symbols of the sequences (see section 5.7 for further details). Depending on the sequence chosen, the resulting Peak-to-Average Ratio (PAR) or the more practical Cubic Metric (CM) value is somewhat lower or higher compared to the QPSK value. In the uplink direction, the CM signal was discussed in Chapter 4 with SC-FDMA.

The use of QPSK modulation allows good transmitter power efficiency when operating at full transmission power as modulation determines the resulting CM (for SC-FDMA) and thus also the required device amplifier back-off. The devices will use lower maximum transmitter power when operating with 16QAM or 64QAM modulation.

In the downlink direction, the modulation methods for user data are the same as in the uplink direction. In theory an OFDM system could use different modulations for each sub-carrier. To have channel quality information (and signaling) with such a granularity would not be feasible due to the resulting excessive overhead. If modulation was sub-carrier specific, there would be too many bits in the downlink for informing the receiver of parameters for each sub-carrier and in the uplink the Channel Quality Indicator (CQI) feedback would need to be too detailed to achieve sub-carrier level granularity in the adaptation.

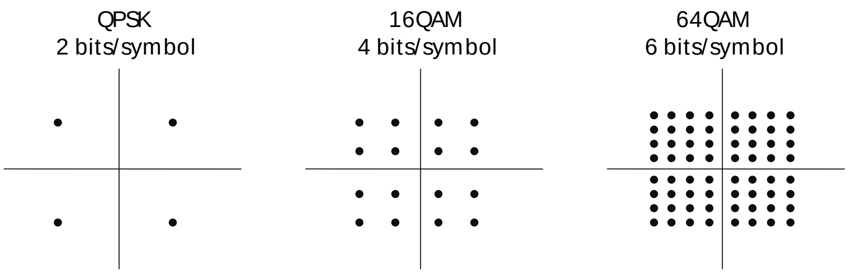


Figure 5.3 LTE modulation constellations

Also Binary Phase Shift Keying (BPSK) has been specified for control channels, which use either BPSK or QPSK for control information transmission. For a control channel, the modulation cannot be freely adapted as one needs to be able to receive them, and a single signaling error must not prevent detecting later control channel messages. This is similar to HSDPA/HSUPA where the control channels have fixed parameterization to prevent error propagation due to frame loss events. The exception is the uplink control data when multiplexed together with the user data – there modulation for data and control is the same – even if 16QAM or 64QAM would be used. This allows the multiplexing rules to be kept simpler.

5.4 Uplink User Data Transmission

The user data in the uplink direction is carried on the PUSCH, which has a 10 ms frame structure and is based on the allocation of time and frequency domain resources with 1 ms and 180 kHz resolution. The resource allocation comes from a scheduler located in the eNodeB, as illustrated in Figure 5.4. Thus there are no fixed resources for the devices, and without prior signaling from the eNodeB only random access resources may be used. For this purpose the device needs to provide information for the uplink scheduler of the transmission requirements (buffer status) it has as well as on the available transmission power resources. This signaling is MAC layer signaling and is covered in detail in Chapter 6.

The frame structure adopts the 0.5 ms slot structure and uses the 2 slot (1 subframe) allocation period. The shorter 0.5 ms allocation period (as initially planned in 3GPP to minimize the round trip time) would have been too signal intensive especially with a large number of users. The 10 ms frame structure is illustrated in Figure 5.5. The frame structure is basically valid for both for FDD and TDD, but TDD mode has additional fields for the uplink/downlink transition point(s) in the frame, as covered in Chapter 12.

Within the 0.5 ms slot there are both reference symbols and user data symbols, in addition to the signaling, covered in a later section. The momentary user data rate thus varies as a function of the uplink resource allocation depending on the allocated momentary bandwidth. The

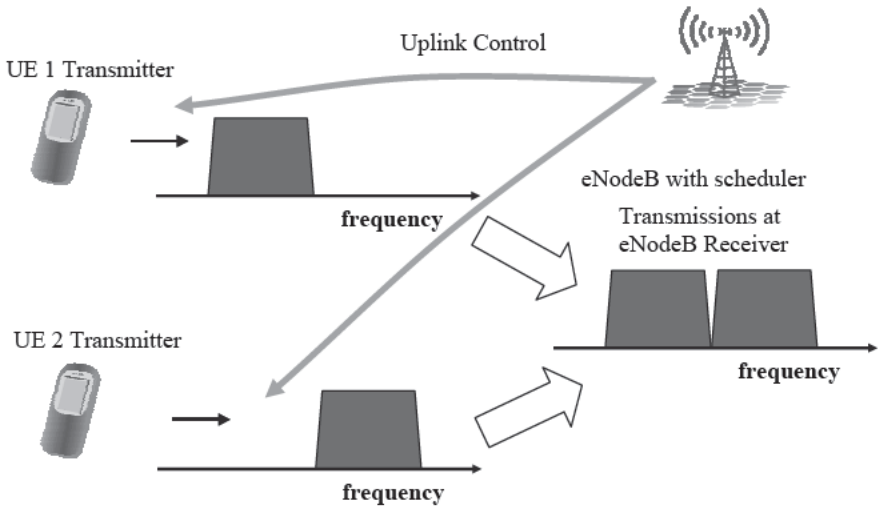


Figure 5.4 Uplink resource allocation controlled by eNodeB scheduler

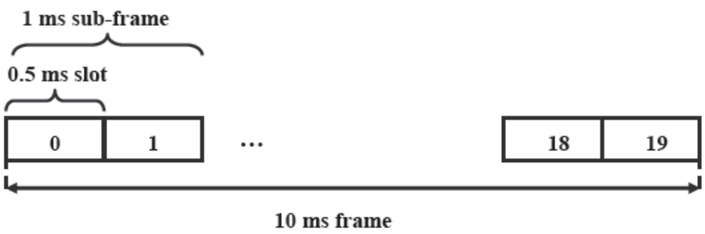


Figure 5.5 LTE FDD frame structure

allocation bandwidth may be between 0 and 20 MHz in the steps of 180 kHz. The allocation is continuous as uplink transmission is FDMA modulated with only one symbol being transmitted at a time. The slot bandwidth adjustment between consecutive TTIs is illustrated in Figure 5.6, where doubling the data rate results in double the bandwidth being used. The reference symbols always occupy the same space in the time domain and thus a higher data rate results in a corresponding increase for the reference symbol data rate.

The cyclic prefix used in uplink has two possible values depending on whether a short or extended cyclic prefix is applied. Other parameters stay unchanged and thus the 0.5 ms slot can accommodate either six or seven symbols as indicated in Figure 5.7. The data payload is reduced if an extended cyclic prefix is used, but it is not used frequently as usually the performance benefit in having seven symbols is far greater than the possible degradation from inter-symbol interference due to channel delay spread longer than the cyclic prefix.

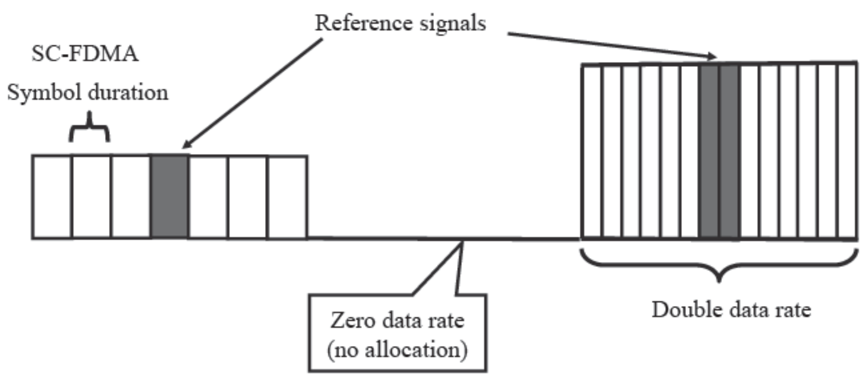


Figure 5.6 Data rate between TTIs in the uplink direction

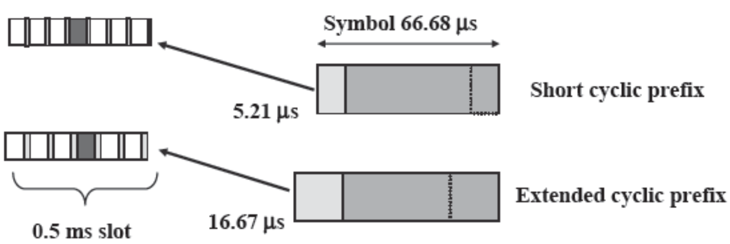


Figure 5.7 Uplink Slot structure with short and extended cyclic prefix

The resulting instantaneous uplink data rate over a 1 ms subframe is a function of the modulation, the number of resource blocks allocated, and the amount of control information overhead as well as of the rate of channel coding applied. The range of the instantaneous uplink peak data rate when calculated from the physical layer resources is between 700 kbps and 86 Mbps. There is no multi-antenna uplink transmission specified in Release 8, as using more than one transmitter branch in a UE is not seen as that attractive from the cost and complexity perspective. The instantaneous data rate for one UE depends on the LTE uplink from:

- Modulation method applied, with 2, 4 or 6 bits per modulations symbol depending on the modulation order for QPSK, 16QAM and 64QAM respectively.
- Bandwidth applied. For 1.4 MHz, the overhead is the largest due to the common channels and synchronization signals. The momentary bandwidth may of course vary between the minimum allocation of 12 sub-carriers (one resource block of 180 kHz) and the system bandwidth, up to 1200 sub-carriers with a 20 MHz bandwidth.
- Channel coding rate applied.
- The average data rate then depends on the time domain resource allocation as well.

The cell or sector specific maximum total data throughput can be increased with the Virtual Multiple Input Multiple Output (V-MIMO). In V-MIMO the eNodeB will treat transmission from two different UEs (with a single transmit antenna each) as one MIMO transmission and separate the data streams from each other based on the UE specific uplink reference symbol sequences. Thus V-MIMO does not contribute to the single user maximum data rate. The maximum data rates taking into account the UE categories are presented in section 5.10, while the maximum data rates for each bandwidth are covered in Chapter 9.

The channel coding chosen for LTE user data was turbo coding. The encoder is Parallel Concatenated Convolution Coding (PCCC) type turbo encoder, exactly the same as in WCDMA/HSPA, as explained in [5]. The turbo interleaver of WCDMA was modified to better fit LTE properties and slot structures and also to allow more flexibility for implementation of parallel signal processing with increased data rates.

LTE also uses physical layer retransmission combining, often referred to as Hybrid Adaptive Repeat and Request (HARQ). In a physical layer HARQ operation the receiver also stores the packets with failed CRC checks and combines the received packet when a retransmission is received. Both soft combining with identical retransmissions and combining with incremental redundancy are facilitated.

The channel coding chain for uplink is shown in Figure 5.8, where the data and control information are separately coded and then mapped to separate symbols for transmission. As the control information has specific locations around the reference symbols, the physical layer control information is separately coded and placed in a predefined set of modulation symbols (but with the same modulation as if the data were transmitted together). Thus the channel interleaver in Figure 5.8 does not refer to truly joint interleaving between control and data.

The data and control information are time multiplexed in the resource element level. Control is not evenly distributed but intended to be either closest for the reference symbols in time domain or then filled in the top rows of Figure 5.9, depending on the type of control information (covered in section 5.6). Data are modulated independently of the control information, but modulation during the 1 ms TTI is the same.

