UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

SAMSUNG ELECTRONICS CO., LTD.
Petitioner

v.

BELL NORTHERN RESEARCH, LLC
Patent Owner

Patent No. 8,416,862

DECLARATION OF DR. INGRID HSIEH-YEE IN SUPPORT OF PETITION FOR *INTER PARTES* REVIEW OF U.S. PATENT NO. 8,416,862

CONTENTS

I, Ingrid Hsieh-Yee, Ph.D., do hereby declare as follows:

I. INTRODUCTION

1. I have been retained by Samsung LLC ("Samsung") as an independent expert witness in this *Inter Partes* Review ("IPR") proceeding before the United States Patent and Trademark Office ("PTO") regarding U.S. Patent No. 8,416,862 ("the '862 patent").

2. I am being compensated for my work in this matter at my accustomed hourly rate. I am also being reimbursed for reasonable and customary expenses associated with my work and testimony in this investigation. My compensation is not contingent on the results of my study, the substance of my opinions, or the outcome of this matter.

II. MATERIALS REVIEWED

3. In the preparation of this declaration, I have reviewed the documents referenced below and any other documents I reference herein, and each of these is a type of material that experts in my field would reasonably rely upon when forming their opinions:

1) Roh, J. C., & Rao, B. D. ("Roh") (March 2004), "An efficient feedback method for MIMO systems with slowly time-varying channels," in *2004 IEEE Wireless Communications and Networking Conference (IEEE Cat. No. 04TH8733)*, Vol. 2, pp. 760-764, obtained from the IEEE on February 3, 2020 (**Exhibit 1008**);

2) IEEE record for Roh, available at the IEEE Xplore Digital Library at https://ieeexplore.ieee.org/document/1311282, accessed and obtained on February 3, 2020 (**Appendix 1008-A**);

3) Roh, J. C., & Rao, B. D., ("Roh") (March 2004), "An efficient feedback method for MIMO systems with slowly time-varying channels," in *2004 IEEE Wireless Communications and Networking Conference (IEEE Cat. No. 04TH8733)*, Vol. 2, pp. 760-764, obtained from the Linda Hall Library on February 6,

2020 (**Appendix 1008-B**);

4) Bibliographic record for *2004 IEEE Wireless Communications and Networking Conference* whose volume 2 contains Roh, available at the online catalog of the Linda Hall Library at http://lhall.hosted.exlibrisgroup.com/vwebv/holdingsInfo?sk=Common&bibId=395501, accessed and obtained on February 6, 2020 (**Appendix 1008-C**);

5) MARC record for *2004 IEEE Wireless Communications and Networking Conference* whose volume 2 contains Roh, available at the online catalog of the Linda Hall Library at http://lhall.hosted.exlibrisgroup.com/vwebv/holdingsInfo?sk=Common&bibId=395501 (select Staff view to display the MARC record), accessed and obtained on February 6, 2020 (**Appendix 1008-D**);

6) Roh, J. C., & Rao, B. D., ("Roh") (March 2004), "An efficient feedback method for MIMO systems with slowly time-varying channels," in *2004 IEEE Wireless Communications and Networking Conference (IEEE Cat. No. 04TH8733)*, Vol. 2, pp. 760-764, obtained from the Library of Congress (**Appendix 1008-**

E);

7) MARC record for *IEEE Wireless Communications and Networking Conference* whose 2004 conference volume 2 contains Roh, available at the online catalog of the Library of Congress at https://catalog.loc.gov/vwebv/staffView?searchId=26968&recPointer=0&recCount=25&searchType=1&bibId=12173784, accessed and obtained on January 24, 2020 (**Appendix 1008-F**);

8) Early citations of Roh (**Appendix 1008-G**);

9) Haykin, S. S., & Moher, M., ("Haykin") (2005), *Modern Wireless Communications*, Pearson/Prentice Hall, obtained from the Library of Congress (**Exhibit 1010**);

10) Bibliographic record for Haykin, available at the online catalog of the Library of Congress at https://lccn.loc.gov/2003061139, accessed and obtained on January 30, 2020 (**Appendix 1010-A**);

11) MARC record for Haykin, available at the online catalog of the Library of Congress at https://catalog.loc.gov/vwebv/staffView?searchId=10557&recPointer=0&recCount=25&searchType=2&bibId=13300678, accessed and obtained on January 30, 2020 (**Appendix 1010-B**);

12) Early citations of Haykin (**Appendix 1010-C**);

13) Yang, B., & Bohme, J. F., ("Yang") (November 1989), "Reducing the computations of the SVD array given by Brent and Luk," in *Advanced Algorithms and Architectures for Signal Processing IV*, SPIE vol. 1152, pp. 92-102, obtained from Linda Hall Library on February 3, 2020 (**Exhibit 1011**);

14) Bibliographic record for *Advanced Algorithms and Architectures for Signal Processing IV* that contains Yang, available at the online catalog of the Linda Hall Library at http://lhall.hosted.exlibrisgroup.com/vwebv/holdingsInfo?sk=Common&bibId=46733, accessed and obtained on January 31, 2020 (**Appendix 1011-A**);

