UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

INTEL CORPORATION and LENOVO (UNITED STATES) INC.
Petitioner,
v.

USTA TECHNOLOGY, LLC.,
Patent Owners.

Case IPR2025-00838

U.S. PATENT NO. RE47,720

DECLARATION OF SYLVIA D. HALL-ELLIS, PH.D. UNDER 37 C.F.R. § 1.68 IN SUPPORT OF PETITION FOR *INTER PARTES* REVIEW

I. INTRODUCTION

1. My name is Sylvia D. Hall-Ellis. I have been retained as an expert by Haynes & Boone LLP, Counsel for Intel Corporation and Lenovo (United States) Inc. (referred to herein as "Petitioner").

2. I have written this declaration at the request of Petitioner to provide my expert opinion regarding the authenticity and public availability of two publications. My declaration sets forth my opinions in detail and provides the basis for my opinions regarding the public availability of these publications.

3. I reserve the right to supplement or amend my opinions, and basis for them, in response to any additional evidence, testimony, discovery, argument, and/or other additional information that may be provided to me after the date of this declaration. If called to testify in the above-captioned matter, I will testify with regard to the opinions and bases set forth below.

4. I am being compensated for my time spent working on this matter at my normal consulting rate plus reimbursement for any additional reasonable expenses. My compensation is not in any way tied to the content of this declaration, the substance of my opinions, or the outcome of this proceeding. I have no other interests in this proceeding or with any of the parties.

5. All of the materials that I considered are discussed explicitly in this declaration.

II. QUALIFICATIONS

6. I am currently an Adjunct Professor in the School of Information at San José State University. I obtained a Master of Library Science from the University of North Texas in 1972 and a Ph.D. in Library and Information Science from the University of Pittsburgh in 1985. Over the last fifty years, I have held various positions in the field of library and information resources. I was first employed as a librarian in 1966 and have been involved in the field of library sciences since, holding numerous positions.

7. I am a member of the American Library Association ("ALA") and its Association for Library Collections & Technical Services ("ALCTS") Division, and I served on the Committee on Cataloging: Resource and Description (which wrote the new cataloging rules) and as the chair of the Committee for Education and Training of Catalogers and the Competencies and Education for a Career in Cataloging Interest Group. I also served as the Chair of the ALCTS Division's Task Force on Competencies and Education for a Career in Cataloging. Additionally, I served as the Chair for the ALA Office of Diversity's Committee on Diversity, as a member of the REFORMA National Board of Directors, and as a member of the Editorial Board for the ALCTS premier cataloging journal, *Library Resources and Technical Services,* as a Co-Chair of the Membership Committee for the Library Research Round Table (LRRT) of the American Library

Association, and as a member of the LRRT Nominating Committee. Currently I serve as a member of the CORE Margaret Mann Citation Committee.

8. I have also given over one-hundred presentations in the field, including several on library cataloging systems and Machine-Readable Cataloging ("MARC") standards. My current research interests include library cataloging systems, metadata, and organization of electronic resources.

9. I have been deposed thirty-eight times: (1) *Symantec Corp. vs. Finjan*, *Inc.,* Petition for *Inter Partes Review* of U.S. Patent No. 7,613,926, May 26, 2016, on behalf of Symantec Corp.; (2) *Symantec Corp. vs. Finjan*, *Inc.,* Northern District of California, 14-cv-299-HSG, on behalf of Symantec Corp., September 14, 2017; (3) one deposition for ten matters: *Intellectual Ventures I LLC vs. AT&T Mobility LLC*; AT&T Mobility II LLC, New Cingular Wireless Services, Inc., SBC Internet Services, Inc., Wayport, Inc., and Cricket Wireless LLC, C.A. No. 12-193 (LPS); *Intellectual Ventures II LLC vs. AT&T Mobility LLC*; AT&T Mobility II LLC, New Cingular Wireless Services, Inc., SBC Internet Services, Inc., Wayport, Inc., and Cricket Wireless LLC, C.A. No. 13-1631 (LPS); *Intellectual Ventures I LLC vs. T-Mobile USA, Inc. and T-Mobile US, Inc.,* C.A. No. 13-1632 (LPS); *Intellectual Ventures II LLC vs. T-Mobile USA, Inc. and T-Mobile US, Inc.,* C.A. No. 13-1633 (LPS); *Intellectual Ventures I LLC, vs. Nextel Operations, Inc., Sprint Spectrum L.P., Boost Mobile, LLC and Virgin Mobile USA, L.P.,* C.A. No. 13-1634

(LPS); *Intellectual Ventures II LLC vs. Nextel Operations, Inc., Sprint Spectrum L.P., Boost Mobile, LLC and Virgin Mobile USA, L.P.,* C.A. No. 13-1635 (LPS); *Intellectual Ventures I LLC, vs. United States Cellular Corporation*, C.A. No. 13-1636 (LPS); *Intellectual Ventures I LLC vs. United States Cellular Corporation*, C.A. No. 13-1637 (LPS); *Intellectual Ventures II LLC vs. AT&T Mobility LLC*, *AT&T Mobility II LLC, New Cingular Wireless Services, Inc.,* C.A. No. 15-799 (LPS); *Intellectual Ventures I LLC vs. T-Mobile USA, Inc. and T-Mobile US, Inc.,* C.A. No. 15-800 (LPS), on behalf of AT&T Mobility LLC; AT&T Mobility II LLC, Boost Mobile, LLC Cricket Wireless LLC, Nextel Operations, Inc., New Cingular Wireless Services, Inc., SBC Internet Services, Inc., Sprint Spectrum L.P., T-Mobile USA, Inc., T-Mobile US, Inc., United States Cellular Corporation Virgin Mobile USA, L.P., and Wayport, Inc., November 15, 2016; (4) *Hitachi Maxell, LTD., v. Top Victory Electronics (Taiwan) Co. Ltd., et al.,* Eastern District of Texas, 2:14-cv-1121 JRG-RSP (E.D. Texas), on behalf of Top Victory Electronics (Taiwan) Co. LTD, *et. al.,* January 20, 2016; (5) *Sprint Spectrum, L.P. vs. General Access Solutions, Ltd*., Petition for *Inter Partes Review* of U.S. Patent No. 7,173,916, on behalf of Sprint Spectrum L.P., July 13, 2018; (6) *Nichia Corporation vs. Vizio, Inc*., Central District of California, 8:16-cv-00545; on behalf of Vizio, Inc., October 12, 2018; (7) *Intellectual Ventures I LLC, vs. T-Mobile USA, Inc., T-Mobile US, Inc., Ericsson Inc., and Telefonaktiebolaget LM Ericsson*,

Middle District of Florida, 2:17-cv-00557 (JRG), on behalf of T-Mobile USA, Inc., T-Mobile US, Inc., Ericsson Inc., and Telefonaktiebolaget LM Ericsson, October 19, 2018; (8) Pfizer, Inc. vs. Biogen, Inc., Petition for *Inter Partes Review* of U.S. Patent No. 8,821,873, on behalf of Pfizer, November 3, 2018; (9) *Finjan, Inc. vs. ESET, LLC and ESET SPOL. S.R.O.,* Southern District of California, 3:17-cv-00183-CAB-BGS, on behalf of ESET, January 15, 2019; (10) *Finjan, Inc. vs. Cisco Systems, Inc.,* Northern District of California, 5:17-cv-00072-BLF-SVK, on behalf of Cisco Systems, Inc., September 6, 2019; (11) *Facebook, Inc., Instagram, LLC and Whatsapp Inc. vs. Blackberry Limited*, Petition for *Inter Partes Review* of U.S. Patent No. 9,349,120 B2, on behalf of Facebook, Inc., Instagram, LLC and Whatsapp Inc. December 20, 2019; (12) *3Shape A/S and Shape Inc. v. Align Technology, Inc.,* Petition for *Inter Partes Review* of U.S. Patent No. 7,156,661, IPR2020-00222 and IPR2020-00223, August 10, 2020, on behalf of 3Shape A/S and 3Shape Inc.; (13) *Finjan Inc. v. Rapid7, Inc. and Rapid7 LLC*, District of Delaware, 1:18-cv-01519-MN, September 15, 2020; (14) *VLSI Technology LLC v. Intel Corporation*, Western District of Texas, 6:19-cv-00254, 6:19-cv-00255, 6:19-cv-00256, on behalf of Intel Corporation, September 23, 2020; (15) *Finjan Inc. v. Sonicwall, Inc.,* Northern District of California, 5:17-cv-04467-BLF-HRL, on behalf of Sonicwall, Inc., October 27, 2020; (16) *VLSI Technology, LLC v. Intel Corporation*, District of Delaware, 1:18-cv-00966-CFC-CJB, February 5, 2021, on

behalf of the Intel Corporation; (17) *Unified Patents, LLC v. Good Kaisha IP Bridge 1*, Petition for *Inter Partes Review* of U. S. Patent 7,817,868, February 11, 2021, on behalf of Unified Patents; (18) *Finjan, Inc. v. Qualsys, Inc.,* Northern District of California, 4:18-cv-07229-YGR, March 1, 2021, on behalf of Qualsys, Inc.; (19) *Qualcomm, Inc. v. Monterey Research LLC*, Petition for *Inter Partes Review* of U. S. Patent 6,534,805, May 6, 2021, on behalf of Qualcomm, Inc.; (20) *Hulu, LLC v. Sound View Innovations, LLC*, Petition for *Inter Partes Review* of U. S. Patent 5,806,062, May 14, 2021, on behalf of Hulu, LLC; (21) *VLSI Technology LLC v. Intel Corporation*, Western District of Texas, 6:19-cv-00254, 6:19-cv-00255 and 6:19-cv-00256, August 3, 2021, on behalf of Intel Corporation; (22) *Liquidia Technologies, Inc. v. United Therapeutics Corporation*, Petition for *Inter Partes Review* of U. S. Patent 10,716,793 B2, October 20, 2021, on behalf of Liquidia Technologies, Inc.; (23) *EcoFactor, Inc. v. Google, Inc.,* Western District of Texas, 6:20-cv-00075 (ADA), 6:20-0078-ADA, and 6:20-cv-00080 ADA, October 27, 2021, on behalf of Google, Inc.; (24) *Liquidia Technologies, Inc. v. United Therapeutics Corporation*, Petition for *Inter Partes Review* of U. S. Patent 10,716,793 B2, March 11, 2022, on behalf of Liquidia Technologies, Inc.; (25) *Juniper Networks, Inc. v. Swarm Technology LLC*, Petition for *Inter Partes Review* of U. S. Patent 9,852,004, May 5, 2022, on behalf of Juniper Networks, Inc.; (26) *ParkerVision, Inc. v. Intel Corporation*, Western District of Texas, 6:20-cv-108

(ADA), October 26, 2022, on behalf of the Intel Corporation; (27) *CommScope v. TQ Delta*, Petition for *Inter Partes Review* of U. S. Patents 9,094,348 and 10,833,809, February 16, 2023, on behalf of CommScope; (28) *WSOU Investments d/b/a Brazos v. Salesforce.com, Inc.* for Western District of Texas, 6:20-cv-01164-ADA and 6:20-cv-01170-ADA, April 18, 2023, on behalf of Salesforce; (29) *Regents of the University of Minnesota v. AT&T Mobility LLC*, District of Minnesota, 14:cv-4999-JRT-TNL & 14-cv-4669-JRT-TNL, May 18, 2023, on behalf of AT & T Mobility LLC; (30) *VLSI Technology LLC v. Intel Corporation*, Northern District of California, 5:17-cv-0571-BLF-NC, July 11, 2023, on behalf of Intel Corporation; (31) *Trustees of Purdue University v. ST Microelectronics*, Western District of Texas, 6:21-cv-00727-ADA, July 27, 2023, on behalf of ST Microelectronics; (32) *Advanced Micro Devices, Inc. v. Realtek Semiconductor Corp.,* Petition for *Inter Partes Review* of U. S. Patents 7,936,245 & 9,590,582, August 10, 2023, on behalf of Advanced Micro Devices, Inc.; (33) Motif Foodworks, Inc. v. Impossible Foods, Inc., Petition for *Inter Partes Review* of U. S. Patent 9,943,096, August 24, 2023, on behalf of Motif Foodworks, Inc.; (34) *Network System Technologies, LLC v. Texas Instruments, Inc.*, Eastern District of Texas, 2:22-cv-00482-RWS, March 20, 2024, on behalf of Texas Instruments, Inc.; (35) *Pardalis Technology Licensing, LLC v. International Business Machines, Corporation*, Eastern District of Texas, 2:22-cv-00452, May 23, 2024, on behalf of

International Business Machines, Corporation; (36) *Pardalis Technology Licensing, LLC v. International Business Machines, Corporation*, Eastern District of Texas, 2:22-cv-00452, May 23, 2024, on behalf of International Business Machines, Corporation; (37) *Meta Platforms, InstaGram, Inc., Whatsapp LLC, Facebook Technologies LLC, and Giphy, Inc. v. VL Collective IP LLC*, Petition for *Inter Partes Review* of U. S. Patent 7,436,980, July 18, 2024, on behalf of Meta Platforms, InstaGram, Inc., Whatsapp LLC, Facebook Technologies LLC, and Giphy, Inc.; and, (38) *LCY Biotechnology Holding, Inc. v. RadiciChimica S.p.A*, Petition for *Inter Partes Review* of U. S. Patent 11,781,148, August 6, 2024, on behalf of LCY Biotechnology Holding, Inc. I have testified at trial three times: (1) *Advanced Micro Devices, Inc. v. Realtek Semiconductor Corp.,* U. S. Patents 7,936,245 & 9,590,582, October 20, 2023, International Trade Commission, Washington, DC, on behalf of Advanced Micro Devices, Inc.; (2) *Trustees of Purdue University v. ST Microelectronics*, Western District of Texas, 6:21-cv-00727-ADA, November 29, 2023, on behalf of ST Microelectronics; and, (3) *Certain Power Converter Modules and Computing Systems Containing the Same*, Investigation ITC-337-TA-1370, International Trade Commission, May 1, 2024, on behalf of Delta Electronics, Inc.

10. My full *curriculum vitae* is submitted herewith as Appendix A.

III. PRELIMINARIES

A. Scope of this declaration.

11. I am informed by counsel to assume a priority date for the patent at issue of October 24, 2002. As I will explain below, it is my opinion that the publications discussed in my declaration were publicly accessible at least one year before October 24, 2002.

12. I am not an attorney and will not offer opinions on the law. I am, however, rendering my expert opinion on the authenticity of the documents referenced herein and on when and how each of these documents 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 documents at least one year before October 24, 2002.

13. 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 documents themselves, such as the appearance, contents, substance, internal patterns, or other distinctive characteristics of the item, taken together with all of the circumstances. I am further informed that an item is considered authentic if it is at least 20 years old, in a condition that creates no suspicion of its authenticity, and in a place where, if authentic, it would likely be. Lastly, I have been informed

that a document's authenticity can be established by comparison with an authentic specimen.

14. I am informed by counsel that a printed publication qualifies as publicly accessible as of the date 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.

15. 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 category. I understand that the cataloging and indexing by a single library of a single instance of a particular printed publication is sufficient, even if the single library is in a foreign country. 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.

16. I understand that 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

17. I am told by counsel that the subject matter of this proceeding relates generally to wireless communication systems and networks.

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

19. I was told by counsel that a POSITA in 2002-2003 timeframe would have had a working knowledge of the wireless communication technologies art that is pertinent to the '720 Patent, including orthogonal frequency division multiplexing (OFDM). POSITA would have had a master's degree in electrical engineering, computer engineering, physics, or equivalent training, and at least two

years of professional experience relating to wireless communication systems and networks. Lack of professional experience can be remedied by additional education, and vice versa.

20. It is my opinion that such a person would have been engaged in research, learning through study, and practice in the field and possibly through formal instruction the bibliographic resources relevant to his or her research. By no later than the early 2000s (and more specifically, before October 24, 2002), such a person would have had access to a vast array of long-established print resources in the field, as well as to a rich set of online resources providing indexing information, abstracts, and full text services for publications relevant to the field of this dispute, including at least the publications discussed in this declaration.

C. Authoritative Databases

21. In preparing this declaration, I used authoritative databases, such as the OCLC WorldCat, the Library of Congress Online Catalog, the U. S. Copyright Office database, and the *IEEE Xplore* database, to confirm citation details of the publications discussed.

22. *OCLC WorldCat Database.* The 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 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."[1] Among other services, OCLC and its members are responsible for maintaining the WorldCat database,[2] used by independent and institutional libraries throughout the world.

23. *U. S. Copyright Office.* Created by Congress in 1897, the Copyright Office is responsible for administering a complex and dynamic set of laws, which include registration, the recordation of title and licenses, a number of statutory licensing provisions, and other aspects of the *1976 Copyright Act* and the *1998 Digital Millennium Copyright Act*. The public catalog in the Copyright Office includes information filed since 1978.[3] Individuals can search by title, personal or corporate name, key word, registration number, and document number. Works filed before 1978 can be located through the Copyright Public Records Reading

[1] Third Article, Amended Articles of Incorporation of OCLC Online Computer Library Center, Incorporated (available at https://www.oclc.org/content/dam/oclc/membership/articles-of-incorporation.pdf)

[2] http://www.worldcat.org/

[3] https://cocatalog.loc.gov/cgi-bin/Pwebrecon.cgi?DB=local&PAGE=First

Room.[4] A researcher can find the date on which an item was published and deposited for copyright.

24. *The Institute of Electrical and Electronics Engineers (IEEE).* IEEE and its members inspire a global community to innovate for a better tomorrow through highly cited publications, conferences, technology standards, and professional and educational activities. IEEE is the trusted "voice" for engineering, computing, and technology information around the globe.[5]

25. The American Institute of Electrical Engineers (AIEE) traces its history to 1884. Its rival, the Institute of Radio Engineers (IRE) was founded in 1912. In 1963 the two professional organizations merged to form the Institute of Electrical and Electronics Engineers.[6] As of 2023, IEEE has over 460,000 members in 190 countries, of whom more than two-thirds live outside of the United States.[7]

26. IEEE claims to produce over 30% of the world's literature in the electrical, electronics, and computer engineering fields, publishing approximately 200 peer-reviewed journals and magazines in addition to more than 1,700

[4] https://www.copyright.gov/circs/circ23.pdf

[5] https://www.ieee.org/

[6] https://ethw.org/Formation_of_IEEE_by_the_Merger_of_AIEE_and_IRE

[7] https://en.wikipedia.org/wiki/Institute_of_Electrical_and_Electronics_Engineers

conference proceedings every year.[8] Published content in the journals, magazines, and IEEE sponsored conference proceedings are available in the IEEE Electronic Library (IEL)[9] are available through *IEEE Xplore* by subscription-based access and individual publication purchases.

27. *IEEE Xplore database.* Librarians in academic, special, and large public libraries are familiar with the *IEEE Xplore* database. In working with undergraduate and graduate students, researchers, scientists, and the public, librarians are intimately familiar with the *IEEE Xplore* database and rely on its content for access to reliable, accurate publications. Established to serve as a database for the IEEE's ebooks, standards, conference papers, technical reports, and journal articles, and related documents dating from 1988 to the present and selectively from 1913 to 1987, *IEEE Xplore* is a scholarly research database that includes 6.5 million documents which is known for its reputable curation and maintenance of documents and publication information. The *IEEE Xplore* database accurately reports dates of publications and events and accurately reports locations of events in accordance with standard practices for major industry journals. Approximately 20,000 new documents are added to *IEEE Xplore* each month.

[8] https://www.ieee.org/about/at-a-glance.html

[9] https://ieeexplore.ieee.org/Xplorehelp/overview-of-ieee-xplore/about-ieee-xplore

Abstracts are free to access, but access to full text requires a subscription or institutional login.

28. The *IEEE Xplore* requires peer review before publishing content. I have used IEEE publications in print and online for nearly 50 years. Currently I have access to IEEE documents as part of the resources for faculty through the King Library at San José State University. In addition to covering material from the IEEE, the *IEEE Xplore* also covers materials from the Institution of Engineering and Technology. The *IEEE Xplore* digital library provides Web access to more than 5.3-million full-text documents from some of the world's most highly cited publications. Approximately 20,000 new documents are added to *IEEE Xplore* each month. Abstracts are free to access, but access to full text requires a subscription or institutional login.

D. Indexing

29. A researcher may discover material relevant to his or her topic in a variety of ways. One common means of discovery is to search for relevant information in an index of periodical and other publications. Having found relevant material, the researcher will then normally obtain it online, look for it in libraries, or purchase it from a publisher, a bookstore, a document delivery service, or other provider. Sometimes, the date of a document's public accessibility will

involve both indexing and library date information. However, date information for indexing entries is often unavailable. This is especially true for online indices.

30. Indexing services use a wide variety of controlled vocabularies to provide subject access and other means of discovering the content of documents. The formats in which these access terms are presented vary from service to service.

31. Before the widespread development of online databases to index articles in journals, magazines, conference papers, and technical declarations, libraries purchased printed volumes of indices. Graduate library school education mandated that students learn about the bibliographic control of disciplines, the prominent indexing volumes, and searching strategies required to use them effectively and efficiently. Half of the courses that I studied in library school were focused on bibliography and resources in academic disciplines.

32. Librarians consulted with information seekers to verify citations, check availability in union catalogs, printed books catalogs, and the OCLC database, and make formal requests for materials, *e.g.*, books, conference proceedings, journal articles. Requests were transmitted using Telex machines, rudimentary email systems, and the United States Postal Service. During my career, I have performed and supervised staff who handled these resource sharing tasks.

33. A major firm known for the breadth of subjects and comprehensive treatment in the preparation of index volumes, the H. W. Wilson Company offered these reference resources since the firm was founded in 1898. The *Reader's Guide to Periodical Literature* is one of the best-known titles available from H. W. Wilson. Each volume includes a comprehensive index for 300 of the most popular and important periodicals published in the United States and Canada. Information seekers have subject access expressed in plain language terminology, author access, and cross references to find the desired results from their searches. The family of index titles included *Science & Technology Index*, *Business Periodicals*, *Applied Science & Technology Index, Humanities Index, Biological & Agricultural Index*, and *Industrial Arts Index*. These printed indices have been superseded by digital database offerings available to information seekers through Ebsco.

34. Online indexing services commonly provide bibliographic information, abstracts, and full-text copies of the indexed publications, along with a list of the documents cited in the indexed publication. These services also often provide lists of publications that cite a given document. A citation of a document is evidence that the document was publicly available and in use no later than the publication date of the citing document.

IV. LIBRARY CATALOGING PRACTICES

A. MARC RECORDS AND THE ONLINE LIBRARY CATALOG

35. 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.[10] MARC was first developed in the 1960s by the Library of Congress. A MARC-compatible library is one that has a catalog consisting of individual MARC records for each of its items. Today, MARC is the primary communications protocol for the transfer and storage of bibliographic metadata in libraries.[11]

36. MARC is a framework into which descriptive bibliographic data are transcribed to interact with the software in online library catalogs to provide access

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

[11] Almost every major library in the world is MARC-compatible. *See, e.g.*, *MARC Frequently Asked Questions (FAQ)*, Library of Congress, https://www.loc.gov/marc/faq.html (last visited March 10, 2025) ("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 2016) standard for Information Interchange Format.

to books, journals, and other resources in the collection. The bibliographic data provide points of access and can be searched by a person of ordinary skill in the art ("POSITA") to identify and obtain resources in the library collection. An information seeker (or POSITA) can search a local online library catalog or the holdings of a group of libraries in a state or region or in the global catalog WorldCat.

37. MARC records are not designed for public viewing. Although a significant number of libraries provide access to the MARC version of a bibliographic record, the public display is designed to show information in a succinct manner that is quickly understood and useful to the information seeker. Libraries determine the default search for the online catalog to make the entry of search terms efficient and result in a successful search. Information seekers can enter a keyword, title, author, or standard number for the item. Libraries may also provide a search capability called "Summon" that allows the information seeker to enter known information about the item to conduct a search.

38. Since at least the early 1970s and continuing to the present day, MARC has been the primary communications protocol for the transfer and storage of bibliographic metadata in libraries.[12] As explained by the Library of Congress:

[12] A complete history of the development of MARC can be found in *MARC: Its History and Implications* by Henrietta D. Avram (Washington, DC: Library of

> You could devise your own method of organizing the bibliographic information, but you would be isolating your library, limiting its options, and creating much more work for yourself. Using the MARC standard prevents duplication of work and allows libraries to better share bibliographic resources. Choosing to use MARC enables libraries to acquire cataloging data that is predictable and reliable. If a library were to develop a "home-grown" system that did not use MARC records, it would not be taking advantage of an industry-wide standard whose primary purpose is to foster communication of information.
>
> Using the MARC standard also enables libraries to make use of commercially available library automation systems to manage library operations. Many systems are available for libraries of all sizes and are designed to work with the MARC format. Systems are maintained and improved by the vendor so that libraries can benefit from the latest advances in computer technology. The MARC standard also allows libraries to replace one system with another with the assurance that their data will still be compatible.

Why Is a MARC Record Necessary? LIBRARY OF CONGRESS, http://www.loc.gov/marc/umb/um01to06.html#part2 (last visited March 10, 2025).

39. Examining the MARC records for a specific item reveals the

Congress, 1975) and available online from the Hathi Trust (https://babel.hathitrust.org/cgi/pt?id=mdp.39015034388556;view=1up;seq=1; last visited March 10, 2025).

comprehensive data transcribed about a particular item at the time that cataloging and classification occurred. In addition to the creator, title, subjects, and standard numbers, additional information may provide additional and relevant data depending on the type of resource. Understanding the full extent of bibliographic data for an item and the points of access associated with it provides essential information that can be used to determine the indexing and public availability for documents described in this Declaration.

B. MARC RECORDS

40. A MARC record 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 follow. For example, a work's title is recorded in field 245, the primary author or creator of the work is recorded in field 100, an item's International Standard Book Number ("ISBN") is recorded in field 020, an item's International Standard Serial Number ("ISSN") is recorded in field 022, an item's Library of Congress call number is recorded in field 050, and the publication date is recorded in field 260 under the subfield "c." *Id.*[13] If a work is a periodical, then its publication frequency is recorded in field

[13] In some MARC records, field 264 is used rather than field 260 to record publication information. *See* http://www.loc.gov/marc/bibliographic/bd264.html (last visited March 10, 2025) ("Information in field 264 is similar to information in

310, alternate publication frequency is recorded in field 321, and the publication dates (*e.g.*, the first and last publication) are recorded in field 362, which is also referred to as the enumeration/chronology field. *See* http://www.loc.gov/marc/bibliographic/bd3xx.html (last visited March 10, 2025).

41. The library that created the record is recorded in Field 040 in subfield "a" with a unique library code. When viewing the MARC record online via Online Computer Library Center's ("OCLC") bibliographic database, hovering over this code with the mouse reveals the full name of the library. I used this method of "mousing over" the library codes in the OCLC database to identify the originating library for the MARC records discussed in this Declaration. Where this "mouse over" option was not available, I consulted the Directory of OCLC Libraries to identify the institution that created the MARC record.[14]

42. 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." *See*

field 260 (Publication, Distribution, etc. (Imprint)). Field 264 is useful for cases where the content standard or institutional policies make a distinction between functions").

[14] https://www.oclc.org/en/contacts/libraries.html

http://www.loc.gov/marc/bibliographic/bd6xx.html. 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.* These authenticated subject 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.*

43. Further, MARC records include call numbers, which themselves indicate a subject and physical location within the library collections. For example, the 050 field is the "Library of Congress Call Number." *See* http://www.loc.gov/marc/bibliographic/bd050.html (last visited February 3, 2025). 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. Each item in a library has a single classification number. A library selects a classification scheme (*e.g.*, the Library of Congress Classification scheme just described or a similar scheme such as the Dewey Decimal Classification scheme or the National Library of Medicine Classification scheme) and uses it consistently. When the Library of Congress assigns the classification number, it appears as part of the 050 field. If a

local library assigns the classification number, it appears in a 090 field. In either scenario, the MARC record includes a classification number that represents a subject matter classification.

44. Each item in a library has a single classification number. A library selects a classification scheme (*e.g.*, the Library of Congress Classification scheme just described or a similar scheme such as the Dewey Decimal Classification scheme) and uses it consistently. When the Library of Congress assigns the classification number, it appears as part of the 050 field, as discussed above. For MARC records created by libraries other than the Library of Congress (*e.g.*, a university library or a local public library), the classification number may appear in a 09X (*e.g.*, 090) field. *See* http://www.loc.gov/marc/bibliographic/bd09x.html (last visited March 10, 2025).

C. OCLC

45. The 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 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."[15] Among other services, OCLC and its members are responsible for maintaining the WorldCat database (http://www.worldcat.org/), used by independent and institutional libraries throughout the world.

46. OCLC also provides its members online access to MARC records through its OCLC bibliographic database. When an OCLC member institution acquires a work, it creates a MARC record for this work in its computer catalog system in the ordinary course of its business. MARC records created at the Library of Congress were initially tape-loaded into the OCLC database through a subscription to MARC Distribution Services daily or weekly. Once the MARC record is created by a cataloger at an OCLC member institution or is tape-loaded from the Library of Congress, the MARC record is then made available to any other OCLC members online, and therefore made available to the public. Accordingly, once the MARC record is created by a cataloger at an OCLC member institution or is tape-loaded from the Library of Congress or another library anywhere in the world, any publication corresponding to the MARC record has been cataloged and indexed according to its subject matter such that a person

[15] Third Article, Amended Articles of Incorporation of OCLC Online Computer Library Center, Incorporated (available at https://www.oclc.org/content/dam/oclc/membership/articles-of-incorporation.pdf).

interested in that subject matter could, with reasonable diligence, locate and access the publication through any library with access to the OCLC bibliographic database or through the Library of Congress.

47. When an OCLC member institution creates a new MARC record, OCLC automatically supplies the date of creation for that record. The date of creation for the MARC record appears in the fixed field (008), characters 00 through 05. The MARC record creation date reflects the date on which the item was first acquired or cataloged. Initially, field 005 of the MARC record is automatically populated with the date the MARC record was created in year, month, day format (YYYYMMDD) (some of the newer library catalog systems also include hour, minute, second (HHMMSS)). Thereafter, the 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). Field 005 is visible when viewing a MARC record via an appropriate computerized interface. The initial field 005 date (*i.e.*, the date the MARC record was created) does appear. The date upon which the most recent update to field 005 occurred also appears in field 005. Thus, when an item's MARC record has been printed to hardcopy—as is the case with the exhibits to this declaration—the date reflected next to field 008 is necessarily on or after the date the library first cataloged and indexed the underlying item.

48. Once one library has cataloged and indexed a publication by creating a MARC record for that publication, other libraries that receive the publication do not create additional MARC records—the other libraries instead rely on the original MARC record. They may update or revise the MARC record to ensure accuracy, but they do not replace or duplicate it. This practice does more than save libraries from duplicating labor, it also enhances the accuracy of MARC records. It also allows librarians around the world to know that a particular MARC record is authoritative. In contrast, a hypothetical system wherein duplicative records were created would result in confusion as to which record is authoritative.

49. The date of creation of the MARC record by a cataloger at an OCLC member institution reflects when the underlying item is accessible to the public. Upwards of two-thirds to three-quarters of book sales to libraries come from a jobber or wholesaler for online and print resources. These resellers make it their business to provide books to their customers as fast as possible, often providing turnaround times of only a single day after publication. Libraries purchase a significant portion of the balance of their books directly from publishers themselves, which provide delivery on a similarly expedited schedule. In general, libraries make these purchases throughout the year as the books are published and shelve the books as soon thereafter as possible in order to make the books available to their patrons. Thus, books are generally available at libraries across the country

within just a few days of publication.

V. PUBLICATIONS IN THIS PROCEEDING

A. *OFDM for Wireless Multimedia Communications* by Richard van Nee and Ramjee Prasad. [Exhibit 1015]

50. Attached hereto as Exhibit 1015 is a copy of excerpts published in the volume titled *OFDM for Wireless Multimedia Communications* by Richard van Nee and Ramjee Prasad (hereafter "Van-Nee") found in the Library of Congress. The excerpts are Chapter 1, "Introduction" (pages 1-31) and Chapter 2, "OFDM Basics" (pages 32-51). Exhibit 1015 is a true and correct copy of the excerpts which I obtained from the Library of Congress. Specifically, the excerpts are complete; no pages are missing, and the text on each page appears to flow seamlessly from one page to the next; further, there are no visible alterations to the document. Exhibit 1015 was found within the custody of a library – a place where, if authentic, a copy of this volume would likely be. Exhibit 1015 is a true and correct copy in a condition that creates no suspicion about authenticity.

51. Attached hereto as Attachment 1A is a true and correct copy of the MARC record for this book from the Library of Congress online catalog. The library ownership is indicated by the presence of the library's code ("DLC") in the 040 field. I personally identified and retrieved the library catalog record which is Attachment 1A.

52. Based on finding a print copy of Exhibit 1015 in the Library of

Congress and MARC record in its online library catalog attached as Attachment 1A, it is my opinion that the book titled *OFDM for Wireless Multimedia Communications* was publicly available at the Library of Congress as of April 17, 2000, as shown in field 955 ("04-17-00").

53. Attached hereto as Attachment 1B is a true and correct copy of the MARC record for the book titled *OFDM for Wireless Multimedia Communications* obtained from the OCLC bibliographic database. I personally identified and retrieved the MARC record that is Attachment 1B. As previously noted, the library that created the record is recorded in field 040 with a unique library code. For Attachment 1B, that library code is "DLC," which means that the MARC record for this book was cataloged at the Library of Congress as part of the Cataloging in Publication (CIP) Program.[16] A cataloger prepares basic information about the forthcoming book which is included on the verso of the title page (also called the copyright page). The information is provided to save time needed for the cataloging process at the library after the book is purchased. The CIP data includes the author (field 100), title and subtitle (field 245), ISBN (field 022), suggested subject headings (field 650), classification numbers for the Library of Congress classification number (field 050), and the Dewey Decimal classification number (field 082). These data elements are included in the MARC record that the Library

[16] https://www.loc.gov/publish/cip/

of Congress contributes to the OCLC bibliographic database. As can be seen in field 008 ("Date entered on file") in the MARC record for this exhibit, a cataloger at the Library of Congress created OCLC record number 42649777 on October 7, 1999 ("991007"). The library continues to update and enhance this MARC record to meet current cataloging rules. The most recent enhancement to Attachment 1B occurred on November 12, 2024, as shown in field 005 ("20241112"). I personally identified and retrieved the MARC record that is Attachment 1B.

54. Attachment 1B further includes an entry in field 050 ("TK5103.2 $b .N44 2000")—as described above, a subject matter classification number consistent with the Library of Congress classification system (analogous to the Dewey Decimal classification system) and an entry in field 082 ("621.3845")—as described above, a subject matter classification number consistent with the Dewey Decimal classification system. Attachment 1B also shows that Exhibit 1015 was catalogued with four descriptor terms reading "Wireless communication systems" (see Attachment 1C, Library of Congress subject heading sh92006740), "Multimedia systems" (Attachment 1D, Library of Congress subject heading sh92002381), "Orthogonal frequency division multiplexing" (see Attachment 1E, Library of Congress subject heading sh2005002695), and Orthogonalization methods" (Attachment 1F, Library of Congress subject heading sh98004572) in the 650 fields. Thus, as of its cataloging, the publication corresponding to the MARC

record attached hereto as Attachment 1B was indexed according to its subject matter by virtue of at least three independently sufficient classifications: the field 050 entry, the field 082 entry, and the field 650 entries. Further, as of October 7, 1999, the MARC record attached hereto as Attachment 1B was accessible through any library with access to the OCLC bibliographic database or the online catalog at a library that acquired the book, which means that the corresponding publication was publicly available on or before that same date through any library with access to the OCLC bibliographic database or through an individual library.

55. WorldCat indicates that the book titled *OFDM for Wireless Multimedia Communications* as cataloged at the Library of Congress is currently available from 256 libraries.[17] In view of the above, the book titled *OFDM for Wireless Multimedia Communications* was publicly available on or shortly after April 17, 2000, because by that date it had been cataloged, indexed, and received at the Library of Congress and made part of the OCLC bibliographic database. For these reasons, it is my opinion that Exhibit 1015 was published and publicly accessible on or shortly after April 17, 2000.

B. *Computer Networks: A Systems Approach* by Larry L. Peterson and Bruce S. Davie. [Exhibit 1022]

56. Attached hereto as Exhibit 1022 is a copy of excerpts published in the

[17] https://search.worldcat.org/title/42649777

volume titled *Computer Networks: A Systems Approach* by Larry L. Peterson and Bruce S. Davie (hereafter "Peterson") found in the Kurt F. Wendt Engineering Library at the University of Wisconsin – Madison. The excerpts are the title page, verso (copyright page), foreword, table of contents, Preface (pages xvii-xxiii), and Chapter 7, "End-to-End Data" (pages 346-360). Exhibit 1022 is a true and correct copy of the excerpts which I obtained from the Karl F. Wendt Engineering Library at the University of Wisconsin – Madison. Specifically, the excerpts are complete; no pages are missing, and the text on each page appears to flow seamlessly from one page to the next; further, there are no visible alterations to the document. Exhibit 1022 was found within the custody of a library – a place where, if authentic, a copy of this volume would likely be. Exhibit 1022 is a true and correct copy in a condition that creates no suspicion about authenticity.

57. Attached hereto as Attachment 2A is a true and correct copy of the MARC record for this book from the Karl F. Wendt Engineering Library at the University of Wisconsin – Madison online catalog. The library ownership is indicated by the presence of the library's code ("GZM") in the 049 field. I personally identified and retrieved the library catalog record which is Attachment 2A.

58. Based on finding a print copy of Exhibit 1022 in the Karl F. Wendt Engineering Library at the University of Wisconsin – Madison and MARC record

in its online library catalog attached as Attachment 2A, it is my opinion that the book titled *Computer Networks: A Systems Approach* was publicly available in the Karl F. Wendt Engineering Library at the University of Wisconsin – Madison shortly after February 7, 1996, as shown in field 008 ("960207").

59. Attached hereto as Attachment 2B is a true and correct copy of the MARC record for the book titled *Computer Networks: A Systems Approach* obtained from the OCLC bibliographic database. I personally identified and retrieved the MARC record that is Attachment 2B. As previously noted, the library that created the record is recorded in field 040 with a unique library code. For Attachment 2B, that library code is "DLC," which means that the MARC record for this book was cataloged at the Library of Congress as part of the Cataloging in Publication (CIP) Program.[18] A cataloger prepares basic information about the forthcoming book which is included on the verso of the title page (also called the copyright page). The information is provided to save time needed for the cataloging process at the library after the book is purchased. The CIP data includes the author (field 100), title and subtitle (field 245), ISBN (field 022), suggested subject headings (field 650), classification numbers for the Library of Congress classification number (field 050), and the Dewey Decimal classification number (field 082). These data elements are included in the MARC record that the Library

[18] https://www.loc.gov/publish/cip/

of Congress contributes to the OCLC bibliographic database. As can be seen in field 008 ("Date entered on file") in the MARC record for this exhibit, a cataloger at the Library of Congress created OCLC record number 34191065 on February 7, 1996 ("960207"). The library continues to update and enhance this MARC record to meet current cataloging rules. The most recent enhancement to Attachment 2B occurred on January 27, 2024, as shown in field 005 ("20240127"). I personally identified and retrieved the MARC record that is Attachment 2B.

60. Attachment 2B further includes an entry in field 050 ("TK5105.5 $b .P479 1996")—as described above, a subject matter classification number consistent with the Library of Congress classification system (analogous to the Dewey Decimal classification system) and an entry in field 082 ("004.6/5")—as described above, a subject matter classification number consistent with the Dewey Decimal classification system. Attachment 2B also shows that Exhibit 1022 was catalogued with a descriptor term reading "Computer networks" (see Attachment 2C, Library of Congress subject heading sh85029513) in the 650 field. Thus, as of its cataloging, the publication corresponding to the MARC record attached hereto as Attachment 2B was indexed according to its subject matter by virtue of at least three independently sufficient classifications: the field 050 entry, the field 082 entry, and the field 650 entry. Further, as of February 7, 1996, the MARC record attached hereto as Attachment 2B was accessible through any library with access

to the OCLC bibliographic database or the online catalog at a library that acquired the book, which means that the corresponding publication was publicly available on or before that same date through any library with access to the OCLC bibliographic database or through an individual library.

61. Further supporting my opinion that Exhibit 1022 was publicly accessible to ordinarily skilled and interested researchers in the field is the fact that the book titled *Computer Networks: A Systems Approach* was registered with the U. S. Copyright Office as item TX0004543416 on October 6, 1997, and indicated a publication date of March 15, 1996 (see Attachment 2D, U. S. Copyright Office Public Catalog). As noted above, this would have provided a POSITA with keyword searching capabilities and other tools to locate this book.

62. WorldCat indicates that the book titled *Computer Networks: A Systems Approach* as cataloged at the Library of Congress is currently available from 2,473 libraries.[19] In view of the above, the book titled *Computer Networks: A Systems Approach* was publicly available on or shortly after March 15, 1996, because by that date it had been cataloged and indexed at the Library of Congress, made part of the OCLC bibliographic database, and received in the Karl F. Wendt Engineering Library at the University of Wisconsin -- Madison. For these reasons, it is my opinion that Exhibit 1022 was published and publicly accessible on or

[19] https://search.worldcat.org/title/34191065

shortly after March 15, 1996.

VI. SUMMARY OF OPINIONS

63. In view of the foregoing, it is my opinion that the publication described above was publicly available no later than the corresponding date listed in the table below:

Exhibit	Publication	Publicly Available By
1015	van Nee, Richard, and Ramjee Prasad. *OFDM for Wireless Multimedia Communications.* Boston, MA: Artech House, 2000.	April 17, 2000
1022	Peterson, Larry L., and Bruce S. Davie. *Computer Networks: A Systems Approach.* San Francisco, CA: Morgan Kaufmann, 1996.	March 15, 1996

64. In signing this Declaration, I recognize that the Declaration will be filed as evidence in a case before the Patent Trial and Appeal Board of the United States 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.

65. I hereby 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.

April 7, 2025

Sylvia D. Hall-Ellis, Ph.D.

Attachment 1A

LIBRARY | CATALOG

Search Navigation 1 of 13

BOOK

OFDM for wireless multimedia communications

Full Record **MARC Tags**

000		01176cam a22003014a 4500
001		11805366
005		20050701093214.0
008		991007s2000 maua b 001 0 eng
906	__	|**a** 7 |**b** cbc |**c** orignew |**d** 1 |**e** ocip |**f** 19 |**g** y-gencatlg
925	0_	|**a** acquire |**b** 2 shelf copies |**x** policy default
955	__	|**a** to ASCD pb02 10-07-99; jf09 (desc) 10-8-99; jf04 (subj.) to S.L. 10-12-99; to Dewey 10-13-99; aa07 10-14-99; CIPver jf05 to sl 04/11/00; jf12 to BCCD 04-17-00
010	__	|**a** 99052312
020	__	|**a** 0890065306 (alk. paper)
040	__	|**a** DLC |**c** DLC |**d** DLC
042	__	|**a** pcc
050	00	|**a** TK5103.2 |**b** .N44 2000
082	00	|**a** 621.3845 |**2** 21
100	1_	|**a** Nee, Richard van.
245	10	|**a** OFDM for wireless multimedia communications / |**c** Richard van Nee, Ramjee Prasad.
260	__	|**a** Boston : |**b** Artech House, |**c** 2000.
300	__	|**a** xvii, 260 p. : |**b** ill. ; |**c** 24 cm.
440	_0	|**a** Artech House universal personal communications series
504	__	|**a** Includes bibliographical references and index.
650	_0	|**a** Wireless communication systems.
650	_0	|**a** Multimedia systems.
650	_0	|**a** Orthogonal frequency division multiplexing.

Ex.1020 / Page 41 of 250
Intel Corporation and Lenovo (United States) Inc.

650	_0	**|a** Orthogonalization methods.
700	1_	**|a** Prasad, Ramjee.

Request this Item | LC Find It

Item Availability

Shelf Location	FLM2015 247984
CALL NUMBER	TK5103.2. .N44 2000 OVERFLOWJ34
Request in	Jefferson or Adams Building Reading Rooms (FLM2)
Status	Not Charged

Shelf Location	FLM2015 247985
CALL NUMBER	TK5103.2. N44 2000 OVERFLOWJ34
Request in	Jefferson or Adams Building Reading Rooms (FLM2)
Status	Not Charged

Attachment 1B

Bibliographic Record - OCLC Number: 42649777

LDR	Record Status	'c' - Corrected or revised
	Type of Record	'a' - Language material
	Bibliographic Level	'm' - Monograph/Item
	Type of Control	' ' - No specified type of control
	Encoding Level	'4' - Core level
	Descriptive Cataloging Form	'a' - AACR2
001	42649777	
005	20241112114320.7	
008	Date Entered on File	'991007'
	Type of Date/Publication Status	's' - Single date
	Date1/Beginning Date of Publication	'2000'
	Date2/Ending Date of Publication	' '
	Place of Publication, Production, or Execution Code	'mau' - Massachusetts
	Illustrations	'a '
	Target Audience	' ' - Unknown or unspecified
	Form of Item	' ' - None of the following
	Nature of Contents Code	'b '
	Government Publication	' ' - Not a government publication
	Conference Publication	'0' - Not a conference publication
	Festschrift	'0' - Not a festschrift
	Index	'1' - Index present
	Literary Form	'0' - Not fiction
	Biography	' ' - No biographical material
	Language Code	'eng' - English
	Modified Record	' ' - Record is not modified
	Cataloging Source Code	' ' - National bibliographic agency

010 99052312

040 DLC **$b** eng **$c** DLC **$d** UKM **$d** BAKER **$d** BTCTA **$d** YDXCP **$d** IG# **$d** HEBIS **$d** STF **$d** DEBBG **$d** ZWZ **$d** BDX **$d** FCC **$d** OCLCF **$d** OCLCQ **$d** DEBSZ **$d** OCLCQ **$d** I8M **$d** OCLCQ **$d** OCLCO **$d** BGU **$d** OCLCO **$d** CNO **$d** UKUOY **$d** OCLCQ **$d** OCLCA **$d** NAG **$d** OCLCO **$d** BUF **$d** OCLCO **$d** UKBTH **$d** IL4J6 **$d** OCLCO **$d** IPL **$d** OCLCO **$d** OKS **$d** OCLCO **$d** DCHUA **$d** OCLCO **$d** NKM **$d** OCLCO **$d** OCLCL

015 GBA010790 **$2** bnb

019 43419280 **$a** 52401285 **$a** 491429160 **$a** 654903164 **$a** 941871106 **$a** 1022672600

020 0890065306 **$q** (alk. paper)

020 9780890065303 **$q** (alk. paper)

024 3 9780890065303

042 pcc

050 0 0 TK5103.2 **$b** .N44 2000

080 688.45

082 0 0 621.3845 **$2** 21

084 ZN 6040 **$2** rvk

100 1 Nee, Richard van.

245 1 0 OFDM for wireless multimedia communications / **$c** Richard van Nee, Ramjee Prasad.
260 Boston : **$b** Artech House, **$c** 2000.
300 xvii, 260 pages : **$b** illustrations ; **$c** 24 cm.
336 text **$b** txt **$2** rdacontent
337 unmediated **$b** n **$2** rdamedia
338 volume **$b** nc **$2** rdacarrier
490 1 Artech House universal personal communications series
504 Includes bibliographical references and index.
505 0 0 **$g** Ch. 1. **$t** Introduction -- **$g** Ch. 2. **$t** OFDM basics -- **$g** Ch. 3. **$t** Coding and modulation -- **$g** Ch. 4. **$t** Synchronization -- **$g** Ch. 5. **$t** Coherent and differential detection -- **$g** Ch. 6. **$t** The peak power problem -- **$g** Ch. 7. **$t** Basics of CDMA -- **$g** Ch. 8. **$t** Multi -carrier CDMA -- **$g** Ch. 9. **$t** Othogonal frequency division multiple access -- **$g** Ch. 10. **$t** Applications of OFDM.
520 A study of OFDM, including a comparison with other forms of single carrier modulation methods. It p rovides the design guidelines for maximising the benefits from this technology. There is practical advi ce on how to plan, design and use OFDM to make wireless multimedia communications happen.
650 0 Wireless communication systems.
650 0 Multimedia systems.
650 0 Orthogonal frequency division multiplexing.
650 0 Orthogonalization methods.
650 6 Transmission sans fil.
650 6 Multimédia.
650 6 Multiplexage par répartition orthogonale de la fréquence.
650 6 Méthodes d'orthogonalisation.
650 7 Multimedia systems **$2** fast
650 7 Orthogonal frequency division multiplexing **$2** fast
650 7 Orthogonalization methods **$2** fast
650 7 Wireless communication systems **$2** fast
650 7 OFDM **$2** gnd
650 7 Mobilfunk **$2** gnd
650 7 WIRELESS COMMUNICATION. **$2** nasat
650 7 MULTIMEDIA. **$2** nasat
650 7 MULTIPLEXING. **$2** nasat
650 7 TELECOMMUNICATION. **$2** nasat
650 7 Orthogonal frequency division multiplexing. **$2** nli
650 7 Wireless communication systems. **$2** nli
650 7 Multimedia systems. **$2** nli
650 7 Signal detection. **$2** nli
650 7 Systèmes de communications sans fil. **$2** ram
650 7 Systèmes d'information multimedia. **$2** ram
650 7 Télécommunications **$x** multiplexage. **$2** ram
700 1 Prasad, Ramjee.
758 **$i** has work: **$a** OFDM for wireless multimedia communications (Text) **$1** https://id.oclc.org/worldc at/entity/E39PCGwDX9tY6ChgM4Jt7XHmr3 **$4** https://id.oclc.org/worldcat/ontology/hasWork
776 0 8 **$i** Online version: **$a** Nee, Richard van. **$t** OFDM for wireless multimedia communications. **$d** Bos ton : Artech House, 2000 **$w** (OCoLC)607412136

776 0 8 **$i** Online version: **$a** Nee, Richard van. **$t** OFDM for wireless multimedia communications. **$d** Boston : Artech House, 2000 **$w** (OCoLC)608565379

830 0 Artech House universal personal communications series.