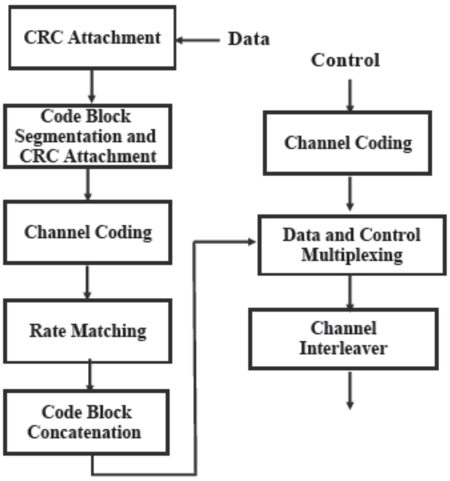


Figure 5.8 PUSCH Channel Coding Chain

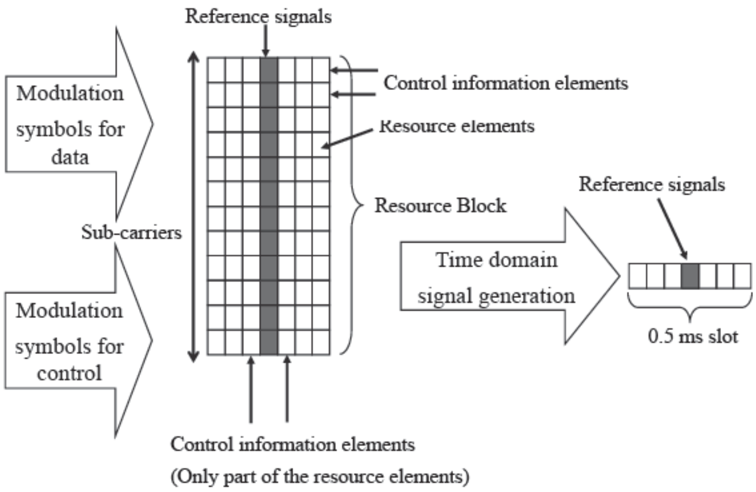


Figure 5.9 Multiplexing of uplink control and data

5.5 Downlink User Data Transmission

The user data rate in the downlink direction is carried on the Physical Downlink Shared Channel (PDSCH). The same 1 ms resource allocation is also valid in the downlink direction. The sub-carriers are allocated to resource units of 12 sub-carriers resulting in 180 kHz allocation units (Physical Resource Blocks, PRBs). With PDSCH, however, as the multiple access is OFDMA, each sub-carrier is transmitted as a parallel 15 kHz sub-carrier and thus the user data rate is dependent on the number of allocated sub-carriers (or resource blocks in practice) for a given user. The eNodeB carries out the resource allocation based on the Channel Quality Indicator (CQI) from the terminal. Similarly to the uplink, the resources are allocated in both the time and the frequency domain, as illustrated in Figure 5.10.

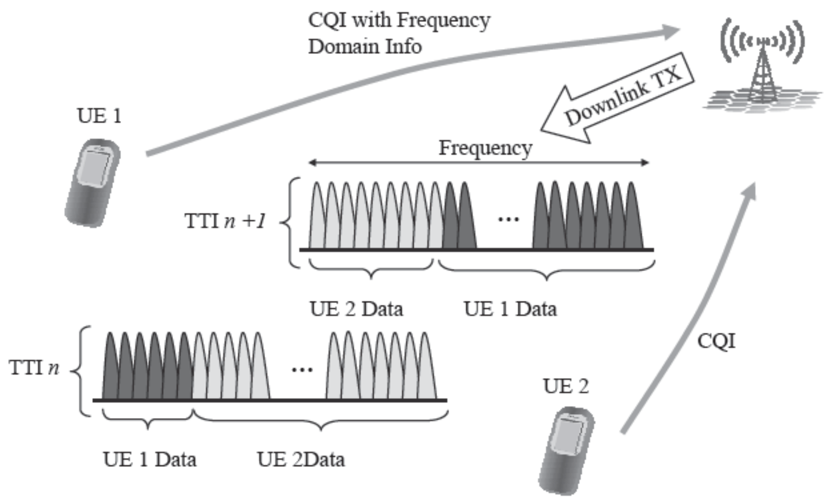


Figure 5.10 Downlink resource allocation at eNodeB

The Physical Downlink Control Channel (PDCCH) informs the device which resource blocks are allocated to it, dynamically with 1 ms allocation granularity. PDSCH data occupy between 3 and 6 symbols per 0.5 ms slot depending on the allocation for PDCCH and depending whether a short or extended cyclic prefix is used. Within the 1 ms subframe, only the first 0.5 ms slot contains PDCCH while the second 0.5 ms slot is purely for data (for PDSCH). For an extended cyclic prefix, 6 symbols are accommodated in the 0.5 ms slot, while with a short cyclic prefix 7 symbols can be fitted, as shown in Figure 5.11. The example in Figure 5.11 assumes there are 3 symbols for PDCCH but this can vary between 1 and 3. With the smallest bandwidth of 1.4 MHz the number of symbols varies between 2 and 4 to enable sufficient signaling capacity and enough bits to allow for good enough channel coding in range critical cases.

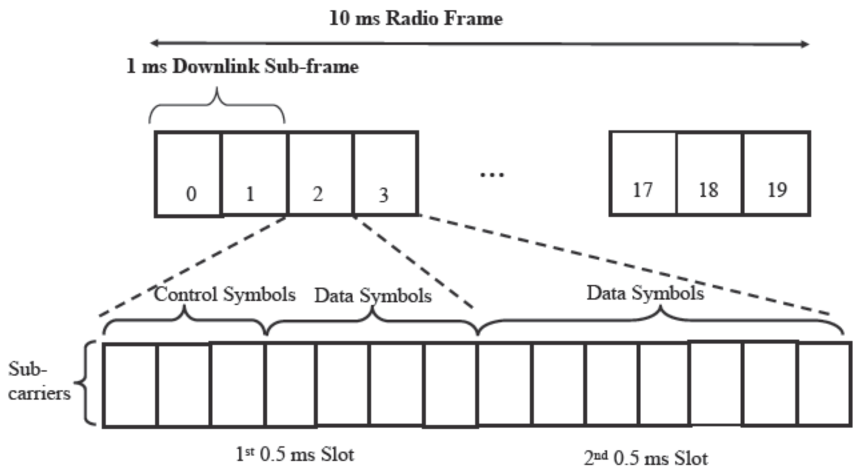


Figure 5.11 Downlink slot structure for bandwidths above 1.4 MHz

In addition to the control symbols for PDCCH, space from the user data is reduced due to the reference signals, synchronization signals and broadcast data. As discussed in Chapter 4, due to channel estimation it is beneficial when the reference symbols are distributed evenly in the time and frequency domains. This reduces the overhead needed, but requires some rules to be defined so that both receiver and transmitter understand the resource mapping in a similar manner. From the total resource allocation space over the whole carrier one needs to account for common channels, such as PBCH, that consume their own resource space. In Figure 5.12 an example of PDCCH and PDSCH resource allocation is presented. Note that the reference symbol placement in Figure 5.12 is purely illustrative and does not represent an actual reference symbol pattern.

The channel coding for user data in the downlink direction was also 1/3-rate turbo coding, as in the uplink direction. The maximum block size for turbo coding is limited to 6144 bits to reduce the processing burden, higher allocations are then segmented to multiple encoding blocks. Higher block sizes would not add anything to performance as the turbo encoder performance improvement effect for big block sizes has been saturated much earlier. Besides the turbo coding, downlink also has the physical layer HARQ with the same combining methods as in the uplink direction. The device categories also reflect the amount of soft memory available for retransmission combining. The downlink encoding chain is illustrated in Figure 5.13. There is no multiplexing to the same physical layer resources with PDCCH as they have their own separate resources during the 1 ms subframe.

Once the data have been encoded, the code words are provided onwards for scrambling and modulation functionality. The scrambling in the physical layer should not be confused with ciphering functionality but is just intended to avoid the wrong device successfully decoding the data should the resource allocations happen to be identical between cells. The modulation mapper applies the desired modulation (QPSK, 16QAM or 64QAM) and then symbols are fed for layer mapping and pre-coding. For multiple transmit antennas (2 or 4) the data are then divided into as many different streams and then mapped to correct resource elements available for PDSCH and then the actual OFDMA signal is generated, as shown in Figure 5.14 with an example of 2 antenna transmission. Should there be only a single transmit antenna available,

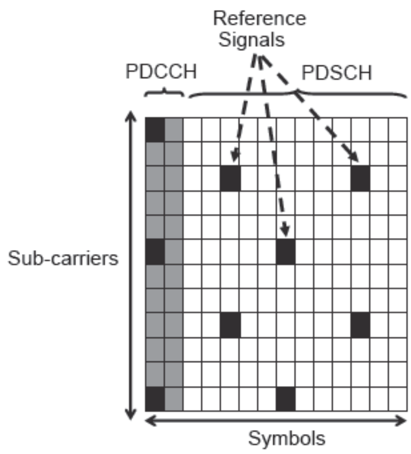


Figure 5.12 Example of downlink resource sharing between PDCCH and PDSCH

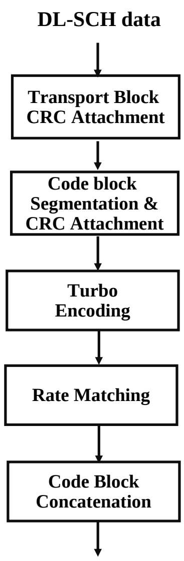


Figure 5.13 DL-SCH Channel Encoding Chain

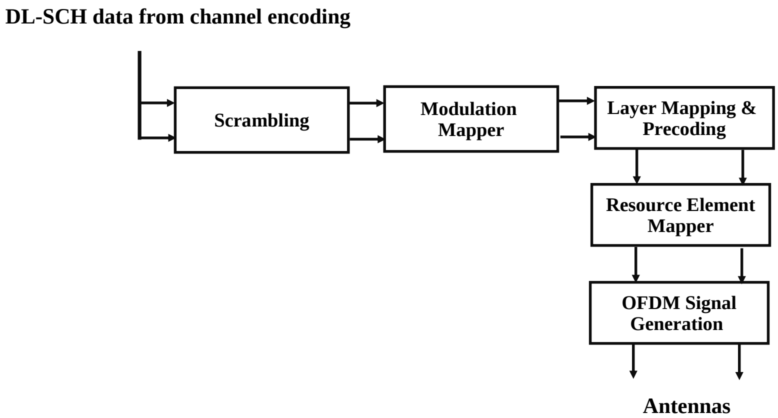


Figure 5.14 Downlink signal generation

then obviously the layer mapping and pre-coding functionalities do not have a role in signal transmission.

The resulting instantaneous data rate for downlink depends on:

- Modulation, with the same methods possible as in the uplink direction.
- Allocated amount of sub-carriers. Note that in the downlink the resource blocks are not necessary having continuous allocation in the frequency domain. The range of allocation is the same as in the uplink direction from 12 sub-carriers (180 kHz) up to the system bandwidth with 1200 sub-carriers.
- Channel encoding rate.
- Number of transmit antennas (independent streams) with MIMO operation.