15) MARC record for *Advanced Algorithms and Architectures for Signal Processing IV* that contains Yang, available at the online catalog of the Linda Hall Library at http://lhall.hosted.exlibrisgroup.com/vwebv/holdingsInfo?sk=Common&bibId=46733 (select Staff view for the MARC record), accessed and obtained on January 31, 2020 (**Appendix 1011-B**);

16) Bibliographic record for *Advanced Algorithms and*

Architectures for Signal Processing IV that contains Yang, available at the online catalog of the US Air Force Institute of Technology Library at https://w95020.eos-intl.net/W95020/OPAC/Details/Record.aspx?BibCode=46744394 accessed and obtained on January 31, 2020 (**Appendix 1011-C**);

17) MARC record for *Advanced Algorithms and Architectures for Signal Processing IV* that contains Yang, available at the online catalog of the US Air Force Institute of Technology Library at https://w95020.eos-intl.net/W95020/OPAC/Details/Record.aspx?BibCode=46744394 (select MARC to view the MARC record), accessed and obtained on January 31, 2020 (**Appendix 1011-D**);

18) Early citations of Yang (**Appendix 1011-E**);

19) Sadrabadi, M. A., Khandani, A. K., & Lahouti, F., ("Sadrabadi") (December 2004), "A new method of channel feedback quantization for high data rate MIMO systems," in *IEEE Global Telecommunications Conference, 2004. GLOBECOM'04*, Vol. 1, pp. 91-95, obtained from IEEE on February 3, 2020, (**Exhibit 1013**);

20) IEEE record for Sadrabadi, available at the IEEE Xplore Digital Library at https://ieeexplore.ieee.org/document/1377919, accessed and obtained on February 3, 2020 (**Appendix 1013-A**);

21) Sadrabadi, M. A., Khandani, A. K., & Lahouti, F., ("Sadrabadi") (December 2004), "A new method of channel feedback quantization for high data rate MIMO systems," in *IEEE Global Telecommunications Conference, 2004. GLOBECOM'04*, Vol. 1, pp. 91-95, obtained from the Library of Congress on February 6, 2020 (**Appendix 1013-B**);

22) Bibliographic record for *Globecom* whose 2004 conference, volume 1 contains Sadrabadi, available at the online catalog of the Library of Congress at https://lccn.loc.gov/2004209774, accessed and obtained on January 31, 2020 (**Appendix 1013-C**);

23) MARC record for *Globecom* whose 2004 conference, volume 1 contains Sadrabadi, available at the online catalog of the Library of Congress at https://catalog.loc.gov/vwebv/staffView?searchId=26982&recPointer=0&recCount=25&searchType=1&bibId=13561198, accessed and obtained on January 31, 2020 (Appendix **1013-D**);

24) Bibliographic record for *Globecom '04 : 2004 IEEE Global Telecommunications Conference* whose volume 1 contains Sadrabadi, available at the online catalog of the Linda Hall Library at http://lhall.hosted.exlibrisgroup.com/vwebv/holdingsInfo?sk=Common&bibId=421475, accessed and obtained on January 31, 2020 (**Appendix 1013-E**);

25) MARC record for *Globecom '04 :* 2004 *IEEE Global Telecommunications Conference* whose volume 1 contains Sadrabadi, available at the online catalog of the Linda Hall Library at http://lhall.hosted.exlibrisgroup.com/vwebv/holdingsInfo?sk=Common&bibId=421475 (use Staff view to display the MARC record), accessed and obtained on January 31, 2020 (**Appendix 1013-F**).

4. In forming the opinions expressed within this declaration, I have considered:

(1) The documents listed above;

(2) The reference materials cited herein; and

(3) My own academic background and professional experiences, as described below.

III. BACKGROUND

5. My complete qualifications and professional experience are described in my academic *curriculum vitae*, a copy of which is provided as **Appendix A**. The following is a brief summary of my relevant qualifications and professional experience.

6. I am currently a Professor in the Department of Library and Information Science at the Catholic University of America. I have experience working in an academic library, a medical library, and a legislative library and have been a professor for more than 25 years. I hold a Ph.D. in Library and Information Studies from the University of Wisconsin-Madison and a Masters in Library and Information Studies from the University of Wisconsin-Madison.

7. I am an expert on library cataloging and classification and have published two books on this subject, *Organizing Audiovisual and Electronic Resources for Access*: *A Cataloging Guide* (2000, 2006). I teach a variety of courses, including Cataloging and Classification, Advanced Cataloging and Classification, Organization of Internet Resources, Organization of Information, Digital Content Creation and Management, Internet Searches and Web Design, Information Literacy Instruction, Advanced Information Retrieval and Analysis Strategies, and The Information Professions in Society. My research interests cover cataloging and classification, information organization, metadata, information retrieval, information architecture, digital collections, scholarly communication, user interaction with information systems, and others.

8. I am very familiar with a library cataloging encoding standard known as the "Machine-Readable Cataloging" standard, also known as "MARC," which became the national standard for sharing bibliographic data in the United States by 1971 and the international standard by 1973. MARC is the primary communications protocol for the transfer and storage of bibliographic metadata in libraries. Experts in my field would reasonably rely upon MARC records when forming their opinions.