938 Ingram Library Services **$b** INGR **$n** in008948357

938 Baker & Taylor **$b** BKTY **$c** 116.00 **$d** 116.00 **$i** 0890065306 **$n** 0003384816 **$s** active

938 Brodart **$b** BROD **$n** 54595231 **$c** $116.00

938 Baker and Taylor **$b** BTCP **$n** 99052312

938 Ingram **$b** INGR **$n** 9780890065303

938 YBP Library Services **$b** YANK **$n** 1609838

029 1 AU@ **$b** 000021027325

029 1 DEBBG **$b** BV013974691

029 1 DEBSZ **$b** 083356533

029 1 HEBIS **$b** 083917020

029 1 IG# **$b** 9780890065303

029 1 NLGGC **$b** 186574339

029 1 NZ1 **$b** 5380632

029 1 YDXCP **$b** 1609838

029 1 ZWZ **$b** 061141844

029 1 AU@ **$b** 000074487984

Attachment 1C

LC control no.: sh 92006740
LCCN Permalink: https://lccn.loc.gov/sh92006740
HEADING: Wireless communication systems

000 01349cz a2200313n 450
001 4847318
005 20120330075715.0
008 921222i| anannbabn |a ana
010 __ |**a** sh 92006740
035 __ |**a** (DLC)sh 92006740
035 __ |**a** (DLC)194003
040 __ |**a** DLC |**c** DLC
053 _0 |**a** TK5103.2
150 __ |**a** Wireless communication systems
450 __ |**a** Communication systems, Wireless
450 __ |**a** Wireless data communication systems
450 __ |**a** Wireless information networks
450 __ |**a** Wireless telecommunication systems
550 __ |**w** g |**a** Telecommunication systems
670 __ |**a** Work cat.: 92-43366: Wireless communications, c1993: |**b** CIP pref. (wireless information networks)
670 __ |**a** LC data base, 12/10/92 |**b** (wireless information networks, wireless communications, wireless data communications)
670 __ |**a** ASTI |**b** (Wireless telecommunications networks)
670 __ |**a** Engr. index: |**b** v. 89, pt. IX, p. 10249 (Wireless communication)
670 __ |**a** Web. 3 |**b** (Wireless; Wireless telephony: relating to radiotelegraphy, radiotelephony, or radio)
680 __ |**i** Here are entered works on networks for transmission of voice or data using either radio or optical (e.g. infrared) technologies.
906 __ |**t** 9304 |**u** te07 |**v** 1
952 __ |**a** 4 bib. record(s) to be changed
952 __ |**a** LC pattern: Broadband communication systems
953 __ |**a** jg12

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LC control no.: sh 92002381
LCCN Permalink: https://lccn.loc.gov/sh92002381
HEADING: Multimedia systems

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001 4843481
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008 920429i| anannbabn |a ana
010 __ |**a** sh 92002381
035 __ |**a** (DLC)sh 92002381
035 __ |**a** (DLC)190166
040 __ |**a** DLC |**c** DLC |**d** DLC
053 _0 |**a** QA76.575
150 __ |**a** Multimedia systems
450 __ |**a** Computer-based multimedia information systems
450 __ |**a** Multimedia computing
450 __ |**a** Multimedia information systems
450 __ |**a** Multimedia knowledge systems
550 __ |**w** g |**a** Information storage and retrieval systems
670 __ |**a** Work cat.: Multimedia review, c1990.
670 __ |**a** ASTI: |**b** p. 1391 (Multimedia information systems)
670 __ |**a** Business period. index, 1990-91: |**b** p. 1134 (Multimedia computers, multimedia software)
670 __ |**a** BYTE, Feb. 1990: |**b** p. 203 ("Multimedia uses the computer to integrate and control diverse electronic media such as computer screens, videodisk players, CD-ROM disks, and speech and audio synthesizers")
670 __ |**a** Computer, Oct. 1985: |**b** p. 92 (Computer-based multimedia information system)
670 __ |**a** Computer data base thes. |**b** (Multimedia technology, multimedia software, multimedia terminals)
670 __ |**a** Computer lib. period., Sept. 1990 |**b** (Multimedia technology)
670 __ |**a** L.C. Nat. Demo. Lab. Info bull. Feb. 24, 1992: |**b** pp. 73-76.
670 __ |**a** LC data base, 4/10/92.
670 __ |**a** Lib. lit., Feb. 1992 |**b** (Multimedia systems)
675 __ |**a** Computer dict.; |**a** IAC; |**a** Legislative index, 1991; |**a** McGraw-Hill dict. sci. tech.; |**a** Stnd. gloss. of comp. terminology

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680 __ |**i** Here are entered works on computer systems that integrate and present diverse media, such as text, graphics, still and moving images, and audio. Works on media containing information that may be interactively manipulated by individual users through the use of software or microprocessing capabilities are entered under |**a** Interactive multimedia.

681 __ |**i** Note under |**a** Interactive multimedia

906 __ |**t** 9412 |**u** te05 |**v** 0

953 __ |**a** yn07 |**b** ta25

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LC control no.: sh2005002695

LCCN Permalink: https://lccn.loc.gov/sh2005002695

HEADING: Orthogonal frequency division multiplexing

000 01203cz a2200301n 450

001 6522373

005 20120403071123.0

008 050425i| anannbabn |a ana

010 __ |**a** sh2005002695

035 __ |**a** (DLC)6522373

035 __ |**a** (DLC)sh2005002695

035 __ |**a** (DLC)329381

040 __ |**a** DLC |**b** eng |**c** DLC

053 _0 |**a** TK5103.484

150 __ |**a** Orthogonal frequency division multiplexing

450 __ |**a** OFDM (Telecommunication)

550 __ |**w** g |**a** Broadband communication systems

550 __ |**w** g |**a** Multiplexing

550 __ |**w** g |**a** Spread spectrum communications

670 __ |**a** Work cat.: 2005-011809: Liu, H. OFDM-based broadband wireless networks, c2005

670 __ |**a** ASTA on FirstSearch, April 25, 2005 |**b** (descriptor: Orthogonal frequency division multiplexing)

670 __ |**a** Inspec on ISI, Apr. 25, 2005 |**b** (Controlled term: OFDM modulation)

670 __ |**a** Newton's telecom dict., c2004 |**b** (under OFDM: orthogonal frequency division multiplexing)

670 __ |**a** The Microsoft encyc. of networking, 2002: |**b** p. 284 (Orthogonal frequency division multiplexing; OFDM)

906 __ |**t** 0521 |**u** te04 |**v** 1

952 __ |**a** 7 bib. record(s) to be changed

952 __ |**a** LC pattern: Wavelength division multiplexing

953 __ |**a** jg12

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LC control no.: sh 98004572
LCCN Permalink: https://lccn.loc.gov/sh98004572
HEADING: Orthogonalization methods

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001 4895094
005 20120402075212.0
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035 __ |**a** (DLC)sh 98004572
035 __ |**a** (DLC)241779
040 __ |**a** DLC |**c** DLC
150 __ |**a** Orthogonalization methods
450 __ |**a** Functions, Orthogonal family of
450 __ |**a** Functions, Orthogonal set of
450 __ |**a** Orthogonal family of functions
450 __ |**a** Orthogonal set of functions
450 __ |**a** Orthogonal sets
450 __ |**a** Orthogonal systems
450 __ |**a** Orthogonalization (Numerical analysis)
450 __ |**a** Sets, Orthogonal
450 __ |**a** Systems, Orthogonal
550 __ |**w** g |**a** Algebras, Linear
550 __ |**w** g |**a** Numerical analysis
670 __ |**a** Work cat.: 98-38391: Orthogonal sets and polar methods in linear algebra, c1999.
670 __ |**a** Math. subj. classif. |**b** (65-XX, Numerical analysis; 65Fxx, Numerical linear algebra; 65F25, Orthogonalization)
670 __ |**a** Eisenreich. Mathematik |**b** (orthogonal system; UF orthogonal family (set) <of functions>)
670 __ |**a** Encyc. math. |**b** (orthogonalization method: a method for solving a system of linear equations Ax=b with a non-singular matrix A based on the Gram-Schmidt method of orthogonalization of a vector system)
906 __ |**t** 9833 |**u** te04 |**v** 1
952 __ |**a** 1 bib. record(s) to be changed
953 __ |**a** jd99

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050	00	$aTK5105.5$b.P479 1996
082	00	$a004.6/5$220
100	1_	$aPeterson, Larry L.
245	10	$aComputer networks :$ba systems approach /$cLarry L. Peterson & Bruce S. Davie.
264	_1	$aSan Francisco, Calif. :$bMorgan Kaufmann Publishers,$c[1996]
264	_4	$c©1996
300		$axxiii, 552 pages :$billustrations (some color) ;$c24 cm
336		$atext$btxt$2rdacontent

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337		$aunmediated$bn$2rdamedia
338		$avolume$bnc$2rdacarrier
504		$aIncludes bibliographical references (pages [511]-520) and index.
650	_0	$aComputer networks.
700	1_	$aDavie, Bruce S.
997		$aMARCIVE

MMS IDs

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Network Electronic IDs:

Network Physical IDs:

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Attachment 2B

Bibliographic Record - OCLC Number: 34191065

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	Type of Record	'a' - Language material
	Bibliographic Level	'm' - Monograph/Item
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	Encoding Level	' ' - Full level
	Descriptive Cataloging Form	'a' - AACR2
001	34191065	
005	20240127100239.6	
008	Date Entered on File	'960207'
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	Date1/Beginning Date of Publication	'1996'
	Date2/Ending Date of Publication	' '
	Place of Publication, Production, or Execution Code	'cau' - California
	Illustrations	'a '
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	Form of Item	' ' - None of the following
	Nature of Contents Code	'b '
	Government Publication	' ' - Not a government publication
	Conference Publication	'0' - Not a conference publication
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	Biography	' ' - No biographical material
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	Modified Record	' ' - Record is not modified
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010 96001590

040 DLC **$b** eng **$c** DLC **$d** BTCTA **$d** YDXCP **$d** BAKER **$d** UAB **$d** ZWZ **$d** OCLCF **$d** OCL CQ **$d** CPO **$d** SNN **$d** OCLCO **$d** OCLCQ **$d** UKUOY **$d** OCLCQ **$d** OCLCO **$d** OCLCQ **$d** OCLCL

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020 1558603689

020 9781558603684

050 0 0 TK5105.5 **$b** .P479 1996

082 0 0 004.6/5 **$2** 20

100 1 Peterson, Larry L.

245 1 0 Computer networks : **$b** a systems approach / **$c** Larry L. Peterson & Bruce S. Davie.

260 San Francisco, Calif. : **$b** Morgan Kaufmann Publishers, **$c** ©1996.

300 xxiii, 552 pages : **$b** illustrations (some color) ; **$c** 24 cm.

336 text **$b** txt **$2** rdacontent

337 unmediated **$b** n **$2** rdamedia

338 volume **$b** nc **$2** rdacarrier

490 1 Morgan Kaufmann series in networking

504 Includes bibliographical references (pages 511-520) and index.

505 0 1. Foundation -- 2. Protocol Implementation -- 3. Direct Link Networks -- 4. Packet Switching -- 5. Internetworking -- 6. End-to-End Protocols -- 7. End-to-End Data -- 8. Congestion Control -- 9. High-Speed Networking -- Appendix: Network Management.

650 0 Computer networks.

650 2 Computer Communication Networks

650 6 Réseaux d'ordinateurs.

650 7 Computer networks. **$2** fast **$0** (OCoLC)fst00872297

650 7 Réseaux d'ordinateurs. **$2** ram

700 1 Davie, Bruce S.

758 **$i** has work: **$a** Computer networks (Work) **$1** https://id.oclc.org/worldcat/entity/E39PCFFKK7bY63xprG6jjjrYvb **$4** https://id.oclc.org/worldcat/ontology/hasWork

776 0 8 **$i** Online version: **$a** Peterson, Larry L. **$t** Computer networks. **$d** San Francisco, Calif. : Morgan Kaufmann Publishers, ©1996 **$w** (OCoLC)604954826

830 0 Morgan Kaufmann series in networking.

938 Baker & Taylor **$b** BKTY **$c** 79.00 **$d** 79.00 **$i** 1558603689 **$n** 0002819370 **$s** active

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029 1 ZWZ **$b** 024944866

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360 __ |**i** subdivision |**a** Computer networks |**i** under subjects
450 __ |**a** Communication systems, Computer
450 __ |**a** Computer communication systems
450 __ |**a** Data networks, Computer
450 __ |**a** ECNs (Electronic communication networks)
450 __ |**a** Electronic communication networks
450 __ |**a** Networks, Computer
450 __ |**a** Teleprocessing networks
550 __ |**w** g |**a** Data transmission systems
550 __ |**w** g |**a** Digital communications
550 __ |**w** g |**a** Electronic systems
550 __ |**w** g |**a** Information networks
550 __ |**w** g |**a** Telecommunication
550 __ |**a** Cyberinfrastructure
550 __ |**a** Electronic data processing |**x** Distributed processing
550 __ |**a** Network computers

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670 __ |**a** U.S. Cong. Senate. Comm. on banking, Housing and Urban Affairs. Subcom. on Securities. The changing face of capital markets and the impact of electronic communications networks (ECNs), hearing ... 2000.

906 __ |**t** 0839 |**u** te04 |**v** 1

953 __ |**a** xx00 |**b** ta39

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Imprint: San Francisco : Morgan Kaufmann Publishers, c1996.
Description: 552 p.
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Date of Publication: 1996-03-15
Names: Peterson, Larry L., 1958-
Davie, Bruce S., 1963-
Morgan Kaufmann Publishers, Inc.

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OFDM Wireless Multimedia Communications

OFDM Wireless Multimedia Communications

Richard van Nee
Ramjee Prasad



Artech House
Boston • London

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2000
0001

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10 9 8 7 6 5 4 3 2 1

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Preface

सर्वद्वारेषु देहेऽस्मिन् प्रकाश उपजायते ।
ज्ञानं यदा तदा विद्याद् विवृद्धं सत्त्वमित्युत

sarva-dvāreṣu dehe 'smin
prakāśa upajāyate
jñānaṁ yadā tadā vidyād
vivṛddhaṁ sattvam ity uta

The manifestations of the mode of goodness can be experienced when all the gates of the body are illuminated by knowledge

The Bhagavad Gita (14.11)

During the joint supervision of a Master's thesis "The Peak-to-Average Power Ratio of OFDM," of Arnout de Wild from Delft University of Technology, The Netherlands, we realized that there was a shortage of technical information on orthogonal frequency division multiplexing (OFDM) in a single reference. Therefore, we decided to write a comprehensive introduction to OFDM. This is the first book to give a broad treatment to OFDM for mobile multimedia communications. Until now, no such book was available in the market. We have attempted to fill this gap in the literature.

Currently, OFDM is of great interest by the researchers in the Universities and research laboratories all over the world. OFDM has already been accepted for the new wireless local area network standards from IEEE 802.11, High Performance Local Area Network type 2 (HIPERLAN/2) and Mobile Multimedia Access Communication (MMAC) Systems. Also, it is expected to be used for the wireless broadband multimedia communications.

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OFDM for Wireless Multimedia Communications is the first book to take a comprehensive look at OFDM, providing the design guidelines one needs to maximize benefits from this important new technology. The book gives engineers a solid base for assessing the performance of wireless OFDM systems. It describes the new OFDM-based wireless LAN standards; examines the basics of direct-sequence and frequency-hopping CDMA, helpful in understanding combinations of OFDM and CDMA. It also looks at applications of OFDM, including digital audio and video broadcasting, and wireless ATM. Loaded with essential figures and equations, it is a must-have for practicing communications engineers, researchers, academics, and students of communications technology.

Chapter 1 presents a general introduction to wireless broadband multimedia communication systems (WBMCS), multipath propagation, and the history of OFDM. A part of this chapter is based on the contributions of Luis Correia from the Technical University of Lisbon, Portugal, Anand Raghawa Prasad from Lucent Technologies, and Hiroshi Harada from the Communications Research Laboratory, Ministry of Posts and Telecommunications, Yokosuka, Japan.

Chapters 2 to 5 deal with the basic knowledge of OFDM including modulation and coding, synchronization, and channel estimation, that every post-graduate student as well as practicing engineers must learn. Chapter 2 contains contributions of Rob Kopmeiners from Lucent Technologies on the FFT design.

Chapter 6 describes the peak-to-average power problem, as well as several solutions to it. It is partly based on the contribution of Arnout de Wild.

Basic principles of CDMA are discussed in Chapter 7 to understand multi carrier CDMA and frequency-hopping OFDMA, which are described in Chapters 8 and 9. Chapter 8 is based on the research contributions from Shinsuke Hara from the University of Osaka, Japan, a postdoctoral student at Delft University of Technology during 1995–96. Chapter 9 is based on a UMTS proposal, with main contributions of Ralf Böhnke from Sony, Germany, David Bhatoolaul and Magnus Sandell from Lucent Technologies, Matthias Wahlquist from Telia Research, Sweden, and Jan-Jaap van de Beek from Lulea University, Sweden.

Chapter 10 was witten from the viewpoint of top technocrats from industries, government departments, and policy-making bodies. It describes several applications of OFDM, with the main focus on wireless ATM in the Magic WAND project, and the new wireless LAN standards for the 5 GHz band from IEEE 802.11, HIPERLAN/2 and MMAC. It is partly based on contributions from Geert Awater from Lucent Technologies, and Masahiro Morikura and Hitoshi Takanashi from NTT in Japan and California, respectively.

We have tried our best to make each chapter quite complete in itself. This book will help generate many new research problems and solutions for future mobile multimedia communications. We cannot claim that this book is errorless. Any remarks to improve the text and correct any errors would be highly appreciated.

Acknowledgments

The material in this book originates from several projects at Lucent Technologies and research activities at Delft University of Technology, The Netherlands. A great deal of OFDM-knowledge was acquired during the Magic WAND project, in which several companies jointly managed to build a wireless ATM network demonstrator based on OFDM. We wish to thank all Magic WAND members who were involved in the design of the OFDM modem, in particular Geert Awater, James Hopper, Rob Kopmeiners, Erik Busking, Han Schmitz, Theo Kleijne, Martin Janssen, Jan Kruys, Urs Bernhard, Urs Lott, Alex Grant, James Aldis, Thomas Mark, Rodolfo Mannpelz, and Ari Vaisanen. Another fruitful source of information was the OFDM-based proposal for UMTS, with main contributions coming from Ralf Böhnke, David Bhatoolaul, Magnus Sandell, and Jan-Jaap van de Beek.

Richard wishes to thank Masahiro Morikura and Hitoshi Takanashi for all their contributions and the pleasant cooperation on the joint OFDM proposal for the IEEE 802.11 wireless LAN standard. All members of IEEE 802.11 and HiperLAN/2 are thanked for numerous contributions, that greatly improved the quality of the final standards and helped to gain more insight in various OFDM techniques.

Geert Awater and Rob Kopmeiners made contributions and corrected numerous mistakes. Neeli Rashmi Prasad helped to prepare the complete manuscript, freeing us from the enormous burden of editorial requirements. Shinsuke Hara from the University of Osaka, Japan, Hiroshi Harada from the Communications Research Laboratory, Ministry of Posts and Telecommunications, Yokosuka, Japan, Luis Correia from the Technical University of Lisbon, Portugal, Anand Raghawa Prasad from Lucent Technologies, and Arnout de Wild from Siemens, The Netherlands, are deeply acknowledged for their valuable contributions.

After the Magic WAND project, we studied several OFDM options for new high-rate wireless LAN products. A circle was completed by the selection of OFDM for the high rate extension of the IEEE 802.11 wireless LAN standard in July 1998. We hope this book will help to gain insight in the principles and design of OFDM-based systems, in particular the new OFDM-based wireless LAN standards.

Richard van Nee
Ramjee Prasad
October 1999

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Chapter 1

Introduction

The spectacular growth of video, voice, and data communication over the Internet, and the equally rapid pervasion of mobile telephony, justify great expectations for mobile multimedia. Research and development are taking place all over the world to define the next generation of wireless broadband multimedia communications systems (WBMCS) that may create the "global information village." Figure 1.1 illustrates the basic concept of the global information village, which consists of various components at different scales ranging from global to picocellular size. As we know, the demand for wireless (mobile) communications and Internet/multimedia communications is growing exponentially. Therefore, it is imperative that both wireless and Internet/multimedia should be brought together. Thus, in the near future, wireless Internet Protocol (IP) and wireless asynchronous transfer mode (ATM) will play an important role in the development of WBMCS.

While present communications systems are primarily designed for one specific application, such as speech on a mobile telephone or high-rate data in a wireless local area network (LAN), the next generation of WBMCS will integrate various functions and applications. WBMCS is expected to provide its users with customer premises services that have information rates exceeding 2 Mbps. Supporting such large data rates with sufficient robustness to radio channel impairments, requires careful choosing of modulation technique. The most suitable modulation choice seems to be orthogonal frequency division multiplexing (OFDM). Before going into the details of OFDM, however, first we give some background information on the systems that will be using it.

The theme of WBMCS is to provide its users a means of radio access to broadband services supported on customer premises networks or offered directly by public fixed networks. WBMCS will provide a mobile/movable wireless extension to

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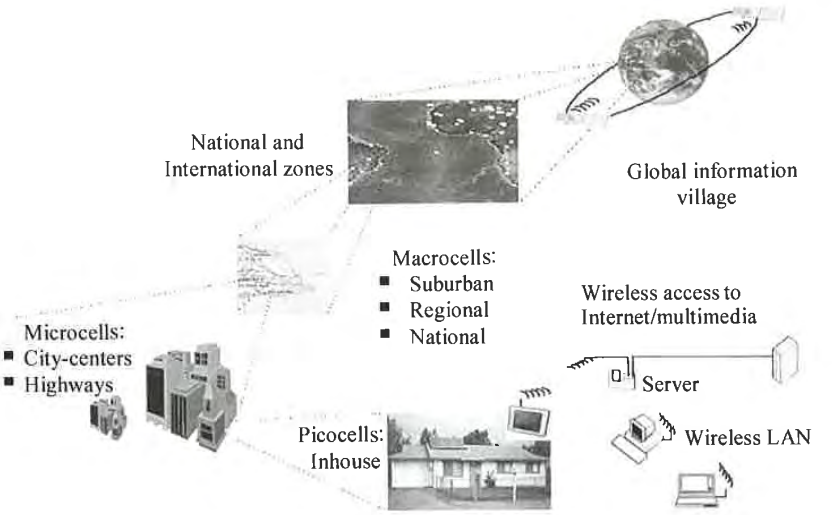


Figure 1.1 Global information village.

WBMCS is under investigation in North America, Europe, and Japan in the microwave and millimeter-wave bands to accommodate the necessary bandwidth. The research in the field of WBMCS has drawn much attention because of the increasing role of multimedia and computer applications in communications. There is a major thrust in three research areas: (1) microwave and millimeter-wave bands for fixed access in outdoor, public commercial networks, (2) evolution of WLAN for inbuilding systems, and (3) use of LAN technology outdoors rather than indoors. In short, WBMCS will provide novel multimedia and video mobile communications services, also related to wireless customer premises network (WCPN) and wireless local loop (WLL).

To implement the wireless broadband communication systems, the following challenges must be considered:

- Frequency allocation and selection;
- Channel characterization;
- Application and environment recognition, including health hazard issues;
- Technology development;
- Air interface multiple access techniques;
- Protocols and networks; and
- Systems development with efficient modulation, coding, and smart antenna techniques.

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- Systems development with efficient modulation, coding, and smart antenna techniques.

A significant number of research and development (R&D) projects are set up in the area of WBMCS. Within the European Advanced Communication Technologies and Services (ACTS) program are four European Union-funded R&D projects, namely Magic Wand (Wireless ATM Network Demonstrator), ATM Wireless Access Communication System (AWACS), System for Advanced Mobile Broadband Applications (SAMBA), and wireless broadband CPN/LAN for professional and residential multimedia applications (MEDIAN) [1–17]. Table 1.1 summarizes the European projects [11].

In the United States, seamless wireless network (SWAN) and broadband adaptive homing ATM architecture (BAHAMA), as well as two major projects in Bell Laboratories and a wireless ATM network (WATMnet), are being developed in the computer and communications (C&C) research laboratories of Nippon Electric Company (NEC) in the United States [2–6].

In Japan, Communication Research Laboratory (CRL) is working on several R&D projects, such as a broadband mobile communication system in the super high frequency (SHF) band (from 3 to 10 GHz) with a channel bit rate up to 10 Mbps and an indoor high speed WLAN in SHF band with a target bit rate of up to 155 Mbps [12].

In the Netherlands, Delft University of Technology has been busy with a multi-disciplinary research project, "Mobile Multimedia Communication (MMC)," since April 1996. The team consists of experts from the telecommunications and traffic control and information theory groups of the department of Electrical Engineering, the Product Ergonomics group of the department of Industrial Design Engineering, and the Organizational Psychology group of the department of Technology and Society.

The MMC has the following objectives to achieve at 60 GHz:

- Wireless access of 155 Mbps using OFDM;
- Both indoor and outdoor use;
- Less complex, inexpensive mobile stations by moving most functionality to the access points;
- Modified OFDM; and
- Constant bit rate (CBR), variable bit rate (VBR), and available bit rate (ABR) services.

Table 1.1
Summary of European ACTS Projects.

ACTS project / Parameter	WAND	AWACS	SAMBA	MEDIAN
Frequency	5 GHz	19 GHz	40 GHz	61.2 GHz
Data rate	20 Mbps	70 Mbps	34 Mbps	155 Mbps
Modulation	OFDM, 16 subcarriers with 8-PSK (phase shift keying)	offset quadrature PSK (OQPSK)	OQPSK	OFDM, 512 carriers, differential QPSK (DQPSK)
Cell radius	20–50m (omnidirectional antennas)	50–100m (directional antennas, line-of-sight only)	10-50m (directional antennas at access point)	10m (directional antennas)
Radio access	time division multiple access/ time division duplex (TDMA/TDD)	TDMA/TDD	time division multiple access /frequency division duplex (TDMA/FDD)	TDMA/TDD

1.1 STANDARDIZATION AND FREQUENCY BANDS

There are three main forums for the standardization of wireless broadband communication systems; namely, IEEE 802.11 [18], European Telecommunication Standards Institute Broadband Radio Access Networks (ETSI BRAN) [19], and Multimedia Mobile Access Communications (MMAC) [20]. IEEE 802.11 made the first WLAN standard for the 2.4-GHz Industrial, Scientific, and Medical band (ISM). It specifies the medium access control and three different physical layers—direct-sequence spread spectrum, frequency hopping, and infrared—which give a data rate of 2 Mbps. Products based on this standard became available in 1998. Figure 1.2 shows an example of an IEEE 802.11 modem in a PCMCIA card. Following the initial 1- and 2-Mbps standard, IEEE 802.11 developed two new physical layer standards. One delivers data rates of up to 11 Mbps in the 2.4-GHz band, using complementary code keying [21,22]. Products based on this standard—with the old 1 and 2 Mbps as fallback rates—are available since mid 1999. An industry alliance called the Wireless Ethernet Compatibility Alliance (WECA) has been established to promote the high rate IEEE

available since mid 1999. An industry alliance called the Wireless Ethernet Compatibility Alliance (WECA) has been established to promote the high rate IEEE 802.11 technology and to certify interoperability of products from different vendors [23]. The second IEEE 802.11 standard extension targets a range of data rates from 6 up to 54 Mbps using OFDM in the 5-GHz band [24]. The OFDM standard was developed jointly with ETSI BRAN and MMAC, making OFDM effectively a worldwide standard for the 5-GHz band.

Table 1.2 lists the main characteristics of the IEEE 802.11 and the ETSI High Performance Local Area Network type 2 (HIPERLAN/2) standards. More details about these standards can be found in Chapter 10.



Figure 1.2 IEEE 802.11 modem for the 2.4-GHz band (WaveLAN™ from Lucent Technologies [25]).

Figure 1.3 shows that 2-, 5- and 60-GHz are the commercially important frequency bands because of geographically wide spectrum allocations in Europe, the United States (U.S.), and Japan for the wireless broadband multimedia communications networks. The 2.4-GHz band is an ISM band, which can be used for many types of transmission systems as long as they obey certain power, spectral density, and spreading gain requirements. The 5-GHz band is designated specifically for WBMCS. In Europe, only HIPERLAN devices are currently allowed in this band. HIPERLAN actually consists of a family of standards, one of which is an OFDM-based standard that is very similar to the IEEE 802.11 5-GHz standard. In Japan, MMAC supports both the IEEE 802.11 and the HIPERLAN standards. Notice that Japan only has 100 MHz available in the 5-GHz band, while the United States and Europe provide 300 and 455 MHz, repectively. In Europe, extra spectrum for HIPERLAN is available in the 17-GHz band, while Japan has allocated spectrum from 10- to 16-GHz to mobile broadband systems (MBS). An analysis of the propagation aspects at the bands foreseen for WBMCS microwaves, millimeterwaves, and infrared is presented in [26–31].

Table 1.2
Comparison of IEEE and HIPERLAN standards.

Parameter	IEEE 802.11 2 GHz	IEEE 802.11 5 GHz	HIPERLAN/2
Configurations	Centralized system with access points connected to wired network, or peer-to-peer networking	Centralized system with access points connected to wired network, or peer-to-peer networking	Centralized system with access points connected to wired network
Range	Up to 60m at 11 Mbps and up to 100m at 2 Mbps with omnidirectional antennas	Up to 30m at 24 Mbps and up to 60m at 6 Mbps with omnidirectional antennas	Up to 30m at 24 Mbps and up to 60m at 6 Mbps with omnidirectional antennas
Channel access	CSMA/CA, variable size data packets (up to 8192 bytes)	CSMA/CA, variable size data packets (up to 8192 bytes)	Reservation based access, scheduled by access point. Contention slots for making slot reservations
Frequency bands	2.4-2.4835 GHz	5.150–5.350 GHz; 5.725–5.825 GHz	5.150–5.350 GHz; 5.470–5.725 GHz;
Duplexing	TDD	TDD	TDD
Data rate	1, 2 Mbps (BPSK/QPSK) 5.5, 11 Mbps (CCK)	6, 9 Mbps (BPSK) 12, 18 Mbps (QPSK) 24, 36 Mbps (16-QAM) 54 Mbps (64-QAM)	6, 9 Mbps (BPSK) 12, 18 Mbps (QPSK) 24, 36 Mbps (16-QAM) 54 Mbps (64-QAM)

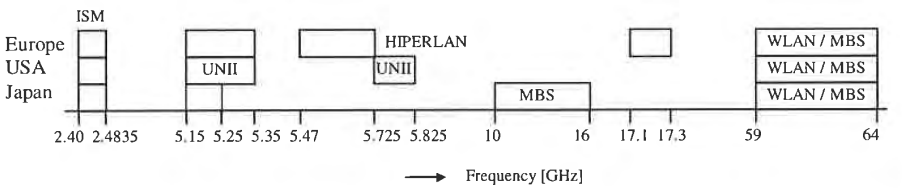


Figure 1.3 Frequency band for wireless broadband communications.

1.2 MULTIMEDIA COMMUNICATIONS

Multimedia and computer communications are playing an increasing role in today's society, creating new challenges to those working in the development of telecommunications systems. Besides that, telecommunications is increasingly relying upon wireless links. Thus, the pressure for wireless systems to cope with increasing data rates is enormous, and WBMCSs with data rates higher than 2 Mbps are emerging rapidly, even if at this moment applications for very high transmission rates do not exist.

Several WBMCSs are being considered for different users with different needs. They may accommodate data rates ranging between 2 and 155 Mbps; terminals can be mobile (moving' while communicating) or portable (static while communicating); moving speeds can be as high as that of a fast train; users may or may not be allowed to use more than one channel if their application requires so; the system bandwidth may be fixed, or dynamically allocated according to the user's needs; communication between terminals may be direct or must go through a base station; possible ATM technology use; and so on. Many other cases can be listed as making the difference between various perspectives of a WBMCS, but two major approaches are emerging: WLANs directed to communication among computers, from which IEEE 802.11 [16, 18] and HIPERLAN [19, 20] are examples, with MBS [17] intended as a cellular system providing full mobility to B-ISDN users.

The different requirements imposed by the various approaches to WBMCSs have consequences on system design and development. The tradeoffs between maximum flexibility on one hand and complexity and cost on the other are always difficult to decide, as they have an impact not only on the deployment of a system, but also on its future evolution and market acceptance. GSM is a good example of a system foreseen to accommodate additional services and capacities to those initially offered, and the fact that operators are already implementing phase 2+ is proof of that.

This means that many decisions must be made on the several WBMCSs that will appear on the market. For IEEE 802.11, for example, those decisions have already been made, as the system will be commercialized in the very near future, but for other systems there are still many undecided aspects. Of course this depends on what are the applications intended to be supported by the systems, and whether these applications are targeted to the mass market or only to some niches. The former (from which mobile telephones are a good example) will certainly include WLANs, because the expansion of personal computers will dictate this application as a great success in WBMCSs; the latter will possibly have television broadcasters among their users (to establish links between HDTV cameras and the central control room).

Not only are market aspects at stake in the development and deployment of WBMCSs, but many technical challenges are posed as well. The transmission of such high data rates over radio in a mobile environment creates additional difficulties,

compared with that of existing systems; these difficulties are augmented by the fact that frequencies higher than UHF are needed to support the corresponding bandwidths, thus pushing mobile technology challenges (size and weight among other things) to frequencies where these aspects were not much considered until now. However, additional challenges are posed to those involved in WBMCSs development: in today's world, where consumers are in the habit of using a communications system that is available in different places (e.g., GSM roaming capability, because users can make and receive telephone calls in an increasing number of countries worldwide), or being able to exchange information among different systems (e.g., the exchange of files between different computer applications and systems), for future use it does not make sense to consider systems that offer a high data rate but do not support these capabilities to some extent.

1.2.1 Need for High Data Rates

Data rate is really what broadband is about. For example, the new IEEE and HIPERLAN standards specify bit rates of up to 54 Mbps, although 24 Mbps will be the typical rate used in most applications. Such high data rates impose large bandwidths, thus pushing carrier frequencies for values higher than the UHF band: HIPERLAN has frequencies allocated in the 5- and 17-GHz bands; MBS will occupy the 40- and 60-GHz bands; and even the infrared band is being considered for broadband WLANs. Many people argue whether there is a need for such high-capacity systems, however, bearing in mind all the compression algorithms developed and the type of applications that do require tens of megabits per second. We can examine this issue from another perspective.

The need for high-capacity systems is recognized by the "Visionary Group" [32], put together by the European Commission, to give a perspective of what should be the hot topics in the telecommunications for research in the next European programs (following R&D in Advanced Communications Technologies for Europe (RACE) and ACTS). In this visionary perspective, to meet the needs of society in the years to come as far as communications is concerned, capacity is one of the major issues to be developed because of the foreseen increase in demand for new services (especially those based on multimedia). Along with this, mobility will impose new challenges to the development of new personal and mobile communications systems.

We can conclude the following: even if at a certain point it may look academic to develop a system for a capacity much higher than what seems reasonable (in the sense that there are no applications requiring such high capacity), it is worthwhile to do so, as almost certainly in the future (which may be not very far off) applications will need those capacities and even more. The story of fiber optics is an example.

1.2.2 Services and Applications

The system concept of a WLAN such as IEEE 802.11 and of a mobile broadband cellular system such as MBS is totally different: each is directed to services and applications that differ in many aspects. A comparison of several systems, based on two of the key features (mobility and data rate), is shown in Figure 1.4 [33], where it is clear that no competition exists between the different approaches.

The applications and services of the various systems are also different. IEEE 802.11 is mainly intended for communications between computers (thus being an extension of wired LANS); nevertheless, it can support real-time voice and image signals, and users are allowed some mobility and can have access to public networks.

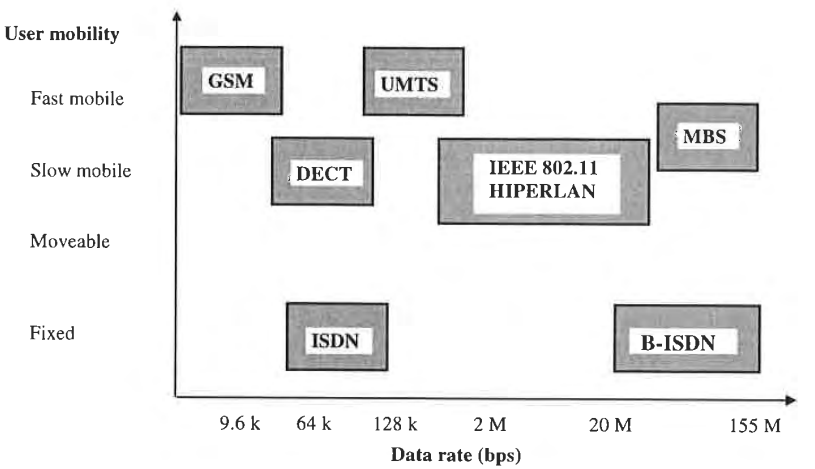


Figure 1.4 Comparison of mobility and data rates for several systems.

1.2.3 Antennas and Batteries

Antennas and batteries play a key role in wireless systems. With the advent of microelectronics and signal processing, antennas and batteries tend to impose the size and weight of mobile terminals. Of course, the higher one goes in frequency, the less developed the technology, and many problems are still found in size and weight at the millimeter-wave band. Power consumption is one example. Though these are likely to be solved in the near future. The number of hours battery-powered equipment can work or operate on stand by, and the percentage of its weight corresponding to the battery, is

not a specific problem of WBMCS. Laptop computers and cellular telephones are the most common terminals relying on batteries these days. This technology continues to demand huge R&D, to extend working time and reduce weight. Although a 100g mobile telephone battery corresponding to several hours of continuous work and a few days on standby is already on the market, users still want more. Mobile multimedia terminals, certainly those to be used in some applications of WBMCSs, will be an extension of the current cellular telephones. Therefore, we foresee that the current problems associated with batteries will be transposed on WBMCS terminals; the same applies to laptops.

Antennas (size, type, technology, etc.) are not a specific problem of WBMCSs as well, but again they are very much related to the type of systems that will be made available for users. It does not make sense to impose restrictions (e.g., pointing in a certain direction or avoiding someone to pass in between) on the type of mobility a mobile terminal can have. Even for portable terminals (e.g., computers), these restrictions make no sense. Hence, there are only two options as far as antennas are concerned: either an omnidirectional antenna (dipole type) or an adaptive array antenna is used. Either way, patch antennas seem a very promising solution for general use in WBMCS. For the frequency bands we consider, isolated patches or adaptive arrays (with many elements) can be made with a small size (e.g., a credit card), thus enabling the terminal not to be limited in size by the antenna system.

The role of antenna radiation patterns is not negligible when discussing system performance, nor is their influence on parameters associated with wave propagation. Although the tradeoff between an omnidirectional and a narrowbeam antenna is not particular of WBMCS, it assumes particular importance at microwave and millimeter waves because of the characteristics of wave propagation at these bands. Using an omnidirectional antenna means a lower gain, but also the possibility of receiving signals from various directions, without the requirement for knowing where the base station is, and allowing the received rays coming from reflections on the propagation scenario. On the other hand, the use of a very directive antenna provides a higher gain, but it must be pointed at the base station and does not receive reflected waves coming from directions very different from the one to which it is pointed. The need for pointing it can be very discouraging, if not a drawback, when a line of sight does not exist. On the other hand, omnidirectional antennas lead to high values of delay spread, but they may ensure that the link still exists, relying on reflections if the line of sight is lost.

1.2.4 Safety Considerations

Until a few years ago, the analysis of possible harmful effects of electromagnetic radiation on people was devoted mainly to power lines and radars, because of the huge power levels involved in those systems. Even when mobile telephone systems appeared, there was no major concern, as the antennas were installed on the roofs of cars. With

the development of personal communication systems, in which users carry mobile telephones inside their coat pockets, and the antenna radiates a few centimeters from the head, safety issues gained great importance and a new perspective. Much research in the literature focuses not only on the absorption of power inside the head, but also on the influence of the head on the antenna's radiation pattern and input impedance. However, these works have addressed only the frequency bands used in today's systems; that is, up to 2-GHz (mainly on the 900- and 1,800-MHz bands), and only very few references are made to systems working at higher frequencies, as it is in the case of WBMCSs.

The problems associated with infrared are different from those posed by microwaves and millimeter waves. Eye safety, rather than power absorption inside the head, is the issue here, because the eye acts as a filter to the electromagnetic radiation, allowing only light and near-frequency radiation to enter into it, and the amount of power absorption inside the human body is negligible. Exposure of the eye to high levels of infrared radiation may cause cataractlike diseases, and the maximum allowed transmitter power seems to limit the range to a few meters [31]. If this is the case, safety restrictions will pose severe limitations to the use of infrared in WBMCSs, as far as general applications are concerned. The question in this case is not that there are always problems during system operation (e.g., mobile telephones), but the damage that may be caused if someone looks at the transmitter during operation.

Microwaves and millimeter waves have no special effect on eyes, other than power absorption. In WLANs, antennas do not radiate very near (1 or 2 cm) to the user as in the mobile telephone case, thus enabling power limitations to be less restrictive; also if mobile multimedia terminals are used as they are in PDAs. But if terminals are used in the same form as mobile telephones, then maximum transmitter powers have to be established, similar to those for the current personal communication systems. The standards for safety levels have already been set in the United States and Europe, as the ones used for UHF extend up to 300 MHz (IEEE/ANSI and CENELEC recommendations are the references). Thus, it is left to researchers in this area to extend their work to higher frequencies, by evaluating SAR (the amount of power dissipated per unit of mass) levels inside the head (or other parts of the human body very near the radiating system), from which maximum transmitter powers will be established. This may not be as straightforward as it seems, however, because the calculation of SAR is usually done by solving integral or differential equations using numerical methods (method of moments or finite difference), which require models of the head made of small elements (e.g., cubes) with dimensions of the order of a tenth of the wavelength. This already requires powerful computer resources (in memory and CPU time) for frequencies in the high UHF band, and may limit the possibility of analyzing frequencies much higher than UHF. On the other hand, the higher the frequency, the smaller the penetration of radio waves into the human body, hence making it possible to have models of only some centimeters deep. This is an area for further research.

1.2.5 ATM-Based Wireless (Mobile) Broadband Multimedia Systems

Recent study of MBS, ATM, and ATM-oriented MBS has drawn the attention of several researchers [34–44]. With enormous complexity of managing and operating the many different types of networks now in use, the door is open for finding a common platform—a network on which all established services can be supported and which will allow new services to be introduced without needing new networks on which to run them. The answer seems to be ATM. This is the technology being defined and standardized for B-ISDN. Thus, ATM, when adequately modified, is also an answer for the future mobile wireless broadband multimedia systems.

ATM is a packet-oriented transmission scheme. The transmission path of the packets of constant length, the so-called ATM cells, is established during connection setup between the two endpoints by assigning a virtual channel. At this time, the necessary resources are provided and the logical channels are assigned. All packets of a virtual channel are carried over the same path. The transmission capacity of the virtual channel is characterized by the parameters, mean bit rate and peak bit rate during connection setup. ATM cells are generated according to the need of the data source. Thus, ATM is a very good method to meet the dynamic requirements of connections with variable data rates.

MBS is the interface between the fixed ATM net at the base station side and mobile ATM net at the mobile station side. Normally, the ATM net at the mobile station side only consists of one end system. For every end station, it is possible to operate several virtual channels with different data rates at the same time.

A conceptual view of the ATM-type broadband communications network is shown in Figure 1.5. The most important benefit of ATM is its flexibility; it is used for the new high bit rate services, which are either VBR or burst traffic. Several factors that tend to favor the use of ATM cell transport in MBS are as follows:

- Flexible bandwidth allocation and service-type selection for a range of applications;
- Efficient multiplexing of traffic from bursty data and multimedia sources;
- End-to-end provisioning of broadband services over wired and wireless networks;
- Suitability of available ATM switching for intercell switching;
- Improved service reliability with packet-switching techniques; and
- Ease of interfacing with wired B-ISDN systems.

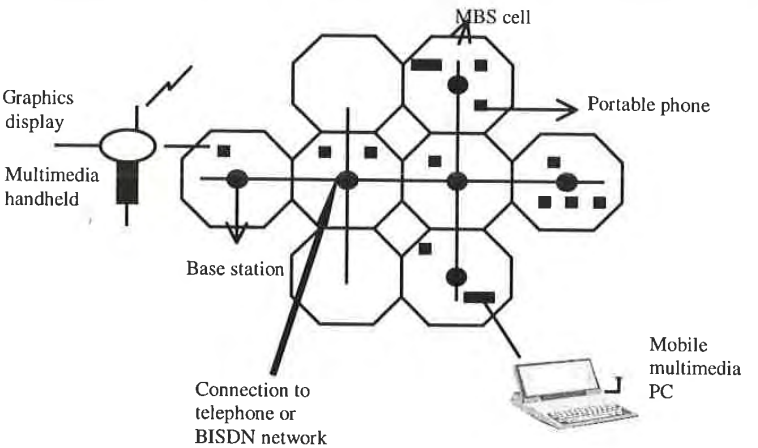


Figure 1.5 Conceptual view of MBS.

Taking the above points into consideration, adoption of ATM-compatible, fixed-length, cell-relay format for MBS is recommended. A possible ATM-compatible MBS approach is shown in Figure 1.6. With this approach, the 48-byte ATM cell payload becomes the basic unit of data within the MBS network. Within MBS, specific protocol layers (e.g., data link and medium-access control layer) are added to the ATM payload as required, and replaced by ATM headers before entering the fixed network [41]. The use of ATM switching for intercell traffic also avoids the crucial problem of developing a new backbone network with sufficient throughput to support intercommunication among large numbers of small cells. ATM multiplexers are used to combine traffic from several base stations into a single ATM port.

For a seamless internetworking mechanism with the wired broadband network, it is vital to have the MBS protocol layering harmonized with the ATM stack. Figure 1.7 shows a protocol reference model. In this approach, new wireless channel-specific physical, medium-access control, and data link layers are added below the ATM network layer. This means that regular network layer and control services such as call setup, virtual channel identifier/virtual path identifier (VCI/VPI) addressing, cell prioritization, and flow-control indication will continue to be used by mobile services. The baseline ATM network and signaling protocol are specified to particular mobility-related functions, such as address registration (roaming), broadcasting, handoff, and so forth.

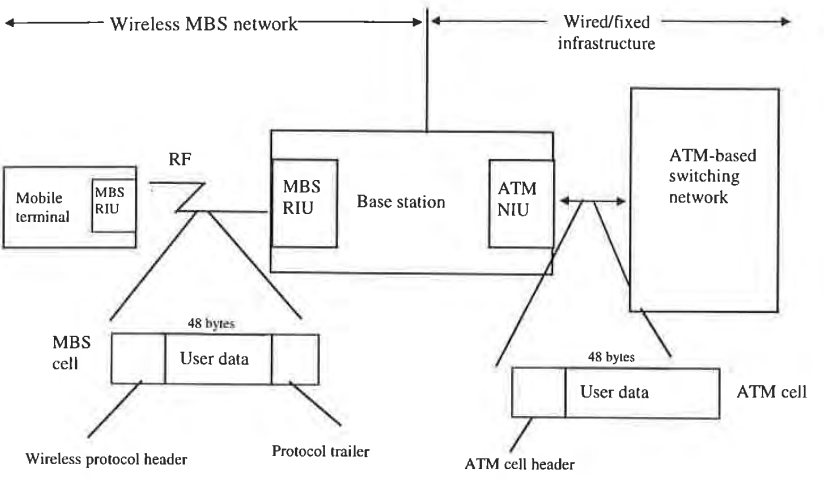


Figure 1.6 ATM-compatible MBS approach. Terms: radio interface unit (RIU); network interface unit (NIU).

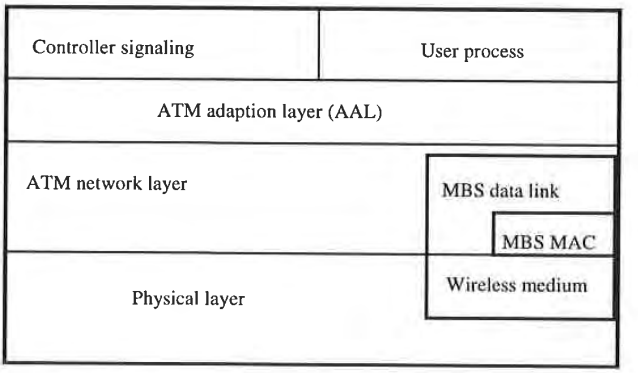


Figure 1.7 Relation of wireless network protocol layers.

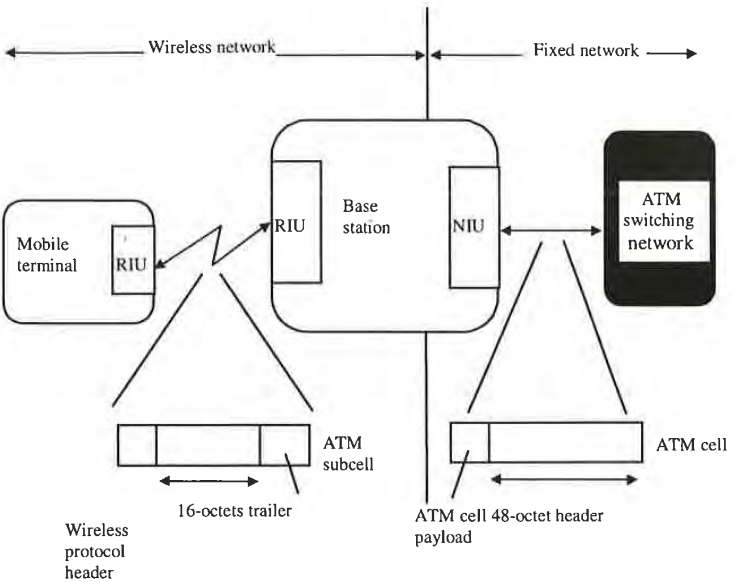


Figure 1.8 Conceptual view of an ATM-compatible air interface.

The payload of an ATM cell consists of 48 octets, meaning that without any segmentation, packet lengths of 384 bits would have to be transmitted over the mobile radio channel. Higher throughput levels over a fading mobile radio channel are achieved when using a packet of smaller lengths. So a suitable integer submultiple of a cell is chosen as the basic unit of data over the wireless radio medium. Based on the system parameters, a submultiple cell size of 16 octets or 128 bits is used as an appropriate value.

The air interface is terminated directly at the base station, as illustrated in Figure 1.8. Also shown is the segmentation of an ATM cell into its three subcells and the addition of an extra wireless ATM header.

1.3 MULTIPATH PROPAGATION

One of the basic reasons to use OFDM is the efficient way it can handle multipath propagation. To understand the effects of multipath fading, this section contains an overview of the most relevant parameters and models.