The instantaneous peak data rate for downlink (assuming all resources to a single user and counting only the physical layer resources available) ranges between 0.7 Mbps and 170 Mbps. Even 300 Mbps or higher could be expected if using 4-by-4 antenna MIMO operation. There is no limit on the smallest data rate, and should the smallest allocation unit (1 resource block) be too high, then padding could be applied. Section 5.10 presents the maximum data rates taking the UE categories into account. The possible data rates for different bandwidth/coding/modulation combinations are presented in Chapter 9.

5.6 Uplink Physical Layer Signaling Transmission

Uplink Layer 1/Layer 2 (L1/L2) control signaling is divided into two classes in the LTE system:

- control signaling in the absence of uplink data, which takes place on PUCCH (Physical Uplink Control Channel);
- control signaling in the presence of uplink data, which takes place on PUSCH (Physical Uplink Shared Channel).

Due to single carrier limitations, simultaneous transmission of PUCCH and PUSCH is not allowed. This means that separate control resources are defined for the cases with and without uplink data. Alternatives considered were parallel transmission in the frequency domain (bad for the transmitter envelope) or pure time division (bad for control channel coverage). The selected approach maximizes the link budget for PUCCH and always maintains the single carrier properties on the transmitted signal.

PUCCH is a shared frequency/time resource reserved exclusively for User Equipment (UE) transmitting only L1/L2 control signals. PUCCH has been optimized for a large number of simultaneous UEs with a relatively small number of control signaling bits per UE.

PUSCH carries the uplink L1/L2 control signals when the UE has been scheduled for data transmission. PUSCH is capable of transmitting control signals with a large range of supported signaling sizes. Data and different control fields such as ACK/NACK and CQI are separated by means of Time Division Multiplexing (TDM) by mapping them into separate modulation symbols prior to the Discrete Fourier Transform (DFT). Different coding rates for control are achieved by occupying a different number of symbols for each control field.

There are two types of uplink L1 and L2 control-signaling information, as discussed in [6]:

- data-associated signaling (e.g. transport format and HARQ information), which is associated with uplink data transmission;
- data-non-associated signaling (ACK/NACK due to downlink transmissions, downlink CQI, and scheduling requests for uplink transmission).

It has been decided that there is no data-associated control signaling in the LTE uplink. Furthermore, it is assumed that eNodeB is not required to perform blind transport format detection. Basically this means that UE just obeys the uplink scheduling grant with no freedom in transport format selection. Furthermore, there is a new data indicator (1 bit) together with implicit information about the redundancy version included in the uplink grant [7]. This guarantees that the eNodeB always has exact knowledge about the uplink transport format.

5.6.1 Physical Uplink Control Channel (PUCCH)

From the single UE perspective, PUCCH consists of a frequency resource of one resource block (12 sub-carriers) and a time resource of one subframe. To handle coverage-limited situations, transmission of ACK/NACK spans the full 1 ms subframe. Furthermore, to support situations where coverage is extremely limited it has been agreed that ACK/NACK repetition is supported in the LTE uplink. Slot-based frequency hopping on the band edges symmetrically over the center frequency is always used on PUCCH, as shown in Figure 5.15. Frequency hopping provides the necessary frequency diversity needed for delay critical control signaling.

Different UEs are separated on PUCCH by means of Frequency Division Multiplexing (FDM) and Code Division Multiplexing (CDM). FDM is used only between the resource blocks whereas CDM is used inside the PUCCH resource block.

Two ways to realize CDM inside the PUCCH resource block are:

- CDM by means of cyclic shifts of a Constant Amplitude Zero Autocorrelation Codes (CAZAC)[1] sequence;
- CDM by means of block-wise spreading with the orthogonal cover sequences.

The main issue with CDM is the well-known near–far problem. Orthogonality properties of the considered CDM techniques were carefully studied during the Work Item phase of LTE standardization. We note that:

- channel delay spread limits the orthogonality between cyclically shifted CAZAC sequences;
- channel Doppler spread limits the orthogonality between block-wise spread sequences.

Orthogonality properties are optimized by means of a staggered and configurable channelization arrangement (see more details in section 5.6.2), proper configuration of block spreading, and a versatile randomization arrangement including optimized hopping patterns used for the control channel resources and the applied CAZAC sequences.

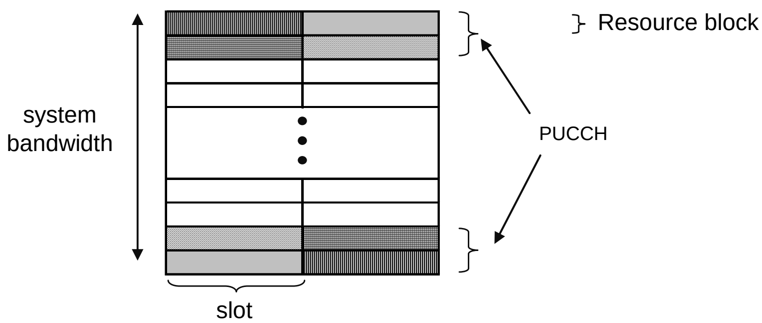


Figure 5.15 PUCCH resource

[1] The applied sequences are not true CAZAC but computer searched Zero-Autocorrelation (ZAC) sequences. The same sequences are applied as reference signals with a bandwidth allocation of one resource block.

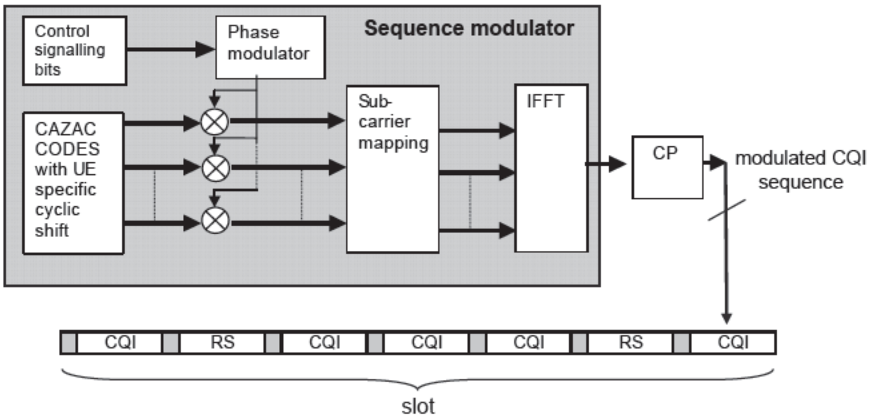


Figure 5.16 Block diagram of CAZAC sequence modulation applied for CQI

5.6.1.1 Sequence Modulation

Control signaling on PUCCH is based on sequence modulation. Cyclically shifted CAZAC sequences take care of both CDM and conveying the control information. A block diagram of the sequence modulator configured to transmit periodic CQI on PUCCH is shown in Figure 5.16. On the PUCCH application CAZAC sequences with a length of 12 symbols (1 resource block) are BPSK or QPSK modulated, thus carrying one or two information bits per sequence. Different UEs can be multiplexed into the given frequency/time resource by allocating different cyclic shifts of the CAZAC sequence for them. There are six parallel channels available per resource block, assuming that every second cyclic shift is in use.

5.6.1.2 Block-wise Spreading

Block-wise spreading increases the multiplexing capacity of PUCCH by a factor of the spreading factor (SF) used. The principle of block-wise spreading is shown in Figure 5.17, which illustrates

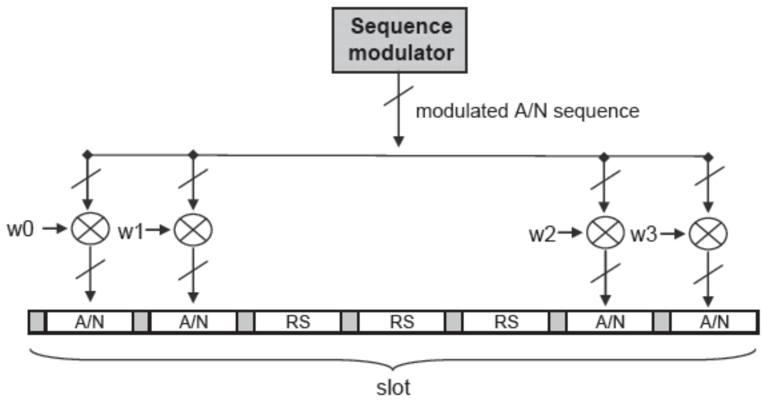


Figure 5.17 Principle of block spreading applied for ACK/NACK, spreading SF = 4

the block spreading operation made for an ACK/NACK data sequence transmitted on PUCCH. A separate block spreading operation is made for the reference signal and the ACK/NACK data parts but for simplicity, block processing related to the Reference Symbol (RS) part is neglected in Figure 5.17. In the example in Figure 5.17, the spreading factor applied for the ACK/NACK data and RS parts is equal to 4 and 3 respectively. Walsh–Hadamard codes are used as block spreading codes with SF = 4 and SF = 2, whereas DFT codes are used when SF = 3.

5.6.1.3 PUCCH Formats

The available PUCCH formats are summarized in Table 5.1. PUCCH Format 1/1a/1b is based on the combination of CAZAC sequence modulation and block-wise spreading whereas PUCCH Format 2/2a/2b uses only CAZAC sequence modulation. As a result, Format 1/1a/1b can only carry one information symbol (1 to 2 bits) per slot while Format 2/2a/2b is capable of conveying 5 symbols per slot (20 coded bits + ACK/NACK per subframe). With Format 2/2a/2b, the CQI data are encoded using a punctured (20, *N*) Reed–Muller block code.

The supported control signaling formats were selected based on a careful evaluation process. The main issues of the evaluation phase were the link performance and multiplexing capacity as well as compatibility with other formats. It is also noted that the number of reference signal blocks were optimized separately for different formats.

Two different approaches were selected for signaling the ACK/NACK and CQI on PUCCH (Format 2a/2b):

- Normal cyclic prefix: ACK/NACK information is modulated in the second CQI reference signals of the slot. The RS modulation follows the CAZAC sequence modulation principle.
- Extended cyclic prefix: ACK/NACK bits and the CQI bits are jointly coded. No information is embedded in any of the CQI reference signals.

The main reason for having different solutions for normal and extended cyclic prefix lengths was that with an extended cyclic prefix there is only one reference signal per slot and hence the method used with the normal cyclic prefix cannot be used.

Support of Format 2a/2b is made configurable in the LTE uplink system. In order to guarantee ACK/NACK coverage, the eNodeB can configure a UE to drop the CQI when ACK/NACK and CQI would appear in the same subframe on PUCCH. In this configuration, Format 1a/1b is used instead of Format 2a/2b.