9. A MARC record consists of several fields, each of which contains specific data about the work. Each field is identified by a standardized, unique, three-digit code corresponding to the type of data that follows. **Appendix B** is a true and correct copy of Parts 7 to 10 of "Understanding MARC Bibliographic: Machine-Readable Cataloging" (http://www.loc.gov/marc/umb/um01to06.html) from the Library of Congress that explains commonly used MARC fields. For example, the personal author of the work is recorded in Field 100, the title is recorded in Field 245, publisher information is recorded in Field 260, the physical volume and characteristics of a publication are recorded in Field 300, and topical subjects are recorded in the 650 fields.

10. The Online Computer Library Center (OCLC) is the largest bibliographic network of the world, with more than 453 million records and thousands of libraries from more than 100 countries.

11. OCLC members can contribute original cataloging records in MARC to the system or derive cataloging records from existing records, an activity referred to as "copy cataloging." When an OCLC participating institution acquires a work, it can create an original MARC record for the work in OCLC's Connexion system (a system for catalogers to create and share MARC records), and the system will automatically generate a code for the date of record creation in the *yymmdd* format, and the creating library's OCLC symbol is recorded in subfield "a" of the 040 field. Once the MARC record is in Connexion, it becomes available to other OCLC members for adoption to their local online catalogs (*i.e.*, copy cataloging).

12. After a MARC record is created in Connexion, it also becomes searchable and viewable on WorldCat, which is a web portal to more than 10,000 libraries worldwide. The record in WorldCat, however, is not presented in MARC fields. Instead, the data elements are labeled to help users interpret the record.

13. WorldCat (http://www.worldcat.org) is "the world's largest network of library content and services" and its features are summarized in "What is WorldCat" (http://www.worldcat.org/whatis/default.jsp). Through WorldCat, users can search for information in their local libraries and libraries around the world. WorldCat allows users to search for books, CDs, videos, and many new types of digital content, such as audiobooks, in many languages. Users can also retrieve research materials and article citations with links to their full text. After an item is retrieved, WorldCat helps users identify a library nearby that holds the item or all the libraries that hold the item. WorldCat is an efficient way to explore the content held by more than 10,000 libraries around the world.

14. Library online catalogs are based on MARC records that represent their collections in order to help the public understand what materials are publicly accessible in those libraries. Most libraries with online catalogs have made their catalogs freely available on the Web. These online catalogs offer user-friendly search interfaces. Strong user interest in keyword searches and the popularity of Google have led to the "googlization" of library search systems. As a result, many library catalogs now provide a single search box for users to conduct keyword searches, with additional support for searches by author, title, subject terms, and other data elements such as ISBN (International Standard Book Number). Library catalogs these days also offer features for users to narrow their search results by language, year, format, and other elements. Many libraries display MARC records on their online catalogs with labels for the data elements to help the public interpret MARC records. Many libraries also offer the option to display MARC records in MARC fields.

15. Libraries create MARC records for works they acquire, including books, serials, motion pictures, and publications in other formats. Monograph cataloging is fairly common in libraries, and most libraries make a newly cataloged monograph available to the public soon after the cataloging work is completed, usually within a week. Libraries may choose to catalog conference proceedings as monographs if the conferences carry distinctive titles and users are likely to look for them as monographs. Conference proceedings from conferences that take place at regular intervals, such as annual conferences, tend to be cataloged as serials to speed up the cataloging process and make new proceedings available to the public as soon as possible, usually within one week after serial check in.

16. The cataloging of serials and the serial check-in process are discussed here to show how libraries usually provide access to newly received serial issues. According to the glossary of the *RDA: Resource Description and Access* cataloging standard, a serial is "a mode of issuance of a manifestation issued in successive parts, usually bearing numbering, that has no predetermined conclusion. A serial includes a periodical, monographic series, newspaper, etc." Because the publisher of a serial makes new issues of the serial available successively, a customary cataloging practice is to create one bibliographic record for the serial, and the MARC serial record typically provides information on the beginning date and frequency of the serial, not the dates of individual issues. In other words, libraries typically do not create MARC records for individual issues of a serial. Instead, they rely on a serial check-in system to track the receipt of new issues. A common check-in practice is to date stamp a new issue when it arrives. This practice has become automated since the late 1990s, and libraries now vary in how they share the receipt date of a new serial issue with the public. Some libraries use a date stamp, some affix a label to indicate the receipt date, some pencil in the receipt date, and some do not provide the information to the public.

17. The serial check-in process usually takes less than an hour, and one of the steps involves placing a date stamp on the new issue to document the date the issue is checked in. After that, the holdings information of the serial is updated in the library's catalog so that users know which issues are available for request or access. After serial check-in is completed, the new issue is placed on the shelf with the previous issues of the serial. Libraries with a public periodical room typically place new issues in the periodical room for easy user access. Because information presented in serials often reflects latest discovery, a general practice of libraries is to make new issues of serials available for user access soon after they are checked in, usually within a week.