1.3.1 Multipath Channel Models

Fundamental work on modeling of the indoor radio channel is published in [45, 46]. One of the results of this work, which is also supported by many other measurements reported in the literature, is that the average received multipath power is an exponentially decaying function of the excess delay. Further, the amplitudes of individual multipath components are Rayleigh distributed. This observation has led to simplified channel models as used in [47, 48]. These models assume a fixed number of paths with equidistant delays. The path amplitudes are independent Rayleigh variables, while the path phases are uniformly distributed. Figure 1.9 shows an example of an average and an instantaneous power delay profile that were generated using this approach.

Compared to the more extensive models in [45, 46], the simplified model of [47, 48] may give somewhat optimistic results because the number of multipath components is fixed to the maximum possible amount. In the models of [45, 46], the number of paths is random. Paths arrive in clusters with Poisson distributed arrival times. Within a cluster, the path amplitudes are independent Rayleigh variables. The average power delay profile, averaged over a large number of channels, is an exponentially decaying function, just as for the models in [47, 48]. Thus, the only difference between the models is that the instantaneous power delay profiles have a slightly different shape, and channels generated by the method of [47, 48] generally show more multipath components than channels generated according to [45, 46]. This may give a somewhat optimistic diversity effect, because diversity is proportional to the number of paths. It probably does not make a difference when the models are used to determine the delay spread tolerance of a particular transmission system, however, because that is not depending on the number of paths, but rather on the amount of power in paths exceeding a certain excess delay. So, the channel models of [47, 48] seem a good basis to determine the delay spread tolerance of different modulation schemes. An additional advantage is that the simulation complexity is much lower than that of the models of [45, 46].

One of the key parameters in the design of a transmission system is the maximum delay spread value that it has to tolerate. For an idea of what typical delay spread figures are, the next section presents some measurement results obtained from the literature [49- 63].

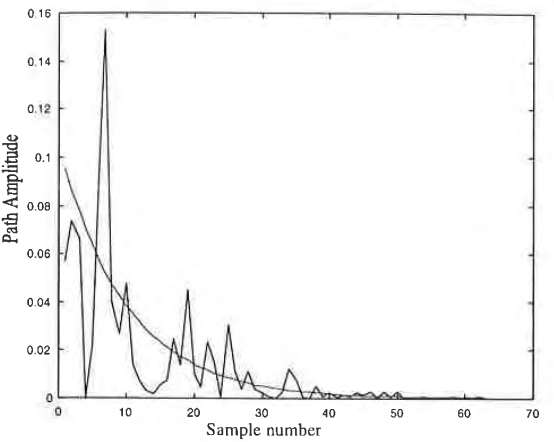


Figure 1.9 Example of generated average and instantaneous power delay profiles for a delay spread of 10 sampling intervals.

1.3.2 Delay Spread Values

Tables 1.3 to 1.5 summarize some delay spread results obtained from literature for frequencies from 800 MHz to 6 GHz. Two delay spread values are given; the *median* delay spread is the 50% value, meaning that 50% of all channels has a delay spread that is lower than the median value. Clearly, the median value is not so interesting for designing a wireless link, because there you want to guarantee that the link works for at least 90% or 99% of all channels. Therefore, the second column gives the measured *maximum* delay spread values. The reason to use maximum delay spread instead of a 90% or 99% value is that many papers only mention the maximum value. From the papers that do present cumulative distribution functions of their measured delay spreads, we can deduce that the 99% value is only a few percent smaller than the maximum measured delay spread.

Table 1.3
Measured delay spreads in frequency range of 800 MHz to 1.5 GHz.

Median delay spread [ns]	Maximum delay spread [ns]	Reference	Remarks
25	50	[46]	Office building
30	56	[58]	Office building
27	43	[59]	Office building
11	58	[60]	Office building
35 40 80 120	80 90 120 180	[61]	Office building Shopping center Airport Factory
50 120	129 300	[62]	Warehouse Factory

Table 1.4
Measured delay spreads in frequency range of 1.8 to 2.4 GHz

Median delay spread [ns]	Maximum delay spread [ns]	Reference	Remarks
40	120	[49]	Large building (New York stock exchange)
40	95	[50]	Office building
40	150	[51]	Office building
60 106	200 270	[54]	Shopping center Laboratory
19	30	[55]	Office building: single room only
20 30 105	65 75 170	[56]	Office building Cafeteria Shopping center
30	56	[58]	Office building
25	30	[63]	Office building: single room only

Table 1.5
Measured delay spreads in frequency range of 4 to 6 GHz

Median delay spread [ns]	Maximum delay spread [ns]	Reference	Remarks
40	120	[49]	Large building (e.g., Stock Exchange)
50 35 10	60 55 35	[52]	Office building Meeting room (5m x 5m) with metal walls Single room with stone walls
40	130	[51]	Office building
40 65 25	120 125 65	[53]	Indoor sports arena Factory Office building
20	30	[63]	Office building: single room only

Interesting results that can be derived from the reported measurements are:

- Measurements done simultaneously on different frequencies show that there is no significant difference in delay spread in the frequency range of 800 MHz to 6 GHz.
- The delay spread is related to the building size; largest delay spreads (up to 270 ns) were measured in large buildings like shopping centers and factories. The reason for this phenomenon is that reflections can have larger delays if the distances between transmitter and reflectors (walls or other objects) are larger.
- For most office buildings, the maximum delay spread is in the range of 40 to 70 ns. Smaller delay spreads around 30 ns occur when both transmitter and receiver are within the same room. Delay spreads of 100 ns or more are seen only in office buildings with large rooms that are some tens of meters in diameter.
- Even small rooms (5m by 5m) can give significant delay spreads around 50 ns when there are metal walls [52]. The reason for this is that reflections from a metal wall only experience a small attenuation, so multiple reflections with significant delays still have considerable power, which increases the delay spread.

1.4 TIME VARIATION OF THE CHANNEL

To classify the time characteristics of the channel [1], the coherence time and Doppler spread are important parameters. The coherence time is the duration over which the channel characteristics do not change significantly. The time variations of the channel are evidenced as a Doppler spread in the frequency domain, which is determined as the width of the spectrum when a single sinusoid (constant envelope) is transmitted. Both

the time correlation function $\varphi_c(\Delta t)$ and the Doppler power spectrum $S_c(f)$ can be related to each other by applying the Fourier transform.

The range of values of the frequency f over which $S_c(f)$ is essentially nonzero is called the Doppler spread B_d of the channel. Because $S_c(f)$ is related to $\varphi_c(\Delta t)$ by the Fourier transform, the reciprocal of B_d is a measure of the coherence time $(\Delta t)_c$ of the channel; that is, $1/B_d$.

The coherence time $(\Delta t)_c$ is a measure of the width of the time correlation function. Clearly, a slow-changing channel has a large coherence time, or equivalently, a small Doppler spread. The rapidity of the fading can now be determined either from the correlation function $\varphi_c(\Delta t)$ or from the Doppler power spectrum $S_c(f)$. This implies that either the channel parameters $(\Delta t)_c$ or B_d can be used to characterize the rapidity of the fading. If the bit time T_b is large compared with the coherence time, then the channel is subject to fast fading. When selecting a bit duration that is smaller than the coherence time of the channel, the channel attenuation and phase shift are essentially fixed for the duration of at least one signaling interval. In this case, the channel is slowly fading or quasistatic. Like coherence bandwidth, there is no exact relationship between coherence time and Doppler spread. If the coherence time $(\Delta t)_c$ is defined as the time over which the time correlation function is above 0.5, $(\Delta t)_c$ is approximately given by $9/(16\pi B_d)$ [79, 80].

Doppler spread is caused by the differences in Doppler shifts of different components of the received signal, if either the transmitter or receiver is in motion. The frequency shift is related to the spatial angle between the direction of arrival of that component and the direction of vehicular motion. If a vehicle is moving at a constant speed V along the X axis, the Doppler shift f_m of the mth plane-wave component is given by $f_m = (V/\lambda)\cos(\alpha_m)$ [81], where α_m is the arrival angle of the mth plane-wave component relative to the direction of movement of the vehicle. It is worth noting here that waves arriving from ahead of the vehicle experience a positive Doppler shift, while those arriving from behind the vehicle have a negative shift. The maximum Doppler shift occurs at $\alpha_m = 0$, assuming $T_b >> (\Delta t)_c$ for fast-fading channel and $T_b << (\Delta t)_c$ for slow-fading channel.

Indoor measurements [82] show that in any fixed location, temporal variations in the received signal envelope caused by movement of personnel and machinery are slow, having a maximum Doppler spread of about 6 Hz.

1.5 HISTORY OF OFDM

OFDM is a special case of multicarrier transmission, where a single datastream is transmitted over a number of lower rate subcarriers. It is worth mentioning here that OFDM can be seen as either a modulation technique or a multiplexing technique. One

of the main reasons to use OFDM is to increase the robustness against frequency selective fading or narrowband interference. In a single carrier system, a single fade or interferer can cause the entire link to fail, but in a multicarrier system, only a small percentage of the subcarriers will be affected. Error correction coding can then be used to correct for the few erroneous subcarriers. The concept of using parallel data transmission and frequency division multiplexing was published in the mid-1960s [64, 65]. Some early development is traced back to the 1950s [66]. A U.S. patent was filed and issued in January, 1970 [67].

In a classical parallel data system, the total signal frequency band is divided into N nonoverlapping frequency subchannels. Each subchannel is modulated with a separate symbol and then the N subchannels are frequency-multiplexed. It seems good to avoid spectral overlap of channels to eliminate interchannel interference. However, this leads to inefficient use of the available spectrum. To cope with the inefficiency, the ideas proposed from the mid-1960s were to use parallel data and FDM with overlapping subchannels, in which each carrying a signaling rate b is spaced b apart in frequency to avoid the use of high-speed equalization and to combat impulsive noise and multipath distortion, as well as to fully use the available bandwidth.

Figure 1.10 illustrates the difference between the conventional nonoverlapping multicarrier technique and the overlapping multicarrier modulation technique. As shown in Figure 1.10, by using the overlapping multicarrier modulation technique, we save almost 50% of bandwidth. To realize the overlapping multicarrier technique, however we need to reduce crosstalk between subcarriers, which means that we want orthogonality between the different modulated carriers.

The word orthogonal indicates that there is a precise mathematical relationship between the frequencies of the carriers in the system. In a normal frequency-division multiplex system, many carriers are spaced apart in such a way that the signals can be received using conventional filters and demodulators. In such receivers, guard bands are introduced between the different carriers and in the frequency domain which results in a lowering of spectrum efficiency.

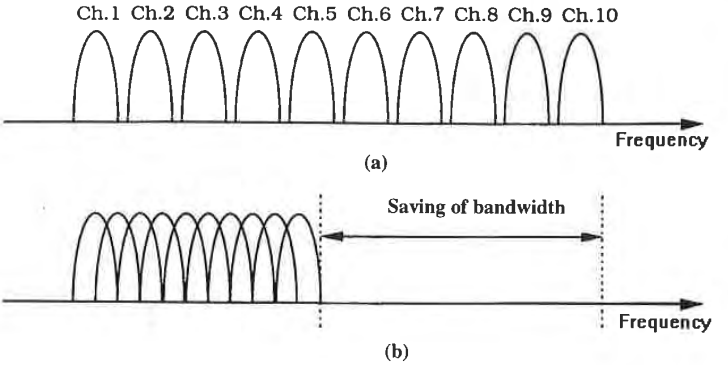


Figure 1.10 Concept of OFDM signal: (a) Conventional multicarrier technique, and (b) orthogonal multicarrier modulation technique.

It is possible, however, to arrange the carriers in an OFDM signal so that the sidebands of the individual carriers overlap and the signals are still received without adjacent carrier interference. To do this the carriers must be mathematically orthogonal. The receiver acts as a bank of demodulators, translating each carrier down to DC, with the resulting signal integrated over a symbol period to recover the raw data. If the other carriers all beat down the frequencies that, in the time domain, have a whole number of cycles in the symbol period T, then the integration process results in zero contribution from all these other carriers. Thus, the carriers are linearly independent (i.e., orthogonal) if the carrier spacing is a multiple of $1/T$. Chapter 2 presents in detail the basic principle of OFDM.

Much of the research focuses on the high efficient multicarrier transmission scheme based on "orthogonal frequency" carriers. In 1971, Weinstein and Ebert [68] applied the discrete Fourier transform (DFT) to parallel data transmission systems as part of the modulation and demodulation process. Figure 1.11 (a) shows the spectrum of the individual data of the subchannel. The OFDM signal, multiplexed in the individual spectra with a frequency spacing b equal to the transmission speed of each subcarrier, is shown in Figure 1.11(b). Figure 1.11 shows that at the center frequency of each subcarrier, there is no crosstalks from other channels. Therefore, if we use DFT at the receiver and calculate correlation values with the center of frequency of each subcarrier, we recover the transmitted data with no crosstalk. In addition, using the DFT-based multicarrier technique, frequency-division multiplex is achieved not by bandpass filtering but by baseband processing.

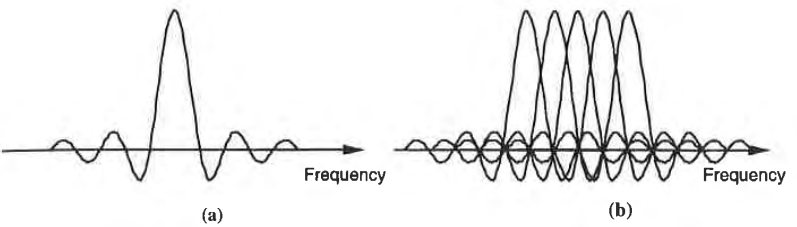


Figure 1.11 Spectra of (a) an OFDM subchannel and (b) an OFDM signal.

Moreover, to eliminate the banks of subcarrier oscillators and coherent demodulators required by frequency-division multiplex, completely digital implementations could be built around special-purpose hardware performing the fast Fourier transform (FFT), which is an efficient implementation of the DFT. Recent advances in very-large-scale integration (VLSI) technology make high-speed, large-size FFT chips commercially affordable. Using this method, both transmitter and receiver are implemented using efficient FFT techniques that reduce the number of operations from N^2 in DFT down to $N\log N$ [69].

In the 1960s, the OFDM technique was used in several high-frequency military systems such as KINEPLEX [66], ANDEFT [70], and KATHRYN [71]. For example, the variable-rate data modem in KATHRYN was built for the high-frequency band. It used up to 34 parallel low-rate phase-modulated channels with a spacing of 82 Hz.

In the 1980s, OFDM was studied for high-speed modems, digital mobile communications, and high-density recording. One of the systems realized the OFDM techniques for multiplexed QAM using DFT [72], and by using pilot tone, stabilizing carrier and clock frequency control and implementing trellis coding are also implemented [73]. Moreover, various-speed modems were developed for telephone networks [74].

In the 1990s, OFDM was exploited for wideband data communications over mobile radio FM channels, high-bit-rate digital subscriber lines (HDSL; 1.6 Mbps), asymmetric digital subscriber lines (ADSL; up to 6 Mbps), very-high-speed digital subscriber lines (VDSL; 100 Mbps), digital audio broadcasting (DAB), and high-definition television (HDTV) terrestrial broadcasting [75–80].

The OFDM transmission scheme has the following key advantages:

- OFDM is an efficient way to deal with multipath; for a given delay spread, the implementation complexity is significantly lower than that of a single carrier system with an equalizer.
- In relatively slow time-varying channels, it is possible to significantly enhance the capacity by adapting the data rate per subcarrier according to the signal-to-noise ratio of that particular subcarrier.

- OFDM is robust against narrowband interference, because such interference affects only a small percentage of the subcarriers.
- OFDM makes single-frequency networks possible, which is especially attractive for broadcasting applications.

On the other hand, OFDM also has some drawbacks compared with single-carrier modulation:

- OFDM is more sensitive to frequency offset and phase noise.
- OFDM has a relatively large peak-to-average power ratio, which tends to reduce the power efficiency of the RF amplifier.

1.6 PREVIEW OF THE BOOK

This book consists of 10 chapters. It covers all the necessary elements to achieve the OFDM-based WBMCS. In Chapter 2, the basics of OFDM are presented. It is explained how an OFDM signal is formed using the inverse fast Fourier transform, how the cyclic extension helps to mitigate the effects of multipath, and how windowing can limit the out-of-band radiation. Basic design rules are given how to choose the OFDM parameters, given a required bandwidth, multipath delay spread, and maximum Doppler spread.

In Chapter 3, we explain how coding and interleaving can be used to mitigate the effects of frequency-selective fading channels. *Quadrature amplitude modulation* is introduced as an appropriate modulation technique for the OFDM subcarriers.

Synchronization of the symbol clock and carrier frequency is the subject of Chapter 4. First, we discuss the sensitivity of OFDM to synchronization errors. Then, we describe different sychronization techniques. Special attention is given to packet transmission, which requires rapid synchronization at the beginning of each packet with a minimum of training overhead.

Chapter 5 describes channel estimation; that is, estimating the reference phases and amplitudes of all subcarriers. Various coherent and differential techniques are explained in conjunction with their relative merits on signal-to-noise ratio performance, overhead, and buffering delay.

The relatively large peak-to-average power (PAP) ratio of OFDM is the subject of Chapter 6. The distribution of the PAP ratio is shown, and various methods to reduce the PAP ratio are explained. This chapter demonstrates that for an arbitrary number of subcarriers, the PAP ratio can be reduced to about 5 dB without a significant loss in performance. This means that the required backoff—and hence the efficiency—of an RF power amplifier for an OFDM system is not much different from that for a single-carrier QPSK system.

In Chapter 7, we explain the basics of direct-sequence and frequency-hopping CDMA, which is especially helpful in understanding the following chapters on combinations of OFDM and CDMA.

Chapter 8 describes multicarrier CDMA. Different techniques with their transmitter and receiver architectures are introduced. Advantages and disadvantages compared with other CDMA techniques are discussed.

Orthogonal FDMA and frequency-hopping CDMA are the subjects of Chapter 9. It shows how OFDM and frequency hopping can be combined to get a multiple-access system with similar advantages as direct-sequence CDMA.

Finally, some applications of OFDM systems are described in Chapter 10: digital audio broadcasting, digital video broadcasting, wireless ATM in the Magic WAND project, and the new IEEE 802.11 and ETSI BRAN OFDM standards.

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Chapter 2

OFDM Basics

2.1 INTRODUCTION

The basic principle of OFDM is to split a high-rate datastream into a number of lower rate streams that are transmitted simultaneously over a number of subcarriers. Because the symbol duration increases for the lower rate parallel subcarriers, the relative amount of dispersion in time caused by multipath delay spread is decreased. Intersymbol interference is eliminated almost completely by introducing a guard time in every OFDM symbol. In the guard time, the OFDM symbol is cyclically extended to avoid intercarrier interference. This whole process of generating an OFDM signal and the reasoning behind it are described in detail in sections 2.2 to 2.4.

In OFDM system design, a number of parameters are up for consideration, such as the number of subcarriers, guard time, symbol duration, subcarrier spacing, modulation type per subcarrier, and the type of forward error correction coding. The choice of parameters is influenced by system requirements such as available bandwidth, required bit rate, tolerable delay spread, and Doppler values. Some requirements are conflicting. For instance, to get a good delay spread tolerance, a large number of subcarriers with a small subcarrier spacing is desirable, but the opposite is true for a good tolerance against Doppler spread and phase noise. These design issues are discussed in Section 2.5. Section 2.6 gives an overview of OFDM signal processing functions, while Section 2. ends this chapter with a complexity comparison of OFDM versus single-carrier systems.

2.2 GENERATION OF SUBCARRIERS USING THE IFFT

An OFDM signal consists of a sum of subcarriers that are modulated by using *phase shift keying (PSK)* or *quadrature amplitude modulation (QAM)*. If d_i are the complex

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QAM symbols, N_s is the number of subcarriers, T the symbol duration, and f_c the carrier frequency, then one OFDM symbol starting at $t = t_s$ can be written as

$$s(t) = \mathrm{Re}\left\{ \sum_{i=-\frac{N_s}{2}}^{\frac{N_s}{2}-1} d_{i+N_s/2} \exp(j2\pi(f_c - \frac{i+0.5}{T})(t-t_s)) \right\} \quad , t_s \le t \le t_s + T \qquad (2.1)$$

$$s(t) = 0 \,, \quad t < t_s \ \wedge \ t > t_s + T$$

In the literature, often the equivalent complex baseband notation is used, which is given by (2.2). In this representation, the real and imaginary parts correspond to the in-phase and quadrature parts of the OFDM signal, which have to be multiplied by a cosine and sine of the desired carrier frequency to produce the final OFDM signal. Figure 2.1 shows the operation of the OFDM modulator in a block diagram.

$$s(t) = \sum_{i=-\frac{N_s}{2}}^{\frac{N_s}{2}-1} d_{i+N_s/2} \exp(j2\pi \frac{i}{T}(t-t_s)) \quad , t_s \le t \le t_s + T \qquad (2.2)$$

$$s(t) = 0 \,, \quad t < t_s \ \wedge \ t > t_s + T$$

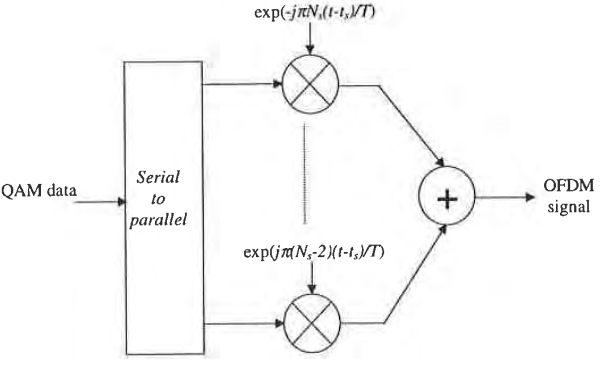


Figure 2.1 OFDM modulator.

As an example, Figure 2.2 shows four subcarriers from one OFDM signal. In this example, all subcarriers have the same phase and amplitude, but in practice the amplitudes and phases may be modulated differently for each subcarrier. Note that each subcarrier has exactly an integer number of cycles in the interval T, and the number of cycles between adjacent subcarriers differs by exactly one. This property accounts for

the orthogonality between the subcarriers. For instance, if the jth subcarrier from (2.2) is demodulated by downconverting the signal with a frequency of j/T and then integrating the signal over T seconds, the result is as written in (2.3). By looking at the intermediate result, it can be seen that a complex carrier is integrated over T seconds. For the demodulated subcarrier j, this integration gives the desired output $d_{j+N/2}$ (multiplied by a constant factor T), which is the QAM value for that particular subcarrier. For all other subcarriers, the integration is zero, because the frequency difference $(i-j)/T$ produces an integer number of cycles within the integration interval T, such that the integration result is always zero.

$$\int_{t_s}^{t_s+T} \exp(-j2\pi \frac{j}{T}(t-t_s)) \sum_{i=-\frac{N_s}{2}}^{\frac{N_s}{2}-1} d_{i+N_s/2} \exp(j2\pi \frac{i}{T}(t-t_s))\,\mathrm{d}t$$
$$= \sum_{i=-\frac{N_s}{2}}^{\frac{N_s}{2}-1} d_{i+N_s/2} \int_{t_s}^{t_s+T} \exp(j2\pi \frac{i-j}{T}(t-t_s))dt = d_{j+N_s/2}T \tag{2.3}$$

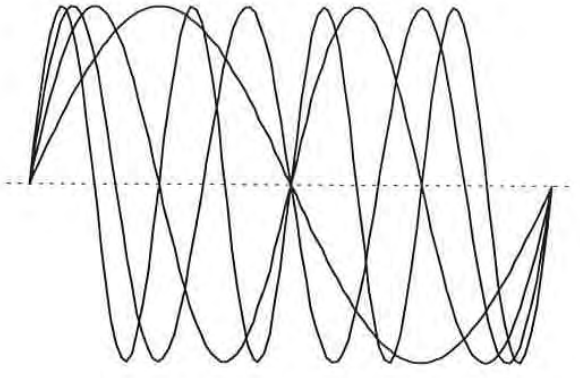


Figure 2.2 Example of four subcarriers within one OFDM symbol.

The orthogonality of the different OFDM subcarriers can also be demonstrated in another way. According to (2.1), each OFDM symbol contains subcarriers that are nonzero over a T-second interval. Hence, the spectrum of a single symbol is a convolution of a group of Dirac pulses located at the subcarrier frequencies with the spectrum of a square pulse that is one for a T-second period and zero otherwise. The amplitude spectrum of the square pulse is equal to $\mathrm{sinc}(\pi fT)$, which has zeros for all frequencies f that are an integer multiple of $1/T$. This effect is shown in Figure 2.2, which shows the overlapping sinc spectra of individual subcarriers. At the maximum of each subcarrier spectrum, all other subcarrier spectra are zero. Because an OFDM

receiver essentially calculates the spectrum values at those points that correspond to the maxima of individual subcarriers, it can demodulate each subcarrier free from any interference from the other subcarriers. Basically, Figure 2.3 shows that the OFDM spectrum fulfills Nyquist's criterium for an intersymbol interference free pulse shape. Notice that the pulse shape is present in the frequency domain and not in the time domain, for which the Nyquist criterium usually is applied. Therefore, instead of inter-symbol interference (ISI), it is intercarrier interference (ICI) that is avoided by having the maximum of one subcarrier spectrum correspond to zero crossings of all the others.

The complex baseband OFDM signal as defined by (2.2) is in fact nothing more than the inverse Fourier transform of N_s QAM input symbols. The time discrete equivalent is the inverse discrete Fourier transform (IDFT), which is given by (2.4), where the time t is replaced by a sample number n. In practice, this transform can be implemented very efficiently by the inverse fast Fourier transform (IFFT). An N point IDFT requires a total of N^2 complex multiplications—which are actually only phase rotations. Of course, there are also additions necessary to do an IDFT, but since the hardware complexity of an adder is significantly lower than that of a multiplier or phase rotator, only the multiplications are used here for comparison. The IFFT drastically reduces the amount of calculations by exploiting the regularity of the operations in the IDFT. Using the radix-2 algorithm, an N-point IFFT requires only $(N/2)\cdot\log_2(N)$ complex multiplications [1]. For a 16-point transform, for instance, the difference is 256 multiplications for the IDFT versus 32 for the IFFT—a reduction by a factor of 8! This difference grows for larger numbers of subcarriers, as the IDFT complexity grows quadratically with N, while the IFFT complexity only grows slightly faster than linear.

$$s(n) = \sum_{i=0}^{N_s-1} d_i \exp(j2\pi \frac{in}{N}) \tag{2.4}$$

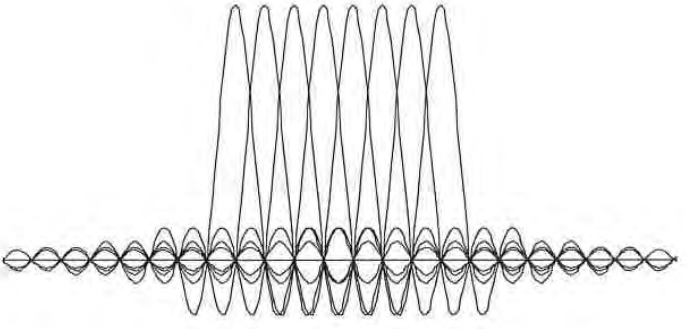


Figure 2.3 Spectra of individual subcarriers.

The number of multiplications in the IFFT can be reduced even further by using a radix-4 algorithm. This technique makes use of the fact that in a four-point IFFT, there are only multiplications by $\{1,-1,j,-j\}$, which actually do not need to be implemented by a full multiplier, but rather by a simple add or subtract and a switch of real and imaginary parts in the case of multiplications by j or $-j$. In the radix-4 algorithm, the transform is split into a number of these trivial four-point transforms, and non-trivial multiplications only have to be performed between stages of these four-point transforms. In this way, an N-point FFT using the radix-4 algorithm requires only $(3/8)N(\log_2 N-2)$ complex multiplications or phase rotations and $N\log_2 N$ complex additions [1]. For a 64-point FFT, for example, this means 96 rotations and 384 additions, or 1.5 and 6 rotations and additions per sample, respectively.

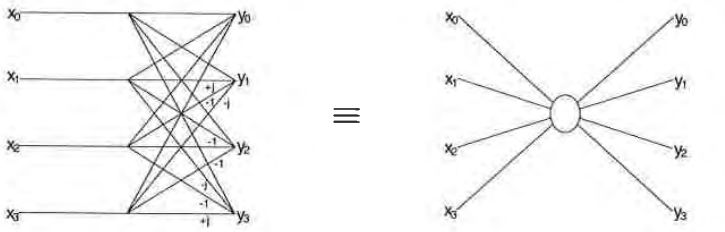


Figure 2.4 The radix-4 butterfly.

Figure 2.4 shows the four-point IFFT, which is known as the *radix-4 butterfly* that forms the basis for constructing larger IFFT sizes [1]. Four input values x_0 to x_3 are transformed into output values y_0 to y_3 by simple additions and trivial phase rotations. For instance, y_1 is given by $x_0 + jx_1 - x_2 - jx_3$, which can be calculated by doing four additions plus a few additional I/Q swappings and inversions to account for the multiplications by j and -1.

The radix-4 butterfly can be used to efficiently build an IFFT with a larger size. For instance, a 16-point IFFT is depicted in Figure 2.5. The 16-point IFFT contains two stages with four radix-4 butterflies, separated by an intermediate stage where the 16 intermediate results are phase rotated by the twiddle factor ω^i, which is defined as $exp(j2\pi i/N)$. Notice that for N=16, rotation by the twiddle factor ω^i reduces to a trivial operation for i=0, 4, 8 and 12, where ω^i is 1, j, -1 and $-j$, respectively. Taking this into account, the 16-point IFFT actually contains only eight non-trivial phase rotations, which is a factor of 32 smaller than the amount of phase rotations for the IDFT. These non-trivial phase rotations largely determine the implementation complexity, because the complexity of a phase rotation or complex multiplication is an order of magnitude larger than the complexity of an addition.

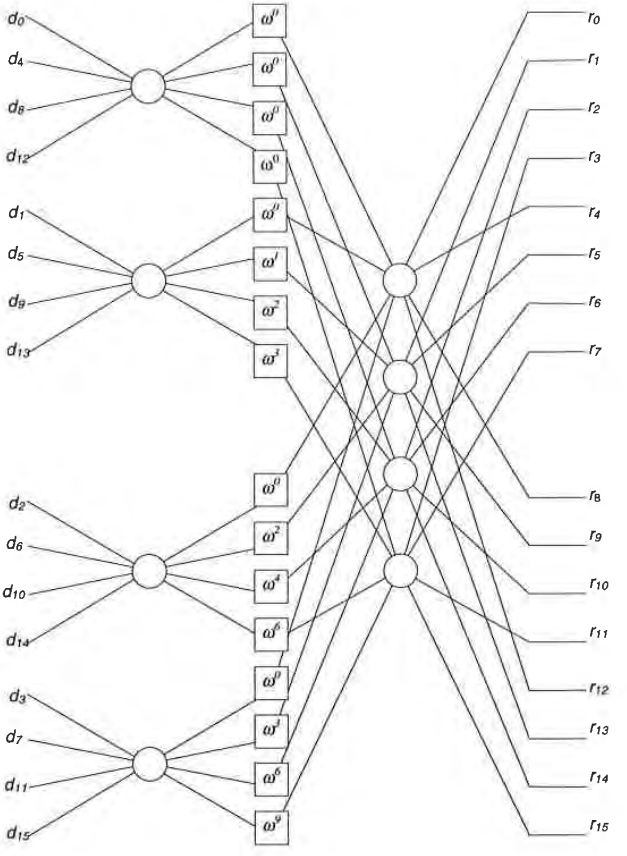


Figure 2.5 16-point IFFT using the radix-4 algorithm.

As an example of how to generate an OFDM symbol, let us assume that we want to transmit eight binary values {1 1 1 –1 1 1 –1 1} on eight subcarriers. The IDFT or IFFT then has to calculate:

$$\frac{1}{8}\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & \frac{1}{2}\sqrt{2}(1+j) & j & \frac{1}{2}\sqrt{2}(-1+j) & -1 & \frac{1}{2}\sqrt{2}(-1-j) & -j & \frac{1}{2}\sqrt{2}(1-j) \\ 1 & j & -1 & -j & 1 & j & -1 & -j \\ 1 & \frac{1}{2}\sqrt{2}(-1+j) & -j & \frac{1}{2}\sqrt{2}(1+j) & -1 & \frac{1}{2}\sqrt{2}(1-j) & j & \frac{1}{2}\sqrt{2}(-1-j) \\ 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 \\ 1 & \frac{1}{2}\sqrt{2}(-1-j) & j & \frac{1}{2}\sqrt{2}(1-j) & -1 & \frac{1}{2}\sqrt{2}(1+j) & -j & \frac{1}{2}\sqrt{2}(-1+j) \\ 1 & -j & -1 & j & 1 & -j & -1 & j \\ 1 & \frac{1}{2}\sqrt{2}(1-j) & -j & \frac{1}{2}\sqrt{2}(-1-j) & -1 & \frac{1}{2}\sqrt{2}(-1+j) & j & \frac{1}{2}\sqrt{2}(1+j) \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 1 \\ -1 \\ 1 \\ 1 \\ -1 \\ 1 \end{bmatrix} = \frac{1}{8}\begin{bmatrix} 4 \\ \sqrt{2}(1+j(\sqrt{2}-1)) \\ 2+2j \\ -\sqrt{2}(1+j(\sqrt{2}+1)) \\ 0 \\ -\sqrt{2}(1-j(\sqrt{2}+1)) \\ 2-2j \\ \sqrt{2}(1-j(\sqrt{2}-1)) \end{bmatrix} \tag{2.5}$$

The left-hand side of (2.5) contains the IDFT matrix, where every column corresponds to a complex subcarrier with a normalized frequency ranging from -4 to +3. The right-hand side of (2.5) gives the eight IFFT output samples that form one OFDM symbol. In practice, however, these samples are not enough to make a real OFDM signal. The reason is that there is no oversampling present, which would introduce intolerable aliasing if one would pass these samples though a digital-to-analog converter. To introduce oversampling, a number of zeros can be added to the input data. For instance, eight zeros could be added to the eight input samples of the previous example, after which a 16-point IFFT can be performed to get 16 output samples of a twice-oversampled OFDM signal. Notice that in the complex IFFT as in (2.5), the first half of the rows correspond to positive frequencies while the last half correspond to negative frequencies. Hence, if oversampling is used, the zeros should be added in the middle of the data vector rather than appending them at the end. This ensures the zero data values are mapped onto frequencies close to plus and minus half the sampling rate, while the nonzero data values are mapped onto the subcarriers around 0 Hz. For the data of the previous example, the oversampled input vector would become {1 1 1 –1 0 0 0 0 0 0 0 0 1 1 –1 1}.

2.3 GUARD TIME AND CYCLIC EXTENSION

One of the most important reasons to do OFDM is the efficient way it deals with multipath delay spread. By dividing the input datastream in N_s subcarriers, the symbol duration is made N_s times smaller, which also reduces the relative multipath delay spread, relative to the symbol time, by the same factor. To eliminate intersymbol interference almost completely, a guard time is introduced for each OFDM symbol. The guard time is chosen larger than the expected delay spread, such that multipath components from one symbol cannot interfere with the next symbol. The guard time could consist of no signal at all. In that case, however, the problem of intercarrier interference (ICI) would arise. ICI is crosstalk between different subcarriers, which means they are no longer orthogonal. This effect is illustrated in Figure 2.6. In this example, a subcarrier 1 and a delayed subcarrier 2 are shown. When an OFDM receiver

tries to demodulate the first subcarrier, it will encounter some interference from the second subcarrier, because within the FFT interval, there is no integer number of cycles difference between subcarrier 1 and 2. At the same time, there will be crosstalk from the first to the second subcarrier for the same reason.

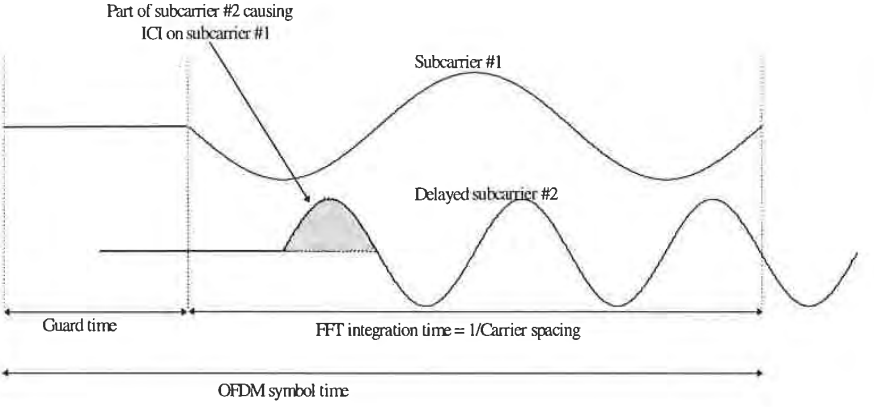


Figure 2.6 Effect of multipath with zero signal in the guard time; the delayed subcarrier 2 causes ICI on subcarrier 1 and vice versa.

To eliminate ICI, the OFDM symbol is cyclically extended in the guard time, as shown in Figure 2.7. This ensures that delayed replicas of the OFDM symbol always have an integer number of cycles within the FFT interval, as long as the delay is smaller than the guard time. As a result, multipath signals with delays smaller than the guard time cannot cause ICI.

As an example of how multipath affects OFDM, Figure 2.8 shows received signals for a two-ray channel, where the dotted curve is a delayed replica of the solid curve. Three separate subcarriers are shown during three symbol intervals. In reality, an OFDM receiver only sees the sum of all these signals, but showing the separate components makes it more clear what the effect of multipath is. From the figure, we can see that the OFDM subcarriers are BPSK modulated, which means that there can be 180-degree phase jumps at the symbol boundaries. For the dotted curve, these phase jumps occur at a certain delay after the first path. In this particular example, this multipath delay is smaller than the guard time, which means there are no phase transitions during the FFT interval. Hence, an OFDM receiver "sees" the sum of pure sine waves with some phase offsets. This summation does not destroy the orthogonality between the subcarriers, it only introduces a different phase shift for each subcarrier. The orthogonality does become lost if the multipath delay becomes larger than the

guard time. In that case, the phase transitions of the delayed path fall within the FFT interval of the receiver. The summation of the sine waves of the first path with the phase modulated waves of the delayed path no longer gives a set of orthogonal pure sine waves, resulting in a certain level of interference.

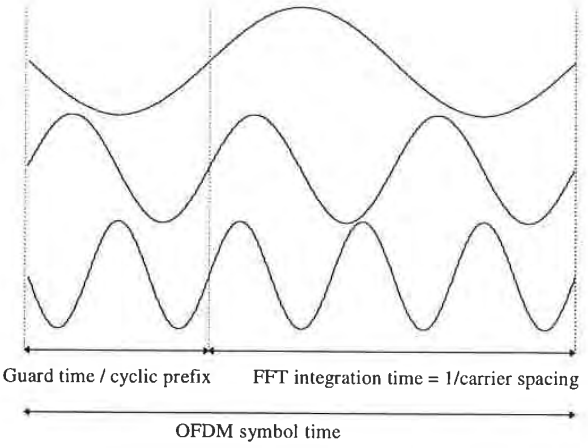


Figure 2.7 OFDM symbol with cyclic extension.

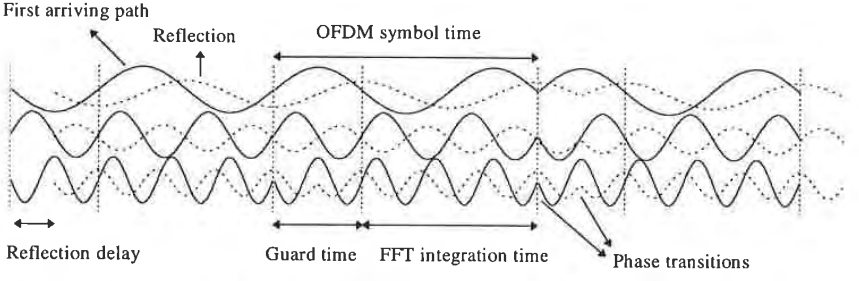
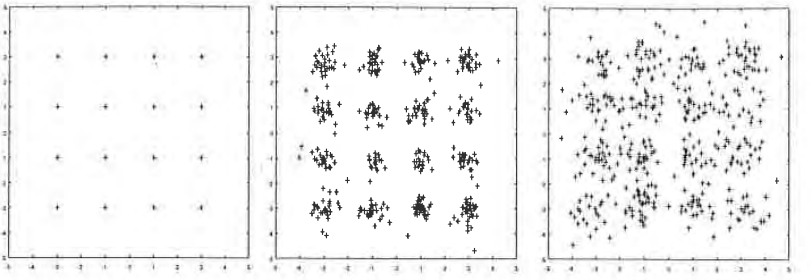


Figure 2.8 Example of an OFDM signal with three subcarriers in a two-ray multipath channel. The dashed line represents a delayed multipath component.

To get an idea what level of interference is introduced when the multipath delay exceeds the guard time, Figure 2.9 depicts three constellation diagrams that were derived from a simulation of an OFDM link with 48 subcarriers, each modulated by using 16-QAM. Figure 2.9(a) shows the undistorted 16-QAM constellation, which is observed whenever the multipath delay is below the guard time. In Figure 2.9(b), the multipath delay exceeds the guard time by a small 3% fraction of the FFT interval.

Hence, the subcarriers are not orthogonal anymore, but the interference is still small enough to get a reasonable received constellation. In Figure 2.9(c), the multipath delay exceeds the guard time by 10% of the FFT interval. The interference is now so large that the constellation is seriously blurred, causing an unacceptable error rate.



(a) (b) (c)

Figure 2.9 16-QAM constellation for a 48-subcarrier OFDM link with a two-ray multipath channel, the second ray being 6 dB lower than the first one. (a) delay < guard time; (b) delay exceeds guard time by 3% of the FFT interval; (c) delay exceeds guard time by 10% of the FFT interval.

2.4 WINDOWING

In the previous sections, it was explained how an OFDM symbol is formed by performing an IFFT and adding a cyclic extension. Looking at an example OFDM signal like in Figure 2.8, sharp phase transitions caused by the modulation can be seen at the symbol boundaries. Essentially, an OFDM signal like the one depicted in Figure 2.8 consists of a number of unfiltered QAM subcarriers. As a result, the out-of-band spectrum decreases rather slowly, according to a sinc function. As an example of this, the spectra for 16, 64, and 256 subcarriers are plotted in Figure 2.10. For larger number of subcarriers, the spectrum goes down more rapidly in the beginning, which is caused by the fact that the sidelobes are closer together. However, even the spectrum for 256 subcarriers has a relatively large –40-dB bandwidth that is almost four times the –3-dB bandwidth.

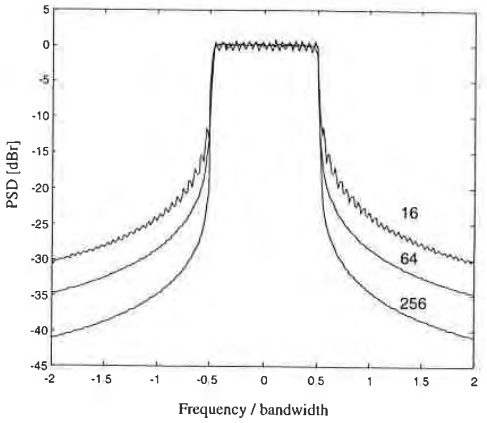


Figure 2.10 Power spectral density (PSD) without windowing for 16, 64, and 256 subcarriers.

To make the spectrum go down more rapidly, windowing can be applied to the individual OFDM symbols. Windowing an OFDM symbol makes the amplitude go smoothly to zero at the symbol boundaries. A commonly used window type is the raised cosine window, which is defined as

$$w(t)=\begin{cases} 0.5+0.5\cos\left(\pi+t\pi/(\beta T_s)\right) & 0 \le t \le \beta T_s \\ 1.0 & \beta T_s \le t \le T_s \\ 0.5+0.5\cos\left((t-T_s)\pi/(\beta T_s)\right) & T_s \le t \le (1+\beta)T_s \end{cases} \qquad (2.6)$$

Here, T_s is the symbol interval, which is shorter than the total symbol duration because we allow adjacent symbols to partially overlap in the roll-off region. The time structure of the OFDM signal now looks like Figure 2.11.

In equation form, an OFDM symbol starting at time $t = t_s = kT_s$ is defined as

$$s_k(t)=\mathrm{Re}\left\{ w(t-t_s)\sum_{i=-\frac{N_s}{2}}^{\frac{N_s}{2}-1} d_{i+N_s(k+1/2)}\exp\left(j2\pi\left(f_c-\frac{i+0.5}{T}\right)(t-t_s-T_{prefix})\right)\right\},\ t_s \le t \le t_s+T_s(1+\beta)$$

$$s_k(t)=0,\ t<t_s \ \wedge\ t>t_s+T_s(1+\beta) \qquad (2.7)$$

In practice, the OFDM signal is generated as follows: first, N_c input QAM values are padded with zeros to get N input samples that are used to calculate an IFFT. Then, the last T_{prefix} samples of the IFFT output are inserted at the start of the OFDM symbol, and the first $T_{postfix}$ samples are appended at the end. The OFDM symbol is then multiplied by a raised cosine window $w(t)$ to more quickly reduce the power of out-of-band subcarriers. The OFDM symbol is then added to the output of the previous OFDM symbol with a delay of T_s, such that there is an overlap region of βT_s, where β is the rolloff factor of the raised cosine window.

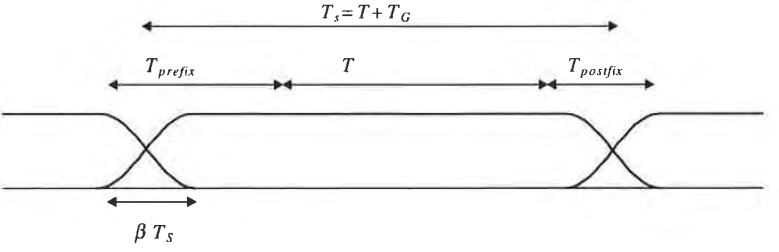


Figure 2.11 OFDM cyclic extension and windowing. T_s is the symbol time, T the FFT interval, T_G the guard time, T_{prefix} the preguard interval, $T_{postfix}$ the postguard interval, and β is the rolloff factor.

Figure 2.12 shows spectra for 64 subcarriers and different values of the rolloff factor β. It can be seen that a rolloff factor of 0.025—so the rolloff region is only 2.5% of the symbol interval—already makes a large improvement in the out-of-band spectrum. For instance, the –40-dB bandwidth is more than halved to about twice the –3-dB bandwidth. Larger rolloff factors improve the spectrum further, at the cost, however, of a decreased delay spread tolerance. The latter effect is demonstrated in Figure 2.13, which shows the signal structure of an OFDM signal for a two-ray multipath channel. The receiver demodulates the subcarriers by taking an FFT over the T-second interval between the dotted lines. Although the relative delay between the two multipath signals is smaller than the guard time, ICI and ISI are introduced because of the amplitude modulation in the gray part of the delayed OFDM symbol. The orthogonality between subcarriers as proved by (2.3) only holds when amplitude and phase of the subcarriers are constant during the entire T-second interval. Hence, a rolloff factor of β reduces the effective guard time by βT_s.

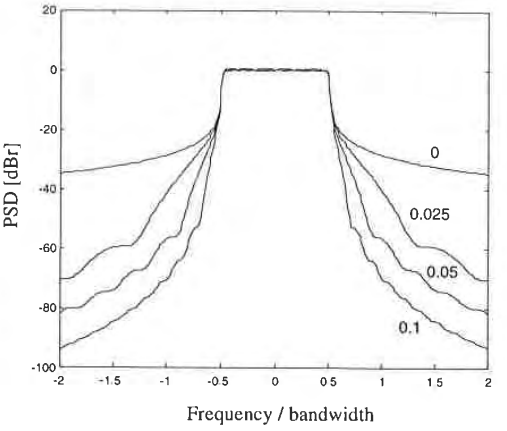


Figure 2.12 Spectra for raised cosine windowing with rolloff factors of 0 (rectangular window), 0.025, 0.05, and 0.1.

Instead of windowing, it is also possible to use conventional filtering techniques to reduce the out-of-band spectrum. Windowing and filtering are dual techniques; multiplying an OFDM symbol by a window means the spectrum is going to be a convolution of the spectrum of the window function with a set of impulses at the subcarrier frequencies. When filtering is applied, a convolution is done in the time domain and the OFDM spectrum is multiplied by the frequency response of the filter. When using filters, care has to be taken not to introduce rippling effects on the envelope of the OFDM symbols over a timespan that is larger than the rolloff region of the windowing approach. Too much rippling means the undistorted part of the OFDM envelope is smaller, and this directly translates into less delay spread tolerance. Notice that digital filtering techniques are more complex to implement than windowing. A digital filter requires at least a few multiplications per sample, while windowing only requires a few multiplications per symbol, for those samples which fall into the rolloff region. Hence, because only a few percent of the samples are in the rolloff region, windowing is an order of magnitude less complex than digital filtering.

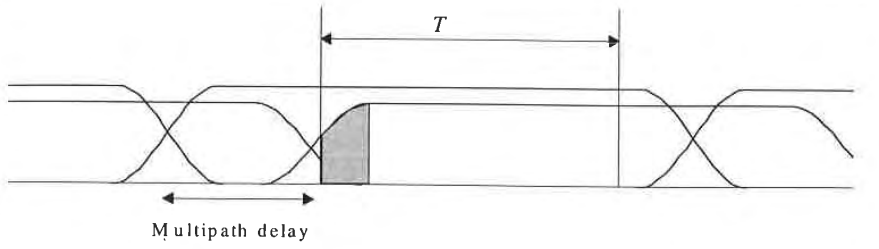


Figure 2.13 OFDM symbol windows for a two-ray multipath channel, showing ICI and ISI, because in the gray part, the amplitude of the delayed subcarriers is not constant.

2.5 CHOICE OF OFDM PARAMETERS

The choice of various OFDM parameters is a tradeoff between various, often conflicting requirements. Usually, there are three main requirements to start with: bandwidth, bit rate, and delay spread. The delay spread directly dictates the guard time. As a rule, the guard time should be about two to four times the root-mean-squared delay spread. This value depends on the type of coding and QAM modulation. Higher order QAM (like 64-QAM) is more sensitive to ICI and ISI than QPSK; while heavier coding obviously reduces the sensitivity to such interference.