Table 5.1 PUCCH formats

PUCCH Formats	Control type	Modulation (data part)	Bit rate (raw bits/ subframe)	Multiplexing capacity (UE/RB)
1	Scheduling request	Unmodulated	– (on/off keying)	36, 18*, 12
1a	1-bit ACK/NACK	BPSK	1	36, 18*, 12
1b	2-bit ACK/NACK	QPSK	2	36, 18*, 12
2	CQI	QPSK	20	12, 6*, 4
2a	CQI + 1-bit ACK/NACK	QPSK	21	12, 6*, 4
2b	CQI + 2-bit ACK/NACK	QPSK	22	12, 6*, 4

*Typical value

5.6.1.4 Scheduling Request

One of the new features of the LTE uplink system is the support of fast uplink scheduling request mechanism for the active mode UE (RRC_CONNECTED) being synchronized by the eNodeB but having no valid uplink grant on PUSCH available. The supported scheduling request procedure is presented in Figure 5.18 [8].

The UE indicates the need for an uplink resource by a Scheduling Request Indicator (SRI). During the Release 8 LTE standardization process, the contention based synchronized RACH and non-contention based SRI mechanisms were compared. It was pointed out that a non-contention based approach is better suited to LTE uplink usage because it provides better coverage, a smaller system overhead and better delay performance than a non-contention based approach [9].

The SRI is transmitted using PUCCH Format 1. On-off keying based signaling is applied with SRI, i.e. only the positive SRI is transmitted. The positive SRI is transmitted using the ACK/NACK structure [1], the only difference between the SRI and the ACK/NACK formats is that with SRI the data part is not modulated. The benefit of this arrangement is that SRI and ACK/NACK can share the same physical resources.

5.6.2 PUCCH Configuration

Figure 5.19 shows the logical split between different PUCCH formats and the way in which the PUCCH is configured in the LTE specifications [1]. The number of resource blocks in a slot reserved for PUCCH transmission is configured by the N_{RB}^{HO}-parameter. This broadcasted system parameter can be seen as the maximum number of resource blocks reserved for PUCCH while actual PUCCH size changes dynamically based on Physical Control Format Indicator Channel (PCFICH) transmitted on the downlink control channel. The parameter is used to define the frequency hopping PUSCH region. The number of resource blocks reserved for periodic CQI (i.e. PUCCH Format 2/2a/2b) is configured by another system parameter, $N_{RB}^{(2)}$.

In general it makes sense to allocate separate PUCCH resource blocks for PUCCH Format 1/1a/1b and Format 2/2a/2b. With narrow system bandwidth options such as 1.4 MHz, however, this would lead to unacceptably high PUCCH overhead [10]. Therefore, sharing the PUCCH resources block between Format 1/1a/1b and Format 2/2a/2b users is supported in the LTE specifications. The mixed resource block is configured by the broadcasted system parameter $N_{CS}^{(1)}$, which is the number of cyclic shifts reserved for PUCCH Format 1/1a/1b on the mixed PUCCH resource block.

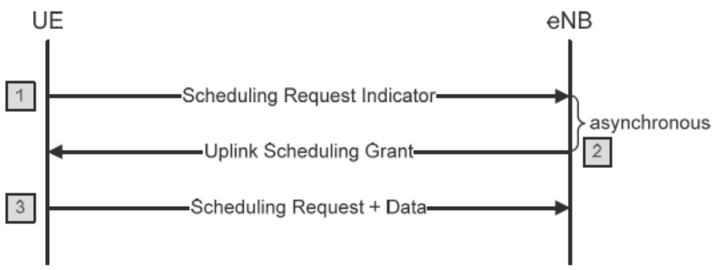


Figure 5.18 Scheduling request procedure

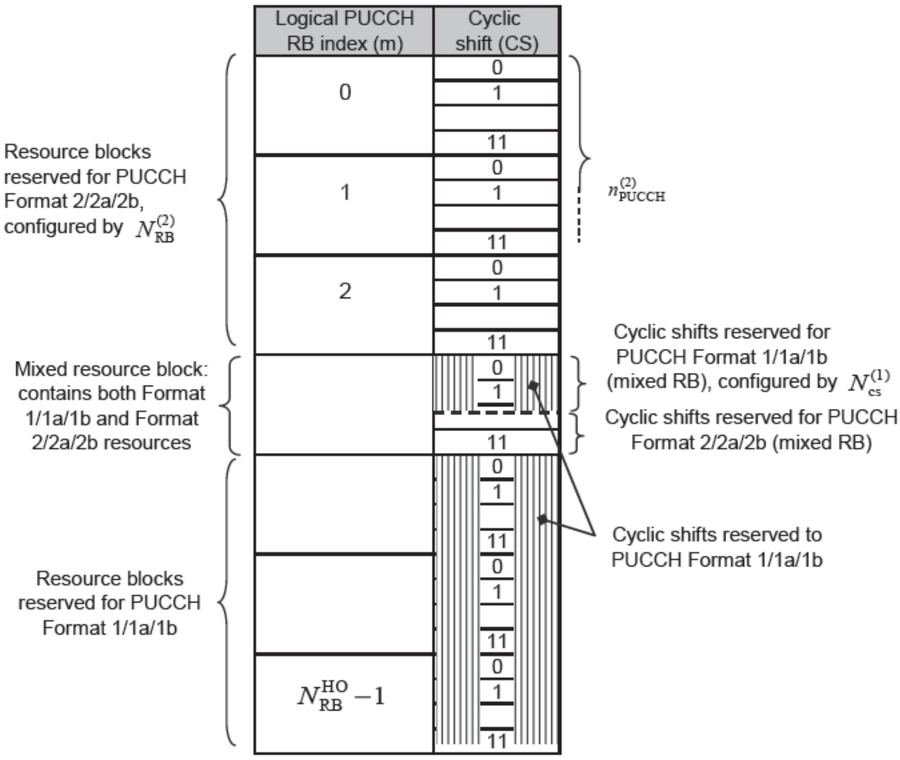


Figure 5.19 PUCCH configuration

Resources used for transmission of PUCCH Format 2/2a/2b are identified by a resource index $n_{PUCCH}^{(2)}$, which is mapped directly into a single CS resource. This parameter is explicitly signaled via UE-specific higher layer signaling.

5.6.2.1 Channelization and Resource Allocation for PUCCH Format 1/1a/1b

PUCCH Format 1/1a/1b resources are identified by a resource index $n_{PUCCH}^{(1)}$. Direct mapping between the PUCCH cyclic shifts and the resource indexes cannot be used with PUCCH Format 1/1a/1b due to the block spreading operation. Instead, PUCCH channelization is used to configure the resource blocks for PUCCH Format 1/1a/1b. The purpose of the channelization is to provide a number of parallel channels per resource block with optimized and adjustable orthogonality properties. Format 1/1a/1b channelization structure is configured by means of broadcasted system parameter, *Delta_shift*.

The number of PUCCH format 1/1a/1b resources per resource block, denoted as $N_{PUCCH\,Format\,1}^{RB}$, can be calculated as follows:

$$N_{PUCCH\,Format\,1}^{RB} = \frac{N_{RS}^{PUCCH} * 12}{Delta\_shift}, \qquad (5.1)$$

where the *Delta_shift* parameter is the cyclic shift difference between two adjacent ACK/NACK resources using the same orthogonal cover sequence [11], and parameter N_{RS}^{PUCCH} is the number of reference signals on PUCCH Format 1/1a/1b ($N_{RS}^{PUCCH} = 3$ with normal CP and 2 with extended CP). Three values are allowed for the *Delta_shift* parameter, namely 1, 2 or 3. This means that the number of PUCCH Format 1/1a/1b resources per resource block equals 36, 18 or 12, with normal CP length.

An example of the PUCCH channelization within the resource block following the staggered resource structure is shown in Figure 5.20. In this example, *Delta_shift* is set to 2 and normal CP length is assumed.

The configuration of the PUCCH Format 1/1a/1b resource is shown in Figure 5.21. PUCCH Format 1/1a/1b resources are divided into available PUCCH resource blocks and are subject to

Cyclic shift	Orthogonal cover code		
	0	1	2
0	0		12
1		6	
2	1		13
3		7	
4	2		14
5		8	
6	3		15
7		9	
8	4		16
9		10	
10	5		17
11		11	

Figure 5.20 Principle of Format 1/1a/1b channelization within one resource block, *Delta_shift* = 2, normal CP

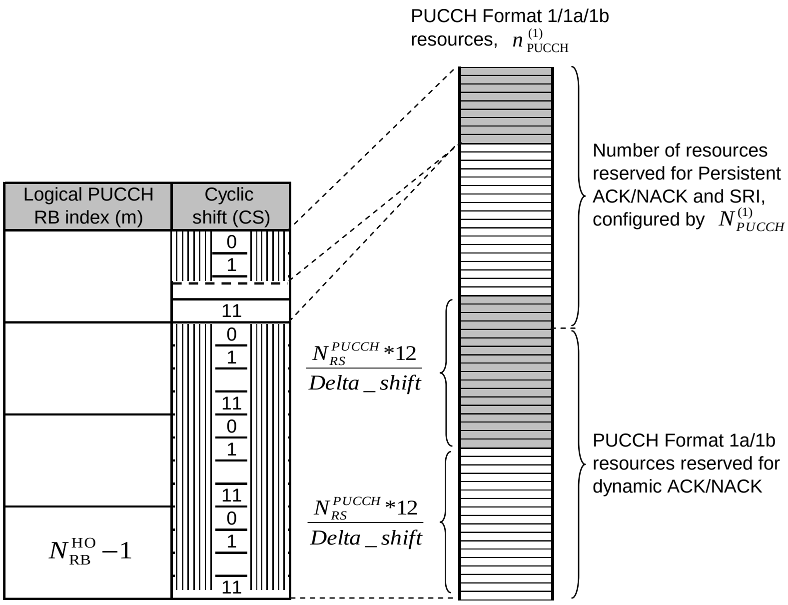


Figure 5.21 Configuration of PUCCH Format 1/1a/1b resource

channelization within the resource block as described earlier. Before that, the Format 1/1a/1b resource is split into persistent and dynamic parts. This is achieved using the broadcasted system parameter $N^{(1)}_{PUCCH}$, which is the number of resources reserved for persistent Format 1/1a/1b resources. These resources are used by the SRI and ACK/NACK related to persistently scheduled PDSCH. Both resources are allocated explicitly by resource index $n^{(1)}_{\mathrm{PUCCH}}$. Dynamic Format 1/1a/1b resources are placed at the end of logical PUCCH resources. Allocation of these ACK/NACK resources, which relate to dynamically scheduled PDSCH, is made implicitly based on the PDCCH allocation.

The idea of implicit allocation in dynamic ACK/NACK resources is to have one-to-one mapping to the lowest PDCCH Control Channel Element (CCE) index. The total number of CCEs depends on the system bandwidth and the number of OFDM symbols allocated for control signaling in a downlink subframe, which is signaled in each subframe using PCFICH (1, 2 or 3 OFDM symbols/subframe for bandwidths above 1.4 MHz, with 2, 3 or 4 OFDM symbols occupied for 1.4 MHz). There has to be a dedicated ACK/NACK resource for each CCE. This means that, for example, with a 20 MHz system bandwidth the number of CCEs can be up to 80 if three OFDM symbols are allocated for control signaling in a subframe.

5.6.2.2 Mapping of Logical PUCCH Resource Blocks into Physical PUCCH Resource Blocks

Mapping of logical resource blocks, denoted as *m*, into physical PUCCH resource blocks is shown in Figure 5.22. Taking into account the logical split between different PUCCH Formats, we note that PUCCH Format 2/2a/2b is located at the outermost resource blocks of the system bandwidth. ACK/NACK reserved for persistently scheduled PDSCH and SRI are located on the PUCCH resource blocks next to periodic CQI while the ACK/NACK resources reserved to dynamically scheduled PDSCH are located at the innermost resource blocks reserved for PUCCH.