18. I am personally familiar with many online catalogs, databases, and search engines. In preparing for this declaration I used authoritative information systems, including WorldCat (https://www.worldcat.org), the IEEE Xplore Digital Library (https://ieeexplore.ieee.org/Xplore/home.jsp), the online catalog of the Library of Congress (https://catalog.loc.gov), the online catalog of the Linda Hall Library (http://lhall.hosted.exlibrisgroup.com/vwebv/searchBasic), the online catalog of the US Air Force Institute of Technology (https://w95020.eos-intl.net/W95020/OPAC/Search/SimpleSearch.aspx#), and Google Scholar (https://scholar.google.com) to search for records. These records are identified and discussed in this declaration. Experts in the field would reasonably rely on the data described herein to form their opinions.

IV. EXHIBITS

A. Ex. 1008 (Roh)

1. Authentication

19. **Ex. 1008** is a true and correct copy of "An efficient feedback method for MIMO systems with slowly time-varying channels" ("Roh"), by J. C. Roh and B. D. Rao, in *2004 IEEE Wireless Communications and Networking Conference*, vol. 2, pp. 760-764, that I obtained from the Institute of Electrical and Electronics Engineering (IEEE), the publisher of *2004 IEEE Wireless Communications and Networking Conference*. When I was asked to prepare this declaration, I searched WorldCat for "efficient feedback method for MIMO systems with slowly time-varying channels" for records, and the search results informed me that the full text of Roh is available from the IEEE Xplore Digital Library. I then followed the link in the WorldCat record for Roh to the IEEE Xplore Digital Library, and found an IEEE record for Roh. I then used the PDF link in this record to purchase Roh. Page 1 of **Ex. 1008** is the first page of Roh that shows "an efficient feedback method for MIMO systems with slowly time-varying channels" as the title, and "June Chul Roh and Bhaskar D. Rao" as the authors. The bottom of this page shows Roh has a "2004" copyright date with IEEE as the copyright holder. It also shows Roh appears in "WCNC 2004 / IEEE Communications Society," which has an ISBN of "0-7803-8344-3." The Roh article begins on page 760 and ends on page 764, including four figures and nine references.

20. **Appendix 1008-A** is the IEEE record for Roh that I personally located, identified and obtained from the IEEE Xplore Digital Library. The record shows the title, authors, and abstract of Roh. It also shows that Roh was published in "2004 IEEE Wireless Communications and Networking Conference (IEEE Cat. No.04TH8733)," the print ISBN (International Standard Book Number) for this publication is "0-7803-8344-3" and the print ISSN (International Standard Serial Number) is "1525-3511." The IEEE record also shows that the 2004 IEEE Wireless Communications and Networking Conference took place in Atlanta, GA, USA from "21-25 March 2004." The Date Added to IEEE Xplore field shows the IEEE record for Roh was added on "19 July 2004" and the DOI (digital object identifier) of Roh is "10.1109/WCNC.2004.1311282."

2. Linda Hall Library Copy of Roh

21. **Appendix 1008-B** is a true and correct copy of "An efficient feedback method for MIMO systems with slowly time-varying channels" ("Roh"), by J. C. Roh and B. D. Rao, in *2004 IEEE Wireless Communications and Networking Conference*, vol. 2, pp. 760-764, that I obtained from the Linda Hall Library. After I searched for records in WorldCat by the title of the Roh article, the search results showed that Linda Hall Library held the publication containing Roh. I then searched the Linda Hall Library online catalog for records for "2004 IEEE

Wireless Communications and Networking Conference*"* and the search results confirmed the holdings information. After that, I asked the Document Delivery Service of the Linda Hall Library to provide me with a scanned copy of Roh and the front matter of *2004 IEEE Wireless Communications and Networking Conference* volume 2. I received the scanned pages on February 6, 2020.

22. Page 1 of **Appendix 1008-B** is the title page of the *2004 IEEE Wireless Communications and Networking Conference*, volume 2, which contains Roh. In addition to the conference title and the volume number, the title page shows "WCNC 2004" printed after the conference title, and also shows that the conference took place from "21-25 March 2004" in the Georgia World Congress Center of Atlanta, GA, USA. It also shows "IEEE, IEEE Communications Society" as the publisher. Page 2 of **Appendix 1008-B** is the copyright page that shows *2004 IEEE Wireless Communications and Networking Conference* has a "2004" copyright date with the Institute of Electrical and Electronics Engineers, Inc. as the copyright holder. In addition, the copyright page shows the IEEE Catalog Numbers of this publication are "04TH8733" for the softbound copy, and "04TH8733C" for the CD-ROM copy. It also shows the ISBN of the softbound copy is "0-7803-8344-3" and the ISBN of the CD-ROM copy is "0-7803-8345-1." The copyright page also shows an ISSN (International Standard Serial Number) of "1525-3511." Page 3 of **Appendix 1008-B** (internal page iii) is the "Letter from the Technical

Program Committee Chair" that carries a stamp of "Linda Hall Library Kansas City, MO." and a hand-written date of "7-15-04" (*i.e.*, July 15, 2004) that indicates the date when this publication was added to the Linda Hall Library Collection. Page 8 of **Ex. 1008** is the first page of the Roh article, which runs from pages 760 to 764, including four figures and nine references. I have closely compared the IEEE copy of Roh (**Ex. 1008**) with the Linda Hall Library copy of Roh (**Appendix 1008-B**) and found them to be substantively identical. The only difference is that the IEEE copy includes color in figures 1, 3 and 4, while the Linda Hall Library copy is black and white.