Now that the guard time has been set, the symbol duration can be fixed. To minimize the signal-to-noise ratio (SNR) loss caused by the guard time, it is desirable to have the symbol duration much larger than the guard time. It cannot be arbitrarily large, however, because a larger symbol duration means more subcarriers with a smaller subcarrier spacing, a larger implementation complexity, and more sensitivity to phase noise and frequency offset [2], as well as an increased peak-to-average power ratio [3, 4]. Hence, a practical design choice is to make the symbol duration at least five times the guard time, which implies a 1-dB SNR loss because of the guard time.

After the symbol duration and guard time are fixed, the number of subcarriers follows directly as the required –3-dB bandwidth divided by the subcarrier spacing, which is the inverse of the symbol duration less the guard time. Alternatively, the number of subcarriers may be determined by the required bit rate divided by the bit rate per subcarrier. The bit rate per subcarrier is defined by the modulation type (e.g., 16-QAM), coding rate, and symbol rate.

As an example, suppose we want to design a system with the following requirements:

- Bit rate: 20 Mbps
- Tolerable delay spread: 200 ns
- Bandwidth: < 15 MHz

The delay-spread requirement of 200 ns suggests that 800 ns is a safe value for the guard time. By choosing the OFDM symbol duration 6 times the guard time (4.8 μs), the guard time loss is made smaller than 1 dB. The subcarrier spacing is now the inverse of 4.8 – 0.8 = 4 μs, which gives 250 kHz. To determine the number of subcarriers needed, we can look at the ratio of the required bit rate and the OFDM symbol rate. To achieve 20 Mbps, each OFDM symbol has to carry 96 bits of information (96/4.8 μs = 20 Mbps). To do this, there are several options. One is to use 16-QAM together with rate ½ coding to get 2 bits per symbol per subcarrier. In this case, 48 subcarriers are needed to get the required 96 bits per symbol. Another option is to use QPSK with rate ¾ coding, which gives 1.5 bits per symbol per subcarrier. In this case, 64 subcarriers are needed to reach the 96 bits per symbol. However, 64 subcarriers means a bandwidth of 64·250 kHz = 16 MHz, which is larger than the target bandwidth. To achieve a bandwidth smaller than 15 MHz, the number of subcarriers needs to be smaller than 60. Hence, the first option with 48 subcarriers and 16-QAM fulfills all the requirements. It has the additional advantage that an efficient 64-point radix-4 FFT/IFFT can be used, leaving 16 zero subcarriers to provide oversampling necessary to avoid aliasing.

An additional requirement that can affect the chosen parameters is the demand for an integer number of samples both within the FFT/IFFT interval and in the symbol interval. For instance, in the above example we want to have exactly 64 samples in the FFT/IFFT interval to preserve orthogonality among the subcarriers. This can be achieved by making the sampling rate 64/4 μs = 16 MHz. However, for that particular sampling rate, there is no integer number of samples with the symbol interval of 4.8 μs. The only solution to this problem is to change one of the parameters slightly to meet the integer constraint. For instance, the number of samples per symbol can be set to 78, which gives a sampling rate of 78/4.8 μs = 16.25 MHz. Now, the FFT interval becomes 64/16.25 MHz = 3.9385 μs, so both guard time and subcarrier spacing are slightly larger than in the case of the original FFT interval of 4 μs.

2.6 OFDM SIGNAL PROCESSING

The previous sections described how the basic OFDM signal is formed using the IFFT, adding a cyclic extension and performing windowing to get a steeper spectral rolloff. However, there is more to it to build a complete OFDM modem. Figure 2.14 shows the block diagram of an OFDM modem, where the upper path is the transmitter chain and the lower path corresponds to the receiver chain. In the center we see the IFFT, which modulates a block of input QAM values onto a number of subcarriers. In the receiver, the subcarriers are demodulated by an FFT, which performs the reverse operation of an IFFT. An interesting feature of the FFT/IFFT is that the FFT is almost identical to an IFFT. In fact, an IFFT can be made using an FFT by conjugating input and output of the FFT and dividing the output by the FFT size. This makes it possible to use the same hardware for both transmitter and receiver. Of course, this saving in complexity is only possible when the modem does not have to transmit and receive simultaneously.

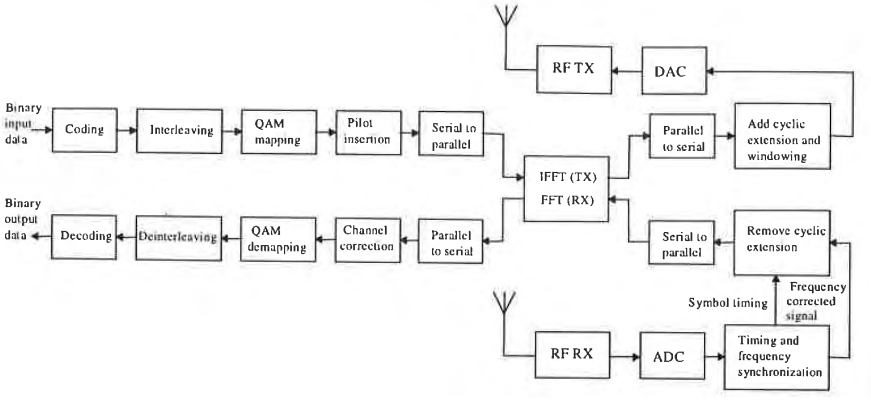


Figure 2.14 Block diagram of an OFDM transceiver.

The functions before the IFFT have not been discussed till now. Binary input data is first encoded by a forward error correction code. The encoded data is then interleaved and mapped onto QAM values. These functions are discussed in more detail in the next chapter.

In the receiver path, after passing the RF part and the analog-to-digital conversion, the digital signal processing starts with a training phase to determine symbol timing and frequency offset. An FFT is used to demodulate all subcarriers. The output of the FFT contains N_s QAM values, which are mapped onto binary values and decoded to produce binary output data. To successfully map the QAM values onto binary values, first the reference phases and amplitudes of all subcarriers have to be acquired. Alternatively, differential techniques can be applied. All of these receiver functions are highlighted in the following chapters.

2.7 IMPLEMENTATION COMPLEXITY OF OFDM VERSUS SINGLE-CARRIER MODULATION

One of the main reasons to use OFDM is its ability to deal with large delay spreads with a reasonable implementation complexity. In a single-carrier system, the implementation complexity is dominated by equalization, which is necessary when the delay spread is larger than about 10% of the symbol duration. OFDM does not require an equalizer. Instead, the complexity of an OFDM system is largely determined by the FFT, which is used to demodulate the various subcarriers. In the following example, it is demonstrated that the processing complexity of an OFDM modem can be significantly less than that of a single carrier modem, given the fact that both can deal with the same amount of delay spread. Notice that some papers mention the use of a

single-tap equalizer for OFDM, when they are referring to the phase correction in case of a coherent OFDM receiver. We will not use this somewhat confusing terminology, because the term equalization suggests that an attempt is made to invert the channel, while an OFDM receiver is doing the opposite; weak subcarriers are not being extra amplified to equalize the channel, but rather, they get a low weight in the decoding. In this way, OFDM avoids the problem of noise enhancement that is present in linear equalization techniques.

Figure 2.15 shows the block diagram of a decision feedback equalizer with symbol-spaced taps. Such an equalizer can be used to combat delay spread in single-carrier systems using quadrature amplitude modulation (QAM) or some form of constant amplitude modulation such as Gaussian Minimum Shift Keying (GMSK) or offset-QPSK. From references [5, 6], it can be learned that at least 8 feedforward and 8 feedback taps are required to handle a delay spread of 100 ns for a GMSK modem at a data rate of 24 Mbps. We can use this information to compare a single carrier system with the 24 Mbps mode of the new IEEE 802.11 OFDM standard, which can handle delay spreads up to 250 ns using a 64-point FFT. In order to increase the delay spread tolerance of a GMSK modem to the same level, the equalizer length has to be increased by a factor of 250/100, so it has 20 feedforward and feedback taps. Fortunately, for GMSK only the real outputs of the complex multiplications are used, so each multiplier has to perform two real multiplications per sample. Hence, the number of real multiplications per second becomes $2 \cdot 20 \cdot 24 \cdot 10^6 = 960 \cdot 10^6$. Notice we only count the feedforward taps here, since the feedback taps consist of trivial rotations, while the feedforward taps consist of full multiplications. For the OFDM system, a 64-point FFT has to be processed by every OFDM symbol duration which is 4 μs, see chapter 10. With a radix-4 algorithm, this requires 96 complex multiplications [1], which gives a processing load of $96 \cdot 10^6$ real multiplications per second. So, in terms of multiplications per second, the equalizer of the single carrier system is 10 times more complex than the FFT of the OFDM system! This complexity difference grows with the bit rate, or rather with the bandwidth – delay spread product, which is a measure of the relative amount of inter-symbol interference. For instance, if we want to double the bit rate in the previous example by doubling the bandwidth, but the delay spread tolerance has to stay the same, then the number of subcarriers and the guard time has to be doubled for OFDM, while for the single-carrier system, both the number of equalizer taps and the sampling rate are doubled. The latter means that the number of multiplications per second is quadrupled, so the equalizer complexity grows quadratically with the bandwidth – delay spread product. For OFDM, a double-sized FFT has to be calculated in the same amount of time in order to double the rate. For the radix-2 algorithm, this means an increase in the number of multiplications of $N\log_2(2N)/(N/2)\log_2 N = 2(1+1/\log_2 N)$, where N is the FFT size for the half-rate system. The complexity of the FFT grows only slightly faster than linear with the bandwidth – delay spread product, which explains why OFDM is more attractive than a single carrier system with equalization for relatively large bandwidth – delay spread products (values around 1 or larger). It should be noted that the complexity difference between the FFT and the equalizer is less if the equalization is done in the frequency domain, as

described in [7]. In this case, equalization is twice as complex, because both an FFT and an IFFT have to be performed to do frequency domain equalization on a signal block.

Another complexity advantage of OFDM is the fact that the FFT does not really require full multiplications, but rather phase rotations, which can be efficiently implemented by the CORDIC algorithm [8]. Because phase rotations do not change the amplitude, they do not increase the dynamic range of the signals, which simplifies the fixed point design.

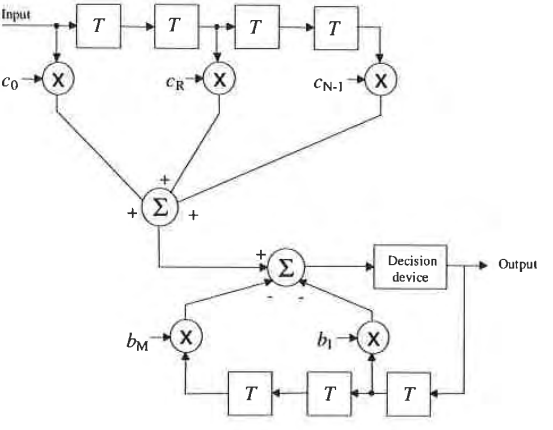


Figure 2.15 Decision-feedback equalizer.

Except for the difference in complexity, OFDM has another advantage over single carrier systems with equalizers. For the latter systems, the performance degrades abruptly if the delay spread exceeds the value for which the equalizer is designed. Because of error propagation, the raw bit error probability increases so quickly that inroducing lower rate coding or a lower constellation size does not significantly improve the delay spread robustness. For OFDM, however, there are no such nonlinear effects as error propagation, and coding and lower constellation sizes can be employed to provide fallback rates that are significantly more robust against delay spread. This is an important consideration, as it enhances the coverage area and avoids the situation that users in bad spots cannot get any connection at all.

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Exhibit 1022

COMPUTER NETWORKS

A Systems Approach

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FOREWORD

David Clark
Massachusetts Institute of Technology

The term *spaghetti code* is universally understood as an insult. All good computer scientists worship the god of modularity, since modularity brings many benefits, including the all-powerful benefit of not having to understand all parts of a problem at the same time in order to solve it. Modularity thus plays a role in presenting ideas in a book, as well as in writing code. If a book's material is organized effectively—modularly—the reader can start at the beginning and actually make it to the end.

The field of network protocols is perhaps unique in that the "proper" modularity has been handed down to us in the form of an international standard: the seven-layer reference model of network protocols from the ISO. This model, which reflects a layered approach to modularity, is almost universally used as a starting point for discussions of protocol organization, whether the design in question conforms to the model or deviates from it.

It seems obvious to organize a networking book around this layered model. However, there is a peril to doing so, because the OSI model is not really successful at organizing the core concepts of networking. Such basic requirements as reliability, flow control, or security can be addressed at most, if not all, of the OSI layers. This fact has led to great confusion in trying to understand the reference model. At times it even requires a suspension of disbelief. Indeed, a book organized strictly according to a layered model has some of the attributes of spaghetti code.

Which brings us to this book. Peterson and Davie follow the traditional layered model, but they do not pretend that this model actually helps in the understanding of the big issues in networking. Instead, the authors organize discussion of fundamental concepts in a way that is independent of layering. Thus, after reading the book, readers will understand flow control, congestion control, reliability enhancement, data representation, and synchronization, and will separately understand the implications of addressing these issues in one or another of the traditional layers.

This is a timely book. It looks at the important protocols in use today—especially the Internet protocols. Peterson and Davie have a long involvement in and much experience with the Internet. Thus their book reflects not just the theoretical issues in protocol design, but the real factors that matter in practice. The book looks at some of the protocols that are just emerging now, so the reader can be assured of an up-to-date perspective. But most importantly, the discussion of basic issues is presented in a way that derives from the fundamental

nature of the problem, not the constraints of the layered reference model or the details of today's protocols. In this regard, what this book presents is both timely and timeless. The combination of real-world relevance, current examples, and careful explanation of fundamentals makes this book unique.

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PREFACE

Without question, computer networking is one of the most exciting computer science topics to emerge in recent years. The media have done a more than adequate job of popularizing networking, and examples of its rapid spread are plentiful: *USA Today* regularly publishes the addresses of interesting World Wide Web sites; we are encouraged to send comments to *NBC Nightly News* via Internet mail; both the White House and Congress are online (as is Her Majesty's Treasury); and, perhaps most impressively, it is possible to order pizza over the Internet. Surely any technology that receives this much attention must be worth understanding.

The concern, of course, is that there might be little or no intellectual substance once we get beyond the buzzwords. Fortunately, this is not the case. When we peel away all the hype, the field of computer networking contains a wealth of interesting problems and clever solutions founded on solid underlying principles. The challenge is to identify and understand these principles. That is why we decided to write this book. Our intent is that the book should serve as the text for an introductory networking class, at either the graduate or upper-division undergraduate level. We also believe that the book's focus on core concepts should be appealing to industry professionals who are retraining for network-related assignments, as well as current network practitioners who want to understand the "whys" behind the protocols they work with every day.

Approach

It is our experience that people learning about networks for the first time often have the impression that network protocols are some sort of edict handed down from on high, and that their job is to learn as many TLAs (Three Letter Acronyms) as possible. In fact, protocols are the building blocks of a complex system developed through the application of engineering design principles. Moreover, they are constantly being refined, extended, and replaced based on real-world experience. With this in mind, our goal with this book is to do more than survey the protocols in use today. Instead, we explain the underlying principles of sound network design.

This goal implies several things about our approach. Perhaps most importantly, the book takes a systems-oriented view of computer networking. What we mean by this is that the book identifies the underlying building blocks, shows how they can be glued together to con-

struct a complete network, measures the resulting system experimentally, and uses this data to quantitatively analyze various design options. This is in contrast to looking at networking through the eyes of a standardization body, a telephone company executive, or a queuing theorist.

In keeping with our systems perspective, this book explains *why* networks are designed the way they are. It does this by starting from first principles, rather than by simply marching through the set of protocols that happen to be in use today. Moreover, we do not adhere to a rigidly layerist point of view, but instead allow ourselves to address issues that cannot be neatly packaged in any single layer. It is our experience that once you understand the underlying concepts, any new protocol that you are confronted with—especially one that cannot be pigeonholed in an existing layer—will be relatively easy to digest. Given the volatility and explosive growth of networking in the 1990s, this focus on principles rather than artifacts is well justified.

The book does two things to help make these underlying concepts more tangible. First, it draws heavily from the lessons of the Internet. As a functioning, global network, the Internet is rich with examples that illustrate how networks are designed in practice. This book exploits the Internet experience in several ways: as a road map that guides the organization of this book, as a source of examples that illustrate the fundamental ideas underlying computer networks, and as a set of design principles that color our way of looking at computer networks. Second, the book includes code segments from a working network subsystem—the *x*-kernel. The book is not an exhaustive inspection of the code. Rather, snippets of *x*-kernel code are given throughout the book to help make the discussion more concrete. The basic strategy is to provide you with not only an understanding of the components of a network, but also a feel for how all the pieces are put together.

How to Use This Book

The chapters of this book can be organized into three groups:

- Introductory material: Chapters 1–2.
- Core topics: Chapters 3–6.
- Advanced topics: Chapters 7–9.

For an undergraduate course, extra class time will most likely be needed to help students digest the introductory material in the first two chapters, probably at the expense of the more advanced topics covered in Chapters 7 through 9. In contrast, the instructor for a graduate course should be able to cover the first two chapters in only a few lectures—with students studying the material more carefully on their own—thereby freeing up additional class time to cover the last three chapters in depth. Both graduate and undergraduate classes will want to cover the core material contained in the middle four chapters, although an undergraduate class might choose to skim the more advanced sections (e.g., 3.2, 3.8, 4.4, and 5.5).

For those of you using the book in self-study, we believe that the topics we have selected cover the core of computer networking, and so we recommend that the book be read sequentially, from front to back. In addition, we have included a liberal supply of references to help you locate supplementary material that is relevant to your specific areas of interest.

There are several other things to note about the topic selection and organization. First, the book takes a unique approach to the topic of congestion control by pulling all topics related to congestion control and resource allocation together in a single place—Chapter 8. We do this because the problem of congestion control cannot be solved at any one level, and we want you to consider the various design options at the same time. (This is consistent with our view that strict layering often obscures important design tradeoffs.) A more traditional treatment of congestion control is possible, however, by studying Section 8.2 in the context of Chapter 4 and Section 8.3 in the context of Chapter 6.

Second, even though Chapter 9 is the only chapter explicitly labeled *High-Speed Networking*, the topic is covered in substantial depth throughout the book. For example, Section 3.8 discusses the role played by network adaptors in delivering high throughput, 4.3 describes ATM networks, 4.4 describes hardware switches used in high-speed networks, 7.2 discusses MPEG video compression, and 8.5 discusses resource reservation. In addition, video applications are used throughout the book to motivate various design decisions. In short, high-speed networking is becoming commonplace, and we believe that it no longer deserves to be treated purely as an advanced topic.

Third, example code from the x-kernel is used throughout the book to illustrate important concepts, with an overview of the x-kernel given in Chapter 2. How much time you spend studying Chapter 2 depends, of course, on how you plan to use the x-kernel throughout the rest of the book. We envision the code being used at one of three levels.

- The code can be *ignored*. Each of the chapters contains a complete discussion of the topic at hand; the code simply punctuates this discussion with tangible evidence that the ideas being presented can be put to practice.
- The code can be *read*. While this certainly involves some effort, the investment is relatively low (the x-kernel was explicitly designed to support network software and so has a high "signal-to-noise" ratio) and the payoff is real (you can see firsthand how the underlying ideas are realized in practice).
- The code can be *written*. Because the complete code is available online, it can be used to provide hands-on experience. Some of the exercises at the end of each chapter suggest programming assignments that you can do using the x-kernel.

Additional information on how (and why) to use the x-kernel is given on page xx.

Finally, the book has several features that we encourage you to take advantage of.

- Each chapter begins with a *Problem* that identifies the next set of issues that must be addressed in the design of a network. Each problem statement introduces the issues

to be explored in the chapter that follows and outlines individual topics covered in that chapter.

- *Shaded sidebars* throughout the text elaborate on the topic being discussed or introduce a related advanced topic. In many cases, these sidebars relate real-world anecdotes about networking.
- Key paragraphs are *highlighted* and marked in the margin with an icon. These paragraphs often summarize an important nugget of information that we want you to take away from the discussion. In many cases, this nugget is a system design principle that you will see applied in many different situations.
- Even though the book's focus is on core concepts rather than existing protocol specifications, real protocols are used to illustrate most of the important ideas. As a result, the book can be used as a source of reference for these example protocols. To help you find the descriptions of the protocols, each applicable section heading parenthetically identifies the protocols defined in that section. For example, Section 6.2, which describes the principles of reliable end-to-end protocols, provides a detailed description of TCP, the canonical example of such a protocol.
- We conclude the main body of each chapter with an *Open Issue.* The idea of this section is to expose you to various unresolved issues that are currently being debated in the research community, the commercial world, and/or society as a whole. We have found that discussing these issues helps to make the subject of networking more relevant and exciting.
- As part of the Further Reading section at the end of each chapter, a specific *recommended reading list* is given. This list generally contains the seminal papers on the topics discussed in the chapter. We strongly recommend that advanced readers (e.g., graduate students) study the papers in this reading list to supplement the material covered in the chapter.

Software

As mentioned above, this book uses the x-kernel to illustrate how network software is implemented. The x-kernel was designed to support the rapid implementation of efficient network protocols. A protocol implementation can be done rapidly because the x-kernel provides a set of high-level abstractions that are tailored specifically to support protocol implementations. x-kernel protocols are efficient because these abstractions are themselves implemented using highly optimized data structures and algorithms. In fact, the world speed record for delivering network data from an ATM network into a desktop workstation—516 Mbps—is held by the x-kernel at the time of this printing.

Because the x-kernel has the dual goals of running fast and making it easy to implement protocols, it has also proved to be an invaluable pedagogical tool, one that is used extensively in

the *Principles of Computer Networking* class at the University of Arizona. There are two aspects to the pedagogical value of the *x*-kernel. First, because the *x*-kernel defines a concise framework for implementing protocols, it can be viewed as simply codifying the essential elements of network protocols. An intimate understanding of the interfaces provided by the *x*-kernel necessarily means appreciating the mechanisms found in all protocols. Second, it provides a convenient means for students to get hands-on experience with network protocols—students are able both to implement protocols and to evaluate their performance.

On the subject of "hands-on experience," many of the exercises at the end of each chapter suggest programming assignments that can be done, some (but not all) of which use the *x*-kernel. Typically, these assignments take on one of the following four forms:

- Write a small program that tests or measures some narrow aspect of a network system. These assignments are independent of the *x*-kernel.
- Run and measure existing protocols currently distributed with the *x*-kernel. Sometimes these assignments involve making simple modifications to existing *x*-kernel code.
- Implement and evaluate standard protocols based on existing protocol specifications. These assignments use the *x*-kernel as a protocol implementation framework.
- Design, implement, and evaluate new protocols from scratch. These assignments use the *x*-kernel as a protocol implementation framework.

For these assignments, students typically run the *x*-kernel as a user process on Unix workstations connected by an Ethernet. Several flavors of Unix are currently supported, including SunOS, Solaris, OSF/1, IRIX, and Linux. In this case, the *x*-kernel generates packets that are delivered between machines over the Ethernet. An alternative is to run the *x*-kernel in *simulation mode*, again on top of Unix. In this case, networks with arbitrary topology, bandwidth, and delay characteristics can be simulated as a single Unix process.

The *x*-kernel source code is available via anonymous `ftp` to `cs.arizona.edu`, `cd`'ing to directory `xkernel`, and accessing file `xkernel.tar.Z`. You can also find the *x*-kernel home page on the Web at URL

`http://www.cs.arizona.edu/xkernel`

This page includes a link to online documentation, as well as instructions on how to obtain help with the *x*-kernel. Additional information about the *x*-kernel and how it can be used in conjunction with this book can be found at URL

`http://www.mkp.com`

Acknowledgments

This book would not have been possible without the help of so many people. We would like to thank them for their efforts in improving the end result. Before we do so, however, we

should mention that we have done our best to correct the mistakes that the reviewers have pointed out and to accurately describe the protocols and mechanisms that our collegues have explained to us. We alone are responsible for any remaining errors. If you should find any of these, please send email to our publisher, Morgan Kaufmann, at netbugs@mkp.com, and we will endeavor to correct them in future printings of this book.

First and foremost, we would like to thank our series editor, Dave Clark. His involvement in the series played no small part in our decision to write this book with Morgan Kaufmann, and the suggestions, expertise, perspective, and encouragement he offered us throughout the writing process proved invaluable.

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Several other people were kind enough to answer our questions and correct our misunderstandings. Rich Salz and Franco Travostino from OSF taught us about NDR. Jeffrey Mogul from Digital's Western Research Lab and John Wroclawski from MIT helped us understand how fast workstations can switch packets. Gregg Townsend from the University of Arizona explained how GIF works. Gail Lalk and Tom Robe of Bellcore answered questions about SONET.

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Finally, we wish to thank our long-suffering wives, Lynn Peterson and Jody Davie, who put up with our complete obsession with the book (and consequent neglect of our families), especially in the final months of writing.

PROBLEM

What Do We Do with the Data?

It is a capital mistake to theorize before one has data.

—Conan Doyle

Our focus up to this point has been on the hierarchy of protocols that deliver messages from one process to another. What we sometimes forget is that these messages carry data—information that is somehow meaningful to the application processes using the network. While this data is by nature application-specific, there are certain common transformations that application programs apply to their data before they send it. This chapter considers three such transformations: presentation formatting, compression, and encryption. These transformations are sometimes called *data manipulations.*

Presentation formatting has to do with translating data from the representation used internally by the application program into a representation that is suitable for transmission over a network. It is concerned with how different data types (e.g., integers, floating-point numbers, character strings) are encoded in messages and with the fact that different machines typically use different encodings. Presentation formatting also deals with the representation of complex data structures (which may include pointers that have only local significance) in a way that they can be transmitted to a remote machine.

Compression is concerned with reducing the number of bits it takes to represent a particular piece of data, with the goal being to transmit the data using as little network bandwidth as possible. Data is typically compressed before it is given to the transport protocol on the sending side and then decompressed on the receiving side before the application begin to process it.

The third transformation, *encryption*, is used to ensure that anyone who might be eavesdropping on the network—that is, snooping packets as they fly by on a shared-access network or as they sit in a router queue—is not able to read the data in the message. Encryption is also used to authenticate participants and to ensure message integrity.

One of the important aspects of the data manipulations studied in this chapter is that they involve processing every byte of data in the message. This is in contrast to most of the protocols we have seen up to this point, which process a mes-

sage without ever looking at its contents. Because of this need to read, compute on, and write every byte of data in a message, data manipulations strongly affect the end-to-end throughput we can achieve over a network. In fact, these manipulations are often the limiting factor.

Note that there is a fourth common function that processes every byte of data in a message—error checking. We considered error checking in an earlier chapter (Section 3.4) because it is usually implemented at lower levels of the protocol hierarchy; it is typically not implemented above the end-to-end protocol.

7

End-to-End Data

7.1 Presentation Formatting

From the network's perspective, application programs send messages to each other. From the application's perspective, however, these messages contain various kinds of *data*—arrays of integers, video frames, lines of text, digital images, and so on. For some of this data, well-established formats have been defined. For example, video is typically transmitted in Moving Pictures Experts Group (MPEG) format, still images are usually transmitted in Joint Photographic Experts Group (JPEG) or Graphical Interchange Format (GIF) format, multimedia documents are transmitted in HyperText Markup Language (HTML) or Multipurpose Internet Mail Extensions (MIME) format, and text is typically transmitted in American Standard Code for Information Interchange (ASCII) format.[1] For other types of data, however, there is no universal agreement about the format; each computer defines its own representation. This is certainly true for the kinds of data that regular programs compute on, such as integers, floating-point numbers, character strings, arrays, and structures.

One of the most common transformations of network data is from the representation used by the application program into a form that is suitable for transmission over a network and vice versa. This transformation is typically called *presentation formatting*. As illustrated in Figure 7.1, the sending program translates the data it wants to transmit from the representation it uses internally into a message that can be transmitted over the network; that is, the data is *encoded* in a message. On the receiving side, the application translates this arriving message into a representation that it can then process; that is, the message is *decoded*. Encoding is sometimes called *argument marshalling*, and decoding is sometimes called *unmarshalling*. This terminology comes from the RPC world, where the client thinks it is invoking a procedure with a set of arguments, but these arguments are then "brought together and ordered in an appropriate and effective way"[2] to form a network message.

You might ask what makes this problem challenging enough to warrant a name like marshalling. One reason is that computers represent data in different ways. For example, some computers represent floating-point numbers in IEEE standard 754 format, while other machines still use their own nonstandard format. Even for something as simple as integers, different architectures use different sizes (e.g., 16 bit, 32 bit, 64 bit). To make matters worse, on some machines integers are represented in *big-endian* form (the most significant bit of a word is in the byte with the highest address), while on other machines integers are represented in *little-endian* form (the most significant bit is in the byte with the lowest address). The Motorola 680x0 is an example of a big-endian architecture and the Intel 80x86 is an example of a little-endian architecture. For example, the big-endian and little-endian representation of the integer 34,677,374 is given in Figure 7.2.

Another reason that marshalling is difficult is that application programs are written in different languages, and even when you are using a single language, there may be more than

[1] We will study GIF, JPEG, and MPEG in Section 7.2, in the context of data compression. In effect, however, these standards combine elements of presentation formatting and data compression.
[2] This is a definition of *marshalling* taken from Webster's New Collegiate Dictionary.

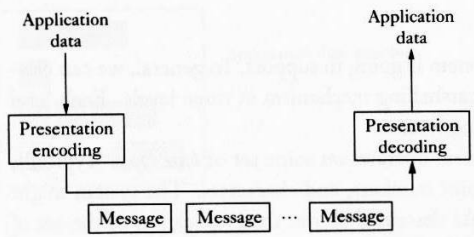


Figure 7.1 Presentation formatting involves encoding and decoding application data.

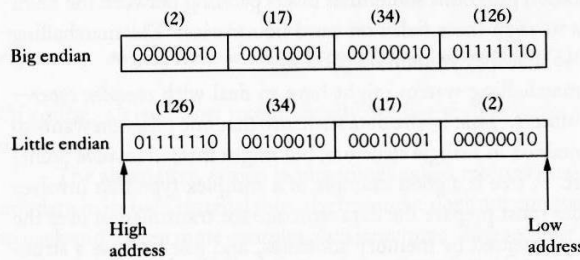


Figure 7.2 Big-endian and little-endian byte order for the integer 34,677,374.

one compiler. For example, compilers have a fair amount of latitude in how they lay out structures (records) in memory, such as how much padding they put between the fields that make up the structure. Thus, you could not simply transmit a structure from one machine to another, even if both machines were of the same architecture and the program was written in the same language, because the compiler on the destination machine might align the fields in the structure differently.

7.1.1 Taxonomy

While anyone who has worked on argument marshalling would tell you that no rocket science is involved—it is a small matter of bit twiddling—there are a surprising number of design choices that you must address. We begin by giving a simple taxonomy for argument marshalling systems. The following is by no means the only viable taxonomy, but it is sufficient to cover most of the interesting alternatives.

Data Types

The first question is what data types the system is going to support. In general, we can classify the types supported by an argument marshalling mechanism at three levels. Each level complicates the task faced by the marshalling system.

At the lowest level, a marshalling system operates on some set of *base types*. Typically, the base types include integers, floating-point numbers, and characters. The system might also support ordinal types and booleans. As described above, the implication of the set of base types is that the encoding process must be able to convert each base type from one representation to another, for example, convert an integer from big-endian to little-endian.

At the next level are *flat types*—structures and arrays. While flat types might at first not appear to complicate argument marshalling, the reality is that they do. The problem is that the compilers used to compile application programs sometimes insert padding between the fields that make up the structure so as to align these fields on word boundaries. The marshalling system typically *packs* structures so that they contain no padding.

At the highest level, the marshalling system might have to deal with *complex types*—those types that are built using pointers. That is, the data structure that one program wants to send to another might not be contained in a single structure, but might instead involve pointers from one structure to another. A tree is a good example of a complex type that involves pointers. Clearly, the data encoder must prepare the data structure for transmission over the network because pointers are implemented by memory addresses, and just because a structure lives at a certain memory address on one machine does not mean it will live at the same address on another machine. In other words, the marshalling system must *linearize* (flatten) complex data structures.

In summary, depending on how complicated the type system is, the task of argument marshalling usually involves converting the base types, packing the structures, and linearizing the complex data structures, all to form a contiguous message that can be transmitted over the network. Figure 7.3 illustrates this task.

Conversion Strategy

Once the type system is established, the next issue is what conversion strategy the argument marshaller will use. There are two general options: *canonical intermediate form* and *receiver-makes-right*. We consider each, in turn.

The idea of canonical intermediate form is to settle on an external representation for each type; the sending host translates from its internal representation to this external representation before sending data, and the receiver translates from this external representation into its local representation when receiving data. To illustrate the idea, consider integer data; other types are treated in a similar manner. You might declare that the big-endian format will be used as the external representation for integers. The sending host must translate each integer it sends into big-endian form and the receiving host must translate big-endian integers into whatever representation it uses. (This is what is done in the Internet for protocol headers.)

Ex.1020 / Page 157 of 250
Intel Corporation and Lenovo (United States) Inc.

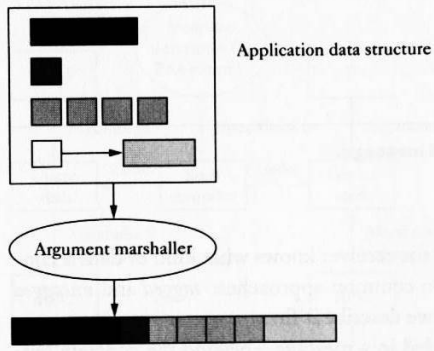


Figure 7.3 Argument marshalling: converting, packing, and linearizing.

Of course, a given host might already use big-endian form, in which case no conversion is necessary.

The alternative, which is sometimes called receiver-makes-right, has the sender transmit data in its own internal format; the sender does not convert the base types, but usually has to pack and flatten more complex data structures. The receiver is then responsible for translating the data from the sender's format into its own local format. The problem with this strategy is that every host must be prepared to convert data from all other machine architectures. In networking, this is known as an *N-by-N solution*: each of N machine architectures must be able to handle all N architectures. In contrast, in a system that uses a canonical intermediate form, each host needs to know only how to convert between its own representation and a single other representation—the external one.

Using a common external format is clearly the correct thing to do, right? This has certainly been the conventional wisdom in the networking community for the past 20 years. The answer is not cut and dried, however. It turns out that there are not that many different representations for the various base classes, or said another way, N is not that large. In addition, the most common case is for two machines of the same type to be communicating with each other. In this situation, it seems silly to translate data from that architecture's representation into some foreign external representation, only to have to translate the data back into the same architecture's representation on the receiver.

A third option, although we know of no existing system that exploits it, is to use receiver-makes-right if the sender knows that the destination has the same architecture; the sender would use some canonical intermediate form if the two machines use different architectures. How would a sender learn the receiver's architecture? It could either learn this information from a name server, or by first using a simple test case to see if the appropriate result occurs.

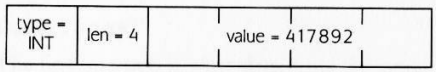


Figure 7.4 A 32-bit integer encoded in a tagged message.

Tags

The third issue in argument marshalling is how the receiver knows what kind of data is contained in the message it receives. There are two common approaches: *tagged* and *untagged* data. The tagged approach is most intuitive, so we describe it first.

A tag is any additional information included in a message—beyond the concrete representation of the base types—that helps the receiver decode the message. There are several possible tags that might be included in a message. For example, each data item might be augmented with a *type* tag. A type tag indicates that the value that follows is an integer, a floating-point number, or whatever. Another example is a *length* tag. Such a tag is used to indicate the number of elements in an array or the size of an integer. A third example is an *architecture* tag, which might be used in conjunction with the receiver-makes-right strategy to specify the architecture on which the data contained in the message was generated. Figure 7.4 depicts how a simple 32-bit integer might be encoded in a tagged message.

The alternative, of course, is not to use tags. How does the receiver know how to decode the data in this case? It knows because it was programmed to know. In other words, if you call a remote procedure that takes two integers and a floating-point number as arguments, then there is no reason for the remote procedure to inspect tags to know what it has just received. It simply assumes that the message contains two integers and a float, and decodes it accordingly. Note that while this works for most cases, the one place it breaks down is when sending variable-length arrays. In such a case, a length tag is commonly used to indicate how long the array is.

It is also worth noting that the untagged approach means that the presentation formatting is truly end to end. It is not possible for some intermediate agent to interpret the message unless the data is tagged. Why would an intermediate agent need to interpret a message, you might ask? Stranger things have happened, mostly resulting from ad hoc solutions to unexpected problems that the system was not engineered to handle. Poor network design is beyond the scope of this book.

Stubs

A stub is the piece of code that implements argument marshalling. Stubs are typically used to support RPC. On the client side, the stub marshals the procedure arguments into a message that can be transmitted by means of the RPC protocol. On the server side, the stub converts the message back into a set of variables that can be used as arguments to call the remote procedure. Stubs can either be interpreted or compiled.

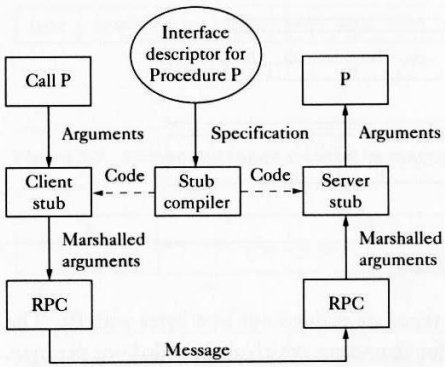


Figure 7.5 Stub compiler takes interface description as input and outputs client and server stubs.

In a compilation-based approach, each procedure has a "customized" client and server stub. This stub is typically generated by a stub compiler, based on a description of the procedure's interface. This situation is illustrated in Figure 7.5. Since the stub is compiled, it is usually very efficient. In an interpretation-based approach, the system provides "generic" client and server stubs that have their parameters set by a description of the procedure's interface. Because it is easy to change this description, interpreted stubs have the advantage of being flexible. Compiled stubs are more common in practice.

7.1.2 Examples (XDR, ASN.1, NDR)

We now briefly describe three popular network data representations in terms of this taxonomy. We use the integer base type to illustrate how each system works.

XDR

External Data Representation (XDR) is the network format used with SunRPC. It supports the C type system but without function pointers, it defines a canonical intermediate form, it does not use tags (except to indicate array lengths), and its stubs are compiled.

An XDR integer is a 32-bit data item that encodes a C integer. It is represented in twos complement notation, with the most significant byte of the C integer in the first byte of the XDR integer, and the least significant byte of the C integer in the fourth byte of the XDR integer. That is, XDR uses big-endian format for integers. XDR supports both signed and unsigned integers, just as C does.

XDR represents variable-length arrays by first specifying an unsigned integer (4 bytes) that gives the number of elements in the array, followed by that many elements of the appropriate type. XDR encodes the components of a structure in the order of their declaration in the structure. For both arrays and structures, the size of each element/component is repre-

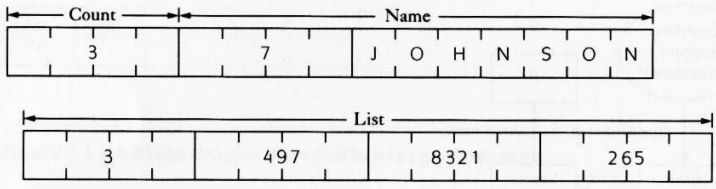


Figure 7.6 Example encoding of a structure in XDR.

sented in a multiple of 4 bytes. Smaller data types are padded out to 4 bytes with 0s. The exception to this "pad to 4 bytes" rule is made for characters, which are encoded one per byte.

The following code fragment gives an example C structure (item) and the XDR routine that encodes/decodes this structure (xdr_item). Figure 7.6 schematically depicts XDR's on-the-wire representation of this structure when the field name is seven characters long and the array list has three values in it.

In this example, xdr_array, xdr_int, and xdr_string are three primitive functions provided by XDR to encode and decode arrays, integers, and character strings, respectively. Argument xdrs is a "context" variable that XDR uses to keep track of where it is in the message being processed; it includes a flag that indicates whether this routine is being used to encode or decode the message. In other words, routines like xdr_item are used on both the client and the server. Note that the application programmer can either write the routine xdr_item by hand or use a stub compiler called rpcgen (not shown) to generate this encoding/decoding routine. In the latter case, rpcgen takes the remote procedure that defines the data structure item as input, and outputs the corresponding stub.

```
#define MAXNAME 256;
#define MAXLIST 100;

struct item {
   int     count;
   char    name[MAXNAME];
   int     list[MAXLIST];
};

bool_t
xdr_item(XDR *xdrs, struct item *ptr)
{
    return(xdr_int(xdrs, &ptr->count) &&
       xdr_string(xdrs, &ptr->name, MAXNAME) &&
       xdr_array(xdrs, &ptr->list, &ptr->count, MAXLIST, sizeof(int), xdr_int));
}
```

Exactly how XDR performs depends, of course, on the complexity of the data. In a simple case of an array of integers, where each integer has to be converted from one byte order to

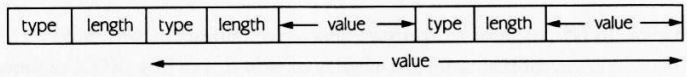


Figure 7.7 Compound types created by means of nesting in ASN.1/BER.

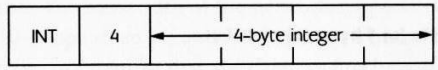


Figure 7.8 ASN.1/BER representation for a 4-byte integer.

another, an average of 2.75 instructions are required for each byte on a DEC Alpha, meaning that converting the whole array is a memory-bound operation. On the 175-MHz Alpha we have been using throughout this book, for example, this means an upper limit on the order of 70 MBps. More complex conversions that require more instructions per byte will run slower.

ASN.1

Abstract Syntax Notation One (ASN.1) is an ISO standard that defines, among other things, a representation for data sent over a network. The representation-specific part of ASN.1 is called the Basic Encoding Rules (BER). ASN.1 supports the C type system without function pointers, defines a canonical intermediate form, uses type tags, and its stubs can be either interpreted or compiled.

ASN.1 represents each data item with a triple of the form

⟨ tag, length, value ⟩.

The tag is typically an 8-bit field, although ASN.1 allows for the definition of multi-byte tags. The length field specifies how many bytes make up the value; we discuss length more below. Compound data types, such as structures, can be constructed by nesting primitive types, as illustrated in Figure 7.7.

If the value is 127 or fewer bytes long, then the length is specified in a single byte. Thus, for example, a 32-bit integer is encoded as a 1-byte type, a 1-byte length, and the 4 bytes that encode the integer, as illustrated in Figure 7.8. The value itself, in the case of an integer, is represented in twos complement notation and big-endian form, just as in XDR. Keep in mind that even though the value of the integer is represented in exactly the same way in both XDR and ASN.1, the XDR representation has neither the type nor the length tags associated with that integer. These two tags both take up space in the message, and more importantly, require processing during marshalling and unmarshalling. This is one reason that ASN.1 is not as efficient as XDR. Another is that the very fact that each data value is preceded by a length field means that the data value is unlikely to fall on a natural byte boundary (e.g., an integer beginning on a word boundary). This complicates the encoding/decoding process.

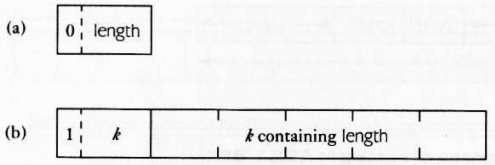


Figure 7.9 ASN.1/BER representation for length: (a) 1 byte; (b) multibyte.

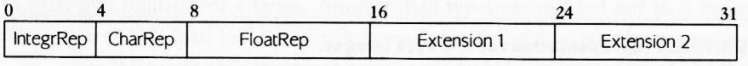


Figure 7.10 NDR's architecture tag.

If the value is 128 or more bytes long, then multiple bytes are used to specify its length. At this point you may be asking why a byte can specify a length of up to 127 bytes rather than 256. The reason is that 1 bit of the length field is used to denote how long the length field is. A 0 in the eighth bit indicates a 1-byte length field. To specify a longer length, the eighth bit is set to 1, and the other 7 bits indicate how many additional bytes make up the length. Figure 7.9 illustrates a simple 1-byte length and a multibyte length.

NDR

Network Data Representation (NDR) is the data-encoding standard used in the Distributed Computing Environment (DCE).[3] Unlike XDR and ASN.1, NDR uses receiver-makes-right. It does this by inserting an architecture tag at the front of each message; individual data items are untagged. NDR uses a compiler to generate stubs. This compiler takes a description of a program written in the Interface Definition Language (IDL) and generates the necessary stubs. IDL looks pretty much like C, and so essentially supports the C type system.

Figure 7.10 illustrates the 4-byte architecture-definition tag that is included at the front of each NDR-encoded message. The first byte contains two 4-bit fields. The first field, IntegrRep, defines the format for all integers contained in the message. A 0 in this field indicates big-endian integers and a 1 indicates little-endian integers. The CharRep field indicates what character format is used: 0 means ASCII and 1 means EBCDIC. Next, the FloatRep byte defines which floating-point representation is being used: 0 means IEEE 754, 1 means VAX, 2 means Cray, and 3 means IBM. The final 2 bytes are reserved for future use.

[3]DCE is defined by the Open Software Foundation (OSF), which is a consortium of companies that includes IBM, Digital, and Hewlett Packard.

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Intel Corporation and Lenovo (United States) Inc.

Note that in simple cases, such as arrays of integers, NDR does the same amount of work as XDR, and so it is able to achieve the same performance.

7.2 Data Compression

It is sometimes the case that application programs need to send more data in a timely fashion than the bandwidth of the network supports. For example, a video application might have a 10-Mbps video stream that it wants to transmit, but it has only a 1-Mbps network available to it. In cases like this, the data can first be *compressed* at the sender, then transmitted over the network, and finally *decompressed* at the receiver.

The field of data compression has a rich history, dating back to Shannon's pioneer work on information theory in the 1940s. If you think of information theory as the study of techniques for encoding data, then compression is about the efficiency of those encodings—how few bits are needed. In a nutshell, data compression is concerned with removing redundancy from the encoding.

In many ways, compression is inseparable from data encoding. That is, in thinking about how to encode a piece of data in a set of bits, we might just as well think about how to encode the data in the smallest set of bits possible. For example, if you have a block of data that is made up of the symbols A through Z, and if all of these symbols have an equal chance of occurring in the data block you are encoding, then encoding each symbol in 5 bits is the best you can do. If, however, the symbol R occurs 50% of the time, then it would be a good idea to use fewer bits to encode the R than any of the other symbols. In general, if you know the relative probability that each symbol will occur in the data, then you can assign a different number of bits to each possible symbol in a way that minimizes the number of bits it takes to encode a given block of data. This is the essential idea of *Huffman codes*, one of the important early developments in data compression.

For our purposes, there are two classes of compression algorithms. The first, called *lossless compression*, ensures that the data recovered from the compression/decompression process is exactly the same as the original data. A lossless compression algorithm is used to compress file data, such as executable code, text files, and numeric data, because programs that process such file data cannot tolerate mistakes in the data. In contrast, *lossy compression* does not promise that the data received is exactly the same as the data sent. This is because a lossy algorithm removes information that it cannot later restore. Hopefully, however, the lost information will not be missed by the receiver. Lossy algorithms are used to compress digital imagery, including video. This makes sense because such data often contains more information than the human eye can perceive, and for that matter, may already contains errors and imperfections that the human eye is able to compensate for. It is also the case that lossy algorithms typically achieve much better compression ratios than do their lossless counterparts; they can be as much as an order of magnitude better.

It might seem that compressing your data before sending it would always be a good idea, since the network would be able to deliver compressed data in less time than uncompressed

data. This is not necessarily the case, however. Compression/decompression algorithms often involve time-consuming computations. The question you have to ask is whether or not the time it takes to compress/decompress the data is worthwhile given such factors as the host's processor speed and the network bandwidth. Specifically, if B_c is the average bandwidth at which data can be pushed through the compressor and decompressor (in series), B_n is the network bandwidth (including network processing costs) for uncompressed data, r is the average compression ratio, and if we assume that all the data is compressed before any of it is transmitted, then the time taken to send x bytes of uncompressed data is x/B_n, whereas the time to compress it and send the compressed data is $x/B_c + x/(rB_n)$. Thus, compression is beneficial if

$$x/B_c + x/(rB_n) < x/B_n$$

which is equivalent to

$$B_c > r/(r-1) \times B_n$$

For example, for a compression ratio of 2, B_c would have to be greater than $2 \times B_n$ for compression to make sense.

7.2.1 Lossless Compression Algorithms

We begin by introducing three lossless compression algorithms. We do not describe these algorithms in much detail—we just give the essential idea—since it is the lossy algorithms used to compress image and video data that are of the greatest interest in today's network environment. We do comment, though, on how well these lossless algorithms work on digital imagery. Some of the ideas exploited by these lossless techniques show up again in later sections when we consider the lossy algorithms that are used to compress images.

Run Length Encoding

Run length encoding (RLE) is a compression technique with a brute-force simplicity. The idea is to replace consecutive occurrences of a given symbol with only one copy of the symbol, plus a count of how many times that symbol occurs; hence the name "run length." For example, the string AAABBCDDDD would be encoded as 3A2B1C4D.

RLE can be used to compress digital imagery by comparing adjacent pixel values and then encoding only the changes. For images that have large homogeneous regions, this technique is quite effective. For example, it is not uncommon that RLE can achieve compression ratios on the order of 8-to-1 for scanned text images. RLE works well on such files because they often contain a large amount of white space that can be removed. In fact, RLE is the key compression algorithm used to transmit faxes. However, for images with even a small degree of local variation, it is not uncommon for compression to actually increase the image byte size, since it takes two bytes to represent a single symbol when that symbol is not repeated.

Differential Pulse Code Modulation

Another simple lossless compression algorithm is Differential Pulse Code Modulation (DPCM). The idea here is to first output a reference symbol, and then for each symbol in the data, to output the difference between that symbol and the reference symbol. For example, using symbol A as the reference symbol, the string AAABBCDDDD would be encoded as A0001123333 since A is the same as the reference symbol, B has a difference of 1 from the reference symbol, and so on. Note that this simple example does not illustrate the real benefit of DPCM, which is that when the differences are small, they can be encoded with fewer bits than the symbol itself. In this example, the range of differences 0–3 can be represented with 2 bits each, rather than the 7 or 8 bits required by the full character. As soon as the difference becomes too large, a new reference symbol is selected.