An interesting issue from the system perspective is the fact that PUCCH defines the uplink system bandwidth. This is because PUCCH always exists and is located at both edges of the frequency spectrum. We note that proper PUCCH configuration allows narrowing down the active uplink system bandwidth by the resolution of two resource blocks. This can be made so that the PUCCH Format 2/2a/2b resource is over-dimensioned and at the same time the pre-defined PUCCH Format 2/2a/2b resources placed at the outermost resource blocks are left unused. Figure 5.23 shows the principle of this configuration.

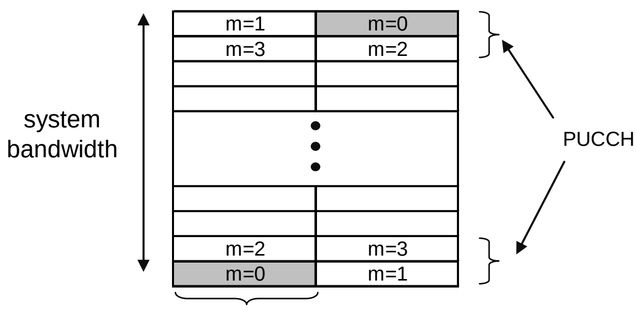


Figure 5.22 Mapping of logical PUCCH RBs into physical RBs [1]

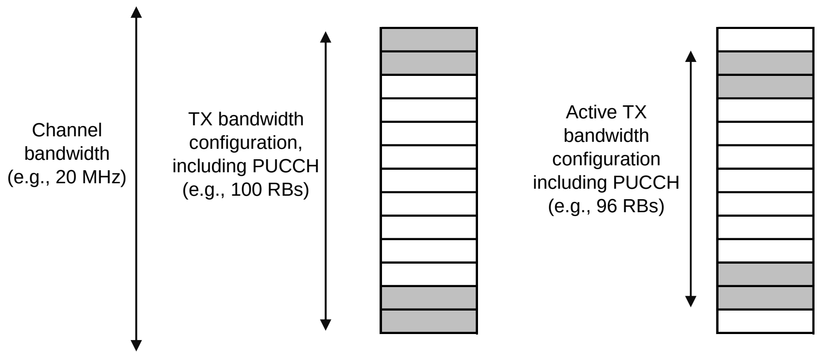


Figure 5.23 Changing the uplink system bandwidth via PUCCH configuration

5.6.3 Control Signaling on PUSCH

PUSCH carries the uplink L1/L2 control signals in the presence of uplink data. Control signaling is realized by a dedicated control resource, which is valid only during the uplink subframe when UE has been scheduled for data transmission on PUSCH. The main issues related to control signal design on PUSCH are:

- how to arrange multiplexing between uplink data and different control fields;
- how to adjust the quality of L1/L2 signals transmitted on PUSCH.

Figure 5.24 shows the principle of control and data multiplexing within the SC-FDMA symbol (block). To maintain the single carrier properties, transmitted signal data and different control symbols are multiplexed prior to the DFT. Data and different control fields (ACK/NAK, CQI/Pre-coding Matrix Indicator [PMI], Rank Indicator [RI]) are coded and modulated separately before multiplexing them into the same SC-FDMA symbol block. Block level multiplexing was also considered, but would have resulted in too large a control overhead [12]. Using the selected symbol level multiplexing scheme the ratio between the data symbols and control symbols can be accurately adjusted within each SC-FDMA block.

Figure 5.25 shows the principle of how uplink data and different control fields are multiplexed on the PUSCH. The actual mix of different L1/L2 control signals and their size vary from subframe to subframe. Both the UE and the eNodeB have the knowledge about the number of symbols reserved by the control part. The data part of PUSCH is punctured by the number of control symbols allocated in the given subframe.

Control and data multiplexing is performed so that control is present at both slots of the subframe. This guarantees that control channels can benefit from frequency hopping when it is

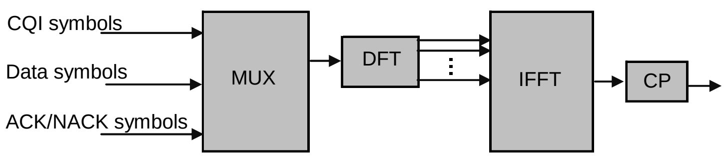


Figure 5.24 Principle of data and control modulation

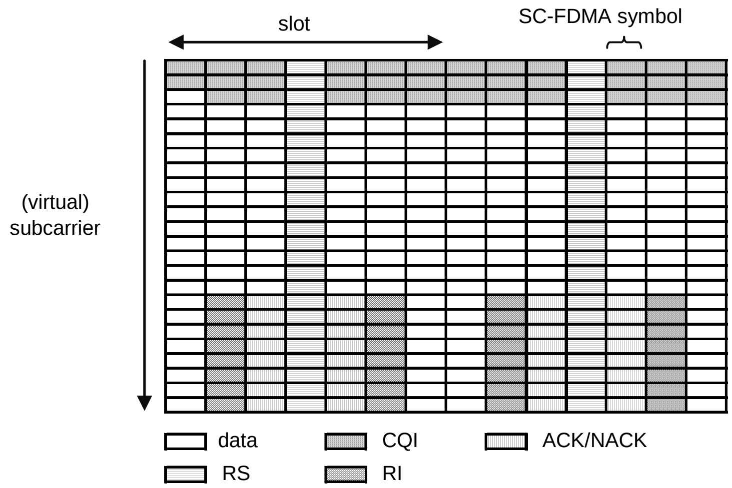


Figure 5.25 Allocation data and different control fields on PUSCH

applied. ACK/NACK is placed at the end of SC-FDMA symbols next to the reference signals. There is a maximum of 2 SC-FDMA symbols per slot allocated to ACK/NACK signaling. The same applies to RI, which is placed on the SC-FDMA symbols next to ACK/NACK. CQI/PMI symbols are placed at the beginning of the SC-FDMA symbols and they are spread over all the available SC-FDMA symbols.

CQI/PMI transmitted on PUSCH uses the same modulation scheme as the data part. ACK/NACK and RI are transmitted so that the coding, scrambling and modulation maximize the Euclidean distance at the symbol level. This means that a modulation symbol used for a ACK/NACK carrier is at most 2 bits of coded control information regardless of the PUSCH modulation scheme. The outermost constellation points having the highest transmission power are used to signal the ACK/NACK and RI for 16QAM and 64QAM. This selection provides a small power gain for ACK/NACK and RI symbols, compared to PUSCH data using higher order modulation.

Four different channel coding approaches are applied with control signals transmitted on PUSCH:

- repetition coding only: 1-bit ACK/NACK;
- simplex coding: 2-bit ACK/NACK/RI;
- (32, N) Reed–Muller block codes: CQI/PMI <11 bits;
- tail-biting convolutional coding (1/3): CQI/PMI ≥11 bits.

An important issue related to control signaling on PUSCH is how to keep the performance of control signaling at the target level. It is noted that power control will set the SINR target of PUSCH according to the data channel. Therefore, the control channel has to adapt to the SINR operation point set for data.

One way to adjust the available resources would be to apply different power offset values for data and different control parts. The problem of the power offset scheme is that single carrier properties are partially destroyed [13]. Therefore this scheme is not used in the LTE uplink system. Instead, a scheme based on a variable coding rate for the control information is used. This is achieved by varying the number of coded symbols for control channel transmission. To minimize the overall overhead from the control signaling, the size of physical resources allocated to control transmission is scaled according to PUSCH quality. This is realized so that the coding rate to be used for control signaling is given implicitly by the Modulation and Coding Scheme (MCS) of PUSCH data. The linkage between data MCS and the size of the control field in made according to Equation 5.2 [14]:

$$O' = \left\lceil \frac{O \cdot offset \cdot M_{SC}^{PUSCH} \cdot N_{symb}^{PUSCH}}{K_{bits}^{PUSCH}} \right\rceil, \tag{5.2}$$

where O' is the number of coded control symbols for the given control type, O is the number of control signaling bits, K_{bits}^{PUSCH} is the number of transmitted bits after code block segmentation and $M_{SC}^{PUSCH} \cdot N_{symb}^{PUSCH}$ is the total number of sub-carriers per subframe carrying PUSCH. Offset is a semi-statically configured parameter related to the coding rate adjustment of control channel and is used to achieve a desired B(L)ER operation point for a given control signaling type. $\lceil \cdot \rceil$ is the operation rounding the control channel size to the nearest supported integer value, towards plus infinity.

As mentioned, the offset-parameter is used to adjust the quality of control signals for the PUSCH data channel. It is a UE-specific parameter configured by higher layer signaling. Different control channels need their own offset-parameter setting. There are some issues that need to be taken into account when configuring the offset-parameter:

- BLER operation point for the PUSCH data channel;
- B(L)ER operation point for the L1/L2 control channel;
- difference in coding gain between control and data parts, due to different coding schemes and different coding block sizes (no coding gain with 1-bit ACK/NACK);
- DTX performance.

Different BLER operation points for data and control parts are because HARQ is used for the data channels whereas the control channels do not benefit from HARQ. The higher the difference in the BLER operation point between data and control channels, the larger is the offset parameter (and vice versa). Similar behavior relates also to the packet size. The highest offset values are needed with ACK/NACK signals due to the lack of coding gain.

5.6.4 Uplink Reference Signals

In addition to the control and data signaling, there are reference signals as discussed in Section 5.4. The eNodeB needs to have some source of known data symbols to facilitate coherent detection, like in the WCDMA where uplink Physical Dedicated Control Channel (PDCCH) was carrying pilot symbols in the uplink direction. In LTE uplink, reference signals (RS) are used as demodulation reference signals (DM RS) on PUCCH and PUSCH. The new purpose of the reference signals, not part of WCDMA operation, is to use them as sounding reference signals (SRS). Additionally, reference signals are used for sequence modulation on PUCCH as discussed in section 5.6.1.1. The sequences used as reference signals are discussed in section

5.6.4.1, while demodulation reference signals and sounding reference signals are considered in sections 5.6.4.2 and 5.6.4.3, respectively.

5.6.4.1 Reference Signal Sequences

Considering first the sequences itself, the most important properties for the RS sequences in LTE uplink are:

- favorable auto- and cross-correlation properties;
- sufficient number of sequences;
- flat frequency domain representation facilitating efficient channel estimation;
- low cubic metric values comparable to the cubic metric of QPSK modulation.

The sequences also need to be suitable for supporting the numerous bandwidth options in uplink allocations. This means that sequences of various lengths, multiples of 12, are needed.

Constant Amplitude Zero Autocorrelation Codes (CAZAC) such as Zadoff–Chu [15] and Generalized Chirp-Like [16] polyphase sequences have most of the required properties. There exist also a reasonable number of Zadoff–Chu sequences when the sequence length is a prime number. However, the sequence lengths needed in LTE uplink are multiples of 12, for which only a modest number of Zadoff–Chu sequences exist. To obtain a sufficient number of RS sequences, computer generated sequences are used for sequence lengths of 12 and 24. They are constructed from QPSK alphabet in frequency domain. Longer sequences are derived from Zadoff–Chu sequences with length of prime number. They are circularly extended in frequency domain to the desired length. These sequences are frequently referred to as extended Zadoff–Chu sequences.