3. Linda Hall Library Records

23. **Appendix 1008-C** is a true and correct copy of the bibliographic record for *WCNC 2004 : 2004 IEEE Wireless Communications and Networking Conference* that contains Roh. I retrieved this record from the online catalog of the Linda Hall Library by searching for "WCNC 2004." The bibliographic record has a link for "staff view," which brings up the MARC record (**Appendix 1008-D**). I personally located, identified and obtained the bibliographic and MARC records, which experts in my field would reasonably rely upon when forming their opinion.

24. As indicated earlier, conference proceedings can be cataloged as serial or monograph. When conferences take place at regular intervals, libraries may choose to catalog their proceedings as serial to expedite the cataloging process and make new proceedings available to the public soon after they are received. When conferences have distinctive themes and users are likely to look for them by title, libraries may choose to catalog the conference proceedings as monographs. In this case, Linda Hall Library has cataloged WCNC 2004 as a monograph.

25. The first six digits of Field 008 of the MARC record (**Appendix 1008-D**) show that the record was created on "040715" (*i.e.*, July 15, 2004). Subfield a of Field 040 shows that "LHL" was the creator of the original record. LHL is the OCLC symbol for Linda Hall Library, according to the Directory of OCLC Members (https://www.oclc.org/en/contacts/libraries.html). The holdings information area of the bibliographic record (**Appendix 1008-C**) shows the book is in the "Open Stacks" of the Linda Hall Library, its call number is "TK5103.2 .I65 2004," the title has four volumes, and the status of the book is "Not Charged" (meaning available to users). Field 035 of the MARC record shows the record has an OCLC number of "55948827," which means the record is available to OCLC members for copy cataloging and interlibrary loan purposes, and also available for searching on WorldCat, the free web portal to more than 10,000 library collections around the world.

26. The title field of the bibliographic record (**Appendix 1008-C**) and Field 245 of the MARC record (**Appendix 1008-D**) show that "WCNC 2004 :

2004 IEEE Wireless Communications and Networking Conference" is the main title, and the subtitle is "Broadband wireless—the time is now" and the title covers proceedings from the conference held from "21-25 March, 2004, Atlanta, GA, USA, Georgia World Congress Center." The 245 field also shows "IEEE and IEEE Communications Society" as contributing bodies. Field 111 of the MARC record shows the author for this publication is the conference whose name is presented in the authorized form here. The MARC record also shows that three variant titles—"Broadband wireless—the time is now," "2004 IEEE Wireless Communications and Networking Conference," and "Wireless communications and networking conference"--are provided as additional access points in the 246 fields to help users discover this publication. The Imprint field of the bibliographic record (**Appendix 1008-C**) and Field 260 of the MARC record (**Appendix 1008-D**) show that IEEE of Piscataway, New Jersey published this publication with a 2004 copyright date. Four 020 fields in the MARC record show the 10-digit and 13-digit ISBNs of the softbound copy and CD-ROM copy, and the 10-digit ISBNs match the information on the copyright page of **Appendix 1008-B**. The MARC record also shows that IEEE and IEEE Communications Society are provided as additional access points for users to discover this publication through them.

27. Field 090 of the MARC record (**Appendix 1008-D**) shows this monograph has a Library of Congress Classification (LCC) number of

"TK5103.2," which is the class number for "general works" in the "Wireless communication systems" category. Users interested in the topic represented by the LCC number could search it as a keyword in the online catalog of the Linda Hall Library to retrieve materials that have been assigned the same classification number. The subjects of this book are also represented in the 650 fields by three Library of Congress subject headings, "Wireless communication systems," "Computer networks," and "Telecommunication," and these subject headings are followed by a form subdivision "Congresses" (encoded in subfield "v") to indicate these topics were covered at a conference.

28. This MARC record (**Appendix 1008-D**) shows that *WCNC 2004 : 2004 IEEE Wireless Communications and Networking Conference* that contains Roh is a book that has been made searchable in the online catalog of the Linda Hall Library, and users interested in the topics of the book can find the book by the LCC number and by subject terms assigned to it. Users can also find this book by the conference name, the main title, three variant titles, two contributing organizations, and the ISBNs of the softbound copy and the CD-ROM copy.