DPCM works better than RLE for most digital imagery, since it takes advantage of the fact that adjacent pixels are usually similar. Due to this correlation, the dynamic range of the differences between the adjacent pixel values can be significantly less than the dynamic range of the original image, and this range can therefore be represented using fewer bits. Using DPCM, we have measured compression ratios of 1.5-to-1 on digital images.

Dictionary-Based Methods

The final lossless compression method we consider is the dictionary-based approach, of which the Lempel-Ziv (LZ) compression algorithm is the best known. The Unix `compress` command uses a variation of the LZ algorithm.

The idea of a dictionary-based compression algorithm is to build a dictionary (table) of variable-length strings (think of them as common phrases) that you expect to find in the data, and then to replace each of these strings when it appears in the data with the corresponding index to the dictionary. For example, instead of working with individual characters in text data, you could treat each word as a string and output the index in the dictionary for that word. To further elaborate on this example, the word "compression" has the index 4978 in one particular dictionary; it is the 4978th word in `/usr/share/dict/words`. To compress a body of text, each time the string "compression" appears, it would be replaced by 4978. Since this particular dictionary has just over 25,000 words in it, it would take 15 bits to encode the index, meaning that the string "compression" could be represented in 15 bits rather than the 77 bits required by 7-bit ASCII. This is a compression ratio of 5-to-1!

Of course, this leaves the question of where the dictionary comes from. One option is to define a static dictionary, preferably one that is tailored for the data being compressed. A more general solution, and the one used by LZ compression, is to adaptively define the dictionary based on the contents of the data being compressed. In this case, however, the dictionary constructed during compression has to be sent along with the data so that the decompression half of the algorithm can do its job. Exactly how you build an adaptive dictionary has been a subject of extensive research; we discuss important papers on the subject at the end of this chapter.

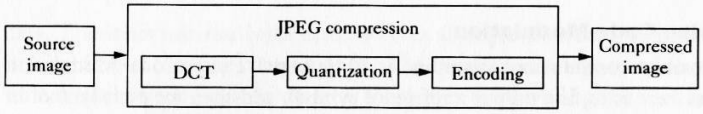


Figure 7.11 Block diagram of JPEG compression.

A variation of the LZ algorithm is used to compress digital images in the Graphical Interchange Format (GIF). Before doing that, GIF first reduces 24-bit color images to 8-bit color images. This is done by identifying the colors used in the picture, of which there will typically be considerably fewer than 2^{24}, and then picking the 256 colors that most closely approximate the colors used in the picture. These colors are stored in a table, which can be indexed with an 8-bit number, and the value for each pixel is replaced by the appropriate index. Note that this is an example of lossy compression for any picture with more than 256 colors. GIF then runs an LZ variant over the result, treating common sequences of pixels as the strings that make up the dictionary. Using this approach, GIF is sometimes able to achieve compression ratios on the order of 10-to-1, but only when the image consists of a relatively small number of discrete colors. Images of natural scenes, which often include a more continuous spectrum of colors, cannot be compressed at this ratio using GIF. As another data point, we were able to get a 2-to-1 compression ratio when we applied the LZ-based Unix `compress` command to the *x*-kernel distribution.

7.2.2 Image Compression (JPEG)

Given the increase in the use of digital imagery in the past few years—this use was spawned by the invention of graphical displays, not high-speed networks—the need for compression algorithms designed for digital imagery data has grown more and more critical. In response to this need, the ISO has defined a digital image format known as JPEG, named after the Joint Photographic Experts Group that designed it. (The "Joint" in JPEG stands for a joint ISO/ITU effort.) This section describes the compression algorithm at the heart of JPEG. The next section then describes a related format—MPEG—that is used for video data.

Before describing JPEG compression, one point that needs to be made is that JPEG, as well as GIF and MPEG, is more than just a compression algorithm. They also define the *format* for image or video data, much the same way that XDR, NDL, and ASN.1 define the format for numeric and string data. However, this section concentrates on the compression aspects of these standards.

JPEG compression takes place in three phases, as illustrated in Figure 7.11. On the compression side, the image is fed through these three phases one 8×8 block at a time. The first phase applies the Discrete Cosine Transform (DCT) to the block. If you think of the image as a signal in the spatial domain, then DCT transforms this signal into an equivalent signal in the *spatial frequency* domain. After the DCT, the second phase applies a quantization

to the resulting signal, and in so doing, loses the least significant bits of that signal. The third phase encodes the final result, but in so doing, adds an element of lossless compression to the lossy compression achieved by the first two phases. Decompression follows these same three phases, but in reverse order.

The following discussion describes each phase in more detail. It is simplified by considering only grayscale images; color images are discussed at the end of this section. In the case of grayscale images, each pixel in the image is given by an 8-bit value that indicates the grayness (brightness) of the pixel, where 0 equals white and 255 equals black.

DCT Phase

DCT is a transformation closely related to the Fast Fourier Transform (FFT). It takes an 8×8 matrix of pixel values as input and outputs an 8×8 matrix of frequency coefficients. You can think of the input matrix as a 64-point signal that is defined in two spatial dimensions (x and y); DCT breaks this signal into 64 spatial frequencies. To get an intuitive feel for spatial frequency, imagine yourself moving across a picture in, say, the x direction. You would see the value of each pixel varying as some function of x. If this value changes slowly with increasing x, then it has a low spatial frequency, and if it changes rapidly, it has a high spatial frequency. So the low frequencies correspond to the gross features of the picture, while the high frequencies correspond to fine detail. The idea behind the DCT is to separate the gross features, which are essential to viewing the image, from the fine detail, which is less essential and, in some cases, might be barely perceived by the eye.

DCT, along with its inverse which is performed during decompression, is defined by the following formulas:

$$DCT(i,j) = \frac{1}{\sqrt{2N}} C(i)C(j) \sum_{x=0}^{N-1} \sum_{y=0}^{N-1} pixel(x,y) \cos\left[\frac{(2x+1)i\pi}{2N}\right] \cos\left[\frac{(2y+1)i\pi}{2N}\right]$$

$$pixel(x,y) = \frac{1}{\sqrt{2N}} \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} C(i)C(j)DCT(i,j) \cos\left[\frac{(2x+1)i\pi}{2N}\right] \cos\left[\frac{(2y+1)i\pi}{2N}\right]$$

$$C(x) = \frac{1}{\sqrt{2}} \quad \text{if } x = 0, \text{ else 1 if } x > 0$$

The first frequency coefficient, at location (0,0) in the output matrix, is called the *DC coefficient*. Intuitively, we can see that the DC coefficient is a measure of the average value of the 64 input pixels. The other 63 elements of the output matrix are called the *AC coefficients*. They add the higher-spatial-frequency information to this average value. Thus, as you go from the first frequency coefficient toward the 64th frequency coefficient, you are moving from low-frequency information to high-frequency information; from the broad strokes of the

image to finer and finer detail. These higher-frequency coefficients are increasingly unimportant to the perceived quality of the image. It is the second phase of JPEG that decides which portion of which coefficients to throw away.

Quantization Phase

The second phase of JPEG is where the compression becomes lossy; DCT does not itself lose information, it just transforms the image into a form that makes it easier to know what information to remove. (Although not lossy, per se, there is of course some loss of precision during the DCT phase due to the use of fixed-point arithmetic.) Quantization is easy to understand—it's simply a matter of dropping the insignificant bits of the frequency coefficients.

To see how the quantization phase works, imagine that you want to compress some whole numbers less than 100, e.g., 45, 98, 23, 66, and 7. If you decided that knowing these numbers truncated to the nearest multiple of 10 is sufficient for your purposes, then you could divide each number by the quantum 10 using integer arithmetic, yielding 4, 9, 2, 6, and 0. These numbers can each be encoded in 4 bits rather than the 7 bits needed to encode the original numbers.

Rather than using the same quantum for all 64 coefficients, JPEG uses a quantization table that gives the quantum to use for each of the coefficients, as specified in the formula given below. You can think of this table (Quantum) as a parameter that can be set to control how much information is lost, and correspondingly, how much compression is achieved. In practice, the JPEG standard specifies a set of quantization tables that have proven effective in compressing digital images; an example quantization table is given in Table 7.1. In tables like this one, the low coefficients have a quantum close to 1 (meaning that little low-frequency information is lost) and the high coefficients have larger values (meaning that more high-frequency information is lost). Notice that as a result of such quantization tables, many of the high-frequency coefficients end up being set to 0 after quantization, making them ripe for further compression in the third phase.

The basic quantization equation is

$$\mathsf{QuantizedValue}(i,j) = \mathsf{IntegerRound}(DCT(i,j)/\mathsf{Quantum}(i,j))$$

where

$$\mathsf{IntegerRound}(x) = \begin{cases} \lfloor x + 0.5 \rfloor & \text{if } x \geq 0 \\ \lfloor x - 0.5 \rfloor & \text{if } x < 0 \end{cases}$$

Decompression is then simply defined as

$$DCT(i,j) = \mathsf{QuantizedValue}(i,j) \times \mathsf{Quantum}(i,j)$$

For example, if the DC coefficient (i.e., DCT(0,0)) for a particular block was equal to 25, then the quantization of this value using Table 7.1 would result in $\lfloor 25/3 + 0.5 \rfloor = 8$. During decompression, this coefficient would then be restored as $8 \times 3 = 24$.

$$\text{Quantum} = \begin{bmatrix} 3 & 5 & 7 & 9 & 11 & 13 & 15 & 17 \\ 5 & 7 & 9 & 11 & 13 & 15 & 17 & 19 \\ 7 & 9 & 11 & 13 & 15 & 17 & 19 & 21 \\ 9 & 11 & 13 & 15 & 17 & 19 & 21 & 23 \\ 11 & 13 & 15 & 17 & 19 & 21 & 23 & 25 \\ 13 & 15 & 17 & 19 & 21 & 23 & 25 & 27 \\ 15 & 17 & 19 & 21 & 23 & 25 & 27 & 29 \\ 17 & 19 & 21 & 23 & 25 & 27 & 29 & 31 \end{bmatrix}$$

Table 7.1 Example JPEG quantization table.

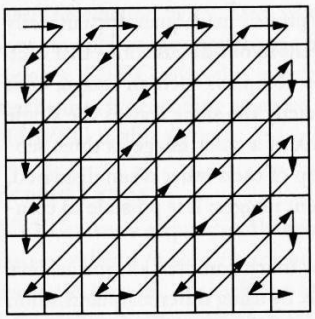


Figure 7.12 Zigzag traversal of quantized frequency coefficients.

Encoding Phase

The final phase of JPEG encodes the quantized frequency coefficients in a compact form. This results in additional compression, but this compression is lossless. Starting with the DC coefficient in position (0,0), the coefficients are processed in the zigzag sequence shown in Figure 7.12. Along this zigzag, a form of run length encoding is used—RLE is applied to only the 0 coefficients, which is significant because many of the later coefficients are 0. The individual coefficient values are then encoded using a Huffman code. (The JPEG standard allows the implementer to use an arithmetic coding instead of the Huffman code.)

In addition, because the DC coefficient contains a large percentage of the information about the 8×8 block from the source image, and images typically change slowly from block

to block, each DC coefficient is encoded as the difference from the previous DC coefficient. This is not unlike the strategy used in DPCM, described in Section 7.2.1.

Color Images

The preceding discussion assumed that each pixel was given by a single grayscale value. In the case of a color image, there are many different representations for each pixel to choose from. One representation, called RGB, represents each pixel with three color components: red, green, and blue. RGB is the representation of color typically supported by graphical input and output devices. Another representation, called YUV, also has three components: one luminance (Y) and two chrominance (U and V). Just like RGB, YUV is a three-dimensional coordinate system. However, compared to RGB, its coordinates are rotated to better match the human visual system. This is advantageous because the human visual system is not uniformly sensitive to colors. For example, we can distinguish the luminance (brightness) of a pixel much better than its hue (color).

Exactly why the three components in each of the two representations can be combined to produce acceptable color is an interesting question. The simple answer is that two-coordinate color systems have been defined, but they have proven inadequate for faithfully reproducing colors as perceived by humans. What is important to our discussion is that each pixel in a color image is given by three separate values. To compress such an image, each of these three components is processed independently in exactly the same way as the single grayscale value was processed. In other words, you can think of a color image as three separate images, where these separate images are overlaid on top of each other when displayed. Note that in general, JPEG is not limited to three-component images; it is possible to compress a multispectral image using JPEG.

JPEG includes a number of variations that control how much compression you achieve versus the fidelity of the image. This can be done, for example, by using different quantization tables. These variations, plus the fact that different images have different characteristics, make it impossible to say with any precision the compression ratios that can be achieved with JPEG. The widely accepted generalization, however, is that JPEG is able to compress 24-bit color images by a ratio of roughly 30-to-1: the image can first be compressed by a factor of three by reducing the 24 bits of color to 8 bits of color (as described for GIF) and then by another factor of 10 by using the algorithm described in this section.

7.2.3 Video Compression (MPEG)

We now turn our attention to the MPEG format, which is named after the Moving Pictures Expert Group that defined it. To a first approximation, a moving picture (i.e., video) is simply a succession of still images (frames) displayed at some video rate. Each of these frames can be compressed using the same DCT-based technique used in JPEG. Stopping at this point would be a mistake, however, because it fails to remove the frame-to-frame redundancy present in a video sequence. For example, two successive frames of video will contain almost identical information if there is not much motion in the scene, so it would be unnecessary to send the

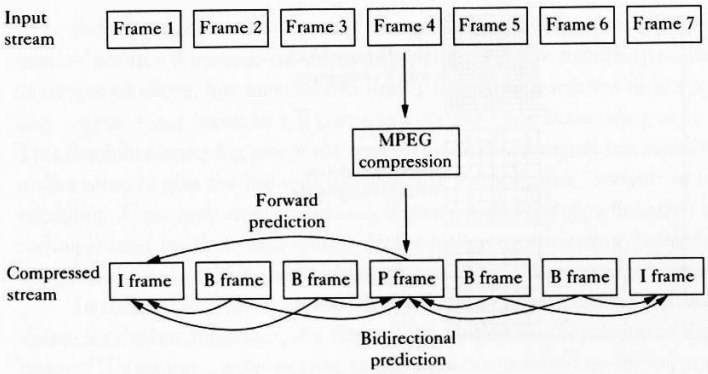


Figure 7.13 Sequence of I, P, and B frames generated by MPEG.

same information twice. Even when there is motion, there may be plenty of redundancy since a moving object may not change from one frame to the next; in some cases, only its position changes. MPEG takes this interframe redundancy into consideration. MPEG also defines a mechanism for encoding an audio signal with the video, but we consider only the video aspect of MPEG in this section.

Frame Types

MPEG takes a sequence of video frames as input and compresses them into three types of frames, called *I frames* (intrapicture), *P frames* (predicted picture), and *B frames* (bidirectional predicted picture). Each frame of input is compressed into one of these three frame types. I frames can be thought of as reference frames; they are self-contained, depending on neither earlier frames nor later frames. To a first approximation, an I frame is simply the JPEG compressed version of the corresponding frame in the video source. P and B frames are not self-contained; they specify relative differences from some reference frame. More specifically, a P frame specifies the differences from the previous I frame, while a B frame gives an interpolation between the previous and subsequent I or P frames.

Figure 7.13 illustrates a sequence of seven video frames that, after being compressed by MPEG, result in a sequence of I, P, and B frames. The two I frames stand alone; each can be decompressed at the receiver independently of any other frames. The P frame depends on the preceding I frame; it can be decompressed at the receiver only if the preceding I frame also arrives. Each of the B frames depend on both the preceding I or P frame and the subsequent I or P frame. Both of these reference frames must arrive at the receiver before MPEG can decompress the B frame to reproduce the original video frame.

Note that because each B frame depends on a later frame in the sequence, the compressed frames are not transmitted in sequential order. Instead, the sequence I B B P B B I

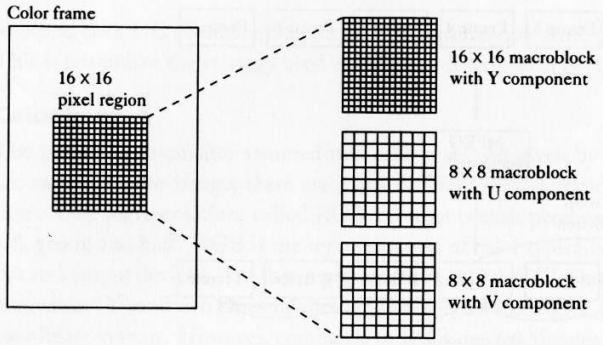


Figure 7.14 Each frame as a collection of macroblocks.

shown in Figure 7.13 is transmitted as I P B B I B B. Also, MPEG does not define the ratio of I frames to P and B frames; this ratio may vary depending on the required compression and picture quality. For example, it is permissible to transmit only I frames. This would be similar to using JPEG to compress the video.

In contrast to the preceding discussion of JPEG, the following focuses on the *decoding* of an MPEG stream. It is a little easier to describe, and it is the operation that is more often implemented in networking systems today, since MPEG coding is so expensive that it is normally done offline, i.e., not in real time. For example, in a video-on-demand system, the video would be encoded and stored on disk ahead of time. When a viewer wanted to watch the video, the MPEG stream would then be transmitted to the viewer's machine which would decode and display the stream in real time.

Let's look more closely at the three frame types. As mentioned above, I frames are approximately equal to the JPEG compressed version of the source frame. The main difference is that MPEG works in units of 16×16 *macroblocks*. For a color video represented in YUV, the U and V components in each macroblock are "down sampled" into an 8×8 block. That is, each 2×2 subblock in the macroblock is given by one U value and one V value—the average of the four pixel values. The subblock still has four Y values. This can be done because the U and V components can be transmitted less accurately without visibly disturbing the image, since humans are less sensitive to color than they are to brightness. The relationship between a frame and the corresponding macroblocks is given in Figure 7.14.

The P and B frames are also processed in units of macroblocks. Intuitively, we can see that the information they carry for each macroblock captures the motion in the video, that is, it shows in what direction and how far the macroblock moved relative to the reference frame(s). The following describes how a B frame is used to reconstruct a frame during decompression; P frames are handled in a similar manner, except that they depend on only one reference frame instead of two.

Before getting to the details of how a B frame is decompressed, we first note that each macroblock in a B frame is not necessarily defined relative to both an earlier and a later frame, as suggested above, but may instead simply be specified relative to just one or the other. In fact, a given macroblock in a B frame can use the same intracoding as is used in an I frame. This flexibility exists because if the motion picture is changing too rapidly, then it sometimes makes sense to give the intrapicture encoding rather than a forward- or backward-predicted encoding. Thus, each macroblock in a B frame includes a type field that indicates which encoding is used for that macroblock. In the following discussion, however, we consider only the general case in which the macroblock uses bidirectional predictive encoding.

In such a case, each macroblock in a B frame is represented with a 4-tuple: (1) a coordinate for the macroblock in the frame, (2) a motion vector relative to the previous reference frame, (3) a motion vector relative to the subsequent reference frame, and (4) a delta (δ) for each pixel in the macroblock (i.e., how much each pixel has changed relative to the two reference pixels). For each pixel in the macroblock, the first task is to find the corresponding reference pixel in the past and future reference frames. This is done using the two motion vectors associated with the macroblock. Then, the delta for the pixel is added to the average of these two reference pixels. Stated more precisely, if we let F_p and F_f denote the past and future reference frames, respectively, and the past/future motion vectors are given by (x_p, y_p) and (x_f, y_f), then the pixel at coordinate (x, y) in the current frame (denoted F_c) is computed as

$$F_c(x, y) = (F_p(x + x_p, y + y_p) + F_f(x + x_f, y + y_f))/2 + \delta(x, y)$$

where δ is the delta for the pixel as specified in the B frame. These deltas are encoded in the same way as pixels in I frames. That is, they are run through DCT and then quantized. Since the deltas are typically small, most of the DCT coefficients are 0 after quantization, hence they can be effectively compressed.

It should be fairly clear from the preceding discussion how encoding would be performed, with one exception. When generating a B or P frame during compression, MPEG must decide where to place the macroblocks. Recall that each macroblock in a P frame, for example, is defined relative to a macroblock in an I frame, but that the macroblock in the P frame need not be in the same part of the frame as the corresponding macroblock in the I frame—the difference in position is given by the motion vector. You would like to pick a motion vector that makes the macroblock in the P frame as similar as possible to the corresponding macroblock in the I frame, so that the deltas for that macroblock can be as small as possible. This means that you need to figure out where objects in the picture moved from one frame to the next. This is the problem of *motion estimation*, and several techniques (heuristics) for solving this problem are known. (We discuss papers that consider this problem at the end of this chapter.) The difficulty of this problem is one of the reasons that MPEG encoding takes longer than decoding on equivalent hardware. MPEG does not specify any particular technique; it only defines the format for encoding this information in B and P frames and the algorithm for reconstructing the pixel during decompression, as given above.

Effectiveness and Performance

MPEG typically achieves a compression ratio of 90-to-1, although ratios as high as 150-to-1 are not unheard of. In terms of the individual frame types, one can expect a compression ratio of approximately 30-to-1 for the I frames (this is consistent with the ratios achieved using JPEG when 24-bit color is first reduced to 8-bit color), while P and B frame compression ratios are typically three to five times smaller than the rates for the I frame. Without first reducing the 24 bits of color to 8 bits, the achievable compression with MPEG is typically between 30-to-1 and 50-to-1.

MPEG involves an expensive computation. On the compression side, it is typically done offline, which is not a problem for preparing movies for a video-on-demand service. Video can be compressed in real time using hardware, but such devices are fairly expensive today. On the decompression side, low-cost MPEG video boards are available, but they do little more than YUV color lookup, which fortunately is the most expensive step. Most of the actual MPEG decoding is done in software. Until recently, processors have not been fast enough to keep pace with 30-frames-per-second video rates when decoding MPEG streams purely in software. With a 175-MHz RISC architecture available in 1994, however, it is possible to decompress MPEG fast enough to keep up with a 320×240 video stream running at 30 frames per second.

7.3 Security

Computer networks are typically a shared resource used by many applications for many different purposes. Sometimes the data transmitted between application processes is confidential, and the applications would prefer that others not be able to read it. For example, when purchasing a product over the World Wide Web, users sometimes transmit their credit card numbers over the network. This is a dangerous thing to do since it is easy for someone to eavesdrop on the network and read all the packets that fly by. Therefore, a third transformation made to data sent over an end-to-end channel is to *encrypt* it, with the goal of keeping anyone who is eavesdropping on the channel from being able to read the contents of the message.

The idea of encryption is simple enough: the sender applies an *encryption* function to the original *plaintext* message, the resulting *ciphertext* message is sent over the network, and the receiver applies a reverse function (called *decryption*) to recover the original plaintext. The encryption/decryption process generally depends on a secret *key* shared between the sender and the receiver. When a suitable combination of a key and an encryption algorithm is used, it is sufficiently difficult for an eavesdropper to break the ciphertext and the sender and receiver can rest assured that their communication is secure.

This familiar use of cryptography is designed to ensure privacy—preventing the unauthorized release of information. Privacy, however, is not the only service that cryptography provides. It can also be used to support other equally important services, including authentication (verifying the identity of the remote participant) and message integrity (making sure that the message has not been altered). This section first introduces the basic idea of

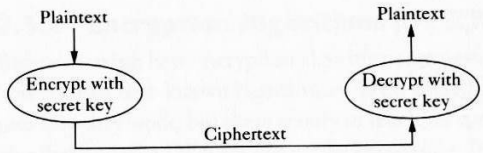


Figure 7.15 Secret key encryption.

cryptography—including a description of the two most common encryption algorithms, the Data Encryption Standard (DES) and Rivest, Shamir, and Adleman (RSA)—and then shows how these algorithms can be used to provide authentication and integrity services.

One thing to keep in mind while reading this section is that the various algorithms and protocols for privacy, authentication, and integrity are being described in isolation. In practice, constructing a secure system requires an intricate combination of just the right set of protocols and algorithms. This is a challenging task because each protocol is vulnerable to a different set of attacks. To make matters worse, determining when a security protocol is "good enough" is as much art and politics as science. A thorough analysis of these different attacks, and how you might build a complete system that minimizes the risk of compromise, is beyond the scope of this book.

7.3.1 Secret Key versus Public Key Cryptography

Broadly speaking, there are two types of cryptographic algorithms: *secret key* algorithms and *public key* algorithms. Secret key algorithms are symmetric in the sense that both participants[4] in the communication share a single key. Figure 7.15 illustrates the use of secret key encryption to transmit data over an otherwise insecure channel. The Data Encryption Standard (DES) is the best-known example of a secret key encryption function.

In contrast to a pair of participants sharing a single secret key, *public key* cryptography involves each participant having a *private* key that is shared with no one else and a *public* key that is published so everyone knows it. To send a secure message to this participant, you encrypt the message using the widely known public key. The participant then decrypts the message using his or her private key. This scenario is depicted in Figure 7.16. RSA—named after its inventors, Rivest, Shamir, and Adleman—is the best-known public key encryption algorithm.

There is actually a third type of cryptography algorithm, called a *hash* or *message digest* function. Unlike the preceding two types of algorithms, cryptographic hash functions involve the use of no keys. Instead, the idea is to map a potentially large message into a small fixed-length number, analogous to the way a regular hash function maps values from a large space into values from a small space.

[4]We use the term *participant* for the parties involved in a secure communication since that is the term we have been using throughout the book to identify the two endpoints of a channel. In the security world, they are typically called *principals*.

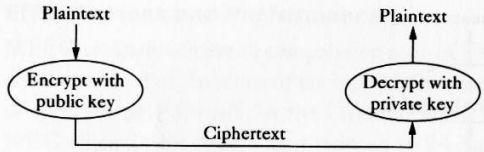


Figure 7.16 Public key encryption.

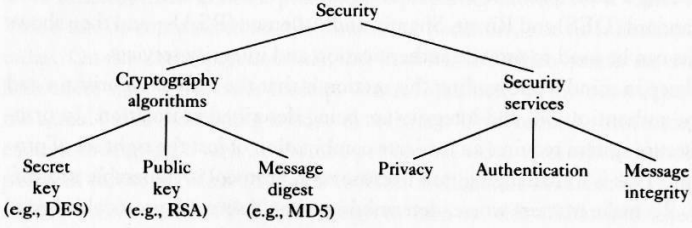


Figure 7.17 Taxonomy of network security.

The best way to think of a cryptographic hash function is that it computes a *cryptographic checksum* over a message. That is, just as a regular checksum protects the receiver from accidental changes to the message, a cryptographic checksum protects the receiver from malicious changes to the message. This is because all cryptographic hash algorithms are carefully selected to be one-way functions—given a cryptographic checksum for a message, it is virtually impossible to figure out what message produced that checksum. Said another way, it is not computationally feasible to find two messages that hash to the same cryptographic checksum. The relevance of this property is that if you are given a checksum for a message (along with the message) and you are able to compute exactly the same checksum for that message, then it is highly likely that this message produced the checksum you were given.

Although we will not describe it in detail, the most widely used cryptographic checksum algorithm is Message Digest version 5 (MD5). An important property of MD5, in addition to those properties outlined in the previous paragraph, is that it is much more efficient to compute than either DES or RSA. We will see the relevance of this fact later in this section.

To re-emphasize, cryptography algorithms like DES, RSA, and MD5 are just building blocks from which a secure system can be constructed. Figure 7.17 gives a simple taxonomy that illustrates this point. In looking at these services and building blocks, we should consider the following question: How did the participants get the various keys in the first place? This is the *key distribution* problem, one of the central problems in security, as we will see in the following subsections.

7.3.2 Encryption Algorithms (DES, RSA)

Before showing how encryption algorithms are used to build secure systems, we first describe how the two best-known algorithms—DES and RSA—work. We will also give some insight into *why* they work, but there is only so much we can do on this front since the design principles that underlie DES are not public knowledge. In the case of RSA, a deep explanation for why it works would require a background in number theory that is beyond the scope of this book, but we can provide some intuition into the underlying principles. Before looking at either algorithm, however, let's step back and ask what we want from an encryption algorithm.

Requirements

The basic requirement for an encryption algorithm is that it be able to turn plaintext into ciphertext in such a way that only the intended recipient—the holder of the decryption key—can recover the plaintext. What this means is that the encryption method should be safe from attacks by people who do not hold the key. As a starting point, we should assume that the encryption algorithm itself is known and that only the key is kept secret. The reason for this assumption is that if you depend on the algorithm being kept secret, then you have to throw it out when you believe it is no longer secret. This means potentially frequent changes of algorithm, which is problematic since it takes a lot of work to develop a new algorithm. Also, one of the best ways to know that an algorithm is effective is to use it for a long time—if no one breaks it, it's probably secure. (Fortunately, there are plenty of people who will try to break algorithms and who will let it be widely known when they have succeeded, so no news is generally good news.) Thus, there is considerable risk in deploying a new algorithm. Therefore, our first requirement is that secrecy of the key, and not of the algorithm itself, is the only thing that is needed to ensure the privacy of the data.

It is important to realize that when someone receives a piece of ciphertext, they may have more information at their disposal than just the ciphertext itself. For example, they may know that the plaintext was written in English, which means that the letter e occurs more often in the plaintext that any other letter; the frequency of many other letters and common letter combinations can also be predicted. This information can greatly simplify the task of finding the key. Similarly, they may know something about the likely contents of the message; e.g., the word "login" is likely to occur at the start of a remote login session. This may enable a "known plaintext" attack, which has a much higher chance of success than a "ciphertext only" attack. Even better is a "chosen plaintext" attack, which may be enabled by feeding some information to the sender that you know the sender is likely to transmit—such things have happened in wartime, for example.

The best cryptographic algorithms, therefore, can prevent the attacker from deducing the key even when the individual knows both the plaintext and the ciphertext. One approach, the one taken in DES, is to make the algorithm so complicated that virtually none of the structure of the plaintext remains in the ciphertext. This leaves the attacker with no choice but to search the space of possible keys exhaustively. This can be made infeasible by choosing a suit-

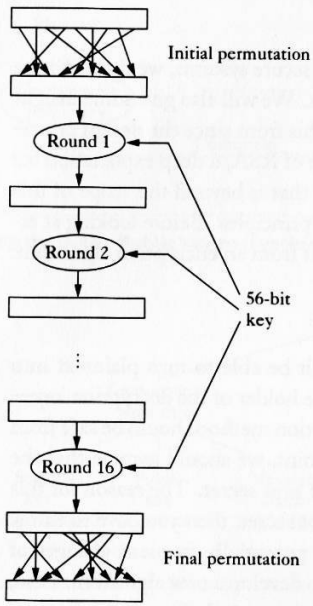


Figure 7.18 High-level outline of DES.

ably large key space and by making the operation of checking a key reasonably costly. As we will see, DES is now becoming only marginally secure on that basis.

DES

DES encrypts a 64-bit block of plaintext using a 64-bit key. The key actually contains only 56 usable bits—the last bit of each of the 8 bytes in the key is a parity bit for that byte. Also, messages larger than 64 bits can be encrypted using DES, as described below.

DES has three distinct phases: (1) the 64 bits in the block are permuted (shuffled), (2) 16 rounds of an identical operation are applied to the resulting data and the key, and (3) the inverse of the original permutation is applied to the result. This high-level outline of DES is depicted in Figure 7.18.

A table representing part of the initial permutation is shown in Table 7.2. The final permutation is the inverse (e.g., bit 40 would be permuted to bit position 1). It is generally agreed that these two permutations add nothing to the security of DES. Some security experts speculate that they were included to make the computation take longer, but it is just as likely that they are an artifact of the initial hardware implementation, involving some restriction of pin layout, for example.

Input Position	1	2	3	4	5	...	60	61	62	63	64
Output Position	40	8	48	16	56	...	9	49	17	57	25

Table 7.2 Initial (and final) DES permutation.

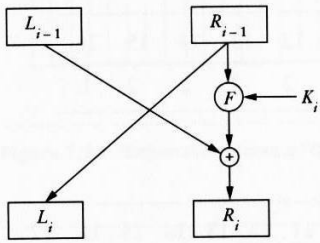


Figure 7.19 Manipulation at each round of DES.

During each round, the 64-bit block is broken into two 32-bit halves, and a different 48 bits are selected from the 56-bit key. If we denote the left and right halves of the block at round i as L_i and R_i, respectively, and the 48-bit key at round i as K_i, then these three pieces are combined during round i according to the following rule:

$$L_i = R_{i-1}$$
$$R_i = L_{i-1} \oplus F(R_{i-1}, K_i)$$

where F is a combiner function described below and $\oplus$ is the exclusive-OR (XOR) operator. Figure 7.19 illustrates the basic operation of each round. Note that L_0 and R_0 correspond to the left and right halves of the 64-bit block that results from the initial permutation, and that L_{16} and R_{16} are combined back together to form the 64-bit block to which the final inverse permutation is applied.

We now need to define function F and show how each K_i is derived from the 56-bit key. We start with the key. Initially, the 56-bit key is permuted according to Table 7.3. Note that every eighth bit is ignored (i.e., bit 64 is missing from the table), reducing the key from 64 bits to 56 bits. Then for each round, the current 56 bits are divided into two 28-bit halves and each half is independently shifted left either one or two digits, depending on the round. The number of bits shifted in each round is given in Table 7.4. The 56 bits that result from this shift are used as both input for the next round (i.e., the preceding shift is repeated) and to select the 48 bits that make up the key for the current round. Table 7.5 shows how 48 of the 56 bits are selected; note that they are simultaneously selected and permuted. For example, the bit in position 9 is not selected because it is not in the table.

Function F combines the resulting 48-bit key for round i (K_i) with the right half of the data block after round $i-1$ (R_{i-1}), as follows. To simplify our notation, we refer to K_i and

Input Position	1	2	3	4	5	...	59	60	61	62	63
Output Position	8	16	24	56	52	...	17	25	45	37	29

Table 7.3 DES key permutation.

Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Shift	1	1	2	2	2	2	2	2	1	2	2	2	2	2	2	1

Table 7.4 DES key shifts per round.

Input Position	1	2	3	4	5	6	7	8	10	11	12	13	14	15	16	17
Output Position	5	24	7	16	6	10	20	18	12	3	15	23	1	9	19	2

Input Position	19	20	21	23	24	26	27	28	29	30	31	32	33	34	36	37
Output Position	14	22	11	13	4	17	21	8	47	31	27	48	35	41	46	28

Input Position	39	40	41	42	44	45	46	47	48	49	50	51	52	53	55	56
Output Position	39	32	25	44	37	34	43	29	36	38	45	33	26	42	30	40

Table 7.5 DES compression permutation.

R_{i-1} as K and R, respectively. First, function F expands R from 32 bits into 48 bits so that it can be combined with the 48-bit K. It does this by breaking R into eight 4-bit chunks and expanding each chunk into 6 bits by stealing the rightmost and leftmost bit from the left and right adjacent 4-bit chunks, respectively. This expansion is illustrated in Figure 7.20, where R is treated as circular in the sense that the first and last chunks get their extra bit from each other.

Next, the 48-bit K is divided into eight 6-bit chunks, and each chunk is XORed with the corresponding chunk that resulted from the previous expansion of R. Finally, each resulting 6-bit value is fed through something called a *substitution box* (S box), which reduces each 6-bit chunk back into 4 bits. There are actually eight different S boxes, one for each of the 6-bit chunks. You can think of an S box as just performing a many-to-one mapping from 6-bit numbers to 4-bit numbers. Table 7.6 gives part of the S box function for the first chunk. We are now done with round i.

Notice that the preceding description does not distinguish between encryption and decryption. One of the nice features of DES is that both sides of the algorithm work exactly

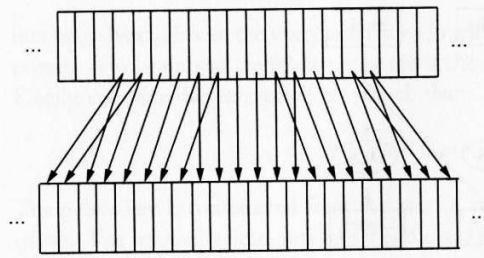


Figure 7.20 Expansion phase of DES.

Input	000000	000001	000010	000011	000100	000101	...
Output	1110	0100	1101	0001	0010	1111	...

Input	...	111010	111011	111100	111101	111110	111111
Output	...	0011	1110	1010	0000	0110	1101

Table 7.6 Example DES S box (bits 1-6).

the same. The only difference is that the keys are applied in the reverse order, i.e., K_{16}, $K_{15}, \ldots, K_1$.

Also keep in mind that the preceding discussion is limited to a single 64-bit data block. To encrypt a longer message using DES, a technique known as *cipher block chaining* (CBC) is typically used. The idea of CBC is simple: the ciphertext for block i is XORed with the plaintext for block $i + 1$ before running it through DES. An *initialization vector* (IV) is used in lieu of the nonexistent ciphertext for block 0. This vector IV, which is a random number generated by the sender, is sent along with the message so that the first block of plaintext can be retrieved. CBC on the encryption side is shown in Figure 7.21 for a 256-bit (four-block) message. Decryption works in the expected way since XOR is its own inverse, with the process starting with the last block and moving toward the front of the message.

We conclude by noting that there is no mathematical proof that DES is secure. What security it achieves it does through the application of two techniques: confusion and diffusion. (Having just plowed through the algorithm, you should now have a deep understanding of these two techniques.) What we can say is that the only known way to break DES is to exhaustively search all possible 2^{56} keys, although on average you would expect to have to search only half of the key space, or $2^{55} = 3.6 \times 10^{16}$ keys. On a 175-MHz DEC Alpha workstation, it is possible to do one encryption in 4 μs, meaning that it would take 1.4×10^{17} μs to break

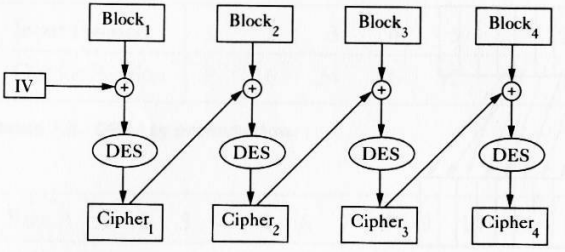


Figure 7.21 Cipher block chaining (CBC) for large messages.

a key (approximately 4500 years). While that may seems like a long time, keep in mind that searching a key space is a *highly* parallel task, meaning that if you could throw 9000 Alphas at the job, it would take only six months to break a key.

This amount of time is considered borderline-secure in many circles, especially considering that processor speeds are doubling every 18 months. For this reason, many applications are starting to use triple-DES, that is, encrypting the data three times. This can be done with three separate keys, or with two keys: the first is used, then the second, and finally the first key is used again.

RSA

RSA is a much different algorithm, not only because it involves different keys for encryption (public key) and decryption (private key), but also because it is grounded in number theory. In fact, the essential aspect of RSA comes down to how these two keys are selected. The act of encrypting or decrypting a message is expressed as a simple function, although this function requires enormous computational power. In particular, RSA commonly uses a key length of 512 bits, making it much more expensive to compute than DES; we discuss this more below.

Breaking RSA

In 1977, a challenge was issued to break a 129-digit (430-bit) message that was encrypted using RSA. It was believed that the code was impregnable, requiring 40 quadrillion years of computation using the currently known algorithms for factoring large numbers. In April of 1994, a mere 17 years later, four scientists reported that they had broken the code. The hidden message was

THE MAGIC WORDS ARE
SQUEAMISH OSSIFRAGE

The task was accomplished using a factoring method that requires approximately 5000 MIP-years. This was done over an eight-month period of time by dividing the

The first task is to generate a public and private key. To do this, choose two large prime numbers p and q, and multiply them together to get n. Both p and q should be roughly 256

bits long. Next, choose the encryption key e, such that e and $(p-1) \times (q-1)$ are relatively prime. (Two numbers are relatively prime if they have no common factor greater than 1.) Finally, compute the decryption key d such that

$$d = e^{-1} \bmod ((p-1) \times (q-1))$$

The public key is constructed from the pair $\langle e, n \rangle$ and the private key is given by the pair $\langle d, n \rangle$. The original prime numbers p and q are no longer needed. They can be discarded, but they must not be disclosed.

Given these two keys, encryption is defined by the following formula:

$$c = m^e \bmod n$$

and decryption is defined by

$$m = c^d \bmod n$$

where m is the plaintext message and c is the resulting ciphertext. Note that m must be less than n, which means that it can be no more than the 512 bits long. A larger message is simply treated as the concatenation of multiple 512-bit blocks.

Notice that when two participants want to encrypt data they are sending to each other using a public key algorithm like RSA, a pair of public/private key pairs is required. It doesn't work to encrypt with your private key and let the other side decrypt with the public key because everyone has access to the public key and so could decrypt the message. In other words, participant A encrypts data it sends to participant B using B's public key and B uses its private key to decrypt this data, while B encrypts data it sends to A using A's public key and A decrypts this message using its private key. Observe that A cannot decrypt a message that it has sent to B; only B has the requisite private key.

RSA security comes from the premise that factoring large numbers is a computationally expensive proposition. In particular, if you could factor n, you could recover p and q, which would compromise d. The speed at which large numbers can be factored is a function

problem into smaller pieces and shipping these pieces, using email, to computers all over the world.

Keep in mind that it doesn't always take 5000 MIP-years to break a key, especially when the key is poorly chosen. For example, a security hole was recently exposed in a WWW browser that used RSA to encrypt credit card numbers that were being sent over the Internet. The problem was that the system used a highly predictable method (a combination of process ID plus time of day) to generate a random number that was, in turn, used to generate a private and public key. Such keys are easily broken.

of both the available processor speed and the factoring algorithm being used. It is estimated that 512-bit numbers will be factorable in the next few years, and in fact, people are already starting to use 768- and 1024-bit keys. Keep in mind that while we are concentrating on the security of data as it moves through the network—i.e., the data is sometimes vulnerable for only a short period of time—in general, security people have to consider the vulnerability of data that needs to be stored in archives for tens of years.

Implementation and Performance

DES is two to three orders of magnitude faster than RSA, depending on whether the implementations are done in hardware or software. When implemented in software, we have measured DES to process data at 36 Mbps and RSA to process data at only 1 Kbps on a 175-MHz DEC Alpha workstation. For comparison, a software implementation of MD5 can process data at a rate of 80 Mbps on the same workstation. When implemented in hardware, that is, by custom VLSI chips, it has been reported that DES can achieve rates approaching 1 Gbps and RSA can achieve a whopping 64 Kbps.

Perhaps surprisingly, DES is the more likely of the two algorithms to be implemented in hardware on a given computer. This is because even when implemented in hardware, RSA is still too slow to be of any practical use in encrypting data messages. Instead, RSA is typically used to encrypt secret keys that are passed between two participants. These participants then use DES, possibly implemented in hardware, to secure their communication using this key. Because the secret key would only be used for as long as these two participants want to communicate, it is called a *session* key. We discuss this more in following subsections.

7.3.3 Authentication Protocols (Kerberos)

Before two participants are likely to establish a secure channel between themselves—i.e., use DES or RSA to encrypt messages they exchange—they must each first establish that the other participant is who he or she claims to be. This is the problem of authentication. If you think about authentication in the context of a client/server relationship, say a remote file system, then it is understandable that the server would want to establish the identity of the client: If the client is going to be allowed to modify or delete John's file, then the server is obligated to make sure that the client is, in fact, John. It is also the case, however, that the client often wants to verify the identity of the server. After all, you would not want to start writing sensitive data to what you thought was a file server, only to later discover that it was an imposter process.

This section describes three common protocols for implementing authentication. The first two use secret key cryptography (e.g., DES), while the third uses public key cryptography (e.g., RSA). Note that it is often during the process of authentication that the two participants establish the session key that is going to be used to ensure privacy during subsequent communication. The following includes a discussion of how this process gets bootstrapped.

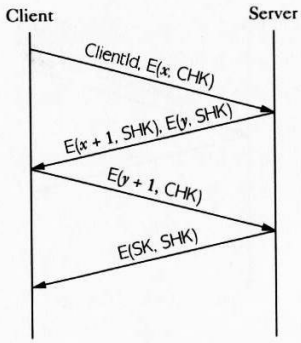


Figure 7.22 Three-way handshake protocol for authentication.

Simple Three-Way Handshake

A simple authentication protocol is possible when the two participants who want to authenticate each other—think of them as a client and a server—already share a secret key. This situation is analogous to a user (the client) having an account on a computer system (the server), where both client and server know the password for the account.

The client and server authenticate each other using a simple three-way handshake protocol similar to the one described in Section 6.2.3. In the following, we use E(m,k) to denote the encryption of message m with key k and D(m,k) to denote the decryption of message m with key k.

As illustrated in Figure 7.22, the client first selects a random number x and encrypts it using its secret key, which we denote as CHK (client handshake key). The client then sends E(x, CHK), along with an identifier (ClientId) for itself to the server. The server uses the key it thinks corresponds to client ClientId (call it SHK for server handshake key) to decrypt the random number. The server adds 1 to the number it recovers, and sends the result back to the client. It also sends back a random number y that has been encrypted with SHK. Next, the client decrypts the first half of this message and if the result is 1 more than the random number x that it sent to the server, it knows that the server possesses its secret key. At this point, the client has authenticated the server. The client also decrypts the random number the server sent it (this should yield y), encrypts this number plus 1, and sends the result to the server. If the server is able to recover $y + 1$ then it knows the client is legitimate.

After the third message, each side has authenticated itself to the other. The fourth message in Figure 7.22 corresponds to the server sending the client a session key (SK), encrypted using SHK (which is equal to CHK). Typically, the client and server then use SK to encrypt any future data they send to each other. The advantage of using a session key is that it means that

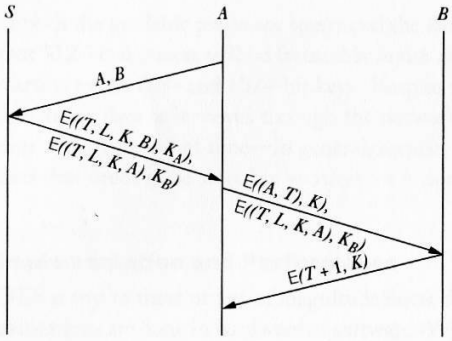


Figure 7.23 Third-party authentication in Kerberos.

the permanent secret key is only used for a small number of messages, making it harder for an attacker to gather data that might be used to determine the key.

This only begs the question of where the client and server handshake keys came from in the first place. One possibility is that they correspond to a password that a user entered; the ClientId could be the login identifier in this situation. Because a user-selected password might not make a suitable secret key, a transformation is often performed to turn it into a legitimate 56-bit DES key, for example.

Trusted Third Party

A more likely scenario is that the two participants know nothing about each other, but both trust a third party. This third party is sometimes called an *authentication server*, and it uses a protocol to help the two participants authenticate each other. There are actually many different variations of this protocol. The one we describe is the one used in Kerberos, a TCP/IP-based security system developed at MIT.

In the following, we denote the two participants who want to authenticate each other as A and B, and we call the trusted authentication server S. The Kerberos protocol assumes that A and B each share a secret key with S; we denote these two keys as K_A and K_B, respectively. As before, E(m,k) denotes message m encrypted with key k.

As illustrated in Figure 7.23, participant A first sends a message to server S that identifies both itself and B. The server then generates a timestamp T, a lifetime L, and a new session key K. Timestamp T is going to serve much the same purpose as the random number in the simple three-way handshake protocol given above, plus it is used in conjunction with L to limit the amount of time that session key K is valid. Participants A and B will have to go back to server S to get a new session key when this time expires. The idea here is to limit the vulnerability of any one session key.

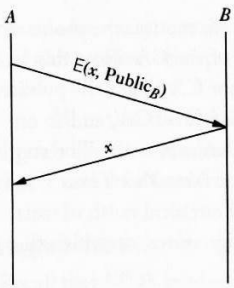


Figure 7.24 Public key authentication.

Server S then replies to A with a two-part message. The first part encrypts the three values T, L, and K, along with the identifier for participant B, using the key that the server shares with A. The second part encrypts the three values T, L, and K, along with participant A's identifier, but this time using the key that the server shares with B. Clearly, when A receives this message, it will be able to decrypt the first part but not the second part. A simply passes this second part on to B, along with the encryption of A and T using the new session key K. (A was able to recover T and K by decrypting the first part of the message it got from S.) Finally, B decrypts the part of the message from A that was originally encrypted by S, and in so doing, recovers T, K, and A. It uses K to decrypt the half of the message encrypted by A, and upon seeing that A and T are consistent in the two halves of the message, replies with a message that encrypts $T + 1$ using the new session key K.

A and B can now communicate with each other using the shared secret session key K to ensure privacy.

Public Key Authentication

Our final authentication protocol uses public key cryptography; e.g., RSA. The public key protocol is a useful one because the two sides need not share a secret key; they only need to know the other side's public key. As shown in Figure 7.24, participant A encrypts a random number x using participant B's public key, and B proves it knows the corresponding private key by decrypting the message and sending x back to A. A could authenticate itself to B in exactly the same way.

As to the question of where a participant learns the other's public key, it is tempting to believe that individual participants should be allowed to post their public keys on a bulletin board. This approach does not work, however, because it would be possible for participant A to post its own public key and claim that it is the key for participant B. This would allow A to masquerade as B. Instead, public keys must be retrieved from a trusted source, typically known as a *certificate authority* (CA). That is, you go to the trusted CA to get some other participant's public key, and you have to prove through some external mechanism that you are

who you say you are when you register your public key with the CA. This reduces the problem to one of every participant having to know just one public key—that of the CA. Note that in general, it is possible to build a hierarchy of CAs: you start at the root CA to get the public key for a second-level CA, which gives you the public key for the third-level CA, and so on, until you learn the public key for the participant you want to communicate with. The root CA would be published in some other trusted source, for example, the *New York Times*.

An alternative to a tree-structured hierarchy is to build a nonhierarchical mesh of trust. We defer discussion of this approach until we have discussed digital signatures, on which this approach depends.

7.3.4 Message Integrity Protocols

Sometimes two communicating participants do not care whether an eavesdropper is able to read the messages they are sending to each other, but they are worried about the possibility of an imposter sending messages that claims to be from one of them. That is, the participants want to ensure the integrity of their messages.