As a result, there are 30 reference signal sequences available for sequence lengths of 12, 24, and 36 and a larger number for longer sequence lengths. The RS sequences do not have constant amplitude in time and, thus, they are not actually CAZAC sequences. However, they have acceptable cubic metric values and zero autocorrelation and, thus, may be referred to as Zero Autocorrelation (ZAC) sequences.

As said, the RS sequences have a periodic autocorrelation function that is zero except for the zero shift value. In other words, the cyclic, or circular, shifts of a sequence, illustrated in Figure 5.26, are orthogonal to each other. This provides a convenient means to derive multiple orthogonal sequences from a single RS sequence, which is used in LTE to multiplex UE. To maintain the orthogonality, however, the time difference between the signals arriving at the base station should not exceed the time interval corresponding to the cyclic shift separation. To accommodate multi-path delay spread, the minimum time separation between the cyclic shifts available in LTE is 5.56 µs for Demodulation RS (DMRS) and 4.17 µs for Sounding RS (SRS). Correspondingly, there are 12 and 8 cyclic shifts specified for DMRS and SRS, respectively, with constant time separation between cyclic shifts irrespective of the reference signal bandwidth.

5.6.4.2 Demodulation Reference Signals

DMRS are primarily used for channel estimation needed for coherent detection and demodulation and it has the same bandwidth as the uplink data transmission. There is one DMRS in every

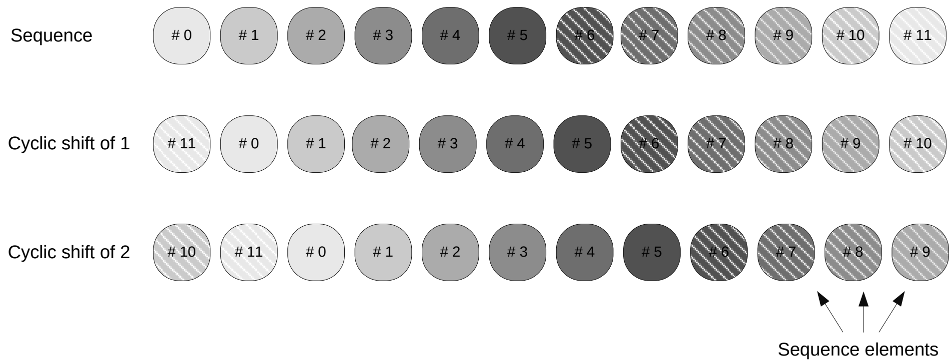


Figure 5.26 Cyclic shifts of a sequence

0.5 ms slot on PUSCH, whereas on PUCCH, there are 2–3 reference signals per slot depending on the used PUCCH format. For PUSCH, DMRS occupies the 4th SC-FDMA symbol in the slot, and the RS sequence length equals the number of allocated sub-carriers. The reference signal locations for PUCCH are discussed in section 5.6.1

As said, there are RS sequences of numerous lengths with 30 or more sequences for each sequence length. For simplicity, the sequences of various lengths are grouped into 30 sequence groups. Each sequence group contains RS sequences for all supported sequence lengths, with one RS sequence for allocations from 1 to 5 PRBs and two RS sequences for larger allocations. As a result, the used demodulation reference signal is defined with four parameters:

- sequence group, with 30 options – this is a cell specific parameter;
- sequence, with 2 options for sequence lengths of 6 PRBs or longer – this is a cell specific parameter;
- cyclic shift, with 12 options – this has both terminal and cell specific components, and 8 different values can be configured with the uplink allocation;
- sequence length, given by the uplink allocation.

Cyclic shifts are used to multiplex reference signals from different terminals within a cell, whereas different sequence groups are typically used in neighboring cells. While cyclic shifts provide good separation within a cell, a more complicated interference scenario is faced between cells. Simultaneous uplink allocations on neighboring cells can have different bandwidths and can be only partially overlapping in frequency. This alone prevents effective optimization of RS cross-correlations between cells. Thus, multiple hopping methods are included to LTE to randomize inter-cell interference for reference signals. The pseudo-random hopping patterns are cell specific and derived from the physical layer cell identity. For PUSCH and PUCCH, LTE supports:

- Cyclic shift hopping, which is always used. A cell specific cyclic shift is added on top of UE specific cyclic shifts. Cyclic shift hops for every slot on PUSCH. Inter-cell interference is expected to be more significant on PUCCH than on PUSCH due to CDM applied on PUCCH. To enhance inter-cell interference randomization, cyclic shift hops for every SC-FDMA symbol on PUCCH. Cyclic shift hopping is applied also for SC-FDMA symbols carrying control data due to the sequence modulation used on PUCCH.

- Sequence group hopping. Sequence group hopping pattern is composed of a group hopping pattern and a sequence-shift. The same group hopping pattern is applied to a cluster of 30 cells. To differentiate cells within a cluster, a cell specific sequence shift is added on top of the group hopping pattern. With this arrangement, the occasional use of the same sequence group simultaneously on neighboring cells is avoided within the cell cluster. Sequence group hopping can be also disabled, thus facilitating sequence planning. Sequence group hops for every slot.
- Sequence hopping, which means hopping between the two sequences within a sequence group. Sequence hopping can be applied for resource allocations larger than 5 RBs if sequence group hopping is disabled and sequence hopping is enabled.

On PUSCH, it is possible to configure cyclic shift hopping and sequence group hopping patterns so that the same patterns are used on neighboring cells. This means that the same sequence group is used on neighboring cells. This is not a feasible solution for PUCCH, however, due to a more intensive use of cyclic shifts. Thus, the hopping patterns are cell-specific and are derived from the cell identity on PUCCH. Therefore, a sequence group is configured separately for PUCCH and PUSCH with an additional configuration parameter for PUSCH.

5.6.4.3 Sounding Reference Signals

SRS is used to provide information on uplink channel quality on a wider bandwidth than the current PUSCH transmission or when a terminal has no transmissions on PUSCH. Channel is estimated on eNodeB and the obtained channel information can be used in the optimization of uplink scheduling as part of the uplink frequency domain scheduling operation. Thus, SRS is in a sense an uplink counterpart for the CQI reporting of downlink channel. SRS can also be used for other purposes, e.g. to facilitate uplink timing estimation for terminals with narrow or infrequent uplink transmissions. SRS is transmitted on the last SC-FDMA symbol of the subframe, as shown in Figure 5.27. Note that the SRS transmission does not need to be in the frequency area used by the PUSCH for actual data transmission but it may locate elsewhere as well.

On SRS, distributed SC-FDMA transmission is used. In other words, UE uses every second sub-carrier for transmitting the reference signal, as illustrated in Figure 5.28. Related sub-carrier offset defines a transmission comb for the distributed transmission. The transmission comb provides another means to multiplex UE reference signals in addition to the cyclic shifts. SRS

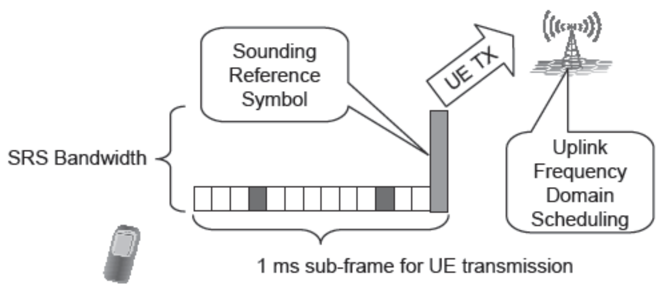


Figure 5.27 Sounding reference signal transmission in the frame

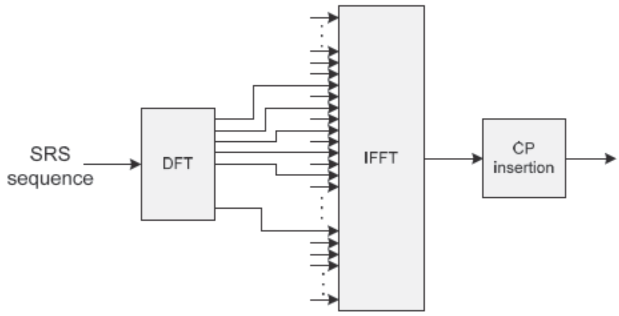


Figure 5.28 Sub-carrier mapping for sounding reference signal

uses the same sequences as DMRS. SRS sequence lengths are multiples of 24, or, correspondingly, SRS bandwidths are multiples of 4 RBs. This follows from the available RS sequence lengths combined with the definition of 8 cyclic shifts for SRS.

SRS transmissions can be flexibly configured. SRS transmission can be a single transmission or periodic with period ranging from 2 ms to 320 ms. There can be up to four different SRS bandwidth options available, depending on the system bandwidth and cell configuration. SRS transmission can also hop in frequency. This is particularly beneficial for the terminals on the cell edge, which cannot support wideband SRS transmissions. Frequency hopping can also be limited to a certain portion of system bandwidth which is beneficial for inter-cell interference coordination [17]. SRS configuration is explicitly signaled via terminal specific higher layer signaling.

Sounding reference signal transmissions from different terminals can be multiplexed in multiple dimensions:

- Time: Periodic SRS transmissions can be interleaved into different subframes with subframe offsets.
- Frequency: To facilitate frequency division multiplexing, the available SRS bandwidths follow a tree structure. This is illustrated in Figure 5.29, where a set of available SRS bandwidths is shown for a certain cell configuration. The SRS frequency hopping pattern also follows the tree structure, as shown in Figure 5.30 with an illustrative example based on the SRS bandwidth set of Figure 5.29.
- With cyclic shifts: Up to 8 cyclic shifts can be configured. The cyclic shift multiplexed signals, however, need to have the same bandwidth to maintain orthogonality. Due to the intensive use of cyclic shifts, the sequence group configured for PUCCH is used also for SRS.
- Transmission comb in the distributed transmission: Two combs are available. Contrary to cyclic shifts, transmission comb does not require that the multiplexed signals occupy the same bandwidth.

In addition to the terminal specific SRS configuration, cell specific SRS configuration defines the subframes that can contain SRS transmissions as well as the set of SRS bandwidths available in the cell. Typically SRS transmissions should not extend into the frequency band reserved for PUCCH. Therefore, multiple SRS bandwidth sets are needed for supporting flexible cell specific PUCCH configuration.