29. Based on the hand-written date of "7-15-04" (*i.e.*, July 15, 2004) on the "Letter from the Technical Program Committee Chair" page of the Linda Hall Library copy **(Appendix 1008-B)**, the bibliographic record (**Appendix 1008-C**), the "040715" (*i.e.*, July 15, 2004) creation date of the MARC record (**Appendix 1008-D**), and my understanding of the ordinary and customary cataloging and processing practices of libraries, it is my opinion that *WCNC 2004 : 2004 IEEE Wireless Communications and Networking Conference* that contains Roh was cataloged by the Linda Hall Library as a monograph on July 15, 2004 and added to their collection. Most academic libraries make newly cataloged monographs available to the public soon after the cataloging work is completed, usually within a week. It is therefore my opinion that the physical copy of *WCNC 2004 : 2004 IEEE Wireless Communications and Networking Conference* that contains Roh would have been available to the public at the Linda Hall Library by July 22, 2004.

4. Library of Congress Copy of Roh

30. My research on Roh in WorldCat also identified the Library of Congress as a holding library of *IEEE Wireless Communications and Networking Conference* that contains Roh, so I searched the online library of the Library of Congress and the search results confirmed the holdings. **Appendix 1008-E** is a true and correct copy of Roh, including the front matter of volume 2 of the *2004 IEEE Wireless Communications and Networking Conference*. I have closely compared the Linda Hall Library copy of Roh (**Appendix 1008-B**) with the Library of Congress copy of Roh (**Appendix 1008-E**) and found them to be substantively the same. One difference is that the Linda Hall Library copy is black and white, and

Library of Congress copy of Roh is colored. Another difference is the Linda Hall Library copy has a hand-written date of "7-15-04" as the date when the monograph was added to their collection, while the Library of Congress copy has a date stamp of "LIBRARY OF CONGRESS JULY 12 2004 COPYRIGHT OFFICE" on the title page of volume 2 of *2004 IEEE Wireless Communication and Networking Conference*.

5. Library of Congress MARC Record

31. **Appendix 1008-F** is a true and correct copy of the MARC record for *IEEE Wireless Communications and Networking Conference* whose 2004 conference contains Roh. I retrieved this record from the online catalog of the Library of Congress by searching for the name of the conference. The MARC record shows that the Library of Congress catalogs the conference proceedings as "PERIODICAL OR NEWSPAPER" (*i.e.*, serial). The first six digits of Field 008 show the record was created on "000914" (*i.e.*, September 14, 2000), and the "c19999999" code following the first six digits indicates that this is a continuing resource that began publication in 1999 and there is no end date for this publication. Field 022 shows the International Standard Serial Number (ISSN) of this publication is "1525-3511," which matches the ISSN on the copyright page of **Appendix 1008-B**. Subfield a of Field 040 shows the record was created by "NSD," which is the OCLC symbol for the National Serial Database Program, according to the list of current CONSER members (https://www.loc.gov/aba/pcc/conser/contact/conmembs.html#endnote5). Field 042 shows the record was authenticated by "pcc" (the Program for Cooperative Cataloging) and "nsdp" (the National Serial Data Program). Field 245 shows "IEEE Wireless Communications and Networking Conference : [proceedings] : WCNC" is the title, Field 111 shows the conference name is the author, and three variant titles are provided in the 246 fields to help users discover this title. Field 260 shows the Institute of Electrical and Electronics Engineers has published this serial since 1999. Field 310 shows the publication frequency of this serial is "Annual". Subject matters of this publication are represented by a Library of Congress Classification number in Field 050, a Dewey Decimal Classification number in Field 082, and two Library of Congress subject headings in the 650 fields. The Item Availability area shows the call number of this serial is "TK5103.2 .I345a" and the Library of Congress holds issues since 1999, including volume 2 of the 2004 conference.

32. This MARC record (**Appendix 1008-F**) shows *IEEE Wireless Communications and Networking Conference* is a long-running serial and the Library of Congress has made it searchable and accessible to the public since 2000.

6. Library of Congress Date Stamp

33. The title page of volume 2 of the 2004 conference (**Appendix 1008-**

E) bears a date stamp of "LIBRARY OF CONGRESS JUL 12 2004 COPYRIGHT OFFICE." The stamp has the appearance and distinctive characteristics of a typical check-in date stamp utilized by libraries to indicate the date a particular publication was received by the library. Based on my knowledge and understanding of library serial check-in practice and the effort to make new journal issues available to users as soon as possible, it is my opinion that the Library of Congress received and date stamped 2004 *IEEE Wireless Communications and Networking Conference* on July 12, 2004, and would have made the volumes of the 2004 conference publicly accessible soon after they were checked in. Most libraries make newly checked-in journal issues available on the same day of serial check-in or within a week after serial check-in is completed. If the workload was very heavy at that time, it might take more than one week for the newly received issue to become available to users. It would be very likely that the 2004 volumes (including volume 2 that contains Roh) would have been available to users at the Library of Congress as early as July 12, 2004, and no later than August 12, 2004, which would be one month after serial check-in was completed.

7. Actual Usage Records

34. Actual usage of a publication is reflected by the papers that make reference to it. The citation history on Google Scholar shows Roh has been cited at least 113 times. **Appendix 1008-G** presents select citations from 2004 to June

2005 to demonstrate early usage, and the earliest citing document is an IEEE article published in December 2004, further demonstrating public availability of Roh in 2004.