One way to ensure the integrity of a message is to encrypt it using DES with cipher block chaining, and then to use the CBC *residue* (the last block output by the CBC process) as a *message integrity code* (MIC). (For the CBC example given in Figure 7.21, cipher_4 is the CBC residue.) The plaintext message plus the MIC would be transmitted to the receiver, with the MIC acting as a sort of checksum—if the receiver could not reproduce the attached MIC using the secret key it shares with the sender, then the message was either not sent by the sender, or it was modified since it was transmitted. Note that you would not want to use DES with CBC to both encrypt the message for privacy and to generate the MIC for integrity, because you would simply end up transmitting the CBC-encrypted message with the last block repeated. Thus, anyone who wanted to tamper with the CBC-encrypted message could take the value of the final block they wanted to send, and send it twice.

This section looks at three alternatives for ensuring message integrity. The first uses RSA to produce a digital signature. RSA used on its own tends to be slow, but it can be used in combination with MD5 to yield a much more efficient technique. The second and third approaches use MD5 in conjunction with RSA to guarantee message integrity.

Digital Signature Using RSA

A *digital signature* is a special case of a message integrity code, where the code can only have been generated by one participant. The easiest digital signature algorithm to understand is an RSA signature, which works in the obvious way—since a given participant is the only one that knows its own private key, the participant uses this key to produce the signature. Any other participant can verify this signature using the corresponding public key. In other words, to sign a message, you encrypt it using your private key, and to verify a signature, you decrypt it using the public key of the purported sender. Clearly, this means that producing an RSA signature is as slow as RSA, which we have already seen is two or three orders of magnitude slower than DES. Observe that the use of keys is exactly reversed relative to their use for privacy:

the sender encrypts with the sender's private key rather than with the receiver's public key, and the receiver decrypts with the sender's public key rather than with the receiver's private key.

Note that the National Institute for Standards and Technology (NIST) has proposed a digital signature standard known as DSS that is similar to the approach just described, except that it uses an alternative algorithm, called El Gamel, instead of RSA.

Keyed MD5

Recall that MD5 produces a cryptographic checksum for a message. This checksum does not depend on a secret key, so it does not prevent an imposter from creating a message that claims to be from someone else and computing an MD5 checksum for that message. However, there are two ways to use MD5 in combination with a public key algorithm like RSA to implement message integrity. Both approaches overcome the performance problems inherent in using RSA alone.

The first method, which is commonly referred to as *keyed MD5*, works as follows. The sender generates a random key k and runs MD5 over the concatenation of the message (denoted m) and this key. In practice, the random key k is attached to either the front or back of the message for the purpose of running MD5; k is then removed from the message once MD5 is finished. The random key is then encrypted using RSA and the sender's private key. The original message, the MD5 checksum, and the encrypted version of the random key are then packaged together and sent to the receiver. The following summarizes the complete message transmitted by the sender:

$$m + \mathsf{MD5}(m + k) + \mathsf{E}(k, \mathit{private})$$

where $\mathsf{MD5}(s)$ represents applying the MD5 algorithm to string s, and $a+b$ denotes the concatenation of strings a and b.

The receiver recovers the random key using the purported sender's public RSA key and then applies MD5 to the concatenation of this random key and the body of the message. If the result matches the checksum sent with the message, then the message must have been sent by the participant who generated the random key.

MD5 with RSA Signature

The second method for using MD5 in combination with RSA works as follows. The sender runs MD5 over the original message it wants to protect, producing an MD5 checksum. It then signs this checksum with its own private RSA key. That is, the sender does not sign the entire message, it just signs the checksum. The original message, the MD5 checksum, and the RSA signature for the checksum are then transmitted. Using the same notation as above, this means that the sender transmits

$$m + \mathsf{MD5}(m) + \mathsf{E}(\mathsf{MD5}(m), \mathit{private}).$$

The receiver verifies the message by making sure that the signature is correct, that is, by decrypting the signature with the sender's public key and comparing the result with the MD5 checksum sent with the message. The two should be equal.

Using Digital Signatures for Key Distribution

We mentioned above that digital signatures can be used to build a mesh of trust by which keys can be distributed, as an alternative to a strict hierarchy. Now that we know how digital signatures work, providing us with a way to say "this message was generated by participant X and has not been altered," we can describe the mesh approach.

To begin, suppose participants A and B exchange public keys while they are in the same room; that is, they can verify that the keys really belong to the right people. At some later time, A exchanges public keys with C. A can now use his or her private key to sign the public key of C and send it to B. In other words, A sends a message that says, in effect, "I was in a room with C and I believe that this is C's public key," and signs this message using his or her own private key. Because B has a trustworthy copy of A's public key, B can verify the signature on this message. As long as B trusts that A was not fooled into mistakenly signing C's key, B now has a trustworthy copy of C's public key.

Thus, a reasonable strategy is for C to get his or her key signed by lots of people, and with luck, anyone with whom C wants to communicate will be able to find one person they trust in the set of people who have signed C's public key. Note that there can be arbitrarily many links in the chain of trust, but if one person in the chain signs a key when they are not sure it really belongs to the right person, then the chain of trust is broken. As an aside, note that key-signing parties—a lot of As, Bs, and Cs in a room with their laptops—have become a regular feature of IETF meetings. This approach to key management is used by the Pretty Good Privacy (PGP) suite of software.

Security Support in IPv6

IPv6 includes hooks to support authentication, message integrity, and encryption. First, IPv6 provides an Authentication extension header, which contains only two fields of interest: a Security Parameters Index (SPI) and some amount of Authentication Data. This provides a very general way to support a wide range of authentication algorithms and key management strategies without needing to redefine the header format. It is assumed that any two parties (hosts or routers) that wish to authenticate packets from each other will be able to agree on everything needed to provide authentication, notably an algorithm and a key. Once they have done this, the sending host uses the SPI to identify the appropriate set of agreements to the receiver. The sender then uses the agreed-upon algorithm and key to calculate a checksum over the entire datagram, and the receiver uses the

7.4 Summary

This chapter has described three different data manipulations that applications apply to their data before sending it over a network. Unlike the protocols described earlier in this book, which you can think of as processing *messages*, these three transformations process *data*.

The first data manipulation is presentation formatting, where the problem is encoding the different types of data that application programs compute on—e.g., integers, floating-point numbers, character strings, arrays, structures—into packets that can be transmitted over a network. This involves both translating between machine and network byte order, and linearizing compound data structures. We outlined the design space for presentation formatting and discussed three specific mechanisms that fall on different points in this design space: XDR, ASN.1, and NDR.

The second data manipulation is compression, which is concerned with reducing the bandwidth required to transmit different types of data. Compression algorithms can be either lossless or lossy, with lossy algorithms being most appropriate for image and video data. JPEG and MPEG are examples of lossy compression protocols for still images and video data, respectively.

The third data manipulation is encryption, which is used to protect the privacy of data sent over a network. We looked at two basic encryption algorithms: shared key algorithms (e.g., DES) and public key algorithms (e.g., RSA). As we have seen, encryption algorithms actually play a much bigger role in network security than just supporting privacy; they also form the basis for protocols that are used to ensure authentication and message integrity.

same algorithm and key to verify the checksum. If the packet has been modified in any way, the checksum will fail, which is how we achieve integrity. If someone other than the purported sender tries to send the packet, since they do not know the key to the algorithm, they will be unable to forge the correct checksum.

A similarly general approach is used for encryption. Specifically, another extension header, called the Encapsulating Security Payload (ESP) header, is used. All headers that precede the ESP header, most notably the IPv6 header, are unencrypted, so that routers do not need to decrypt packets before forwarding them. The only mandatory field of the ESP header is the SPI, which again provides an identifier by which the receiver can look up the algorithm and key needed to decrypt the data. Everything that follows the ESP header in the packet is then encrypted.

OPEN ISSUE

Presentation—Layer of the 90s

At one time, data manipulations such as the ones discussed in this chapter were treated as an afterthought by networking people. There were various reasons for this. In the case of presentation formatting, the network was so slow that no one cared how bad the encoding strategy was. In the case of compression, it is the recent advances in CD-ROM and graphical I/O devices (i.e., the growing popularity of multimedia) that have made the compression of images a fruitful area to pursue. In the case of security, it is the recent explosion of the World Wide Web, and the implications of using the Web for commerce, that have made people more security conscious. (Of course, the military has always been highly interested in security.) Today, however, one could argue that the data manipulation level of the network architecture is where the action is. In short, it is the set of data manipulation functions available to application programs that is limiting what we can do with computer networks.

Network security is a good example of services that are just around the corner. Using the basic cryptography algorithms like DES, RSA, and MD5, people are designing security protocols that do much more than ensure privacy, authentication, and message integrity. For example, there are now protocols that support anonymous digital cash, certified mail, secure elections, and simultaneous contract signing.

In the case of data compression, formats like MPEG were not specifically designed for use on a network; they were designed to provide a format for storing video on disk. It is not completely clear that MPEG makes sense for sending video over a network. For example, if a B or P frame is dropped by the network, then it is possible to simply replay the previous frame without seriously compromising the video; 1 frame out of 30 is no big deal. On the other hand, a lost I frame has serious consequences—none of the subsequent B and P frames can be processed without it. Thus, losing an I frame would result in losing multiple frames of the video. While you could retransmit the missing I frame, the resulting delay would probably not be acceptable in a real-time video conference. One interesting avenue of research is to have the application "teach" the network how to treat different types of messages; for example, it is OK to drop messages carrying B and P frames but not messages carrying I frames. Note, however, that this is a significant departure from the current model in which all messages are treated equally by the network.

One final issue to consider is the relationship among these three transformations. In most cases, you would perform presentation encoding before compression or encryption—the application first packs and linearizes a data structure before trying to compress or encrypt it. Between compression and encryption, you would always compress before encrypting. This is for two reasons. First, if the encryption algorithm is a good one, then there is no obvious redundancy for the compression algorithm to remove. The second reason is that by first compressing the data, you are able to make the ciphertext that results from encryption even more obscure, and therefore more difficult to break.

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Intel Corporation and Lenovo (United States) Inc.

FURTHER READING

Our recommended reading list for this chapter includes two papers on compression and two papers on network security. The two articles on compression give an overview of the JPEG and MPEG standards, respectively. Their main value is in explaining the various factors that shaped the standards. The two security-related papers, taken together, give a good overview of the topic. The article by Lampson et al. contains a formal treatment of security, while the Satyanarayanan paper gives a nice description of how a secure system is designed in practice.

The final paper on the reading list discusses the importance of data manipulations to network performance and gives two architectural principles that should guide the design of future protocols.

- Wallace, G. K. The JPEG still picture compression standard. *Communications of the ACM* 34(1):30–44, April 1991.
- Le Gall, D. MPEG: A video compression standard for multimedia applications. *Communications of the ACM* 34(1):46–58, April 1991.
- Lampson, B., et al. Authentication in distributed systems: Theory and practice. *ACM Transactions on Computer Systems* 10(4):265–310, November 1992.
- Satyanarayanan, M. Integrating security in a large distributed system. *ACM Transactions on Computer Systems* 7(3):247–280, August 1989.
- Clark, D., and D. Tennenhouse. Architectural considerations for a new generation of protocols. *Proceedings of the SIGCOMM '91 Symposium*, pages 200–208, September 1991.

Unfortunately, there is no single paper that gives a comprehensive treatment of presentation formatting. Aside from the XDR, ASN.1/BER, and NDR specifications (see Srinivasan [Sri95b], the CCIT recommendations [dTeT92a, dTeT92b], and the Open Software Foundation [Ope94]), three other papers cover topics related to presentation formatting: those by O'Malley et al. [OPM94], Lin [Lin93], and Chen et al. [CLNZ89]. All three discuss performance-related issues.

On the topic of compression, a good place to start is with Huffman encoding, which was originally defined in [Huf52]. The original LZ algorithm is presented in Ziv and Lempel [ZL77], and an improved version of that algorithm by the same authors can be found in [ZL78]. Both of these papers are of a theoretical nature. The work that brought the LZ approach into widespread practice can be found in Welch [Wel84]. For a more complete overview of the topic of compression, Nelson's article [Nel92] is recommended. You can also learn about compression in any of several recent books on multimedia. We recommend Witten et al. [WMB94], which has an extremely high science-to-hype ratio, and Buford [Buf94], which is a collection of contributed chapters that span the range of multimedia topics.

On the topic of network security, there are several good books to choose from. We recommend Schneier [Sch94] and Kaufman et al. [KPS95]. The former gives a comprehensive

treatment of the topic, including sample code, while the latter gives a very readable overview of the subject.

Finally, we recommend the following two live references:

- http://roger-rabbit.cs.berkeley.edu/mpeg/index.html: a collection of MPEG-related programs, some of which are used in the following exercises;
- ftp://cert.org/pub: a collection of security-related notices posted by the Computer Emergency Response Team (CERT).

EXERCISES

1 Consider the following C structure definitions:

```
#define  MAXSTR 100

struct date {
    char  month[MAXSTR];
    int   day;
    int   year;
};

struct employee {
    char   name[MAXSTR];
    int    ssn;
    struct date *hireday;
    int    salary_history[10];
    int    num_raises;
}
```

where num_raises + 1 corresponds to the number of valid entries in array salary_history. Show the on-the-wire representation of structure employee that is generated by XDR.

2 For the data structures given in the previous problem, give the XDR routine that encodes/decodes these structures. If you have XDR available to you, run this routine and measure how long it takes to encode and decode an example instance of structure employee.

3 Using Unix utilities like bcopy and htonl, implement a routine that generates the same on-the-wire representation of the structures given in the problem 1 as XDR does. Compare the performance of your "by hand" encoder/decoder with the corresponding XDR routines.

4 Retrieve the Universal Stub Compiler (USC) byte-swapping program from ftp.cs.arizona.edu, and write the USC specification that encodes/decodes the data struc-

tures given in problem 1. (USC does not handle pointers, so you will need to encode/decode that part by hand.) Compare the performance of your USC encoder/decoder with the XDR and by-hand versions from the previous two exercises.

5 Use USC, XDR, and htonl to encode a 1000-element array of integers. Measure and compare the performance of each. How do the three compare to a simple loop that reads and writes a 1000-element array of integers? Perform the experiment on a computer for which the native byte order is the same as the network byte order, as well as on a computer for which the native byte order and the network byte order are different.

6 Give the ASN.1 encoding for the following three integers:

(a) 101

(b) 10,120

(c) 21,645

7 Give the big-endian and little-endian representation for the integers from the previous problem.

8 Determine the byte order for the following architectures: Alpha, MIPS, Sparc, and PA-RISC.

9 XDR is used to encode/decode the header for the SunRPC protocol described in Chapter 6. What difficulties might arise in using XDR in this way?

10 Why might you want to compress your data before doing presentation formatting?

11 Write a routine that implements RLE and DPCM compression. Apply these routines to different types of data, and report the compression ratios that each algorithm achieves.

12 Experiment with the Unix compress utility. What compression ratios is this program able to achieve? See if you can generate data files for which compress can achieve 5:1 or 10:1 compression ratios.

13 Think about what functions might reasonably be expected from a video standard: fast forward, editing capabilities, random access, and so on. (See the paper by LeGall, "MPEG: A video compression standard for multimedia applications," given in this chapter's recommended reading list, for further ideas.) Explain MPEG's design in terms of these features.

14 The frequency of I frames in the MPEG stream defines the granularity of fast forward and reverse. Explain why.

15 Use mpeg_play to play an MPEG-encoded video. Experiment with options, particularly -nob and -nop, which are used to omit the B and P frames, respectively, from the stream. What are the visible effects of omitting these frames?

16 The mpeg_stat program can be used to display statistics for video streams. Use it to determine, for several streams:

(a) number and sequence of I, B, and P frames.

(b) average compression rate for the entire video.

(c) average compression rate for each type of frame.

17 Write a program that implements forward and backward DCT. Run the program on a sample grayscale image. (It would be easiest to use PBM to read and write images.) Since DCT is lossless, the image output by the program should match the input. Now modify your program so that it throws away or changes some of the higher-frequency components and see how the output image is affected.

18 The Unix des command encrypts and decrypts data using the Data Encryption Standard algorithm. If it is available on your system, read the man page and experiment with it. Measure how fast it is able to encrypt or decrypt data.

19 Prove that the RSA decryption algorithm recovers the original message.

20 In the three-way handshake described as an authentication mechanism, why is the server unsure of the client's identity until it receives the third message?

21 Figure 7.21 shows CBC encryption. Give the corresponding diagram for decryption.

22 Show how two-way authentication works using RSA.

23 Learn about the Clipper encryption scheme. What are the pros and cons of Clipper?

24 What sort of attacks are authentication schemes like Kerberos susceptible to?

Appendix A

CURRICULUM VITAE SYLVIA D. HALL-ELLIS

EDUCATION

Ph.D., University of Pittsburgh, Pittsburgh, Pennsylvania, 1985
M.P.S., University of Denver, Denver, Colorado, 2014
Post Graduate Studies, University of Texas – San Antonio, Texas, 1975-1976
M.L.S., University of North Texas, Denton, Texas, 1972
B.A., Rockford University, Rockford, Illinois, 1971

PROFESSIONAL EXPERIENCE

1981- **Consultant for higher education, non-profit organizations, and corporations.**

2002- **Adjunct Professor, School of Information, San José State University, San José, California.** Serve as part-time faculty member teaching graduate students in technical services (cataloging, bibliographic control, classification), "core courses," and special topics.

2014-2016 **Director, Grants and Resource Development, Colorado Community College System.** Provided leadership and vision to foster the continued growth of rigorous scholarship, innovative projects, and creative work for statewide system, 13 campuses, and 50 teaching sites serving 155,000 students. Responsible for leadership and ensured efficient functioning of contract and grants in compliance with state & federal requirements and successful implementation and management. Served as a subject matter expert and liaison for college Grant Directors for all issues relating to grants and subcontracts.

2010-2014 **Senior Grant Administrator, Morgridge College of Education, University of Denver (Colorado).** Provided leadership and vision to foster continued growth of rigorous scholarship, innovative research, and creative work in the Morgridge College of Education. Ensure that contract and grants processes function effectively and efficiently for 60 faculty and researchers with a focus on the successful progression and efficient management of grants totaling $13M. Worked effectively and collegially with Department Chairs and Program Coordinators on operational grant-related management activities and with a broad range of internal and external constituencies. Supported the dissemination and promotion of faculty research and scholarship to outside constituents at conferences and through publications. Assisted Principal Investigators and grant project teams by coaching, mentoring, and financial management.

2011-2013 **Interim Director & Assistant Dean, Westminster Law Library, Sturm College of Law, University of Denver.** Planned, organized, and directed all administrative activities for the library serving students, faculty, and alumni; oversaw the employment, retention, promotion, transfer and termination of library personnel; represented the library at professional conferences and public meetings; created and promoted a climate and culture of acceptance for new programs and services, a positive high-quality image of the law library, and that reflect the organization's values, encourage excellent performance, and reward high productivity and innovation; provided leadership and set strategic direction of the organization; ensured that the library provided excellent customer service through solution-oriented staff response to patron needs and by responsiveness and continuous improvement of the organization; promoted, developed, and maintained positive working relationships with colleagues and customers including key stakeholders and groups, higher education institutions, the legal community, other regional libraries and districts statewide, and national library organizations.

2007-2014	**Associate Professor, Library & Information Science, Morgridge College of Education, University of Denver (Colorado).** Served in leadership role and worked collaboratively in program, college, campus and community environments. Advised and supervised students, taught core and specialized courses at the graduate level in an integrative, student-centered learning environment. Served on LIS, College, and University committees, and maintained working relationships with colleagues in other academic units and information professionals in the Rocky Mountain region and beyond. Served on and chair doctoral student dissertation committees. Oversaw and facilitated the College and LIS graduate student association.
2002-2007	**Assistant Professor, Library & Information Science, College of Education, University of Denver (Colorado).** Served as tenure-track faculty member teaching graduate students in "core courses," resource description and access, service learning, and independent studies. Advised graduate students, participate on LIS and College committees, and serve on doctoral student dissertation committees. Oversaw and facilitated the LIS graduate student association and alumni association.
2000-2002	**Affiliate Faculty, Library & Information Science, College of Education, University of Denver (Colorado).** Served as part-time faculty member teaching graduate students in technical services (cataloging, bibliographic control, classification), "core courses," and special topics. Oversaw and facilitated the LIS graduate student association and alumni association.
2000-2001	**Special Assistant to the Secretary's Regional Representative, U.S. Department of Education, Region VIII, Denver, Colorado.** Served as the principal advisor and representative of the U. S. Secretary of Education's Regional Representative (SRR). Ensured the implementation of major goals of the SRR and the Secretary. Provided leadership on behalf of the SRR in contacts with high-level officials in Region VIII requiring sensitive policy interpretation in communication with senior Department officials to solve problems and resolve issues raised by State and local education officials. Served as the primary contact for School-to-Work/Career, Children's Health Insurance Program, and Safe and Drug-Free Schools. Delivered technical assistance to local education agencies and institutions of higher education in technology, professional development, and school construction.
1999-2000	**Catalog Librarian, Jefferson County Public Library, Lakewood, Colorado.** Performed original, copy cataloging and classification of library materials (English and Spanish) using standard library protocols; completed original descriptive cataloging and subject analysis; enhanced brief catalog and authority records in III.
1997-1999	**Development Officer, McREL International, Aurora, Colorado.** Served as senior member of corporate management team in strategic planning, development of proposals and contracts, implementation, and evaluation of new services, products, and programs for educational agencies. Provided creative leadership to corporate committees to solicit ideas, identify goals and objectives, plan, develop, present, and evaluate professional development opportunities.
1995-1997	**Education Specialist, Education Service Center, Region One, Edinburg, Texas.** Served as member of Administrative Cabinet team in strategic planning, development of proposals and contracts, implementation, and evaluation of telecommunications capabilities, services, products, and programs for 40 school districts serving 283,000 students in 7 counties. Provided creative leadership to regional and state committees to solicit ideas, identify strategic goals and objectives, plan, develop, present, and evaluate funding opportunities and professional development for 400 librarians.

1993-1996	**Assistant Professor of Library Science, Sam Houston State University, Huntsville, Texas.** Served a faculty member teaching 400 graduate students in technical services (cataloging, bibliographic control, classification), automation, and networking. Participated in distance education program and coordinated annual conference. Conducted university and Texas Library Association-funded field research focused on library collection development and academic achievement.
1992-1993	**Head Librarian, Rocky Mountain College of Art & Design, Denver, Colorado.** Responsible for the daily operation, selection and acquisition of materials, formulation of policies for library operations, media center, and photography/slides archives. Designed and implemented library automation and delivery of electronic resources to college community.
1981-1985	**Development Officer, PRLC, Inc., Pittsburgh, Pennsylvania.** Served as senior member of corporate management team in strategic planning, development of proposals and contracts, implementation, and evaluation of new services, products, and programs for 100 institutional member organizations. Coordinated the development of proposals and contracts totaling $4,000,000 annually. Provided creative leadership to corporate committees to solicit ideas, identify goals and objectives, plan, develop, present, and evaluate professional development opportunities.
1981	**Director of Library Development, Pennsylvania Department of Education, Harrisburg, Pennsylvania.** Responsible for statewide development, technical assistance, professional development, resource sharing, children's services, institutional library services, networking, and state aid program for all libraries throughout the Commonwealth. Functioned as liaison to Governor's Advisory Council, LSCA Advisory Council, District Administrators, private colleges, universities, consortia managers, and network directors. Supervised $14,000,000 formula-based state aid program and $3,000,000 grant awards to individual libraries, consortia, and networks.
1978-1981	**Assistant Director, Southern Tier Library System, Corning, New York.** Coordinated operation of system-wide programs (technical assistance, professional development, resource sharing, technical services, outreach) to 40 public libraries in 5 counties serving 500,000 residents. Solicited ideas, identified goals, sponsored, and evaluated professional development opportunities and technical assistance sessions.
1976-1978	**Division Librarian for Technical Services, Corpus Christi Public Libraries, Corpus Christi, Texas.** Provided leadership in acquisitions, cataloging, serials control, and processing for main library and 4 branches serving 250,000 residents. Participated as senior member of library management team. Compiled and prepared technical evaluations, reports, and statistical analyses of Division operations to measure the achievement and cost of annual goals, objectives, and staff performance.
1975-1976	**System Coordinator, San Antonio Major Resource Center, San Antonio, Texas.** Served as senior member of the management team for District X Office, charged to provide technical assistance, resource sharing, media services, and professional development to librarians and staff representing 30 public library jurisdictions in 21 counties serving 1,500,000 residents. Functioned as liaison to System Director, staff, and members of governing bodies with the System Board of Directors and the Texas State Library and Historical Commission. Prepared LSCA grant applications and monitored awards totaling $1,100,000 annually.

1973-1975	**Bilingual Branch Librarian, San Antonio Public Library, San Antonio, Texas.** Worked as librarian providing reference, information, and readers' advisory services in branch serving 50,000 Spanish-speaking residents in southwest San Antonio. Participated in collection development and resource acquisition activities, specializing in children's work, Spanish language resources, and multicultural studies.
1972-1973	**Librarian, Holding Institute, Laredo, Texas.** Worked as high school librarian serving 500 boarding students in Spanish-speaking environment of private school. Provided reference, research assistance, and library instruction to students and 35 faculty members.
1966-1971	**Rockford Public Library, Rockford, Illinois.** Worked in branches as part-time as a Library Assistant, Clerk, and Page in city library serving 150,000 residents.

PUBLICATIONS

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Other Publications

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Hall-Ellis, Sylvia D., and Robert O. Ellett, Jr., guest editors. *RDA Testing: Lessons Learned and Challenges Revealed: A Special Issue of Cataloging & Classification Quarterly* 49, no. 7-8 (November 2011).

Hall-Ellis, Sylvia D. and Robert O. Ellett, Jr. *Fundamentals of Cataloging I: An Online ALCTS Course.* Chicago, Ill.: American Library Association, 2009.

Hall-Ellis, Sylvia D., Angela J. Kinney and Martha Ann Bace, editors. *Best Practices in Cataloging Education Identified at the 2007 ALCTS Pre-conference: A Special Issue of the Journal for Library and Information Science Education* 49, no. 2 (Spring 2008).

Hall-Ellis, Sylvia D. *Cataloging Education: A New Emphasis for the Library and Information Science Curriculum.* Presentation delivered to the ALCTS Pre-conference, 132nd Annual Conference, American Library Association, Washington, D.C., June 22, 2007. http://www.loc.gov/aba/professional/

Hall-Ellis, Sylvia D. "*Cataloger Competencies: Do the Employers Require What the Professors Teach?*" Presentation delivered to the ALCTS CCS Heads of Cataloging Discussion Group, 131st Annual Conference, American Library Association, New Orleans, Louisiana, June 26, 2006. http://dlist.sir.arizona.edu/

Hall-Ellis, Sylvia D., guest editor, with Deborah S. Grealy, Clara L. Sitter, and Tassos Petrou. *Library Students' Voices in Colorado: An Issue of Colorado Libraries* 31:1 (Spring 2005).

Hall-Ellis, Sylvia D., ed. *Library and Information Science Program Self-Study Document for Accreditation by the American Library Association.* Denver, Colo.: University of Denver, College of Education, 2003. 125 p. with CD-ROM.

Hall-Ellis, Sylvia D. and Deborah S. Grealy, guest editors. *Library Education in Colorado: An Issue of Colorado Libraries* 29, no. 2 (Summer 2003).

Hall-Ellis, Sylvia D., ed. *Library and Information Science Program Self-Study Document for Accreditation by the American Library Association.* Denver, Colo.: University of Denver, College of Education, 2003.

Hall-Ellis, Sylvia D. "Adaptive Furniture for the ADA-Qualified: An Investigative Study." 2001. Unpublished manuscript.

Hall-Ellis, Sylvia D. "Cataloging Electronic Serials: A Study in User Access and Article Delivery." 2001. Unpublished manuscript.

Hall-Ellis, Sylvia D. "E-books: Acquisition and Circulation Issues in Public Libraries." 2001. Unpublished manuscript.

Hall-Ellis, Sylvia D. "Authority Control and Its Importance in School Library Media Online Catalogs." 1999. Unpublished manuscript.

Hall, Sylvia D. "Cooperation Improving Service in San Antonio System." *Texas Libraries* XXXVII (Spring 1976): 27-29.

Hall, Sylvia D. "Summer is Sea Monstrously Fun!" *Texas Library Journal* L (December 1974): 224-226.

Hall, Sylvia D. "A Brief Annotated Bibliography of Non-book Materials on the Mexican American." *Texas Library Journal* XLVIII (October 1972): 213-232.

Book Reviews

ALA Book of Library Grant Money. Ann Kepler, ed. 8th ed. Chicago, IL: American Library Association, 2011. 978-0-8389-1058-0, $175.00 [*Colorado Libraries,* June 2012]

Developing a Compensation Plan for Your Library. Paula M. Singer and Laura L. Francisco, comps. 2nd ed. Chicago, IL: American Library Association, 2009. 978-0-8389-0985-0, $57.00 [*Colorado Libraries,* March 2012]

Frugal Librarian. Carol Smallwood, ed. Chicago, IL: American Library Association, 2011. 978-0-83891-075-7, $42.00 [*Colorado Libraries,* February 2012]

Dowlin, Ken. *Getting the Money: How to Succeed in Fundraising for Public and Nonprofit Libraries.* Westport, Conn.: Libraries Unlimited, 2008. 978-1-59158-597-X, $50.00 [*Colorado Libraries,* February 2009]

Lundahl, Mats. *Bebo de Cuba; Bebo Valdés y Su Mundo*, by Mats Lundahl. Traducción de Linda Oakeshott Dragó. Barcelona: RBA Libros, 2008. 978-849-86-7259-6, $33.99 [*Críticas*, November 2008]

Bonelli, Florencia. *Marlene*, by Florencia Bonelli. Buenos Aires: Aguilar, Altea, Taurus, Alfaguara, 2008. 978-987-04-0995-3, $24.95 [*Críticas*, October 2008]

Keret, Etgar. Traducción de Ana María Bejarano. *Pizzería Kamikaze y Otras Relatos.* México, D.F.: Editorial Sexto Piso, 2008. 968-5679-29-0, no price given [*Críticas*, September 2008]

Littauer, Marita, and Florence Littauer. *Enriquece tu Comunicación. Miami, Fla.: Editorial Unilit, 2008.* 978-0-7899-1521-4, $11.99 [*Críticas*, August 2008]

Martínez, Guillermo. *La Muerte Lenta de Luciana B.* New York: Rayo Planeta, 2008. 978-0-06-156551-9, $14.95 [*Críticas*, May 2008]

Matthews, Joseph R. *The Evaluation and Measurement of Library Services.* Westport, Conn.: Libraries Unlimited, 2007. 978-1-59158-532-9, $50.00 [*Colorado Libraries,* April 2008]

Gómez-Jurado, Juan. *A Masacre de Virginia Tech: Anatomía de una Mente Torturada.* Barcelona: Ediciones El Andén, 2007. 978-84-935789-4-7, €16.50 [*Críticas*, February, 2008]

Matthews, Joseph R. *Library Assessment in Higher Education.* Westport, Conn.: Libraries Unlimited, 2007. 978-1-59158-531-2, $45.00 [*Colorado Libraries,* February 2008]

Chacón, Inma. *La Princesa India: Cuando el Viento Azul.* México: Alfaguara, 2006. 970-770398-9, $19.95 [*Críticas*, June 2006]

Vargas Llosa, Mario. *Israel/Palestina: Paz o Guerra Santa.* fotogs. by Morgana Vargas Llosa. Spain/U.S.: Aguilar: Santillana, 2006. 84-03-09691-7, paper, $19.95 [*Críticas*, May 2006]

Findlay, Diane. *Digging into Dewey.* Fort Atkinson, Wisc.: Upstart Books, 2005. 978-1-932146-18-9, $16.95 [*Colorado Libraries,* May 2006]

Pequeñas Resistencias 4: Antología del Nuevo Cuento Norteamericano y Caribeño. Menéndez, Ronaldo, Ignacio Padilla & Enrique del Risco, eds. Madrid**:** Páginas de Espuma, 2005. 84-95642-59-X, paper, $36.95 [*Críticas*, April 2006]

Rueda, André. *Vengo a Salvar a España: Biografía de Un Franco Desconocido.* Madrid**:** Nowtilus (Investigación Abierta), 2005. photogs., bibliog. 84-9763-202-8, paper, $23.95 [*Críticas*, March 2006]

Becerra, Ángela. *El Penúltimo Sueño.* 1st ed. Barcelona: Planeta, 2005. 84-08-05795-2, $25.95. [*Críticas*, January 2006]

Aguilar Camín, Héctor. *La Conspiración de la Fortuna.* 1st ed. México: Planeta, 2005. 970-37-0368-2, $19.95 [*Críticas*, October 2005]

México en Sus Libros. Enrique Florescano with Pablo Mijangos, editors & compilers. 1st ed. México, D.F.: Taurus Aguilar, 2004. 968-19-0783-3, $16.95 [*Críticas*, September 2005]

Historia Económica de México. Coordinator, Enrique Semo. México: Universidad Nacional Autónoma de México, Editorial Oceano de México, 2004. 13 vols. 970-32-0805+3 (obra completa), $9.25 each [*Críticas*, August 2005]

Czarnowsky, Christyne A. and Michael H. Williams. *Managing Your Wired Workforce: A Practical Guide.* Denver, Colo.: Bradford Pub., 2003. 1-883726-79-4, $24.95 [*Colorado Libraries,* 2004]

Abraham Lincoln. Colección Grandes Biografías. Madrid: Edimat Libros, 2003. 84-8403-858-0, €4.95 [*Críticas*, 2004]

Alponte, Juan María. *Colón: el Hombre, el Navegante, la Leyenda.* México, D.F.: Aguilar, 2003. 968-19-1260-8, $16.95 [*Críticas*, 2004]

Olcese Salvatecci, Alfieri. *Cómo Estudiar con Èxito: Téchnicas yHhábitos Para Aprender Major.* México, D.F.: Alfaomega Grupo Editor, 2002. 970-15-0764-9 [*Críticas*, 2003]

Mujeres Como Islas: Antología de Narradoras Cubanas, Dominicanas, Puertoriqueñas. Edición: Olga Marta Pérez, Thelma Jiménez, Andrés Blanco D., eds. Santo Domingo, República Dominicana: Ediciones Ferilibro, 2002. 959-209-419-5 [*Críticas*, 2003]

Tibol, Raquel. *Los Murales de Diego Rivera: Universidad Autónoma Chapingo.* México, D.F.: Editorial RM, Universidad Autónoma Chapingo, 2002. 968-5208-08-5 [*Críticas*, 2003]

Lindsay-Poland, John. *Emperors in the Jungle: the Hidden History of the U.S. in Panama.* Durham, N.C.: Duke University Press, 2003. 0-8223-3098-9, $18.95 [*Críticas*, 2003]

Kaplan, Allison G. and Ann Marlowe Riedling. *Catalog It! A Guide to Cataloging School Library Materials.* Worthington, Ohio: Linworth Pub., 2002. 1-58683-014-7, $44.95 [*Colorado Libraries,* 2002]

Bardach, Ann Louise. *Cuba Confidential: Love and Vengeance in Miami and Havana.* New York: Random, 2002. 0-375-50489-3, $25.95 [*Library Journal*, 2002]

Swan, James. *Fundraising for Libraries: 25 Proven Ways to Get More Money for Your Library.* New York: Neal Schuman, 2002. 1-55570-433-6, $69.95 [*Colorado Libraries,* 2002]

Puíg de Lange, Victoria. *Sol Con Agua.* Nashville, Tenn.: Editorial Vistazo/Ediciones Reio Negro, 2002. 0-9724506-0-2, $17.75 [*Críticas*, 2002]

The Encyclopedia of Latin American Politics. Edited by Diana Kapiszewski; assistant editor, Alexander Kazan. Westport, Conn.: Oryx Press, 2002. 1-57356-306-4, $74.95 [*Library Journal*, 2002]

Vargas Lizano, Isabel. *Y Si Quieres Saber de Mi Pasado.* Con la colaboración de J.C. Vales. Madrid: Santillana Ediciones Generales, S.L., 2002. 84-03-09278-4, $18.95 [*Críticas*, 2002]

Ruy Sánchez, Alberto. *Los Jardines Secretos de Mogador: Voces de Tierra.* México, D.F.: Alfaguara, S.A., 2001. 968-19-0879-1, $16.95 [*Críticas*, 2002]

Chávez, Ricardo and Celso Santajuliana. *El Final de las Nubes.* Barcelona: RBA Libros, S.A., 2001. 84-7901-760-0, $11.95 [*Críticas*, 2002]

The Power of Language / El Poder de la Palabra: Selected Papers from the Second REFORMA National Conference. Edited by Lillian Castillo-Speed and the REFORMA National Conference Publications Committee. Englewood, Colo.: Libraries Unlimited, 2001. 1-563089459, $35.00 [*Colorado Libraries,* 2001]

Martínez, Rubén. *Crossing Over: A Mexican Family on the Migrant Trail.* Metropolitan: Holt, 2001. 0-8050-4908-8, $26.00 [*Library Journal*, 2001]

Guevara, Ernesto "Che." *The African Dream: the Diaries of the Revolutionary War in the Congo.* Translated from the Spanish by Patrick Camiller. With an introduction by Richard Gott and a foreword by Aleida Guevara March. New York: Grove Press, 2001. 0-8021-3834-9, $13.00 [*Library Journal*, 2001]

Cooper, Gail and Garry Cooper. *New Virtual Field Trips.* Englewood, Colo.: Libraries Unlimited, 2001. 1-56308-887-8, $27.50 [*Colorado Libraries,* 2001]

NATIONAL SERVICE & PROFESSIONAL AFFILIATIONS

American Library Association, Life Member

Association for Library Collections & Technical Services (now CORE)

Cataloging, Classification, and Metadata Section

Margaret Mann Citation Committee, 2023-

ALCTS Editorial Board, Member, 2015-2019

Committee on Cataloging: Description and Access, Member, 2008-2012

Test Site for RDA, Manager, 2009-2011

Nominating Committee, Member, 2007-2008

Committee for Education and Training of Catalogers, Chair, 2006-2007, Member, 2003-2007

Competencies & Education for a Career in Cataloging Interest Group, Chair, 2010-2012; Member, 2010-

President's Program Committee, 2015-2016

Education Committee, Member, 2005-2007

Task Force on Competencies and Education for a Career in Cataloging, Chair, 2007-2009

2007 Annual Meeting Pre-conference, "What They Don't Teach in Library School: Competencies, Education and Employer Expectations for a Career in Cataloging," Steering Committee Chair

Fundraising Committee, Member, 2004-2006

Office of Diversity

Committee on Diversity, Chair, 2010-2011

Diversity Research Advisory Committee, Member, 2009-2010

Spectrum Scholar Mentor, 2009

Diversity Grants Review Committee, Member, 2007, 2010, 2012

Office of Statistics and Research

Research and Statistics Committee, Member, 2005-2007; Intern, 2003-2005

Library Research Round Table

Nominating Committee, 2022-2023

Membership Committee, 2019-2021

Board of Directors, Member At-Large, 2009-2012

Office of Accreditation

Accreditation Panel Member (training completed 2004)

Accreditation Review Panel Member (training completed 2004)

REFORMA, Life Member

National Board of Directors, 2005-2013

National Fundraising Chair, 2005-2013

National Recruiting and Mentoring Committee, 2008-2010

Colorado Chapter, Secretary, 2004-2005

Colorado Chapter Liaison to National Board of Directors, 2004-2013

American Association of Law Libraries (AALL), Life Member Online Audiovisual Catalogers Association (OLAC) Colorado Association of Law Librarians (CoALL)

American Association of University Women Association for Library and Information Science Education (ALISE)

University of Denver ALISE Representative, 2003-2008; 2010-2011

Membership Advisory Committee, 2007-2010

Technical Services Education Special Interest Group, 2003-

Garfield Doctoral Dissertation Award Reviewer, 2012

Garfield Doctoral Dissertation Scholarship Reviewer, 2014

American Association of University Professors (AAUP), 2006-

American Grant Writers Association, 2014- Grant Professionals Institute, 2016- National Grants Management Association, 2014-

Grant Reviewer (National and Regional Team Leader), U.S. Department of Education, 1998- Grant Reviewer, Broadband Technologies Opportunity Program, U.S. Department of Commerce, 2009
Grant Reviewer, Institute of Museum and Library Services, 1998-2000
Grant Reviewer, Colorado Department of Education, 2014-
Grant Reviewer, Colorado State Library, 1998-
Grant Reviewer, American Association of Community Colleges *Working Connections* program, 1999
Peer Reviewer, *Journal for Library and Information Science Education,* 2005-
Peer Reviewer, *Journal of Library Metadata,* 2009
Peer Reviewer, *International Journal of Library and Information Science,* 2011
Regular Columnist, *The Bottom Line*, 2013-2016
Book Reviewer, *Library Journal*, 2001
Book Reviewer, *Críticas*, 2002-2009
Book Reviewer, *Colorado Libraries,* 2000-2012

REGIONAL SERVICE & PROFESSIONAL AFFILIATIONS

Mountain Plains Library Association

Professional Development Grants Committee, Member, 2005-2006
Professional Development Policy and Guidelines Sub-committee Chair, 2006

Colorado Association of Libraries

"Student Voices" Column Editor, *Colorado Libraries,* 2005-2006
Conference Planning Committee, Member, 2002
Technical Services and Automation Division, Chair, 2002-2003; Member, 2000-
Academic Libraries Division, Peer Review Conference Papers Committee, Member, 2007-2009
Education Committee, Member, 1988-1993
Diverse Populations Committee, Member, 2009-2013

SERVICE TO THE UNIVERSITY OF DENVER

Center for Teaching and Learning Faculty Advisory Board, 2007-2008; 2010-2012
Center for Community Engagement and Service Learning Advisory Board, 2007-2012
Faculty Senate
Executive Committee, 2008-2013
Nominations, Rules & Credentials Committee, Chair, 2008-2013; Member 2007-2013
Appointment, Promotion, and Tenure Revision Committee, 2010-2012
Grievance Policy Committee Member, 2007-2010
Law Library Director Search Committee Chair, 2012-2013
PROF Grant Review, College Representative to the University Review Team, 2006, 2008
Project Homeless Connect Evaluations, Principal Investigator, 2006-2009
University Technology Council, 2007-2009
University of Denver Hyde Interviews for Incoming Freshmen, 2003-2012

SERVICE TO THE MORGRIDGE COLLEGE OF EDUCATION

Appointment, Tenure & Review Committee
Member, voting, 2003-2005; 2007- 2009
Chair, Clinical Faculty Promotion & Tenure Policy Subcommittee, 2008-2009
Member, Community Engagement Subcommittee, 2007-2009
Member, Tenure Review Panel, 2003
Advancement and Alumni Relations Committee, Chair, 2003-2007; Member, 2002-2007
College Building Committee Member, 2004-2010

College of Education Student Association, Faculty Advisor, 2004-2007; 2009-2010
Faculty Senator, 2007-2013
Research and Scholarship Committee, Chair, 2008-2009; Member, 2002-2003, 2008-2009
Research and Grant Mentoring Committee, Chair, 2009-2010
Research Task Force Member, 2010-2012
Search Committee Member, Assistant Professor for Curriculum & Instruction, 2010-2011
Workload Task Force Member, 2010-2011

SERVICE TO THE LIBRARY & INFORMATION SCIENCE PROGRAM

Library and Information Science Student and Alumni Association, Faculty Advisor, 2002-2008
ALA Student Chapter, Faculty Advisor, 2005-2008
Beta Phi Mu Phi Chapter, Faculty Advisor, 2004-2014
Steering Committee Member, Accreditation by the American Library Association, 2001-2004
Search Committee Member, Associate Professor for LIS, 2006
Search Committee Chair, Assistant Professors for LIS, 2003, 2005, 2006, 2007
Search Committee Ex-Officio Member, Director for LIS, 2004

SERVICE TO SAM HOUSTON STATE UNIVERSITY

Rio Roundup: South Texas Literature Conference, Conference Coordinator, 1993
External Relations, Fund Raising, Grants Committee, Chair, 1993-1995
Advisory Council Committee, Chair, 1993-1995
Students, Admissions, and Advisement Committee, Chair, 1994
Institutional Effectiveness Committee, Member, 1993-1995

SERVICE TO THE COLLEGE OF EDUCATION AND APPLIED SCIENCE

Faculty Affairs Committee, Member, 1993-1995
Curriculum Committee, Member, 1993-1995
Continuing Education Committee, Member, 1993-1995

SERVICE TO THE COMMUNITY

French Teacher & Student Exchange with Laon, France, Monarch High School, Boulder Valley School District (Boulder, Colorado), 2017-
Denver/Boulder Games 2022, Board of Directors, Secretary-Treasurer, 2015-2018
United Way Campaign Committee, College of Education, 2006
Arapahoe County, Election Judge for the County Clerk and Recorder, 2000-2005
Arthritis Foundation, Rocky Mountain Chapter, Certified Educator & Trainer, 1999-2008
Bonfils Blood Center, Silver Level Donor, 2000-2016
Denver Museum of Natural History, Docent, 1992
Tech Prep of the Lower Rio Grande Valley, Inc. (Harlingen, Texas) Board of Directors, 1995-1997
Executive Committee, 1996-1997; Chair, Development Committee, 1995-1997; Chair, Fiscal Agency Committee, 1995-1996; Chair, Colleges and Universities Committee, 1996-1997
Gilpin County (Colorado) Public Library Board of Trustees, 1986-1989; Vice President, 1987-1989
City of Central (Colorado) Economic Development Committee, 1987-1989
Columbine Family Health Centers, Inc. (Nederland and Black Hawk, Colorado) Board of Directors, 1988-1989

CERTIFICATION

Permanent Public Librarian Certificate - Pennsylvania, New York, Texas
Westlaw Expert Witness, 2008-
Certified Grant Writer®, 2016-

AWARDS AND HONORS

Advanced Practitioner for Service Learning and Community Engagement, University of Denver, 2011
Platinum Star Alumnae, College of Information, Library Science & Technologies, University of North Texas, 2009
Commendation for Integration of Technologies in Teaching & Learning Environment, University of Denver, 2006
Outstanding Adjunct Faculty Member Award, College of Education, University of Denver, 2002
Beta Phi Mu, Pi, University of Pittsburgh, 1985
Alpha Lambda Sigma, University of North Texas, 1972
Albert Nelson Marquis Lifetime Achievement Award, Who's Who in America
Who's Who in American Women
Who's Who of Women Executives
Dictionary of International Biography
Who's Who in the East
Who's Who in the South and Southwest
Who's Who in the World
Who's Who of Online Professionals
Who's Who in Library and Information Science
2,000 Notable Women
Who's Who of Emerging Leaders
Who's Who in Professional and Executive Women
Who's Who in American Education
International Who's Who of Professional and Business Women
International Leaders in Achievement
International Educator of the Year
Who's Who in Finance and Industry
Who's Who in Finance and Business

Invited International and National Conference Presentations

Hall-Ellis, Sylvia D. *Presentation of the Robert O. Ellett Endowed Scholarship.* Presentation delivered to the School of Information at San Jose State University Alumni & Student Program, American Library Annal Conference, San Diego, Calif., June 29, 2024.

Driscoll, Margaret, Christy Confetti Higgins, Scott Brown, and Sylvia D. Hall-Ellis. *A View from Within: Open House Tour of Three Canvas Core Courses*. Presentation to be delivered at the School of Information, San José State University Professional Development Seminar, San José, California, October 17, 2019.

Hall-Ellis, Sylvia D. *Invest in Me -- I'm Your Future: Succession Planning for Libraries.* Keynote presentation delivered at the ALCTS President's Symposium, Boston, Mass., January 8, 2016.

Seidel, Kent E. and Sylvia D. Hall-Ellis. *Making Grants Work for You: Strategies for Doctoral Students and Early Career Scholars.* Presentation delivered at the University Council for Educational Administration, Early Career Scholars Session, Indianapolis, Ind., November 9, 2013.

Hall-Ellis, Sylvia D. *So You Want to be a Manager; Leadership Skills and Competencies for Technical Services Managers and Administrators.* Presentation delivered at the 138th Annual Conference, American Library Association, Chicago, Ill., June 29, 2013.

Seidel, Kent E., Karen S. Riley, Lyndsay Agans, Susan Korach, and Sylvia D. Hall-Ellis. *Making Grants Work for You (Instead of Just Working for Grants).* A panel discussion delivered at the University Council for Educational Administration, Early Career Scholars Session, Denver, Colo., November 17, 2012.

Hall-Ellis, Sylvia D. *After the Great TS Reorganization: The Westminster Law Library.* Presentation delivered at the 137th Annual Conference, American Library Association, Anaheim, Calif., June 23, 2012.

Hall-Ellis, Sylvia D. *Conversations with Catalogers in the 21st Century.* A panel discussion sponsored by the ALCTS Competencies for a Career in Cataloging Interest Group, delivered at the 137th Annual Conference, American Library Association, Anaheim, Calif., June 22, 2012.

Hall-Ellis, Sylvia D., moderator. *Mid-Career Leaders Program.* A panel discussion sponsored by the ALA Committee on Diversity delivered at the 136th Annual Conference, American Library Association, New Orleans, La., June 26, 2011.

Hall-Ellis, Sylvia D., moderator. *Diversity Town Hall.* A community conversation sponsored by the ALA Committee on Diversity delivered at the 136th Annual Conference, American Library Association, New Orleans, La., June 24, 2011.

LaBarre, Kathryn, Sylvia D. Hall-Ellis, Karen Anderson, Rick Hasenyager, Christopher Cronin, and Penny Baker. *Briefings from RDA Test Participants.* A panel discussion delivered at the Midwinter Conference, American Library Association, San Diego, Calif., January 7, 2011.

Miksa, Shawne, Marjorie Bloss, and Sylvia D. Hall-Ellis. *Educating the Next Generation of Catalogers: Teaching RDA.* A panel discussion delivered at the 97th Annual Conference, Association for Library and Information Science Education, San Diego, Calif., January 7, 2011.

Hall-Ellis, Sylvia D., Robert Maxwell, John Hostage, and George Prager. *RDA Panel: What Cataloging Managers Need to Know.* Presentation delivered at the 103rd Annual Conference, American Association of Law Librarians, Denver, Colo., July 12, 2010.

Hall-Ellis, Sylvia D. and Stacey L. Bowers. *Catalogers in the RDA Environment: Skill Sets, Expectations and Challenges.* Presentation delivered at the 103rd Annual Conference, American Association of Law Librarians, Denver, Colo., July 11, 2010.

Hall-Ellis, Sylvia D. *Comfortable in Your Cataloging and Metadata Specialist Skin? Or, So You Want to Hire a Cataloger.* Presentation delivered to the ALCTS Research Group at the 134th Annual Conference, American Library Association, Chicago, Ill., July 11, 2009.