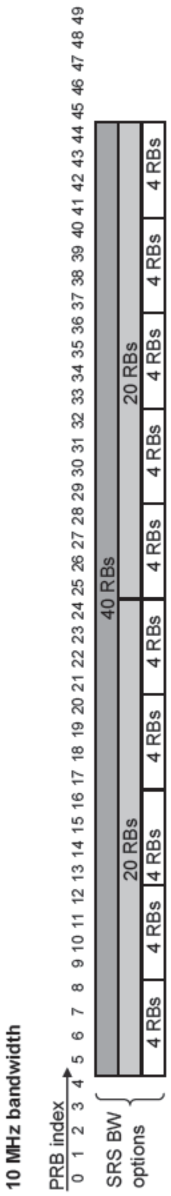


Figure 5.29 A SRS bandwidth set with a tree structure

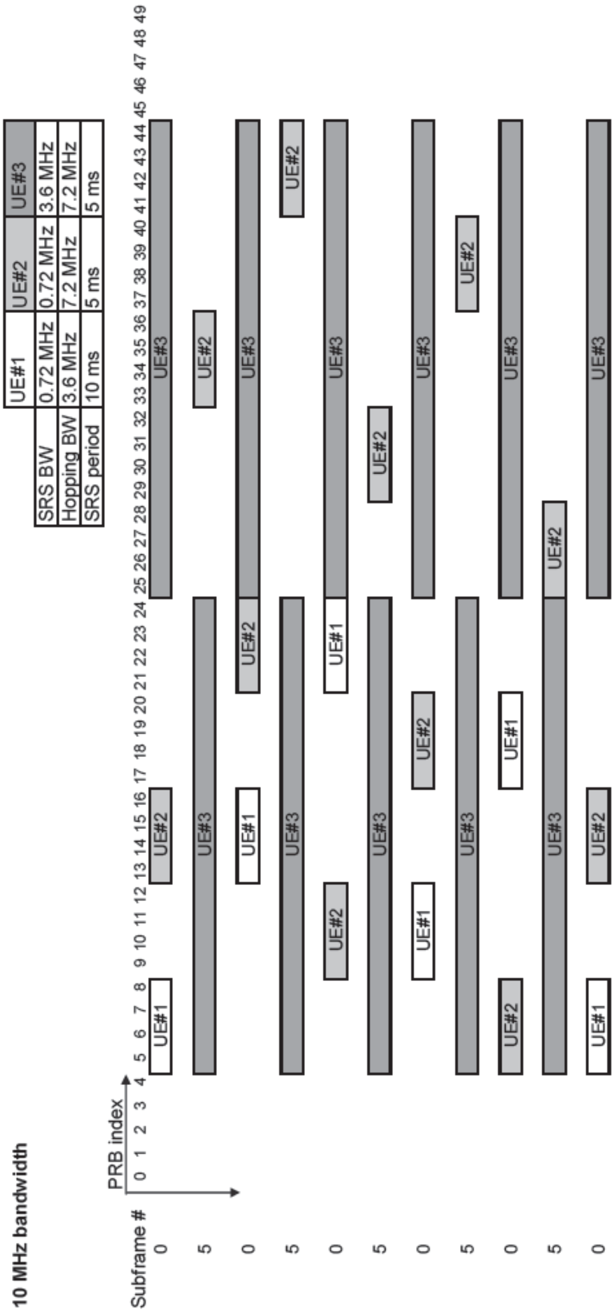


Figure 5.30 An example of SRS frequency hopping patterns

5.7 PRACH Structure

5.7.1 Physical Random Access Channel

Random access transmission is the only non-synchronized transmission in the LTE uplink. Although the terminal synchronizes to the received downlink signal before transmitting on RACH, it cannot determine its distance from the base station. Thus, timing uncertainty caused by two-way propagation delay remains on RACH transmissions.

Appropriately designed Physical Random Access Channel (PRACH) occurs reasonably frequently, provides a sufficient number of random access opportunities, supports the desired cell ranges in terms of path loss and uplink timing uncertainty, and allows for sufficiently accurate timing estimation. Additionally, PRACH should be configurable to a wide range of scenarios, both for RACH load and physical environment. For example, LTE is required to support cell ranges up to 100 km, which translates to 667 μs two-way propagation delay, as facilitated in the timing advance signaling range in the MAC layer.

In a LTE frame structure type 1 (FDD), only one PRACH resource can be configured into a subframe. The periodicity of PRACH resources can be scaled according to the expected RACH load, and PRACH resources can occur from every subframe to once in 20 ms. PRACH transmission is composed of a preamble sequence and a preceding cyclic prefix with four different formats as shown in Figure 5.31. Multiple preamble formats are needed due to the wide range of environments. For example, the long CP in preamble formats 1 and 3 assists with large cell ranges in terms of increased timing uncertainty tolerance whereas repeated preamble sequences in formats 2 and 3 compensate for increased path loss. The guard period that is necessary after an unsynchronized preamble is not explicitly specified, but PRACH location in the subframe structure provides a sufficient guard period. Particular considerations are needed only in very special cases. For each cell, 64 preamble sequences are configured and, thus, there are 64 random access opportunities per PRACH resource. PRACH occupies 1.08 MHz bandwidth, which provides reasonable resolution for timing estimation.

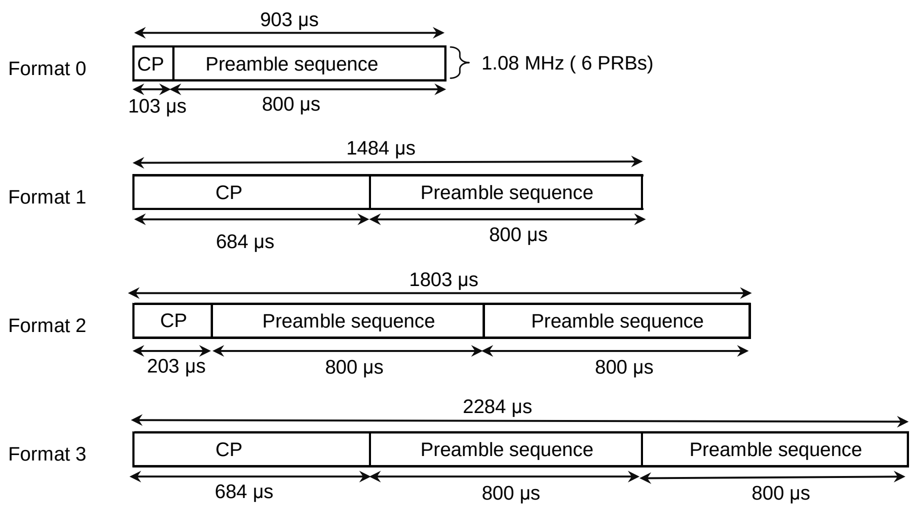


Figure 5.31 LTE RACH preamble formats for FDD

5.7.2 Preamble Sequence

Zadoff–Chu sequences [15] belonging to CAZAC are used as RACH preamble sequences due to several desirable sequence properties:

- They have a periodic autocorrelation function that is zero except for the zero shift value. This is desirable for preamble detection and timing estimation. Additionally, the cyclic, or circular, shifts of a sequence are orthogonal to each other. As a result, multiple preamble sequences are obtained from a single Zadoff–Chu sequence with cyclic shifts.
- As the preamble sequence length is set to a prime number of 839, there are 838 sequences with optimal cross-correlation properties.
- Sequences also have reasonable cubic metric properties.

The cyclic shifts used as different preambles need to have a sufficient separation. The cyclic shift separation needs to be sufficiently wide to accommodate the uplink timing uncertainty, as illustrated in Figure 5.32. The propagation delay and, thus, the cyclic separation are directly related to the cell range. To accommodate the wide range of cell ranges supported by LTE, 16 different cyclic shift separations can be configured for a cell, providing 1 to 64 preambles from a single Zadoff–Chu sequence.

A particular high speed mode, or a restricted set, is defined for RACH due to the peculiar properties of Zadoff–Chu sequences for Doppler spread. Essentially, high speed mode is a set of additional restrictions on the cyclic shifts that can be used as preambles.

Discrete Fourier Transform of Zadoff–Chu sequence is also a Zadoff–Chu sequence defined in frequency. Due to the Doppler, the transmitted preamble sequence spreads on cyclic shifts adjacent in frequency to the transmitted cyclic shift and particularly on the cyclic shift neighboring the transmitted cyclic shift in frequency. Particularly, a Doppler frequency corresponding to the inverse of sequence length, i.e. 1.25 kHz for LTE, transforms the transmitted cyclic shift (of sequence) completely to the cyclic shift neighboring the transmitted one in frequency. As a result, the received sequence is orthogonal with the transmitted sequence for a Doppler frequency of 1.25 kHz.

There is a tractable one-to-one relation between the cyclic shifts neighboring each other in frequency and the cyclic shifts in time. Thus, three uplink timing uncertainty windows can be defined for a preamble, with the windows separated by a shift distance as shown in Figure 5.33. The shift distance is a function of the Zadoff–Chu sequence index. The shifting of the timing uncertainty windows is circular, as illustrated in Figure 5.33.

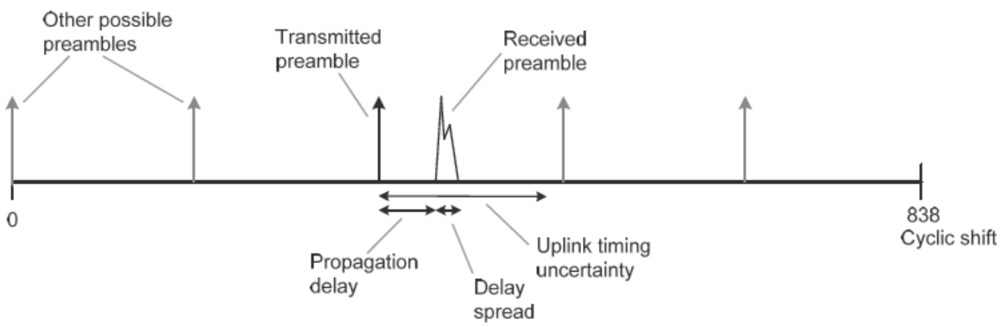


Figure 5.32 Illustration of cyclic shift separation N_{cs} between preamble sequences