8. Summary on Roh

35. Taken together, the "JULY 12 2004" date stamp on the Library of Congress copy (**Appendix 1008-E)**, the hand-written add date of "7-15-04" (*i.e.*, July 15, 2004) on the Linda Hall Library copy (**Appendix 1008-B**), the "040715" (*i.e.*, July 15, 2004) record creation date of the Linda Hall Library MARC record (**Appendix 1008-D**), the record entry date of "July 19, 2004" in the IEEE record from the IEEE Xplore Digital Library (**Appendix 1008-A**), and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that the Library of Congress has cataloged *IEEE Wireless Communications and Networking Conference* as a serial, and the 2004 conference proceedings of this serial was received and date stamped by the Library of Congress on July 12, 2004, so the volumes would have been available there to the public by July 19, 2004. Linda Hall Library cataloged the 2004 conference proceedings as a monograph on July 15, 2004, so its volume would have become available for public access at that library by July 22, 2004. The IEEE record for Roh was added to the IEEE Xplore Digital Library on July 19, 2004, so the record would have been searchable in the IEEE Xplore Digital Library since July 19,

2004. Early citations of Roh show that the earliest citing article was published in December 2004, further demonstrating public availability of *2004 IEEE Wireless Communications and Networking Conference*, whose volume 2 contains Roh, in 2004.

B. Ex. 1010 (Haykin)

1. Authentication

36. **Ex. 1010** is a true and correct copy of a portion of MODERN WIRELESS COMMUNICATIONS ("Haykin"), by S. S. Haykin and M. Moher, published by Pearson/Prentice Hall in 2005, that I located and identified at the Library of Congress. When I was asked to prepare this declaration, I searched WorldCat by the title of this book for records, and the search results informed me that the Library of Congress held this title. I then searched the Library of Congress online catalog for records and the search results confirmed the holdings information. The "Item Availability" area of the library records shows that the Library of Congress has one copy of this book, and its call number is "TK5103.2 .H39 2005." The copy can be requested in the "Jefferson or Adams Building Reading Rooms." I obtained the Library of Congress copy and a scan of the book was produced. The following discussion is based on the Library of Congress copy while I have it in my personal possession.

37. **Ex. 1010** is a true and correct copy of a portion of Haykin. The first page of **Ex. 1010** is the cover that shows "Modern Wireless Communications" as the title and Simon Haykin and Michael Moher as the authors. It also shows a call number label of "TK 5103.2 .H39 2005 Copy 1." Page 5 of **Ex. 1010** is the title page that shows the same title and author information as the cover, and identifies Pearson/Prentice Hall of Upper Saddle River, NJ, as the publisher. Page 6 of **Ex. 1010** is the copyright page that shows a copyright date of "2005" with "Pearson Foundation, Inc." as the copyright holder. The copyright page also shows the ISBN (International Standard Book Number) of this title as "0-13-022472-3" and includes a brief record of "Library of Congress Cataloging-in-Publication." This page also carries a date stamp of "LIBRARY OF CONGRESS APR 05 2004 COPYRIGHT OFFICE." Pages 9-16 of **Ex. 1010** are the table of contents that show the book has seven chapters, nine appendices, a bibliography and an index, and the last numbered page is 560. Page 474 of **Ex. 1010** is the back cover that shows the same ISBN number as the copyright page, and a barcode label of "LIBRARY OF CONGRESS 0 012 004 571 4."

2. Library of Congress Records

38. **Appendix 1010-A** a true and correct copy of the bibliographic record for Haykin. I personally identified, located, and obtained this record from the online catalog of the Library of Congress for this declaration. This is the type of record experts in my field would reasonably rely upon when forming their opinion. **Appendix 1010-A** shows that the main title is "Modern wireless communications," the authors are "Simon Haykin and Michael Moher," and the publisher is Pearson/Prentice Hall of Upper Saddle River, N.J. that published this book with a copyright date of 2005. The ISBN field shows "0130224723" as the ISBN assigned to this title. The authors, title, publisher, copyright date, and ISBN match the information contained in **Ex. 1010**. The "Item Availability" area shows that the book's call number is "TK5103.2 .H39 2005" and copy 1, which I obtained, was "due on 03-28-2020" (*i.e.*, March 28, 2020).

39. **Appendix 1010-B** is a true and correct copy of the MARC record for Haykin. I personally identified, located, and obtained this record from the online catalog of the Library of Congress for this declaration. This is the type of record experts in my field would reasonably rely upon when forming their opinion.

40. The first six digits of Field 008 show the MARC record was created on "030805" (*i.e.*, August 5, 2003). Field 955, the local note field for cataloging activity dates, shows that "2004-07-14 bk rec'd., to CIP ver." (*i.e.*, the book was received on July 14, 2004, and sent to the Cataloging in Publication Program for record verification), then on "2004-09-24 to BCCD, copy 1" (*i.e.*, on September 24, 2004, copy 1 was sent to the Binding and Collections Care Division for processing). The Cataloging in Publication Program (CIP) at the Library of Congress is responsible for cataloging books in advance of publication to alert the library community to forthcoming new publications and to facilitate acquisition.