Perez, Megan, Sylvia D. Hall-Ellis, and Denise Anthony. *From Novice to Expert: Collaboration for Succession Planning.* A "hot topic" presentation delivered at the 14th ACRL Conference, Seattle, Wash., March 13, 2009.

Hall-Ellis, Sylvia D. *Cataloging in the RDA Environment: Skill Sets, Expectations and Challenges.* Presentation delivered to the ALCTS Research and Publications Committee at the Midwinter Conference, American Library Association, Denver, Colo., January 24, 2009.

Hall-Ellis, Sylvia D. *LIS Cataloging Education for the 21st Century: Expectations and Challenges.* A panel discussion held at the 95th Annual Conference, Association for Library and Information Science Education, Denver, Colo., January 23, 2009.

Chu, Clara, Sylvia D. Hall-Ellis, and Mark Winston. *The Doctoral Degree & Building a Career.* A panel discussion delivered at the ALA Office of Diversity Spectrum Doctoral Fellows E.J. Josey Leadership Institute, Midwinter Conference, American Library Association, Denver, Colo., January 20, 2009.

Hall-Ellis, Sylvia D. and Robert O. Ellett, Jr. *Fundamentals of Cataloging Course: An Overview of the ALCTS Online Course.* Presentation delivered to the ALCTS Big Heads Group, 133rd Annual Conference, American Library Association, Anaheim, Calif., June 30, 2008.

Hall-Ellis, Sylvia D. *Employers' Expectations for Technical Services Librarians: What We Don't Know.* Presentation delivered to the ALCTS Research and Publications Committee Program, 133rd Annual Conference, American Library Association, Anaheim, Calif., June 28, 2008.

Hall-Ellis, Sylvia D., Virginia R. Maloney, and Mary Stansbury. *Institutional Responses to Engaged Scholarship: The Carnegie Foundation Engaged University Classification at Two Universities.* Presentation delivered to the 94th Annual Conference, Association for Library and Information Science Education, Philadelphia, Pa., January 11, 2008.

Hall-Ellis, Sylvia D. *Puzzles, Problems, and Predicaments.* Presentation delivered to the ALCTS Research Discussion Group, 132nd Annual Conference, American Library Association, Washington, D.C., June 23, 2007.

Hall-Ellis, Sylvia D. *Cataloging Education: A New Emphasis for the Library and Information Science Curriculum.* Presentation delivered to the ALCTS Pre-conference, 132nd Annual Conference, American Library Association, Washington, D.C., June 22, 2007. http://www.loc.gov/catdir/cpso/careercat.html

Ellett, Jr., Robert O. and Sylvia D. Hall-Ellis. *Copy Cataloging Done Smarter.* Presentation delivered to the International Conference on Interdisciplinary Information Sciences and Technologies (InSciT2006), October 25-28, 2006.

Hall-Ellis, Sylvia D. and Robert O. Ellett, Jr. *Cooperative Cataloging: Challenges and Opportunities for Defense Libraries.* Presentation delivered to the 1st Annual Conference of Defense Libraries, Spanish Ministry of Defense, Madrid, Spain, July 7, 2006.

Hall-Ellis, Sylvia D. *Cataloger Competencies: Do the Employers Require What the Professors Teach?* Presentation delivered to the ALCTS CCS Heads of Cataloging Discussion Group, 131st Annual Conference, American Library Association, New Orleans, La., June 26, 2006.

Grealy, Deborah S. and Sylvia D. Hall-Ellis. *From Research to Practice: The Scholarship of Teaching and Learning in LIS Education.* Presentation delivered to the at the 92nd Annual Conference, Association for Library and Information Science Education, San Antonio, Tex., January 18, 2006.

Hall-Ellis, Sylvia D. *Employers' Expectations for Entry-Level Catalogers: What Position Announcement Data Indicate.* Research paper delivered to the Technical Services Special Interests Group, 91st Annual Conference, Association for Library and Information Science Education, Boston, Mass., January 12, 2005. http://dlist.sir.arizona.edu/

Hall-Ellis, Sylvia D. *Common Errors in MARC Records Prepared by LIS Students: What Does It Mean?* Research paper delivered to the ALCTS CCS Cataloging Norms Discussion Group, Mid-Winter Conference, 90th American Library Association, San Diego, Calif., January 10, 2004.

Hall-Ellis, Sylvia D. *Visual Arts as Foundation for Successful Library Automation: The Rocky Mountain College of Art & Design Experience.* Paper delivered at the 6th Annual Conference of Higher Education, Charleston, S. C., 1993.

Hall, Sylvia D. *Design Elements for Bibliographic Databases: An Overview.* Paper delivered at the 14th Online National Conference, New York, 1983.

Invited Regional Conference Presentations

Hall-Ellis, Sylvia D., Hudson, Christopher D., Brittany Cronin, and Kathryn Michaels. "The Colorado Law Project: Meeting the Public's Need for Legal Information." Panel discussion delivered at the Mountain Plains Library Association Conference, Billings, Mont., April 9, 2011.

Grealy, Deborah S. and Sylvia D. Hall-Ellis. *Education for Information Professionals in New Mexico: Library & Information Science Graduate Education at the University of Denver.* Presentation delivered at the New Mexico Library Education Summit, Las Vegas, N.M., September 26, 2005.

Hall-Ellis, Sylvia D. *Public Library-School Library Partnerships.* Presentation delivered at the 3rd Annual Colorado Association of Libraries Conference with the Mountain Plains Library Association, Denver, Colo., October 22, 2004.

Hall-Ellis, Sylvia D. *Learn All You Can – Educational Partnership Opportunities for the Lewis and Clark Bicentennial Commemoration.* Paper delivered at the 3rd Annual Lewis and Clark Bicentennial Council National Planning Conference, Bismarck, N.D., April 26, 1998.

Invited State Conference Presentations

Grealy, Deborah S. and Sylvia D. Hall-Ellis. *Academic Library Leadership Changes: Using Succession Planning and Mentoring*. Presentation delivered at the Minnesota Library Education Conference, St. Cloud, Minn., October 10, 2013.

Hall-Ellis, Sylvia D., Merrie Valliant, and Melissa Powell. *RDA: What Is It and What Do You Need To Do With It At Your Library?* Presentation delivered at the Colorado Library Consortium Spring Conference, Ft. Morgan, Colo., April 26, 2013.

Hall-Ellis, Sylvia D. *Service Learning and the Library & Information Science Graduate Education at the University of Denver.* Presentation delivered at the 4th LEADS Scholars Orientation, Denver, Colo., August 5, 2009.

Hall-Ellis, Sylvia D. *Service Learning: Enhancement to Library & Information Science Graduate Education at the University of Denver.* Presentation delivered at the 3rd LEADS Scholars Orientation, Denver, Colo., June 2008.

Hall-Ellis, Sylvia D. *Law Librarianship: A Community Conversation.* Sponsored by the Colorado Association of Law Libraries. Paper delivered at the Colorado Supreme Court Library, Denver, Colo., May 14, 2008.

Hall-Ellis, Sylvia D. *Opportunities and Challenges in Law Librarianship: A Community Conversation.* Presentation delivered at the Sturm College of Law, Denver, Colo., November 7, 2007.

Ellis, Sylvia D. *Grant Writing Resources for Nursing Professionals.* Presentation delivered at the Presbyterian / St. Luke's Health One Medical Center 1st Annual Research Symposium, Denver, Colo., October 17, 2007.

Hall-Ellis, Sylvia D. *Project Homeless Connect 4 Event Evaluation – Insights and Lessons Learned.* Presentation delivered at the Homelessness Research Symposium: What is DU Doing about Homelessness in Denver, Denver, Colo., September 14, 2007.

Hall-Ellis, Sylvia D. *Service Learning and the Library & Information Science Graduate Education at the University of Denver.* Presentation delivered at the 2nd LEADS Scholars Orientation, Denver, Colo., August 10, 2007.

Hall-Ellis, Sylvia D. *Education for Information Professionals in a Digital Environment: Library & Information Science Graduate Education at the University of Denver.* Presentation delivered at the 15th Spring Mountains and Plains Parapros Conference, Denver, Colo., February 24, 2007.

Hall-Ellis, Sylvia D. *Public Library Service to Spanish-Speaking and Latino Residents in Denver: A Case Study.* Presentation delivered at the 4th Annual Colorado Association of Libraries Conference, Denver, Colo., November 10, 2005.

Hall-Ellis, Sylvia D. *Education for Information Professionals in a Digital Environment: Library & Information Science Graduate Education at the University of Denver.* Presentation delivered at the 14th Annual Mountains and Plains Parapros Conference, Aurora, Colo., July 29, 2005.

Hall-Ellis, Sylvia D. *Educational Opportunities: Library & Information Science Graduate Education at the University of Denver.* Presentation delivered at the 13th Annual Mountains and Plains Parapros Conference, Centennial, Colo., August 6, 2004.

Hall-Ellis, Sylvia D. *Library Education & Training: Focus on the West: An LIS Faculty Member's Personal Response*. Presentation delivered at the 1st Annual Colorado Association of Libraries Conference, Keystone, Colo., October 18, 2002.

Hall-Ellis, Sylvia D. *Grant Writing for School Librarians.* Presentation delivered at the 2002 Annual Colorado Education Media Association Conference, Colorado Springs, Colo., February 15, 2002.

Hall-Ellis, Sylvia D. *Grants – Opportunities for the Future.* Paper delivered at the Southeast Regional Accountability Annual Conference, Lamar, Colo., November 12, 1998.

Hall-Ellis, Sylvia D. *The Texas Library Connection and Interlibrary Loan: An Experiment in Resource Sharing.* Paper delivered at the Texas Computer Educators' Association Annual Conference, Austin, Tex., February 6, 1997.

Hall-Ellis, Sylvia D. *Finding Grant Sources on the Internet: A Guide for Librarians.* Paper delivered at the 2nd Annual Institute for School Library Personnel, Pharr-San Juan-Alamo North High School, Pharr, Tex., July 29, 1996**.**

Hall-Ellis, Sylvia D. *Mathematical and Logical Thinking: A Critical Intelligence.* Paper delivered at the 3rd Annual Paraprofessional Conference at the University of Texas - Pan American, Edinburg, Tex., March 8, 1996.

Hall-Ellis, Sylvia D. *Cataloging Trends and Issues: Update Session.* Paper delivered at the 1st Annual Institute for School Library Personnel, South Texas Community College, McAllen, Tex., July 19, 1995.

Hall-Ellis, Sylvia D. *Grant Writing: Tips and Encouragement for School Librarians.* Paper delivered at the 1st Annual Institute for School Library Personnel, South Texas Community College, McAllen, Tex., July 18 and 19, 1995.

Hall-Ellis, Sylvia D. *How to Become an Expert Grant Writer.* Paper delivered at the 3rd Annual High School Principals' Academy, South Padre Island, Port Isabel, Tex., June 19, 1995.

Texas Library Study: Results from Regions I and II. Paper delivered at the 3rd Annual Technology Conference, Texas A&M University, College Station, Tex., November 18, 1994.

Hall-Ellis, Sylvia D. *Academic Achievement and Middle School Students.* Paper delivered at the 8th Annual Young Adult Conference, Sam Houston State University, Huntsville, Tex., November 5, 1994.

Hall-Ellis, Sylvia D. *Multimedia Resources for Library Leaders.* Paper delivered at the Institute for Librarians in A Multicultural Environment, Sam Houston State University, Huntsville, Tex., June 10, 1994.

Hall-Ellis, Sylvia D. *Finding the Resource: Empowering the User, or, the Case for Curriculum Based Subject Access to Learning Resource Center Collections.* Paper delivered at the 81st Annual Texas Library Association Conference, Corpus Christi, Tex., April 12-16, 1994.

Hall-Ellis, Sylvia D. and William H. Pichette. *Sam Houston State University Makes Use of OCLC/AMIGOS Collection Analysis CD.* Paper delivered at the 81st Annual Texas Library Association Conference, Corpus Christi, Tex., April 12-16, 1994.

Hall, Sylvia D. *Funding and Library Development in Pennsylvania: A Symbiotic Relationship.* Paper delivered at the Annual Graduate Student Colloquia, University of Pittsburgh, School of Library and Information Science, 1982.

Hall, Sylvia D. *Leadership for Public Library Trustees.* Paper delivered for the Trustees Division, Pennsylvania Library Association Annual Conference, Lancaster, Penn., 1981.

Seminar and Professional Development Presentations

Taylor, Meredith, and Sylvia D. Hall-Ellis. *Talent Management and Succession Planning.* ALCTS eForum, held March 22, 2017.

Hirsh, Sandra, Heather O'Brien, Michelle Holschuh Simmons, Michael Krasulski, and Sylvia D. Hall-Ellis. *Information Services Today: An Introduction. Part 3: Information Services: Roles in the Digital Age*. Rowan and Littlefield in partnership with Library Journal webinar, recorded February 5, 2015.

Hall-Ellis, Sylvia D. and Jennifer Sweda. *Copy Cataloging in an RDA Environment.* ALCTS eForum, held May 14 and 15, 2013.

Hall-Ellis, Sylvia D. *Law Librarianship: A Community Conversation.* Sponsored by the Colorado Association of Law Libraries, presented at the Colorado Supreme Court Library, Denver, Colo., May 14, 2008.

Hall-Ellis, Sylvia D. and Beatrice Z. Gerrish. *Reading and Libraries: Recent Research in Reading.* Presentation at the Ricks Center for Gifted Education, Denver, Colo., March 4, 2008.

Hall-Ellis, Sylvia D. *Cataloger Competencies: Do the Employers Require What the Professors Teach?* Presentation for the School of Library and Information Science, San José State University, February 12, 2008.

Hall-Ellis, Sylvia D. and Robert O. Ellett, Jr. *Cooperative Cataloging: Rules, Tools, and Conventions for Building a Multi-institutional Catalog.* Sponsored for the Spanish Ministry of Defense, Madrid, Spain, July 10, 2006.

Hall-Ellis, Sylvia D. *Cash for Kids: Grant Writing Opportunities for Youth Services Librarians.* Sponsored by the Colorado Young Adult Librarians; presented at Bemis Memorial Library, Littleton, Colo., November 13, 2002.

Hall-Ellis, Sylvia D. *MARC Records and Authority Control: Planning for Bibliographic Database Migration.* Sponsored and held at the Douglas County Public Library, Castle Rock, Colo., May 28, 2002.

Grant Writing: A Refresher for Librarians. Sponsored by Library and Information Science Program, College of Education, University of Denver; presented at University Center at Chaparral, August 12, 2000.

Hall-Ellis, Sylvia D. *Shaking the Money Tree – Basic Grant Writing for Colorado Educators.* Sponsored by the Office of Educational Telecommunications of the Colorado Department of Education.
Pikes Peak Community College, Colorado Springs, Colo., November 16, 1998.

Pueblo School District 60, Pueblo, Colo., November 12, 1998.
University of Northern Colorado, Greeley, Colo., November 10, 1998.
United Technology Educational Partnership, Grand Junction, Colo., November 9, 1998.

Hall-Ellis, Sylvia D. *Cataloging Multimedia, Kits, Globes and Map Materials in USMARC.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., April 24, 1997 and December 12, 1996.

Hall-Ellis, Sylvia D. *New Standards for School Library Media Centers.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., April 15, 1997.

Hall-Ellis, Sylvia D. *The School Library Media Specialist in the 21st Century: Visions for the Future.* Sponsored and hosted by Pharr-San Juan-Alamo Independent School District, Pharr, Tex., April 4, 1997.

Hall-Ellis, Sylvia D. *Cataloging Sound Recordings and Audio Materials in USMARC.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., March 20, 1997 and November 21, 1996.

Hall-Ellis, Sylvia D. *Evaluating and Selecting CD-ROMS for School Library Media Collections.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., March 18, 1997.

Hall-Ellis, Sylvia D. *Cataloging Audiovisual Materials in USMARC.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., February 27, 1997, November 7, 1996 and October 24, 1996.

Hall-Ellis, Sylvia D. *Introduction to Dialog: Basic Searching Strategies.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., February 14, 1997.

Hall-Ellis, Sylvia D. *Cataloging Books in USMARC.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., January 30, 1997, October 10, 1996, September 26, 1996 and August 8, 1996.

Hall-Ellis, Sylvia D. *Advanced Internet Searching Techniques for Librarians.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., January 21, 1997.

Hall-Ellis, Sylvia D. *Texas Library Connection Full-Text Searching.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., December 13, 1996 and October 25, 1996.

Hall-Ellis, Sylvia D. *Developing Evaluation Strategies for Grants and Proposals.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., December 10, 1996.

Hall-Ellis, Sylvia D. *Developing Needs Assessment for Grants and Proposals.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., November 12, 1996.

Hall-Ellis, Sylvia D. *Texas Library Connection Union Catalog Searching.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., November 8, 1996 and September 6, 1996.

Hall-Ellis, Sylvia D. *Grant Resources on the Internet.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., October 23, 1996.

Hall-Ellis, Sylvia D. *Preparing a Response to the Telecommunications Infrastructure Fund Board: Needs Assessment, Professional Development Framework, and Evaluation Strategies.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., October 16, 1996.

Hall-Ellis, Sylvia D. *Texas Library Connection: Building the Districtwide Bibliographic Database.* Sponsored and hosted by Mercedes Independent School District, Mercedes, Tex., September 13, 1996 and August 8, 1996. Sponsored and hosted by Los Fresnos Consolidated Independent School District, Los Fresnos, Tex., August 12, 1996.

Hall-Ellis, Sylvia D. *School-to-Work and Special Education: An Inclusive Partnership for Success.* Sponsored and hosted by the Office of Special Education, Region One Education Service Center, Edinburg, Tex., September 11, 1996.

Hall-Ellis, Sylvia D. *Telecommunications Infrastructure Fund Board: An Overview of Funding for Secondary Schools.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., August 31, 1996.

Hall-Ellis, Sylvia D. *Cataloging Books, Multimedia, and Realia in USMARC.* Sponsored and hosted by Edinburg Consolidated Independent School District, Edinburg, Tex., August 6, 1996.

Hall-Ellis, Sylvia D. *Internet Resources for Grant Writers.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., April 20, 1996.

Hall-Ellis, Sylvia D. *Enhanced Grant Writing Skills for Mathematics Educators: Writing Skills for Campus Teams.* Sponsored and hosted by the Office of General Education, Region One Education Service Center, Edinburg, Tex., March 22, 1996.

Hall-Ellis, Sylvia D. *Internet Resources for Grant Writers.* Sponsored and hosted by the College of Education and Applied Science, Sam Houston State University, Huntsville, Tex., March 9, 1996.

Hall-Ellis, Sylvia D. *Grant Writing for Mathematics Educators: A Development Process for Campus Teams.* Sponsored and hosted by the Office of General Education, Region One Education Service Center, Edinburg, Tex., March 4, 1996.

Hall-Ellis, Sylvia D. *Shaking the Money Tree: Preparing Successful Technology Grant Applications.* Sponsored and hosted by the Office of Technology and Media Services, Region One Education Service Center, Edinburg, Tex., February 29, 1996 and April 29, 1996.

Hall-Ellis, Sylvia D. *District-wide Technology Planning: Technical Assistance for the Texas Education Agency Initiative.* Sponsored and hosted by the Office of Technology and Media, Region One Education Service Center, Edinburg, Tex., February 2, 1996.

Hall-Ellis, Sylvia D. *Enhanced Grant Writing Skills.* Sponsored and hosted by Pharr-San Juan-Alamo Independent School District, Pharr, Tex., January 27, 1996.

Hall-Ellis, Sylvia D. *United States Copyright Act of 1976, Video Transmissions, Computer Software and the Internet.* Sponsored and hosted by the Office of Technology and Media, Region One Education Service Center, Edinburg, Tex., January 24, 1996.

Hall-Ellis, Sylvia D. *The Grant Writing Development Process.* Sponsored and hosted by Pharr-San Juan-Alamo Independent School District, Pharr, Tex., January 20, 1996.

Hall-Ellis, Sylvia D. *MARC Cataloging of Materials for Library Media Centers.* Sponsored and hosted by the Office of Media Services, Region One Education Service Center for the Donna Independent School District, Donna, Tex., August 17, 1995.

Hall-Ellis, Sylvia D. *Classification.* Sponsored by AJ Seminars, Rockville, Maryland; presented at University Hilton Hotel, Houston, Tex., May 10, 1995.

Hall-Ellis, Sylvia D. *Library Technical Services.* Sponsored by AJ Seminars, Rockville, Maryland; presented at University Hilton Hotel, Houston, Tex., April 26, 1995.

Hall-Ellis, Sylvia D. *Grant Writing: An Introduction for Public School Administrators.* Sponsored and hosted by the Office of Administrative Services, Region One Education Service Center, Edinburg, Tex., April 19, 1995.

Hall-Ellis, Sylvia D. *The School Library Media Specialist in the 21st Century: Visions for the Future.* Sponsored and hosted by the United Independent School District, Laredo, Tex., March 31, 1995.

Hall-Ellis, Sylvia D. *Using USMARC.* Sponsored by AJ Seminars, Rockville, Maryland; presented at University Hilton Hotel, Houston, Tex., March 29, 1995.

Hall-Ellis, Sylvia D. *Library Media Center Policies and Guidelines: How to Prepare for School Board Adoption.* Sponsored and hosted by the Office of Technology and Media Services, La Joya Independent School District, La Joya, Tex., March 10, 1995.

Hall-Ellis, Sylvia D. *Developing District-wide Policies and Guidelines for Library Media Centers.* Sponsored and hosted by the Office of Technology and Media Services, La Joya Independent School District, La Joya, Tex., January 10, 1995.

Hall-Ellis, Sylvia D. *MARC Cataloging of Audiovisual Materials for Library Media Centers.* Sponsored and hosted by the Office of Library Media and Technology Services, Cypress-Fairbanks Independent School District, Houston, Tex., December 1, 1994.

Hall-Ellis, Sylvia D. *The School Library Media Specialist in the 21st Century: Visions for the Future.* Sponsored and hosted by United Independent School District, Laredo, Tex., October 14, 1994.

Hall-Ellis, Sylvia D. *The School Library Media Specialist in the 21st Century: Visions for the Future.* Sponsored and hosted by the Laredo Independent School District, Laredo, Tex., October 7, 1994.

Hall-Ellis, Sylvia D. *MARC Cataloging for Library Media Centers.* Sponsored by the Office of Library Media and Technology Services, Cypress-Fairbanks Independent School District, Houston, Tex., October 5, 1994.

Hall-Ellis, Sylvia D. *Jump to the Head of the Class: Undergraduate Library Resources Available at Sam Houston State University.* Sponsored by the Office of the Associate Vice President for Student Services, Sam Houston State University, Huntsville, Tex., October 4, 1994.

Hall-Ellis, Sylvia D. *CD-ROMs - 1994's Newest and the Best for Secondary Level Media Centers.* Sponsored and hosted by Clear Lake Independent School District, Houston, Tex., June 3, 1994.

Hall-Ellis, Sylvia D. *Introduction to Classification.* Sponsored by AJ Seminars, Rockville, Maryland; presented at Holiday Inn, Market Center, Dallas, Tex., May 18, 1994.

Hall-Ellis, Sylvia D. *Basic Descriptive Cataloging.* Sponsored by AJ Seminars, Rockville, Maryland; presented at University Hilton Hotel, Houston, Tex., May 4, 1994.

Hall-Ellis, Sylvia D. *Shaking the Money Tree - Part II: Writing Successful Grant Applications.* Sponsored by Donna Independent School District, Donna, Texas, and Region One Education Service Center Edinburg, Texas; presented at South Texas Community College Library, McAllen, Tex., April 29, 1994.

Hall-Ellis, Sylvia D. *Using MARC.* Sponsored by AJ Seminars, Rockville, Maryland; presented at Holiday Inn, Market Center, Dallas, Tex., April 6, 1994.

Hall-Ellis, Sylvia D. *Automated Authority Control.* Sponsored by AJ Seminars, Rockville, Maryland; presented at University Hilton Hotel, Houston, Tex., March 23, 1994.

Hall-Ellis, Sylvia D. *Automating the District School Library Media Centers: Choices and Opportunities.* Sponsored and hosted by the Office of Technology and Library Media Services, Fort Bend Independent School District, Sugar Land, Tex., March 4, 1994.

Hall-Ellis, Sylvia D. *Shaking the Money Tree - Part I: Preparing Successful Grant Applications.* Sponsored and hosted by the Office of Library Media Services, Donna Independent School District, Donna, Tex., February 4, 1994.

GRADUATE COURSES TAUGHT

San José State University, School of Library and Information Science
INFO 249 – Advanced Cataloging and Classification (Fall 2015, 2016; Summer 2016)
INFO 287 – Special Topics in Cataloging and Classification (Spring 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024; Fall 2020, 2021, 2022, 2023, 2024)
LIBR 248 – Beginning Cataloging and Classification (Summer 2002, 2003, 2004, 2005, 2006)
LIBR 249 – Advanced Cataloging and Classification (Summer 2003; Fall 2014; Summer 2015)

University of Denver, University College
Grant Writing Certificate Seminar for Non-Profit Organizations (Fall 2020, 2021; Spring 2021)

University of Denver, Morgridge College of Education HED
5991 – Grant Writing in Higher Education (Spring 2011)
LIS 4010 – Organization of Information (Fall 2002-2009; Winter 2005; Spring 2004-2006)
LIS 4020 – Professional Principles and Ethics (Summer 2000)
LIS 4040 – Management of Libraries and Information Centers (Fall 2010; Spring 2003, 2009 (DS); Winter 2005)
LIS 4070 – Cataloging and Classification (Winter 2008, 2009, 2010, 2011, 2012; Fall 2009 (DS)) LIS
4321 – Collection Management (Spring 2005)
LIS 4326 – LIS Research (Winter 2009 (DS); Spring 2009 (DS))
LIS 4350 – Adult Materials and Services (Summer 2006, 2009)
LIS 4379 – Social Sciences Resources (Spring 2009)
LIS 4400 – Cataloging and Classification (Spring 2000, 2001; Winter 2002-2009; Summer 2005, 2006 – course renumbered LIS 4070, September 2007)
LIS 4401 – Descriptive Cataloging (Winter 2001; Spring 2002, 2003, 2006-2009; Summer 2005)
LIS 4402 – Subject Cataloging (Spring 2001, 2009; Summer 2005, 2006, 2007, 2008)
LIS 4403 – Classification Schemes (Fall 2007, 2008, 2009 (DS)) LIS
LIS 4405 – Authority Control (Winter 2009)
LIS 4510 – Materials and Services for Children (Winter 2004; Summer 2005)
LIS 4620 – Grant Writing and Fundraising (Summer 2000, 2002, 2004, 2010; Winter 2006; Fall 2006-2009)
LIS 4700 – Seminar in Technical Services (Fall 2001)
LIS 4700 – Seminar in Public Libraries (Summer 2002)
LIS 4804 – Management of Electronic Records (Spring 2004; Fall 2005)
LIS 4902 – Capstone Projects (Winter 2003, Spring 2008, 2009, 2011)
LIS 4910 – Independent Study (every quarter Winter 2000 through Spring 2011)
LIS 4920 – Service Learning (every quarter Summer 2004 through Spring 2011)
RMS 4954 – Grant Writing (Summer 2013, 2014)
RMS 4959 – Content Analysis Methodology (Spring 2015)
QRM 4978 – Grant Writing (Summer 2011, 2012)

Rutgers University, School of Communication and Information
SC&I 522 – Cataloging and Classification (Summer 2013)

University of Arizona, College of Behavioral and Social Sciences
LIS 602 – Cataloging and Classification (Summer 1995)
LIS 612 – Advanced Online Search and Retrieval (Summer 1995)

Sam Houston State University, College of Education & Applied Science
LIS 532 - Cataloging and Classification (Fall 1993, 1994, 1995)
LIS 563 - Advanced Cataloging and Classification (Summer 1994)
LIS 567 - Research Methods (Spring 1994, Spring 1995)
LIS 591 - Educational Technology (Spring 1994, 1995)
LIS 596 - Networking and Computer Technologies in Education (Fall 1993, Summer 1994, Fall 1995)

Dissertations at the University of Denver

Bowers, Stacey L. *Library Anxiety of Law School Students: A Study Utilizing the Multidimensional Library Anxiety Scale.* Chair, May 5, 2010.

Fattor, Melissa M. *Student Engagement Differences by Ethnicity and Scale for Ninth Grade Students.* Chair, November 1, 2010.

Fulton, Roseanne. *A Case Study of Culturally Responsive Teaching in Middle School Mathematics.* Kent Seidel, Chair, June 18, 2009, Outside Chair.

Grealy, Deborah S. *Tribes and Territories in Library and Information Studies Education.* Bruce Uhrmacher, Chair, June 10, 2008, Committee Member.

McCord, J. Michael. *Developing a Standard of Care for Educational Malpractice.* Chair, April 15, 2011.

Priebe, Sarah J. *Distinguishing Effects of Domain and General Knowledge on Passage Fluency and Comprehension.* Jan Keenan, Chair. July 21, 2011, Outside Chair.

Snyder-Mondragon, Sandra M. *Institutional Factors that Impact the Retention of Graduate Students of Color in Schools of Library and Information Science: A Metaregression of Accredited Library School Statistics on Student Retention and Graduation Rates.* Kathy Green, Chair, July 24, 2009, Committee Member.

Taylor, Karen Pickles. *Effective Teaching.* Elinor Katz, Chair, July 15, 2009, Outside Chair.

Thompson, Jennifer. *Distinguishing a Western Women's College: A History of the Curriculum and Student Experience at Colorado Women's College.* Edith W. King, Chair, July 16, 2010, Committee Member.

Walker, Emelda. *Influence of Organizational Factors on Job Satisfaction of Disability Service Providers at Postsecondary Institutions.* Chair, April 29, 2010.

Dissertation Proposals at the University of Denver

Bowers, Stacey L. *Library Anxiety of Law School Students: A Study Utilizing the Multidimensional Library Anxiety Scale.* Chair, November 5, 2009.

McCord, J. Michael. *Developing a Standard of Care for Educational Malpractice.* Edith W. King, Chair. April 23, 2010.

Thompson, Jennifer. *History of Colorado Women's College.* Edith W. King, Chair, October 30, 2008. Committee Member.

Walker, Emelda. *Influence of Organizational Factors on Job Satisfaction of Disability Service Providers at Postsecondary Institutions.* Chair, July 21, 2009.

Dissertations at Other Institutions

Rodríguez-Mori, Howard. *The Information Behavior of Puerto Rican Immigrants to Central Florida, 2003-2009: Grounded Analysis of Six Case Studies Use of Social Networks during the Migration Process.* Kathleen Burnett, Chair, April 10, 2009, Florida State University, Committee Member.

Schwartz, Brian *More than a Look-up Skill: Medical Information Literacy Education in Osteopathic Medical Schools.* D. Mirah Dow, Chair, July 18, 2017. Emporia State University, Committee Member.

Snow, Karen. *A Study of the Perception of Cataloging Quality among Catalogers.* Shawne D. Miksa, Chair, August 1, 2011. University of North Texas, Committee Member.

Dissertation Proposals at Other Institutions

Schwartz, Brian *More than a Look-up Skill: Medical Information Literacy Education in Osteopathic Medical Schools.* D. Mirah Dow, Chair, December 4, 2015. Emporia State University, Committee Member.

Snow, Karen. *A Study of the Perception of Cataloging Quality among Catalogers.* Shawne D. Miksa, Chair, May 11, 2010. University of North Texas, Committee Member.

Master's Thesis at the University of Denver

Hemingson, Jeff. *Recital Paper.* Lamont School of Music, February 2010, Outside Chair.

Capstones at the University of Denver

Anthony, Alisa. *Correlation of Library and Information Science Program outcomes and Vacant Position Qualifications Listed on the Colorado State Library Jobline by Employers During the Period September 1, 2000 through August 31, 2002.* Chair, Winter Quarter, 2003.

Borden, Donna M. *Improving Emergency Communications Systems: Is a Radio Communications Network the Answer?* Fall Quarter, 2014.

Bowden, Heather L.M. *Exploring Biological Models for Long-term Data Preservation.* Chair, Spring Quarter, 2008.

Casenada, Cassandra Y. *Challenges to the Recruitment, Education, and Retention of Librarians of Color*. Chair, Spring Quarter, 2008.

Chang, Jennifer C. *Legal Research Practice and Preference: A Law Firm Perspective.* Chair, Spring Quarter 2011.

Ellis, Megan S. Fitzgerald. *Design of a Public Library Adult Volunteer Recruitment Program and Training Curriculum.* Chair, Winter Quarter, 2003.

Kircher, Kathy. *Development of a Library Pathfinder for Exobiology and Posting it on the Internet.* Chair, Winter Quarter, 2003.

Melhado, Loretta. *Design of St. John's Episcopal Church Library.* Chair, Spring Quarter, 2008.

Radcliff, Kathy. *Original Cataloging of Archival materials in the HERS Collection in Penrose Library.* Chair, Winter Quarter, 2003.

Sass, Carol Ann. *ACT Periodical Index: Access to Catholic Thinking Periodical Index: Web Index to Select Catholic Periodicals.* Spring Quarter 2000.

Stone, Sergio D. *Conducting Community Analysis for the Bemis Public Library (Littleton, Colorado) Using 2002 U.S. Census Data and the Online Outcome-Based Evaluation Toolkit.* Chair, Winter Quarter, 2003.

Tureson, Tamara. *Design and Use of an Information Audit Tool for Use in a Law Library.* Chair, Winter Quarter, 2003.

Tweed, Beth. *Evaluation of Email Reference Service in a Consumer Health Library Environment.* Chair, Winter Quarter, 2003.

GRANTS AND CONTRACTS

Student Learning in Agriculture STEM through Teacher Professional Development. Research team: Stanton Gartin (PI) and Cyndi Hofmeister, Northeast Junior College; Jeff Cash, Cheryl Sánchez, Anne-Marie Crampton, Lamar Community College; Suzanna Spears, Morgan Community College; Jack Wiley, Kerry Gabrielson, Trinidad State Junior College; Michael J. Miller, Colorado State University; Michael Womochil (Co-PI), Casey Sacks, and Sylvia D. Hall-Ellis, Colorado Community College System. U.S. Department of Agriculture, Agriculture and Food Research Initiative, Food, Agriculture, Natural Resources and Human Sciences Education and Literacy Initiative, $404,460 (2017-2020)

Leading and Achieving: the Colorado Agriculture Regional Consortium. Research team: Jack Wiley (PI), Kerry Gabrielson, Trinidad State Junior College; Jeff Cash (PI), Cheryl Sánchez, Anne-Marie Crampton, Lamar Community College; Suzanna Spears, Morgan Community College; Cyndi Hofmeister, Northeast Junior College; Michael Womochil (Co-PI), Casey Sacks, and Sylvia D. Hall-Ellis, Colorado Community College System. U.S. Department of Agriculture, Hispanic Serving Institutions Education Grants Program, $504,414 (2017-2020)

Cyber Prep Program Planning Grant. Research team: Debbie Sagen (PI), Brenda Lauer, Pikes Peak Community College; Gretchen Martin, Koiosa Insights; and, Sylvia D. Hall-Ellis, Colorado Community College System. U.S. Department of Commerce, Regional Alliances and Multi-stakeholder Partnerships to Stimulate (RAMPS) Cybersecurity Education and Workforce Development, $199,681 (2016-2018)

Career and Technical Education in Colorado: Pathways to Education and Employment. Research team: Heather McKay (PI), Rutgers University; Sarah Heath, Casey Sacks, Sylvia D. Hall-Ellis, Colorado Community College System. U.S. Department of Education, Institute of Education Sciences, $1,400,000 (2017-2021)

Pre-Alliance Planning Grant Colorado Community College Alliance. Research team: Victor Vialpondo (PI) and Janel Highfill, Community College of Aurora; Heidi Loshbaugh (Co-PI), Community College of Denver; Rick Reeves, Bill McGreevy, Liz Cox, and Kristin Aslin, Red Rocks Community College; Cathy Pellish, Front Range Community College; Samuel DeVries, Arapahoe Community College; Sylvia D. Hall-Ellis, Colorado Community College System. National Science Foundation, Louis Stokes Alliance for Minority Participation (LSAMP), $86,817 (2016-2017)

Towards Scalable Differentiated Instruction Using Technology-enabled, Competency-based, Dynamic Scaffolding. Research team: Karen Wilcox (PI) and Vijay Kumar, Center for Computational Engineering, Massachusetts Institute of Technology; Flora McMartin, Broad-based Knowledge; Quinsigamond Community College; and, Casey Sacks, and Sylvia D. Hall-Ellis, Colorado Community College System. U.S. Department of Education, First in the World Developmental Grant, $2,891,882 (2015-2019)

Colorado Strategic Partnerships Emergency Grant. Research team: Elise Lowe-Vaughn (PI), Amy Hodson, Celia Hardin, Barbara McBride, James Newby, Christopher Dewhurst, Nina Holland, Kate Anderson, MaryAnn Roe, Chrystalynn Chrystalynn, Elaine Edon, Mona Barnes, Tom Morgan, Rob Hanni, and Marie Valenzuela, Colorado Department of Labor and Employment; Steve Anton, Joelle Brouner, and, Katie Griego, Colorado Department of Human Services; Rebecca Holmes, Judith Martinez, and Jennifer Jirous, Colorado Department of Education; Emily Templin Lesh, Colorado Workforce Development Council; Cory Everett, Colorado Department of Regulatory Agencies; and, Casey Sacks and Sylvia D. Hall-Ellis, Colorado Community College System. U.S. Department of Labor, Strategic Partnerships Emergency Grant, $5,000,000 (2015-2017)

CAEL Jump Start Program: Competency-Based Education. Research team: Jerry Migler (PI), Casey Sacks, Debra Cohn, Thomas Hartman, and Sylvia D. Hall-Ellis, Colorado Community College System; Matt Jamison, Front Range Community College; Mike Coste, Red Rocks Community College; Amanda Corum, Pueblo Community College; Janet Colvin, Pikes Peak Community College; and, MaryAnn Matheny, Community College of Denver. Council for Adult and Experiential Learning, $15,000 (2015)

Summit on the Redesign of Developmental Education. Research team: Jerry Migler (PI), Casey Sacks, and Sylvia D. Hall-Ellis, Colorado Community College System; Chip Nava, Pueblo Community College; Kim Moultney, Arapahoe Community College; Debbie Ulibarri, Trinidad State Junior College; and, Kris Bernard, Front Range Community College. American Association of Community Colleges, $15,000 (2015-2016)

Equity in Excellence at Colorado Community Colleges. Research team: Keith Howard (PI) and Sylvia D. Hall-Ellis, Colorado Community College System; Estela Mata Bensimon, Center for Urban Education, University of Southern California; and Kerry Gabrielson, Trinidad State Junior College. Colorado Department of Higher Education, Colorado Opportunity Scholarship Program, $150,000 (2015-2016)

MBA High School of Business in Colorado. Research team: Laurie Urich (PI) and Sylvia D. Hall-Ellis, Colorado Community College System; Rudolph Sumpter and Beatrice Gerrish, Boulder Valley Schools; Keith Curry Lance, RSL Research Group. Colorado Department of Higher Education, Colorado Opportunity Scholarship Program, $501,295 (2015-2016)

Fullbridge Program in Colorado. Research team: Keith Howard (PI) and Sylvia D. Hall-Ellis, Colorado Community College System; Suzanna Spears, Fort Morgan Community College; and, Cheryl Sánchez and Anne-Marie Compton, Lamar Community College. Colorado Department of Higher Education, Colorado Opportunity Scholarship Program, $300,000 (2015-2017)

Colorado Community College System Alternative Credit Program. Research team: Jerry Migler (PI), Keith Howard, and Sylvia D. Hall-Ellis, Colorado Community College System. American Council on Education, $13,000 (2015)

Internationalization in Higher Education. Researcher: Samuel D. Museus. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Internationalization, $8,000 (2014-2015)

International Perspectives on Bilingual Education. Researcher: Sharolyn Pollard-Durodola. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Internationalization, $3,700 (2014-2015)

Cultivating Culturally Relevant and Responsive Curriculum and Pedagogy in College. Researcher: Samuel Museus. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, iRise Grant, $5,000 (2014-2015)

Project EMERGE (Educational Model for Evaluation and Replicability in Gifted Environments). Research team: Norma Hafenstein (PI) and Bruce Uhrmacher. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Lynde and Harry Bradley Foundation, $235,000 (2014-2015)

Collecting Asian American Refugee Stories. Researcher: Samuel Museus. Technical reviewer for MCE: Sylvia D. Hall-Ellis. American Educational Research Association, Research Grant, $5,000 (2014-2015)

Developing Expertise in Teaching K-5 Mathematics. Research team: Julie Sarama (PI) and Douglas H. Clements (Co-PI), in partnership with the School of Education at the University of Michigan. Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Science Foundation, $130,344 (2013-2015)

Investigation of the Long-Term Outcomes for Special Education Students. Researcher: Antonio Olmos-Gallos. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Jefferson County School District, Office of Assessment, $40,000 (2014)

Refugee Community Collaboration. Researcher: Vicki Tomlin (PI) in partnership with the African Community Center and Jewish Family Service. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Community Engagement and Service Learning, $14,854 (2014-2015)

Access to Mathematics for All. Research team: Richard S. Kitchen (PI), Nicole M. Russell (Co-PI), and Terrence Blackman (Co-PI), Curriculum Studies and Teaching Program, Morgridge College of Education; Álvaro Árias (Co-PI, Department of Mathematics); and, James Gray (Co-PI), Department of Mathematics, Community College of Aurora. Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Science Foundation, The Robert Noyce Scholarship Program, Capacity Building Project, $349,926 (2014-2016)

Cognitive Test Battery for Intellectual Disabilities. Research team: Karen Riley (PI), Lyndsay Agans, Jessica Lerner, and Karin Dittrick-Nathan in partnership with David Hessl (PI), The MIND Institute at the University of California – Davis, and Elizabeth Berry-Kravis, Rush University Medical Center. Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Institutes of Health, Outcome Measures for Use in Treatment Trials for Individuals with Intellectual and Developmental Disabilities (R01), $2,499,996 ($588,672 at DU) (2014- 2019)

Broadening Participation in Engineering among Women and Latino/as: A Longitudinal, Multi-Site Study. Researcher: Patton Garriott (PI) in partnership with the University of North Dakota and the University of Missouri. Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Science Foundation, HER Core Research, $677,390 ($69,992 at DU) (2014-2019)

Designing a Teacher Evaluation System to Improve Teacher Effectiveness for Culturally and Linguistically Diverse Learners. Research team: María del Carmen Sálazar (PI), Jessica Lerner, and Kathy Green. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Professional Research Opportunities for Faculty, $29,988 (2014-2016)

Developing a College-Going Culture in Latina/O Families: Exploring the Influence of Funds of Knowledge on Family Outreach Programs. Researcher: Judy Marquez Kiyama. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Professional Research Opportunities for Faculty, $18,720 (2014-2016)

Assessment of Quality of Life in Neutral Implantation Surgery for the Treatment of Parkinson's Disease. Researcher: Cynthia McRae. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Internationalization, $3,967 (2014-2015)

Pura Vida: Cloud Forest, Curriculum and Cross-Cultural Study. Research team: Norma Hafenstein (PI) and Bruce Uhrmacher (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Internationalization, $8,000 (2014-2015)

Online Course Development for Curriculum and Instruction. Researcher: Ruth Chao. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Teaching and Learning, $3,000 (2014)

Online Course Development for Curriculum and Instruction. Researcher: María del Carmen Sálazar. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Teaching and Learning, $3,000 (2014)

Online Course Development for Curriculum and Instruction. Researcher: Jessica Lerner. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Teaching and Learning, $3,000 (2014)

Online Course Development for Curriculum and Instruction. Researcher: Duan Zhang. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Teaching and Learning, $3,000 (2014)

The Mathematics Education of African Americans, 1866 – 1954. Researcher: Nicole M. Russell. Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Academy of Education, Spencer Foundation Postdoctoral Fellowship, $55,000 (2014-2016)

Early Childhood Care and Education Study. Research team: Carrie Germeroth (PI), Melissa Mincic, and Douglas H. Clements. Technical reviewer for MCE: Sylvia D. Hall-Ellis. State of North Dakota, Department of Public Instruction, $73,500 (2013-2014)

Graduate Level Specialty in Addiction Counselor Training with Emphasis on Integration of Native American Specific Content. Research team: Ruth Chao (PI) and Michael J. Faragher (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. The Galena Foundation, $289,732 (2013-2016)

The Collecting Asian American and Pacific Islander Refugee Stories (CARS) Project. Researcher: Samuel Museus. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Community Engagement and Service Learning, $15,000 (2014)

Parents in Transition: A Multiple Case Study of Parent and Family Orientation Programs. Researcher: Judy Marquéz Kiyama. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Faculty Research Fund, $1,500 (2014-2015)

The Sistah Network: Black Women Graduate Students Supporting and Retaining Each Other. Researcher; Nicole M. Russell. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Faculty Research Fund, $2,708 (2014-2015)

Evaluation of the Northeast Denver Babies Ready for College Program. Research team: Carrie Germeroth (PI), Melissa Mincic, and Douglas H. Clements. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Mile High Montessori, $9,922 (2013-2014)

Developing Teaching Expertise in K-5 Mathematics. Research team: Julie Sarama (PI) and Douglas Clements (University of Denver), in partnership with Timothy Boerst (PI), Meghan Shaughnessy, Deborah Ball, Hyman Bass (School of Education at the University of Michigan). Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Science Foundation, $449,827 ($130,344 at the University of Denver (2013-2015)

Early Learning Care and Education Study Program Grant for the State of North Dakota. Research team: Carrie Germeroth (PI), Melissa Mincic, and Sheridan Green. Technical reviewer for MCE: Sylvia D. Hall-Ellis. State of North Dakota Department of Public Instruction, $73,500 (2013-2014)

Local Professional Learning Community for School Leaders. Research team: Susan Korach (PI), Kristina Hesbol, and Rebecca McClure. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Education Development Center, $10,950 (2013)

Healthy Eaters, Lifelong Movers 2: Implementing Evidence-Based School Environment, Policy, and Curricular Changes to Increase Opportunities for Healthy Eating and Physical Activity in Low Income, Rural Colorado. Research team: Elaine Berlansky, University of Colorado at Denver (PI), Nicholas Cutforth, University of Denver (Co-PI), and Allison Reeds. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Health Foundation, $3,103,108 (2013-2017)

Hughes Rare Books Library Room Renovation in the Sturm College of Law. Project team: Patti H. Marks, Sylvia D. Hall-Ellis, and Leigh Elliott. Mabel T. Hughes Charitable Trust, $34,000 (2013-2014)

The Promise Center Partnership with the Marsico Institute for Early Learning and Literacy and the City and County of Denver. Research team: Karen Riley (PI), Douglas H. Clements (Co-PI), and Sheridan Green. Technical reviewer for MCE: Sylvia D. Hall-Ellis. The Piton Foundation, $223,468 (2013-2014)

Center of Excellence for Problem Gambling. Research team: Ruth Chao (PI) and J. Mike Faragher. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Department of Behavioral Health, $68,021 (2012-2013)

United Way Implementation and Validation Review. Research team: Douglas H. Clements (PI), Amanda Moreno, and Sheridan Green. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Mile High United Way, $19,737 (2013)

Math/Science Partnership in Rural Districts. Research team: Kristen Bunn (PI, Eagle County Schools), Paul Michalec (Co-PI), and Alegra Reiber. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Department of Education, Colorado's Mathematics and Science Partnership Program, $750,000 (2013-2014)

Mathematics and Science Education of African Americans. Research team: Nicole Russell (PI), Sylvia D. Hall-Ellis, Steve Fisher (Penrose Library). Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Professional Research Opportunities for Faculty, $29,994 (2013-2015)

Online Course Development for Curriculum and Instruction. Researcher: Nicole Russell. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Teaching and Learning, $3,000 (2013)

Discourse and Opportunity: Undocumented Students and Higher Education Policy. Researcher: Ryan Gildersleeve. Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Academy of Education, Spencer Foundation Postdoctoral Fellowship, $55,000 (2012-2014)

An Anthropological Study of the Latino Graduation Ceremony. Researcher: Ryan Gildersleeve. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Spencer Foundation, $39,900 (2012-2013)

Fragile-X and Pharmaceutical Company: Clinical Trial of AFQ056. University of California – Davis Children's Hospital MIND Institute (Sacramento), Children's Hospital Denver, and Rush Children's Hospital at Rush University Medical Center (Chicago). Karen Riley, PI. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Novartis Pharmaceuticals Corporation, $394,206 (2012-2014)

Project Engage, Phase 2, a DAPRA Grant in partnership with Total Immersion Systems, Inc., and Texas A&M University. Research team: Karen Riley (PI) and Lyndsay Agans (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. U.S. Department of Defense, $60,000 (2011-2013)

International School Psychology Practicum Exchange. Researcher: Gloria L. Miller. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Community Engagement and Service Learning, $14,951 (2012-2013)

Online Course Development for Curriculum and Instruction. Research team: Bruce Uhrmacher (PI) and Norma Hafenstein (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Teaching and Learning, $18,193 (2012-2014)

Writers in the Schools. Research team: Karen Riley (PI) and Amanda Moreno (Co-PI).Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Humanities, $4,965 (2012-2013)

Learning Ecosystem Validation Grant. Research team: Karen Riley (PI), Lyndsay Agans, Kent Seidel, and Shimelis Assefa. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Bill & Melinda Gates Foundation, $315,000 (2012-2013)

Project Words of Oral Reading and Language Development (WORLD). Research team: Jorge E. Gonzalez (PI), Texas A&M University; Laura Saenz (Co-PI), University of Texas – Pan American; and, Sharolyn Pollard-Durodola (Co-PI), University of Denver. Technical reviewer for MCE: Sylvia D. Hall-Ellis. U.S. Department of Education, Institute of Education Sciences, $53,354 (2012-2015); award $640,718, transfer from Texas A&M University

Increasing the Efficacy of an Early Mathematics Curriculum with Scaffolding Designed to Promote Self-Regulation. Research team: Douglas H. Clements (PI) and Julie Sarama (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. U.S. Department of Education, Institute of Education Sciences, $1,445,315 (2008-2014); award $4,541,975, transfer from University at Buffalo, The State University of New York

Using Rule Space and Poset-based Adaptive Testing Methodologies to Identify Ability Patterns in Early Mathematics and Create a Comprehensive Mathematics Ability Test. Research team: Douglas H. Clements (PI) and Julie Sarama (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Science Foundation, $323,791 (2010-2014); award $1,194,944, transfer from University at Buffalo, The State University of New York

Comprehensive Postdoctoral Training in Scientific Education Research. Researcher: Julie Sarama (PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. U.S. Department of Education, Institute of Education Sciences, $133,458 (2010-2014); award $613,353, transfer from University at Buffalo, The State University of New York

Longitudinal Study of a Successful Scaling Up Project: Extending TRIAD. Research team: Douglas H. Clements (PI), Julie Sarama (Co-PI), and Abt Associates (Carolyn Layzer, Fatih Unlu, Laurie Bozzi, Lily Fesler, Alina Martinez, Cristofer Price, James van Orden). Technical reviewer for MCE: Sylvia D. Hall-Ellis. Institute of Education Sciences, $384,940 (2011-2015; award $1,250,286, transfer from University at Buffalo, The State University of New York

Early Childhood Education in the Context of Mathematics, Science, and Literacy. Research team: Julie Sarama (PI), Douglas H. Clements (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Science Foundation, $990,020 (2010-2014; award $2,285,228, transfer from University at Buffalo, The State University of New York

Early Childhood Clearinghouse Information Center Redesign. Research team: Karen Riley (PI) and Amanda Moreno (Co-PI).Technical reviewer for MCE: Sylvia D. Hall-Ellis. Office of the Lt. Governor of Colorado, $12,000 (2012-2013)

Morgridge Rural Educational Leadership Initiative. Research team: Lyndsay Agans (PI), Linda Brookhart (Co-PI), Susan Korach, and Rebecca McClure. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Morgridge Family Foundation, $100,000 (2012-2014)

Center of Excellence for Problem Gambling. Research team: Patrick Sherry (PI) and J. Mike Faragher. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Department of Behavioral Health, $55,000 (2012-2013)

Intermodal Transportation Institute Research Initiatives. Researcher: Patrick Sherry. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University Transportation Centers Program, Research and Innovative Technology Administration, U.S. Department of Transportation. $600,000 (2012-2014)

Mile High United Way Social Innovation Fund Early Literacy Initiative. Gloria L. Miller, PI, Amanda Moreano, Kim Hartnett-Edwards, and Sheridan Green. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Mile High United Way, $89,992 (2012-2013)

International School Psychology Practicum Exchange. Researcher: Gloria L. Miller. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Community Engagement and Service Learning, $1,000 (2012-2013)

Refugee Student Art Outreach. Researcher: Karin Dittrick-Nathan. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Faculty Research Fund, $3,000 (2012-2013)

Resistance, Resilience, and Reciprocity: Centering the Voices of Black Doctoral Women with Faculty Aspirations. Researcher: Nicole M. Russell. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Faculty Research Fund, $2,965 (2012-2013)

Assessing Learning through Student Notebooks. Research team: Keith Miller, Nancy Sasaki, and Kathy Green. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Professional Research Opportunities for Faculty, $30,000 (2012-2014)

International School Psychology Practicum Exchange. Researcher: Gloria L. Miller. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Internationalization, $2,000 (2012-2013)

ELO in Colorado. Research team: Cynthia Hazel and Duan Zhang. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Legacy Foundation, $150,000 (2012-2013)

Creating Online LIS Courses. Research team: Mary C. Stansbury (PI), Shimelis Assefa, Denise Anthony, Xiao Hu, and Krystyna Matusiak. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Teaching and Learning, $15,000 (2011-2013)

Maritime Piracy Seminar. Researcher: Ved Nanda, The Nanda Center, Sturm College of Law. Technical reviewer for Sturm College of Law: Sylvia D. Hall-Ellis. Arsenault Family Foundation, $15,000 (2012-2013).