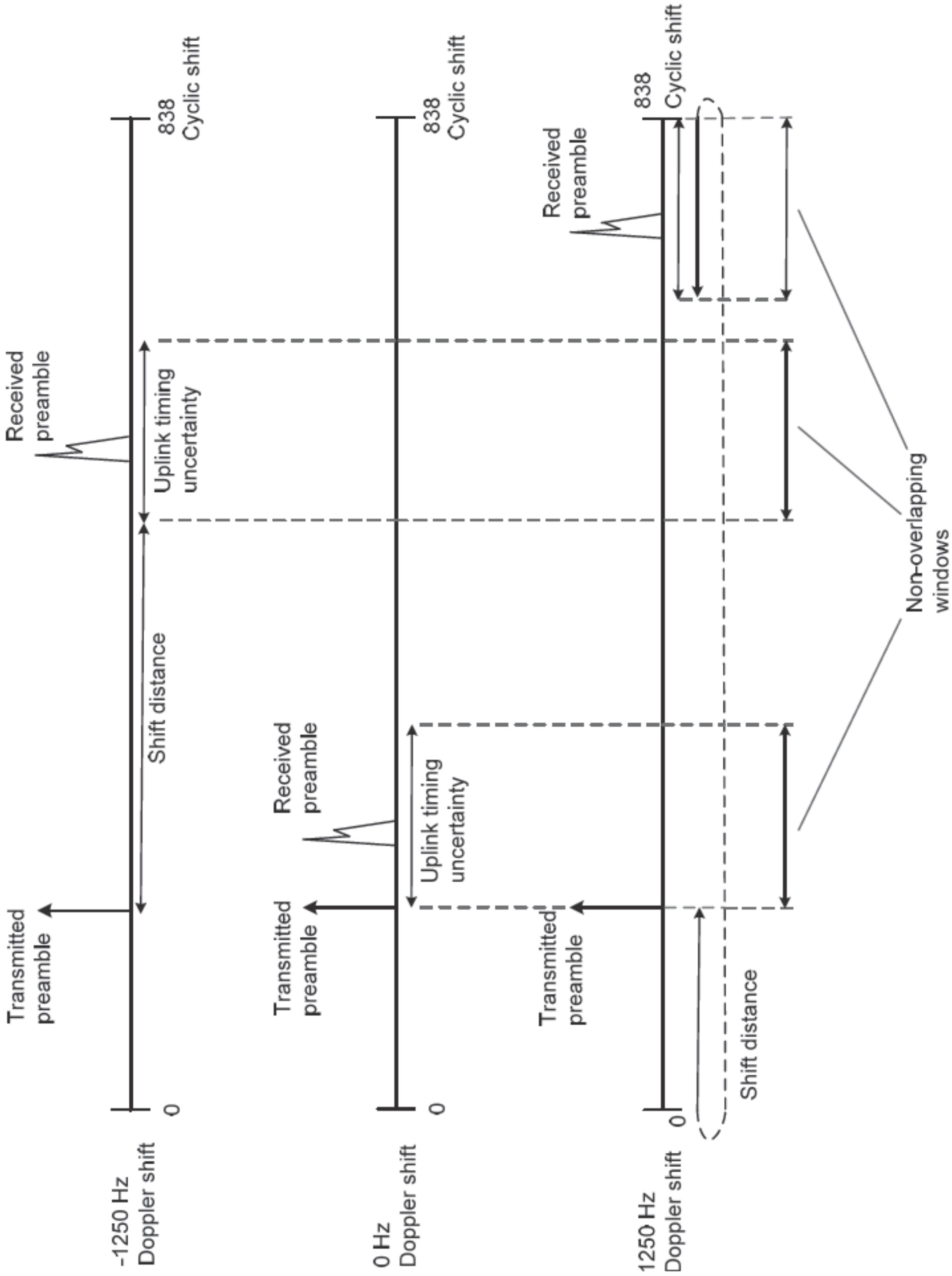


Figure 5.33 Illustration of uplink timing uncertainty windows for RACH preamble with considerable Doppler

There are several consequences of the aforementioned when detecting preambles with considerable Doppler:

- Signal energy needs to be collected from all three windows for reliable preamble detection.
- The windows of a preamble should not overlap each other to allow for initial uplink timing estimation.
- The windows of the different preambles should not overlap each other to prevent unnecessary false alarms.

As a result, the preamble cyclic shifts for high speed mode need to be selected so that the timing uncertainty windows do not overlap each other for each preamble as well as between preambles. Although these requirements, as well as the dependency of the shift distance on the sequence index, complicate the calculation of cyclic shift for preambles, tractable equations have been found and standardized [18].

5.8 Downlink Physical Layer Signaling Transmission

The control information in the downlink direction is carried using three different types of control messages:

- Control Format Indicator (CFI), which indicates the amount of resources devoted to control channel use. CFI is mapped to the Physical Control Format Indicator Channel (PCFICH).
- HARQ Indication (HI), which informs of the success of the uplink packets received. The HI is mapped on the Physical HARQ Indicator Channel (PHICH).
- Downlink Control Information (DCI), which controls with different formats basically all the physical layer resource allocation in both uplink and downlink direction and has multiple formats for different needs. The DCI is mapped on the Physical Downlink Control Channel (PDCCH)

5.8.1 Physical Control Format Indicator Channel (PCFICH)

The sole purpose of PCFICH is to dynamically indicate how many OFDMA symbols are reserved for control information. This can vary between 1 and 3 for each 1 ms subframe. From the PCFICH, UE knows which symbols to treat as control information. Location and modulation of PCFICH is fixed. The use of dynamic signaling capability allows the system to support both a large number of low data rate users (e.g. VoIP) as well as to provide sufficiently low signaling overhead when higher data rates are used by fewer simultaneously active users. The extreme situations are illustrated in Figure 5.34, where the PDCCH allocation is changed from 1 symbol to 3 symbols. When calculating the resulting overhead, note that PDCCH is only allocated to the first 0.5 ms slot in the 1 ms subframe, thus the overhead is from 1/14 to 3/14 of the total physical layer resource space.

With the 1.4 MHz operation, the PDCCH resource is 2, 3 or 4 symbols to ensure enough payload size and a sufficient range for all signaling scenarios. In big cells it is important to have enough room for channel coding together with signaling, especially for the operation with RACH.

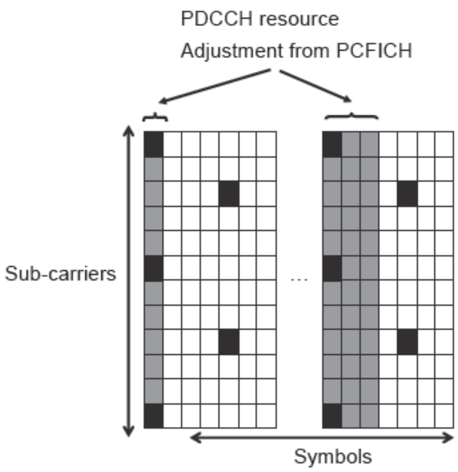


Figure 5.34 PDCCH resource allocation from PCFICH for bandwidths above 1.4 MHz

5.8.2 Physical Downlink Control Channel (PDCCH)

The UE will obtain from the PDCCH information for both uplink and downlink resource allocations the UE may use. The DCI mapped on the PDCCH has different formats and depending on the size DCI is transmitted using one or more Control Channel Elements (CCEs). A CCE is equal to 9 resource element groups. Each group in turn consists of 4 resource elements. The different PDCCH formats are shown in Table 5.2, where it can be seen that as PDCCH is using QPSK modulation, then a single resource element carries 2 bits and there are 8 bits in a resource element group.

The UE will listen to the set of PDCCHs and tries to decode them (checking all formats) in all subframes except during the ones where DRX is configured. The set of PDCCHs to monitor is up to 6 channels. Depending on the network parameterization, some of the PDCCHs are so-called common PDCCHs and may also contain power control information.

The DCI mapped to PDCCH has four different formats and further different variations for each format. It may provide the control information for the following cases:

- PUSCH allocation information (DCI Format 0);
- PDSCH information with one codeword (DCI Format 1 and its variants);
- PDSCH information with two codewords (DCI Format 2 and its variants);.
- Uplink power control information (DCI Format 3 and its variants)

Table 5.2 PDCCH format and their size

PDCCH format	Number of CCEs	Number of resource-element groups	Number of PDCCH bits
0	1	9	72
1	2	18	144
2	4	36	288
3	8	72	576

The PDCCH containing PDSCH related information is often referred to as the downlink assignment. The following information is carried on the downlink assignment when providing downlink resource allocation information related to PDSCH:

- Resource block allocation information. This indicates the position of the resources allocated for the user in question in the resource block domain. The allocation can be based on, for example, a bitmap pointing the given PRBs or an index of the first PRB and the number of contiguously allocated PRBs.
- The modulation and coding scheme used for downlink user data. The 5 bit signaling indicates the modulation order and the transport block size (TBS). Based on these parameters and the number of allocated resource blocks the coding rate can be derived.
- The HARQ process number needs to be signaled as the HARQ retransmission from the eNodeB point of view is asynchronous and the exact transmission instant is up to the eNodeB scheduler functionality. Without the process number the UE could confuse the different processes and combine the wrong data. This also prevents error propagation from this part if control signaling is lost for a single TTI. The number of HARQ processes was fixed to 8 in both uplink and downlink.
- A new data indicator to tell whether the transmission for the particular process is a retransmission or not. This again follows similar principles to those applied with HSDPA.
- Redundancy version is a HARQ parameter that can be used with incremental redundancy to tell which retransmission version is used.
- The power control commands for the PUCCH are also included on the PDCCH. The power control command has two bits and it can thus use 2 steps up and downwards to adjust the power.

Additionally, when MIMO operation is involved, there are MIMO specific signaling elements involved, as discussed with the MIMO in section 5.9.7.

The PDCCH containing PUSCH related information is also known as the uplink grant. The following information is carried on the uplink grant.

- Hopping flag and resource block assignment and hopping resource allocation. The number of bits for this depends on the bandwidth to be used. Uplink resource allocation is always contiguous and it is signaled by indicating the starting resource block and the size of the allocation in terms of resource blocks.
- Modulation and coding scheme and the redundancy version.
- A new data indicator, which is intended to be used for synchronizing the scheduling commands with the HARQ ACK/NACK message status.
- TPC command for scheduled PUSCH which can represent four different values.
- Cyclic shift for the Demodulation Reference Symbols – 3 bits.
- Aperiodic CQI report request.

Besides these purposes, the PDCCH can also carry power control information for several users. The options supported are both the 1 bit and 2 bit formats. The maximum number of users listening to a single PDCCH for power control purposes is *N*. Higher layers indicate to the device which bit or bits it needs to receive for the power control purposes.

As mentioned earlier, the PCFICH indicates the amount of resources reserved for the PDCCH with 1 ms basis. The UEs in the cell check the PCFICH and then blindly decode the PDCCH to see

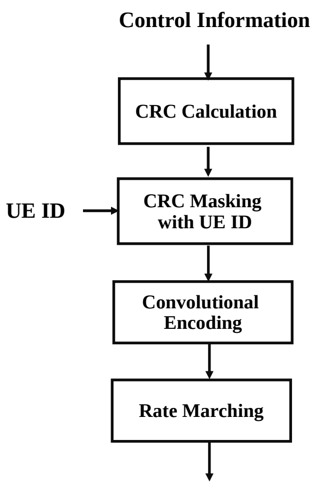


Figure 5. 35 PDCCH channel coding chain

which of the control channels (if any) is intended for them. The user identification is based on using UE specific CRC, which is generated after normal CRC generation by masking the CRC with the UE ID. The PDCCH channel coding is based on the same 1/3-rate convolutional coding as other convolutionally encoding channels. The PDCCH encoding chain is illustrated in Figure 5. 35.

5.8.3 Physical HARQ Indicator Channel (PHICH)

The task for the Physical HARQ Indicator Channel (PHICH) is simply to indicate in the downlink direction whether an uplink packet was correctly received or not. The device will decode the PHICH based on the uplink allocation information received on the PDCCH.

5.8.4 Downlink Transmission Modes

For robust and efficient system operation, it is important that the UE knows beforehand which type of transmission to expect. If the transmission mode could change dynamically from one subframe to another the UE would need to monitor all the possible DCI formats simultaneously, leading to a considerable increase in the number of blind decodings and receiver complexity (and possibly an increased number of signaling errors). Furthermore, the UE would not be able to provide meaningful channel feedback since, for example, the CQI value depends on the transmission mode assumed.

Therefore each UE is configured semi-statically via RRC signaling to one transmission mode. The transmission mode defines what kind of downlink transmissions the UE should expect, e.g. transmit diversity or closed loop spatial multiplexing, and restricts the channel feedback to modes corresponding to the desired operation. In LTE Release 8, seven transmission modes have been defined:

1 Single-antenna port; port 0
   This is the simplest mode of operation with no pre-coding.