Early Childhood Librarianship: An Interdisciplinary, Experiential Learning MLIS. Researcher: Mary C. Stansbury (PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. Laura Bush's 21st Century Librarians Program, Institute for Museums and Library Services, $249,066 (2012-2014)

Learning Ecosystem Planning Grant. Research team: Karen Riley (PI), Lyndsay Agans, Kent Seidel, and Shimelis Assefa. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Bill & Melinda Gates Foundation, $281,217 (2011-2012)

Advanced Service Learning Practitioner Faculty Grant, Sylvia D. Hall-Ellis, University of Denver, Center for Community Engagement and Service Learning, $400 (2011)

Evaluating and Enhancing the EspeciallyMe Program. Research team: Lori D. Patton and Nicole Russell. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Community Engagement and Service Learning, Public Good Fellowship Grant, $24,780 (2012)

Choosing Excellence: Let Every Child Bloom. Research team: Shimelis Assefa (PI) and Mary C. Stansbury (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Community Engagement and Service Learning, Public Good Grant, $7,657 (2012)

K-8 STEM Content Specific Professional Development to Improve Elementary Student Achievement. Research team: Kent Seidel (PI), Nicole Russell (Co-PI), Kimberly Hartnett-Edwards, Paul Michalec, Jeff Farmer, Keith Miller, Alegra Reiber, and Nancy Sasaki. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Department of Education, Improving Teacher Quality Grant, (Title II ESEA), $307,299 (2011-2012)

Building a Better Principal Pipeline to Boost Student Achievement. Researcher: Susan Korach. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Denver Public Schools; a subcontract from the Wallace Foundation Grant, $170,000 (2011-2017)

Center of Excellence for Problem Gambling. Research team: J. Mike Faragher (Co-PI) and Bobbie Vollmer (PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Department of Behavioral Health, $79,999 (2011-2012)

An Exploration of Novice Teachers' Core Competencies: Impacts on Student Achievement, and Effectiveness of Preparation. Research team: Kent Seidel (PI), Kathy Green (Co-PI), Kimberly Hartnett-Edwards, and Duan Zhang. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Institute of Education Sciences, Effective Teachers and Effective Teaching, $990,987 (2012-2015)

Project Engage, a DAPRA Grant in partnership with Total Immersion Systems, Inc., and Texas A&M University. Research team: Karen Riley (PI) and Lyndsay Agans (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. U.S. Department of Defense, $49,964 (2011-2014)

User-centered Evaluation of Music Search Engines. Researcher: Xiao Hu. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Faculty Research Fund, $2,931 (2011-2012)

Educational Practicum in Vietnam and China to Promote the Inclusion of Young Children with Disabilities. Researcher: Gloria L. Miller. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Internationalization, $5,000 (2011-2012)

Evaluation of Colorado's Enhancing Quality in Infant-Toddler (EQIT) Initiative. Research team: Virginia R. Maloney and Amanda Moreno. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Buell Foundation, $395,884 (2011-2013)

Creating Engaging Environments to Teach Pre-Algebra Mathematics to Elementary Students. Research team: Álvaro Arias, Mario López, María del Carmen Salazar, and Lyndsay Agans. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver Interdisciplinary Grant, $60,000 (2011-2012)

Morgridge Education Technology Accessible (META) Resource Project. Research team: Lyndsay Agans (PI) and Shimelis Assefa (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. Morgridge Family Foundation, $36,000 (2011)

MCE Connect: A 21st Century Framework for Faculty Development. Research team: Bruce Uhrmacher (PI), Shimelis Assefa (Co-PI), Lyndsay Agans (Co-PI), Kimberly Hartnett-Edwards, Norma Hafenstein, Xiao Hu, Paul Michalec (Co-PI), María del Carmen Salazar (Co-PI), and Sandra Snyder-Mondragon. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Teaching and Learning, $22,355 (2011-2012)

Parent Education and Parent Leadership and Advocacy. Research team: Virginia Maloney (PI) and Amanda Moreno, Marsico Institute for Early Learning and Literacy. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Health Foundation, $27,358 (2010-2011)

Intentional School Culture. Researcher: Cynthia Hazel. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Denver Public Schools, $38,040 (2010-2011)

Healthy Eaters, Lifelong Movers: Implementing Evidence-Based School Environment, Policy, and Curricular Changes to Increase Opportunities for Healthy Eating and Physical Activity in Low Income, Rural Colorado. Research team: Elaine Berlansky, University of Colorado at Denver (PI), Nicholas Cutforth, University of Denver (Co-PI), and Allison Reeds. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Health Foundation, $1,683,277 (2011-2014)

Second Life Learning Community. Research team: Don McCubbrey (PI), Sylvia D. Hall-Ellis (Co-PI), Walter LaMendola, and Paul Novak. University of Denver, Center for Teaching and Learning, $13,000 (2010-2011)

Reintroducing the Value of Law Librarians to Academic and Public Librarians in Colorado through the Identification and Use of Emerging Technologies. Research team: Sylvia D. Hall-Ellis (Co-PI), Stacey L. Bowers (PI), and Christopher Hudson, in partnership with Denver Public Library, Arapahoe Library District, and the Colorado State Supreme Court Library. University of Denver, Center for Community Engagement and Service Learning, $5,773 (2010-11)

Reintroducing the Value of Law Librarians to Public Librarians through the Identification and Use of Emerging Technologies and Resources. Research team: Stacey Bowers (PI) and Sylvia D. Hall-Ellis (Co-PI). American Association of Libraries, Wolters Kluwer Law & Business Grant Program, $2,725 (2010-2011)

Faculty Service Learning Pod. Research team: María del Carmen Salazar and Nicholas Cutforth (Curriculum and Instruction Program), Frank Tuitt (Higher Education Program), Cynthia Hazel and Gloria Miller (Child, Family, and School Psychology Program), and Sylvia D. Hall-Ellis (Library and Information Science Program). University of Denver, Center for Community Engagement and Service Learning, $8,000 (2010-2011)

Lincoln Collaborative. Research team: Antonio Esquibel (Principal, Lincoln High School), María del Carmen Salazar (Curriculum and Instruction Program), and. Sylvia D. Hall-Ellis. School Improvement Grant, Denver Public Schools, $375,000 (2010-2012)

Future LEADers of America: Leaders III. Research team: Denver Public Library (Kristen Svendson, PI), the University of Denver (Sylvia D. Hall-Ellis), the Colorado Chapter of REFORMA (Orlando Archibeque), and the Colorado Association of Libraries (Martin Garnar). Laura Bush's Recruiting Librarians for the 21st Century Program, Institute for Museums and Library Services, $988,366 (2009-2012)

Teaching for Success in the Library Environment: LIS 4030 in Library 2.0. Research team: Deborah S. Grealy (PI) and Sylvia D. Hall-Ellis (Co-PI). University of Denver, Center for Teaching and Learning, $ 9,350 (2009-10)

Writing Group Faculty Grant, Sylvia D. Hall-Ellis, University of Denver, Center for Community Engagement and Service Learning, $750 (2008-2009)

Collaborative Learning Faculty Grant, Sylvia D. Hall-Ellis, University of Denver, Center for Teaching and Learning, $1,500 (2008)

Connecting Information Literacy to Learning. Research team: Lori Micho, Merrie Valliant, Amanda Samland, and Sylvia D. Hall-Ellis. Colorado State Library, LSTA Discretionary Grant Program, $19,548 (2008-2009)

Law Librarianship Fellows Program. Research team: Sylvia D. Hall-Ellis (PI), Stacey Bowers (Co-PI), and Christopher Hudson, Westminster Law Library. Laura Bush's 21st Century Librarians Program, Institute for Museums and Library Services, $999,370 (2008-2012)

Grant Writing in a Cooperative Learning Environment. Sylvia D. Hall-Ellis. University of Denver, Center for Teaching and Learning, $2,000 (2008-2009)

Project Homeless Connect 6 Event Evaluation. Research team: Sylvia D. Hall-Ellis and Duan Zhang. University of Denver Center for Community Engagement and Service Learning, $9,785 (2008)

Project Ecuador: International Learning Service Libraries – A Faculty Development Experience in Ecuador. Sylvia D. Hall-Ellis, Office of Internationalization, University of Denver, $600 (2007)

Project Ecuador: International Learning Service Libraries – A Faculty Development Experience in Ecuador. Sylvia D. Hall-Ellis, International Service Learning Office, University of Denver, $400 (2007)

Project Homeless Connect 5 Event Evaluation. Research team: Sylvia D. Hall-Ellis and Duan Zhang. University of Denver Center for Community Engagement and Service Learning, $1,000 (2007)

Project Homeless Connect 4 Event Evaluation. Research team: Sylvia D. Hall-Ellis and Duan Zhang. University of Denver Center for Community Engagement and Service Learning, $4,595 (2007)

Future LEADers of America: Leaders II. Research team: Denver Public Library (Kristen Svendson, PI), the University of Denver (Sylvia D. Hall-Ellis), and the Colorado Chapter of REFORMA (Orlando Archibeque). Laura Bush's Recruiting Librarians for the 21st Century Program, Institute for Museums and Library Services, $988,518 (2007-2010)

Strategic Planning Assistance for the Denver Medical Library. Sylvia D. Hall-Ellis. Denver Medical Library, Inc., $30,000 (2006-2007)

Destiny Software for JMAC Student Lab. Sylvia D. Hall-Ellis, gift from the Sagebrush Corporation, Minneapolis, Minnesota, $10,000 (2006)

Libraries: Tools for Education and Development Worldwide: A Faculty Development Experience in France. Sylvia D. Hall-Ellis, Office of Internationalization, University of Denver, $800 (2005)

Denver Public Library: Opportunities for Change. Sylvia D. Hall-Ellis, Colorado Community Based Research Network, $2,000 (2005)

Future LEADers of America. Research team: Denver Public Library (Letty Icolari and Steve Taylor, PIs), Emporia State University (Jim Agee), and the University of Denver (Sylvia D. Hall-Ellis). Recruiting Librarians for the 21st Century Program, Institute for Museums and Library Services, $670,315 (2005-2008)

American Association of University Professors Summer Institute Professional Development Grant. Sylvia D. Hall-Ellis, American Association of University Professors, $300 (2005)

Beta Phi Mu Alumni Tea. Sylvia D. Hall-Ellis, gift from the Office of Alumni and Parent and Relations, University of Denver, $2,000 (2005)

Spectrum Software for LIS Student Lab. Sylvia D. Hall-Ellis, gift from the Sagebrush Corporation, Minneapolis, Minnesota, $5,000 (2005)

Developing Research Capacity in Community Organizations and Residents through Training and Technical Assistance. Nicholas J. Cutforth (PI) and Sylvia D. Hall-Ellis. Piton Foundation, $25,000 (2005-2006)

Libraries: Tools for Education and Development Worldwide: A Faculty Development Experience in Argentina. Sylvia D. Hall-Ellis, Office of Internationalization, University of Denver, $500 (2004)

Developing Research Capacity in Community Organizations and Residents through Training and Technical Assistance. Research team: Nicholas J. Cutforth (PI), Gary Lichtenstein and Sylvia D. Hall-Ellis, Piton Foundation, $25,000 (2003-2004)

Increasing Spanish-Speaking and Hispanic Diversity among Library and Information Science Students at the University of Denver: Development of a Student Recruitment Model. Researcher: Sylvia D. Hall-Ellis (PI), Office of Multicultural Excellence, University of Denver, $2,750 (2003-2004)

Collection Development Enrichment to Support the Cataloging & Classification Specialization and School Librarianship within the Library & Information Science Program at the University of Denver. Research team: Sylvia D. Hall-Ellis (PI) and Deborah S. Grealy. Women's Library Association, University of Denver, $4,000 (2003)

Collection Development Enrichment to Support the Library & Information Science Program at the University of Denver. Research team: Deborah S. Grealy (PI) and Sylvia D. Hall-Ellis. Women's Library Association, University of Denver, $4,000 (2001)

Wireless LAN for Library Education. Research team: Deborah S. Grealy (PI) and Sylvia Hall-Ellis. University of Denver, Center for Teaching and Learning, $24,000 (2001-2002)

Upward Bound – A Program for South Texas Youth. Research team: Monte Churchill, Executive Director of Community Relations; Gary R. Sauceda, Outreach Coordinator; Raymond Hernandez, (PI) Associate Dean for Student Success; and Sylvia D. Hall-Ellis, South Texas Community College (McAllen, Texas). U.S. Department of Education, Office of Postsecondary Education, $2,672,003 (1999-2003)

Write Now! Improving Elementary Students' Writing Skills. Research team: Caryl G. Thomason, Assistant Superintendent (PI); Karen Tankersley, Principal; and, Hal Anderson, Director of Technology, Cheyenne Mountain School District 12 (Colorado Springs, Colorado); and Sylvia D. Hall-Ellis. Colorado Department of Education, Educational Telecommunications Unit, $189,453 (1999-2001)

Operation Quick Start -- Distance Learning in Rural Colorado. Research team: Randal Weigum, Technology Coordinator (PI); Bonnie Barns, Director of Federal Programs and Staff Development; and, Adam "Joe" Raskop, Executive Director, Southeastern Board of Cooperative Educational Services (Lamar, Colorado); and Sylvia D. Hall-Ellis. Colorado Department of Education, Educational Telecommunications Unit, $400,000 (1999-2001)

Advanced Technological Training for Information Professionals for the 21st Century. Research team: Mario Reyna, Division of Business Director (PI) and Sylvia D. Hall-Ellis, South Texas Community College (McAllen, Texas). Phi Delta Kappa and the National Science Foundation, $250,000 (1999-2001)

Working Connections – Training Information Technologies Professionals for the 21st Century. Research team: Mario Reyna, Division of Business Director (PI) and Sylvia D. Hall-Ellis, South Texas Community College (McAllen, Texas). Microsoft Corporation and the American Association of Community Colleges, $1,147,775(1999-2001)

The ROAD (Research Oriented Amplification of Development to Literacy) Program. Research team: Deborah J. Leong (PI), Metropolitan State University; Elena Bodrova, Metropolitan State University; Dmitri Semenov, Robert J. Marzano, and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). Hewlett-Packard Foundation, $25,000 (1998-1999)

Press to Literacy. Research team: Deborah J. Leong (PI), Metropolitan State University; Elena Bodrova, Metropolitan State University; Dmitri Semenov, Robert J. Marzano, and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). The Denver Post and the Robert S. McCormick Foundation, $49,818 (1998-1999)

International Telementor Center. Research team: David Neils, David B. Frost (PI), and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). Hewlett-Packard Philanthropy, $100,000 (1998-1999)

America Reads: Providing Tutor Training for the America Reads Challenge. Research team: Louis F. Cicchinelli (PI) and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). U.S. Department of Education, Office of Educational Research and Improvement, $306,000 (1998-1999)

Comprehensive School Reform. Research team: Louis F. Cicchinelli (PI), J. Timothy Waters, and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). U.S. Department of Education, Office of Educational Research and Improvement, $285,000 (1998-1999)

Sustainable Energy Education (SEE) Program for Grades 4-8: Preparing Today's Youth for Lifelong Learning and Responsible Actions in Energy Conservation. Research team: Mary Gromko, Colorado Department of Education; Gene McCarthy, Rocky Flats Field Office, U.S. Department of Energy; Gina Kissell, National Renewable Energy Laboratory; and Barbara L. McCombs (PI), Janet L. Bishop, and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). State of Colorado Governor's Office for Energy Conservation, $499,936 (1997-1999)

Review of Kansas Curriculum Standards in Mathematics and Language Arts. Research team: Robert J. Marzano (PI), John S. Kendall, David B. Frost, and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). Submitted to the Kansas State Department of Education, $25,903 (1998)

International Telementor Center. Research team: David Neils, John Kuglin, Chris Rapp, David B. Frost (PI), and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). Hewlett-Packard Company, $54,752 (1998)

Genesis Mission: Education Public Outreach. Developed in partnership by the Jet Propulsion Laboratory, California Institute of Technology, Los Alamos National Laboratory, Lockheed Martin Astronautics, and the Mid-continent Regional Educational Laboratory (Aurora, Colorado). Research team: John T. Sutton (PI), Alice Krueger, Martha Henry, Greg Rawls, Shae Isaacs, Jeff Johnson, Deb Jordan, Arlene Mitchell, David B. Frost, Jana Caldwell, J. Timothy Waters, and Sylvia D. Hall-Ellis. National Aeronautics and Space Administration, $139,700,000; subcontract award, $4,750,000 (1997-2007)

North Dakota Mathematics Assessment Project. Developed in partnership by the North Dakota Department of Education and Mid-continent Regional Educational Laboratory (Mid-continent Regional Educational Laboratory). Research team: Ann Clapper, Clarence Bina, Greg Gallagher, North Dakota Department of Education; Don Burger (PI), Hillary Michaels, and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). U.S. Office of Education, $1,618,214; subcontract award, $389,076 (1997-2001)

Pacific Resources for Education and Learning Distance Education: Project Evaluation. Developed in partnership by the Pacific Educational Community, the Pacific Resources for Education and Learning (PREL), and Mid-continent Regional Educational Laboratory (McREL). Research team: John W. Kofel (PI), Executive Director, PREL; J. Timothy Waters, Executive Director; Joan Buttram, Robert Keller, and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). U.S. Office of Education, Star Schools Program, $10,000,000; subcontract award, $500,000 (1997-2002)

Identification of Bilingual Gifted and Talented Children: A Comprehensive School Grants for Bilingual Education. Developed in partnership by Hidalgo (Texas) ISD, Los Fresnos (Texas) CISD, Progreso (Texas) ISD, University of Texas – Pan American (Edinburg, Texas), and Education Service Center, Region One (Edinburg, Texas). Research team: Hilda Medrano, Dean, College of Education, University of Texas – Pan American; Linda Phemister (PI), Janie Navarro, and Sylvia D. Hall-Ellis, Education Service Center, Region One. U.S. Department of Education, Office of Bilingual Education and Minority Languages Affairs, $1,670,633 (1997-2002)

Academics 2000: First Things First -- The Texas Goals 2000. Developed for Jim Hogg (Hebbronville, Texas) County ISD, Mirando City (Texas) ISD, and San Isidro (Texas) ISD. Research team: Hilda Medrano, Dean, College of Education, University of Texas - Pan American (Edinburg, Texas); Angie Lehmann, Amy Mares, Ellen Gonzalez (PI), and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg, Texas). Texas Education Agency, $339,987 (1997-2000)

Southwestern Bell's Learning Communities Initiative. Developed for Tech Prep of the Rio Grande Valley, Inc. (Harlingen, Texas); the Center for Professional Teacher Development, University of Texas – Brownsville; Teach for America – Rio Grande Valley (McAllen, Texas); and Education Service Center, Region One (Edinburg, Texas). Research team: Patricia G. Bubb, Executive Director (PI), Tech Prep of the Rio Grande Valley; Martin Winchester, Executive Director, Teach for America – Rio Grande Valley; Aileen Johnson, Director, School of Education, University of Texas – Brownsville; and Sylvia D. Hall-Ellis. Southwestern Bell Foundation, $100,000 (1997-1998)

Texas School to Work: Regional Implementation. Developed for Tech Prep of the Rio Grande Valley, Inc. (Harlingen), South Texas Community College (McAllen), Texas State Technical College (Harlingen), Texas Southmost College (Brownsville), Empowerment Zone of the Rio Grande Valley (Mercedes), Project VIDA (Weslaco), Youth Fair Chance (McAllen), and Education Service Center, Region One (Edinburg). Research team: Patricia G. Bubb (PI), Tech Prep of the Rio Grande Valley; Stephen Vassberg, Texas State Technical College; Ellen Trevino, Youth Fair Chance; Wanda Garza, Project VIDA; Leonardo Olivares, University of Texas – Pan American; Michael Bell, South Texas Community College; and Sylvia D. Hall-Ellis. Texas Workforce Commission, $4,250,000 (1997-2002).

Comprehensive Bilingual Education Grant for Hidalgo ISD and Roma ISD. Developed for Hidalgo (Texas) ISD, Roma (Texas) ISD, College of Education, University of Texas – Pan American (Edinburg, Texas), and Education Service Center, Region One (Edinburg, Texas). Research team: Tomas Thomas (PI), Director, Office of Bilingual Education and Sylvia D. Hall-Ellis. U.S. Department of Education, Office of Bilingual Education and Minority Languages Affairs, $1,531,361 (1997-2002)

Lopez High School, Porter High School, Rivera High School, Central Middle School, and Perkins Middle School, Brownsville (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $1,473,611 (1997-1998)

Donna High School, Todd Middle School, and Solis Middle School, Donna (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $704,052 (1997-1998)

Memorial Middle School and Nellie Schunior Middle School, La Joya Independent School District (Texas). Telecommunications Infrastructure Fund Board, $293,641 (1997-1998)

Martin High School, Christen Middle School, Cigarroa Middle School, Lamar Middle School, Laredo (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $1,200,000 (1997-1998).

Lasara Middle School, Lasara (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $246,210 (1997-1998)

Los Fresnos High School and Resaca Middle School, Los Fresnos (Texas) Consolidated Independent School District. Telecommunications Infrastructure Fund Board, $500,000 (1997-1998)

Lyford Junior High School, Lyford (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $354,997 (1997-1998)

Travis Middle School, McAllen (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $269,139 (1997-1998)

Mission High School, Mission (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $297,010 (1997-1998)

Progreso High School, Progreso (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $300,000 (1997-1998)

San Perlita High School, San Perlita (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $293,490 (1997-1998)

Myra Green Junior High School, Raymondville (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $225,000 (1997-1998)

Rio Grande City High School, Ringgold Middle School, Gruella Middle School, Rio Grande City (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $809,934 (1997-1998)

Rio Hondo Junior High School, Rio Hondo (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $297,024 (1997-1998)

Roma High School, Roma (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $333,178 (1997-1998)

San Benito High School, Miller Jordan Junior High School, San Benito (Texas) Consolidated Independent School District. Telecommunications Infrastructure Fund Board, $547,000 (1997-1998)

Santa Maria High School and Santa Maria Middle School, Santa Maria (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $400,000 (1997-1998)

Salvador High School, United Independent School District (Laredo, Texas). Telecommunications Infrastructure Fund Board, $250,879 (1997-1998)

Weslaco High School, Cabaza Middle School, Cuellar Middle School, Weslaco (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $874,242 (1997-1998)

Principals' Assessment and Training Center. Developed for Education Service Center, Region One (Edinburg, Texas). Research team: Roberto Zamora, Leonel Barrera, William H. Parry, and Sylvia D. Hall-Ellis. Texas Principals' Leadership Initiative, Texas Association of Secondary School Principals, Texas Association of Elementary School Principals, and the Sid Richardson Foundation. $461,439 (1996-1998)

The Texas Library Connection -- Integrating and Sharing Resources. Developed for Hidalgo County Library System (McAllen), Cameron County Library System (Brownsville), South Texas Community College (McAllen), the University of Texas - Pan American (Edinburg), University of Texas – Brownsville, and Education Service Center, Region One (Edinburg). Research team: William R. McGee, Coordinator, Hidalgo County Library System; Joe Garcia, Director, Cameron County Library System; Michael D. Bell, Library Director, South Texas Community College; Eleanor Folger Foster, University Library, University of Texas - Pan American; Jaime Vela (PI), Director of Instructional Technology and Media Services, Ron Pontius, Instructional Technology, and Fabiola Fuentes, Media Services, Education Service Center, Region One; and Sylvia D. Hall-Ellis. Office of Library Media Services, Technology Services, Texas Education Agency. $8,000 (1996-1997)

Developing Leadership Communities for Improving Algebra I for All Students. Developed for a partnership of the Region One Statewide Systemic Initiative Team. Research team: Noel Villarreal (PI), Eduardo Cancino, and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Texas Statewide Systemic Initiative for Reform in Mathematics, Science and Technology Education to The Charles A. Dana Center for Mathematics and Science Education, The University of Texas at Austin. $25,000 (1996-1997)

Academics 2000: First Things First -- The Texas Goals 2000. Developed for Edinburg (Texas) CISD. Research team: Hilda Medrano, Dean, College of Education, University of Texas - Pan American (Edinburg); Helen Jones, Director (PI), Gifted and Talented Education, Edinburg CISD; and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Texas Education Agency, $750,000 (1996-2001)

Texas Teachers Empowered for Achievement in Mathematics (TEXTEAM) Institute for Algebra I. Developed for Hidalgo ISD, Jim Hogg (Hebbronville) County ISD, La Joya ISD, La Villa ISD, Lyford ISD, Mission CISD, Pharr-San Juan-Alamo ISD, Rio Hondo ISD, San Isidro ISD, San Perlita ISD, Santa Maria ISD, Santa Rosa, Sharyland ISD, Valley View ISD, Webb (Laredo) CISD, Weslaco ISD, and Zapata County (Zapata) ISD. Research team: Noel Villarreal (PI), Chuck McInteer, Ellen M. Gonzalez, Education Service Center, Region One (Edinburg); and Sylvia D. Hall-Ellis. Charles A. Dana Center for Mathematics and Science Education, University of Texas - Austin, $15,975 (1996)

Community Learning Center for La Villa, Texas. Developed for Edcouch-Elsa Independent School District. Research team: Noe Gonzalez (PI), Assistant Superintendent, Edcouch-Elsa Independent School District, and Sylvia D. Hall-Ellis. Delta Region Subzone, Rio Grande Valley (Texas) Rural Empowerment Zone, $325,000 (1996-1997)

Monte Alto (Texas) Community Learning Center. Developed for Monte Alto Independent School District. Research team: Homero A. Diaz (PI), Superintendent, Monte Alto Independent School District, and Sylvia D. Hall-Ellis. Delta Region Subzone, Rio Grande Valley (Texas) Rural Empowerment Zone, $300,000 (1996-1997)

Community Learning Center for La Villa, Texas. Developed for La Villa Independent School District. Research team: Sam Gonzalez (PI), Assistant Superintendent, La Villa Independent School District; and Sylvia D. Hall-Ellis. Delta Region Subzone, Rio Grande Valley (Texas) Rural Empowerment Zone, $325,000 (1996-1997)

Building Project for Taylor Elementary. Developed for Mercedes (Texas) Independent School District. Research team: Mrs. Denise Rivera, Librarian, and Eduardo Infante, Principal, Taylor Elementary School; Ismael S. Cantu (PI), Federal Programs Director, Mercedes Independent School District; and Sylvia D. Hall-Ellis. Delta Region Subzone, Rio Grande Valley (Texas) Rural Empowerment Zone, $375,000 (1996-1997)

Border Education Network (BEN) - Distance Education through Cable Television. Developed for Edinburg (Texas) Consolidated Independent School District. Research team: Noe Torres (PI), Library Media Specialist, Magdalena Rosas, Library Media and Technology Coordinator, Edinburg Consolidated Independent School District; and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Edinburg (Texas) Consolidated School District, $250,000 (1996-1997)

Multiservice One-Stop Open Enrollment Charter School. Developed for the Information Referral Resource Assistance, Inc. (McAllen, Texas). Research team: Pablo Perez and Aguie Pena (PI), Executive Director, Information Referral Resource Assistance, Inc.; Roberto Zamora and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Texas Education Agency, $3,066,000 (1996-2001)

Project OK: A Community Youth Opportunities Grant for Summer, 1996. Developed for McAllen (Texas) Independent School District, St. Joseph the Worker Catholic Church, and the Office of Adult Education, Education Service Center, Region One. Research team: Father Bart Flatt, St. Joseph the Worker Catholic Church; Noe Calvillo (PI), Office of Adult Education; Maria Louisa Garcia, McAllen Independent School District; and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Texas Protective and Regulatory Agency through the Office of the Mayor, City of McAllen, $350,000 (1996-2001).

Early Childhood: a Time of Discovery. Developed for a partnership of Lasara ISD, Rio Hondo ISD, San Perlita ISD, the School of Education, University of Texas - Brownsville, and Education Service Center, Region One (Edinburg). Research team: Hugo Rodriguez, Dean, School of Education, University of Texas - Pan American; Leonel Barrera and Jack Damron, Field Service Agents, Ellen M. Gonzalez (PI), Administrator for Student Instructional Services, Ruth Solis, Education Specialist in Special Education, and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Texas Education Agency, $722,090 (1996-2001)

Innovative Gifted and Talented Programs for Early Childhood and Elementary Education Students. Developed for a partnership of Edinburg (Texas) CISD, the School of Education, University of Texas - Pan American (Edinburg), and Education Service Center, Region One (Edinburg). Research team: Hilda Medrano, Dean,

School of Education, University of Texas - Pan American; Helen de la Garza (PI), Director of Elementary Curriculum and Instruction, Edinburg CISD; and Sylvia D. Hall-Ellis. Texas Education Agency, $750,000 (1996-2001)

Reading Recovery in Early Elementary Grades. Developed for a partnership of La Villa (Texas) ISD the School of Education, University of Texas - Pan American (Edinburg), and Education Service Center, Region One (Edinburg). Research team: Hilda Medrano, Dean, School of Education, University of Texas - Pan American; Marcario Salinas (PI), Supervisor of Elementary Curriculum and Instruction, La Villa ISD; and Sylvia D. Hall-Ellis, Education Service Center, Region One. Texas Education Agency, $750,000 (1996-2001)

Connected Mathematics Project for Middle and Junior High Students. Developed for a partnership of Michigan State University, The Charles A. Dana Center for Mathematics and Science Education, The University of Texas at Austin and Region One Statewide Systemic Initiative Team. Research team: Jack Damron, Chuck McInteer, Noel Villarreal (PI), and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). National Science Foundation through Michigan State University to the Charles A. Dana Center at the University of Texas - Austin, $539,610 (1996-1999)

Sharing Resources: Testing the Interlibrary Loan Potential of the Texas Library Connection -- Integrating Media Resources. Developed under the sponsorship of the Hidalgo County Library System (McAllen) and Education Service Center, Region One (Edinburg). Research team: William H. McGee, Hidalgo County System Coordinator; Fabiola Fuentes, Library Media; Ronald Pontius (PI), Instructional Technology, Education Service Center, Region One; and Sylvia D. Hall-Ellis. Library Media Services Program, Office of Technology Services, Texas Education Agency, $25,000 (1996-1997)

State and Federal Adult Education JOBS Program. Developed for Education Service Center, Region One (Edinburg). Research team: Noe Calvillo (PI), Director, Adult Education Program, and Sylvia D. Hall-Ellis. Adult Education Program, Texas Education Agency, $532,846 (1995-1996)

Creating Safe and Drug-Free Schools and Communities. Developed for a partnership of the Region One Consortium for Safe and Drug-Free Education Environments. Research team: Clara Contreras (PI), Health Specialist, and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Texas Education Agency, $150,000 (1995-1996)

Developing Leadership Communities for Improving Mathematics Performance for All Students on Title I Campuses. Developed for a partnership of the Region One Statewide Systemic Initiative Team. Research team: Jack Damron, Chuck McInteer, Noel Villarreal (PI), and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Texas Statewide Systemic Initiative for Reform in Mathematics, Science and Technology Education to The Charles A. Dana Center for Mathematics and Science Education, The University of Texas at Austin, $50,669 (1995-1996)

The Impact of Library Resource Centers on Academic Achievement in Selected Public Schools in South Texas. Sylvia D. Hall-Ellis (PI). Developed under the sponsorship of the Department of Library Science, College of Education and Applied Science, Sam Houston State University (Huntsville). Texas Association of School Librarians, Children's Services Round Table, and Young Adults Round Table (Austin, Texas), $2,500 (1995)

School Library Media Specialists Fellowship Program. Sylvia D. Hall-Ellis (PI). Developed under the sponsorship of the Department of Library Science, College of Education and Applied Science, Sam Houston State University (Huntsville, Texas). U.S. Department of Education, HEA Title II-B, Library Education and Human Resource Development Program, $44,000 (1995-1996)

Planning for Educational Technology. Research team: Ruth Ann Riggins (PI), Director of Library Media and Technology Services, Donna (Texas) Independent School District; Noe Torres, Education Service Center,

Region One; Patricia G. Bubb, Tech Prep of the Rio Grande Calley, Inc; Michael D. Bell, South Texas Community College; and Sylvia D. Hall-Ellis, Sam Houston State University. Developed under the sponsorship of Donna (Texas) Independent School District, Education Service Center, Region One (Edinburg), Tech Prep of the Rio Grande Valley, Inc. (Harlingen), South Texas Community College (McAllen), and the Department of Library Science, Sam Houston State University (Huntsville). Funded through Infusion of Educational Technology Planning Grant Program (H.B. 18: Models). Texas Education Agency, $18,000 (1993-1994)

The Impact of Library Resource Centers on Academic Achievement in Selected Public Schools in South Texas. Sylvia D. Hall-Ellis (PI) and Mary Ann Berry. Developed under the sponsorship of the Department of Library Science, College of Education and Applied Science, Sam Houston State University (Huntsville). Sam Houston State University Research Enhancement Fund, $7,500 (1993-1994)

Electronic Mail Resource Sharing System: Management and Operation of the Iowa Computer-Assisted Network. State Library of Iowa, $294,000 (1986-1993)

The Iowa Locator: A CD-ROM Resource Sharing Tool. State Library of Iowa, $567,000 (1986-1992)

Statewide Database Development: An OCLC Tape Analysis To Determine Feasibility. State Library of South Dakota, $15,000 (1987)

The Iowa Locator: A Feasibility Study. State Library of Iowa, $50,000 (1986)

Electronic Mail Resource Sharing System: A Feasibility Study for Libraries in the State of Iowa. State Library of Iowa, $5,000 (1985)

Access Pennsylvania: A Feasibility Study. State Library of Pennsylvania, $50,000 (1984)

Automating Library Administrative and Management Tasks: Procurement and Distribution of Microcomputer Systems for District Library Centers in the Commonwealth of Pennsylvania. State Library of Pennsylvania, $495,000 (1982)

Sharing Serial Titles Resources: Procurement and Distribution of Microfiche Readers for 550 Libraries in the Commonwealth of Pennsylvania. State Library of Pennsylvania, $500,000 (1982)

Electronic Mail System: A Pilot Project for Libraries throughout the Commonwealth of Pennsylvania. State Library of Pennsylvania, $125,000 (1982)

Literacy Program for Adults in Rural Upstate New York State: Program Outreach and Evaluation - Phase 3. Appalachian Regional Commission, $50,000 (1981)

Database Building: A Cooperative Project of the Finger Lakes Library System (Ithaca), Four County Library System (Binghamton), and the Southern Tier Library System (Corning). New York State Library, $450,000 (1980-1985)

Faces of the Southern Tier: A Professional Photographer-in-Residence. New York State National Endowment for the Humanities, $25,000 (1980)

Literacy Program for Adults in Rural Upstate New York State: Program Implementation - Phase 2. Appalachian Regional Commission, $50,000 (1980)

Small Business Resources Center: A Pilot Project for Rural Public Libraries. New York State Library, $50,000 (1980)

Media Programming: A Professional Development Program for Public Librarians in Upstate New York: A Program in Allegheny, Chemung, Schuyler, Steuben, and Yates Counties. New York State Library, $35,000 (1979)

Information and Library Resources for Inmates and Prisoners in Selected Upstate New York Facilities: A Cooperative Program in Allegheny, Chemung, Schuyler, Steuben, and Yates Counties. New York State Library, $25,000 (1979)

Library Resources for Homebound Adults in Upstate New York: An Outreach Program in Allegheny, Chemung, Schuyler, Steuben, and Yates Counties. New York State Library, $40,000 (1979)

Literacy Program for Adults in Rural Upstate New York State: Program Initiation and Establishment - Phase 1. Funded by the Appalachian Regional Commission. Awarded to the Corning (New York) Public Library, $50,000 (1979)

Information Reference Services to Homebound Adults. New York State Library, $31,000 (1978)

Books-By-Mail Services to Homebound Adults. New York State Library, $31,000 (1978)

System Headquarters Services and Programs for Public Libraries in District 10. Funded through Library Services and Construction Act Title I. Texas State Library and Historical Commission, $880,000 (1976)

County Library Development Grant for Atascosita County. Funded through Library Services and Construction Act Title I. Texas State Library and Historical Commission, $15,000 (1976)

Spanish Language Materials Collection Development Program. Texas State Library and Historical Commission, $40,000 (1975)

Establishment of System Headquarters for Alamo Regional Library System (District 10) Headquartered at the San Antonio (Texas) Public Library. Texas State Library and Historical Commission, $800,000 (1975)

SELECTED CONSULTANTSHIPS

Project Strategic Planning & Funding Proposal Development

Walden University, 2015.
Pikes Peak Library District, 2014.
Douglas County Public Libraries, 2011-2012.
Denver School for Science and Technology, 2008-2011.
Johnson & Wales University, Denver Campus, 2007-2009.
Challenges, Choices, and Images K-12 Charter School, Denver Public Schools, 2007.
Denver Medical Library, Inc., 2006-2010.
Bemis Public Library (Littleton), Ergonomic Design and Facilities Enhancement Consultant, 2003.
Curtis Park Community Center (Denver), Community Technology Center Evaluation and Proposal Development Consultant, 2003.
Colorado Community Based Research Network (Denver), Funding Research Associate, 2002.
Our Lady of the Rosary Academy (Edgewater), Learning Resource Center Development Project Consultant, 2001-2003
University of Southern Colorado (Pueblo). Technology Integration and Curriculum Enhancement into Higher Education Learning Environment. Proposal Development Consultant, 2000.
Jefferson County Library System (Lakewood), 1999-2000.
Southeastern BOCES (Lamar, CO). Distance Learning Curriculum Content Development Project. Proposal Development Consultant, 1998-2004.
Cheyenne Mountain School District 12 (Colorado Springs, CO). Technology Integration into Elementary Writing Curriculum Project. Proposal Development Consultant, 1998.
Telecommunications Infrastructure Fund Board Round #2 Application, 1997. Technical assistance to the following: La Villa (Texas) Independent School District; Mirando City (Texas) Independent School District; Monte Alto (Texas) Independent School District; San Isidro (Texas) Independent School District.
Telecommunications Infrastructure Fund Board Round #1, 1996. Technical assistance to the following: Brownsville (Texas) Independent School District; Donna (Texas) Independent School District; Edinburg (Texas) Consolidated Independent School District; Harlingen (Texas) Consolidated Independent School District; Jim Hogg County Independent School District (Hebbronville, Texas); La Feria (Texas) Independent School District; La Joya (Texas) Independent School District; La Villa (Texas) Independent School District; Los Fresnos (Texas) Consolidated Independent School District; Progreso (Texas) Independent School District; Raymondville (Texas) Independent School District; Rio Hondo (Texas) Independent School District; San Benito (Texas) Independent School District; Sharyland Independent School District (Mission, Texas); Weslaco (Texas) Independent School District; Zapata (Texas) County Independent School District.
South Texas Community College (McAllen). Strategy Development to Meet the Technology Instructional Needs for Vocational, School-To-Work and Academic Programs, 1994-2000. Development Consultant.
Donna (Texas) Independent School District. Planning for the Infusion of Technology in Middle Schools Serving High At-Risk Students, 1994-1995. Research Associate.
Pettus (Texas) Independent School District. Planning for District-wide Automation in School Library Media Centers: Preparation of Data, and CD-ROM Hardware/Software Configuration Evaluation, 1994. Principal Investigator.
Fort Bend Independent School District (Sugar Land, TX). Planning for District-wide Automation in School Library Media Centers, Preparation of Data, and CD-ROM Hardware/Software Configuration Evaluation, 1994-1995. Principal Investigator.
Northern Waters Library Services (Ashland, WI). Professional Consulting Services to Make Recommendations on the Development of System-Wide Efforts of the Northern Waters Library Service, 1988-1989. Research Associate.
State Library of Iowa (Des Moines). The Iowa Locator Compact Disc to Support Multi-Type Libraries Resource Sharing including Database Design, Building, Production, and Distribution, 1986-1991. Project Director.
State Library of Iowa (Des Moines). Iowa Computer-Assisted Network Development, Enhancement, and Operation, 1985-1992. Technical Director.
State Library of South Dakota (Pierre). Statistical Sampling and Analysis of Multi-Institutional OCLC Archive Tape for Statewide Online Database Building, 1985-1986. Research Associate.
District of Columbia Public Library (Washington, DC). Planning Document for the Retrospective Conversion of Bibliographic Records and Automation Issues in the 1990's, 1984-1985. Research Associate.

State Library of Pennsylvania (Harrisburg). Database Development for High School Libraries, 1984-1985. Research Associate.
MINITEX (Minneapolis, MN). Workshops for Retrospective Conversion, Bar Coding, Library Statistics, and OCLC Serials Format, 1985. Presenter and Research Associate.
ABC Film Consortium (Altoona, Bellefonte, Johnstown, PA). Database Building, System Design, and Implementation of Online Film Booking System, 1983-1985. Database Manager.

Library Automation -- System Design & Implementation

Douglas County Library District (Castle Rock, CO). Library Automation Technical and System Performance Specifications, 2001.
Pharr-San Juan-Alamo Independent School District (Pharr, TX). Library Automation Technical and System Performance Specifications, 1997. Project Development Consultant.
Harlingen (Texas) Independent School District. Planning for District-wide Automation in Junior High School Library Media Centers: Preparation of Data, and CD-ROM Hardware/Software Configuration Evaluation, 1996. Principal Investigator.
Sharyland (Texas) Independent School District. Design and Construction of New Elementary School Library and Technology Resources Center, 1995-1996. Principal Investigator.
South Texas Independent School District (Mercedes, TX). Design and Construction of a New High School Library and Technology Resources Center, 1995-1996. Principal Investigator.
Citizens' Library (Washington, PA). Online Community Resources Files: Design and Implementation, 1984. Research Associate.
Altoona (Pennsylvania) Hospital. Integrated Online System Upgrade Study, 1984. Research Associate.
State Library of South Dakota (Pierre). Automation Plan and State Database Development, 1982-1983. Principal Investigator.
State Library of Pennsylvania (Harrisburg). COM Production and Preparation of the Technical Specifications Document, Procurement, and Distribution of Microcomputers in the Commonwealth of Pennsylvania, 1983-1984. Research Associate.
Altoona (Pennsylvania) Area Public Library. Integrated System (Circulation/Online Catalog) Study, 1982-1983. Principal Investigator.
COPSCAULD (Council of Pennsylvania State College and University Library Directors, Edinboro, PA). Design of Online Media Catalog, 1982. Principal Investigator.
Erie (Pennsylvania) County Library System. Operations Research and Design for Automated Circulation, Hardware Upgrade and Re-Retrospective Conversion, 1982. Research Associate.
Michigan Library Consortium (Lansing, MI). Tape Management System Design and Implementation, 1982-1984. Research Associate.
State Library of Pennsylvania (Harrisburg). Preparation of the Technical Specifications Document, Procurement and Distribution of Microfiche Readers in the Commonwealth of Pennsylvania, 1982. Research Associate.
Community College of Allegheny County, Allegheny Campus (Pittsburgh, PA). Integrated Systems Study, 1981. Principal Investigator.
Community College of Allegheny County, South Campus (West Mifflin, PA). Retrospective Conversion Training Program for Handicapped Students, 1981. Technical Director.
Southern Tier Library System (Corning, NY). OCLC Acquisitions Subsystem Evaluation, 1981. Principal Investigator.
South Central Reference and Research Council (Ithaca, NY). South Central Regional Delivery System, 1980. Principal Investigator.
Southern Tier Library System (Corning, NY). Newspapers on Microfilm in the Chemung-Southern Tier Library System, 1979-1981. Principal Investigator.

Cataloging & Bibliographic Database Building

Challenges, Choices, and Images K-12 Charter School, Denver Public Schools, 2007.
Denver Medical Library, Inc., 2006-2010.
Ricks Gifted and Talented School Library, 2005-
American Humane Society (Englewood), 2004-2006.
Fisher Early Learning Center Library, 2004-

Colorado Community Based Research Network (Denver), 2004-
Boulder Valley School District (Boulder), 2002-2003.
Douglas Public Library District (Castle Rock), 2001-2002.

Bibliographic Center for Research, Inc. (Denver). Original Cataloging, 2001-2003 & 1992-1993. Professional Cataloger. Libraries include Arapahoe Library District (Centennial); Clarke College (Clarke, IA); Kaiser Permanente Center for Health Research (Portland, KS); Douglas County Library System (Carson City, NV); Grinnell College (Grinnell, IA); Kansas State University (Manhattan, KS); Kansas State Library (Topeka, KS); McPherson College (McPherson, KS); Newman University (Wichita, KS); Montana Technical University (Helena, MT); Montana State Library (Helena, MT); University of Texas Southwest Medical Center Library (Dallas, TX); Community College of Southern Nevada (Las Vegas, NV); Pikes Peak Library District (Colorado Springs); Mesa Community College (Grand Junction); Coe College (Cedar Rapids, IA); Briar Cliff College (Sioux City, IA); Tri-Care Health Systems (Aurora); The Penrose-St. Francis Healthcare System (Colorado Springs); Westminster Public Library (Westminster); Lutheran Medical Center Medical Library (Wheat Ridge); American Heritage Center, University of Wyoming (Laramie, WY); National Wildlife Research Center Library (Lakewood); University of Colorado Health Sciences Center, Denison Memorial Library (Denver); Water Resources Library, Denver District Office, Bureau of Land Management (Lakewood); Mesa State Community College Learning Resources Center (Pueblo); Front Range Community College Learning Resources Center (Westminster).

Colorado Historical Society Library (Denver). Original Cataloging of Serials for Multi-Institutional Union Listing Project, 1993. Technical Services Associate. Institutional partners: Denver Art Museum, Denver Museum of Natural History Library, and Denver Botanical Gardens Library.

Arapahoe Library District (Centennial). Original Cataloging of Major Media, 1991.

Original Cataloging Projects: Davis and Elkins College (Elkins, WV), 1989-1990; Waldorf College (Forest City, IA), 1989-1990; Kennametal Corporation (Latrobe, PA), 1984-1985; Pennsylvania Public Libraries Film Center (Harrisburg), 1982-1985.

Retrospective Conversion Projects: North Central Regional Library Service (Mason City, IA), 1987-1988; Southeastern Library Services (Davenport, IA), 1986-1987; Virginia Theological Seminary (Alexandria), 1984-1985; California University of Pennsylvania (California, PA), 1984-1985; Kennametal Corporation (Latrobe, PA), 1984-1985; West Virginia University (Morgantown), 1983-1985; Altoona Area Public Library (Altoona, PA), 1983-1984; George Washington University (Washington, DC), 1983-1984; Indiana University of Pennsylvania (Indiana, PA), 1983-1985; Health Education Center (Pittsburgh), 1983-1984; Central Pennsylvania District Library Center (Bellefonte, PA), 1982-1985; Duquesne University Law School Library (Pittsburgh), 1982-1983; Allegheny County Law Library (Pittsburgh), 1982-1984; Calgon Technical Information Center (Pittsburgh), 1982; Dow Corning Corporation, Technical Information Center (Midland, MI), 1982-1983; Tri-System Public Library Retrospective Conversion Project (Binghamton, Corning, and Ithaca, NY), 1978-1981, Technical Project Director.

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