41. Subfield "a" of Field 040 of the MARC record (**Appendix 1010-B**) shows that "DLC" is the library that created the original MARC record. According to the Directory of OCLC Members (https://www.oclc.org/en/contacts/libraries.html), "DLC" is the OCLC symbol for the Library of Congress. These data inform my opinion that the MARC record (**Appendix 1010-B**) was first created on August 5, 2003 as a Cataloging-in-Publication record, based on the information presented by the publisher. After the CIP record was completed, it was sent to the publisher for inclusion in the physical volume. The brief record identified as "Library of Congress Cataloging in Publication" on the copyright page of **Ex. 1010** reflects this practice. After the physical volume was published and received by the Library of Congress, catalogers of the Cataloging-in-Publication Program used the volume to verify the CIP MARC record in July 2004. After that, the physical copy was sent to the processing unit on September 24, 2004.

42. Field 010 of the MARC record (**Appendix 1010-B**) shows the Library of Congress control number of this book is "2003061139," which matches the number included in the brief record on the copyright page of **Ex. 1010**. Fields 020 shows the ISBN of this book, and it matches the number on the copyright page and back cover of **Ex. 1010**. Field 245 shows the title is "Modern wireless communications" and the authors are "Simon Haykin and Michael Moher." Field 100 presents the first author's name in the authorized form "Haykin, Simon S., 1931- " to make it an access point for users to discover this book. Field 260 shows that Pearson/Prentice Hall of Upper Saddle River of New Jersey published this book with a 2005 copyright date. Field 300 indicates that the book has 560 pages. The number "560" matches the last numbered page included in **Ex. 1010**.

43. Field 050 of the MARC record (**Appendix 1010-B**) shows this book has a Library of Congress Classification (LCC) number of "TK5103.2," which is the class number for "general works" in the "Wireless communication systems" category. Field 082 shows the book has a Dewey Decimal Classification (DDC) number of "621.382," which is the class number for the "communications engineering" category. Users interested in the topic represented by the LCC number or the DDC number could search it as a keyword in the Library of Congress catalog to retrieve materials that have been assigned the same classification number. The subjects of this book are also represented in the 650 fields by two Library of Congress subject headings, "Wireless communication systems" and "Spread spectrum communications." Field 700 shows that the second author, Michael Moher, is included as an additional access point for users to discover this title.

44. This MARC record (**Appendix 1010-B**) shows that MODERN WIRELESS COMMUNICATIONS by Haykin and Moher is a book that has been made searchable in the online catalog of the Library of Congress, and users interested in the topics of the book can find it by the LCC and DDC numbers and by subject terms assigned to it. Users can also find this book by its title, authors, and ISBN.

45. Based on the information above, it is my opinion that *Modern Wireless Communications* by Haykin and Moher **(Ex. 1010)** is a book that has been made available by the Library of Congress, meaning that members of the public with an interest in the topics covered by the book would be able to search for and access *Modern Wireless Communications*.

3. Library of Congress Date Stamp

46. The copyright page of Haykin in **Ex. 1010** bears a stamp of "LIBRARY OF CONGRESS APR 05 2004 COPYRIGHT OFFICE" that indicates the date when the Library of Congress received the physical volume of Haykin. The stamp has the appearance and distinctive characteristics of a typical check-in date stamp utilized by libraries to indicate the date a particular publication was received by the library. The date stamp on the copyright page of **Ex. 1010** and the dates in the MARC record for Haykin (**Appendix 1010-B**) inform my opinion that Library of Congress received the physical volume of Haykin on April 5, 2004, the book was received for CIP verification in July 2004, and the physical copy was sent to the Binding and Collections Care Division for processing on "2004-09-24" (*i.e.*, September 24, 2004).

47. The record creation date in Field 008 and the cataloging dates in Field 955 of the MARC record (**Appendix 1010-B**) inform my opinion that the MARC record was created by Library of Congress catalogers on "030805" (*i.e.*, August 5, 2003) as a Cataloging in Publication (CIP) record, that the physical volume was received by Library of Congress on "2004-07-14" (*i.e.*, July 14, 2004) and CIP catalogers then used the physical volume to verify the CIP record, and that on "2004-09-24" (*i.e.*, on September 24, 2004) copy 1 was sent to the Binding and Collections Care Division for processing. In most academic libraries a newly cataloged book becomes available for the public soon after the cataloging record is completed, usually within a week. Considering the volume of materials the Library of Congress needs to catalog and process, it is very likely that Haykin would have become available for public access by December 24, 2004, at the latest, which would be three months after the physical copy was sent to the processing unit.

48. Based on the date stamp on the copyright page of **Ex. 1010**, the bibliographic record (**Appendix 1010-A**), the MARC record (**Appendix 1010-B**), and my understanding of the ordinary and customary cataloging and processing practices of libraries, it is my opinion that Haykin (**Ex. 1010**) was cataloged and the record became searchable as early as August 5, 2003, and the physical copy would have become accessible to the public by December 2004, three months after the physical copy was sent to the processing unit.

4. Actual Usage Records

49. Actual usage of a publication is reflected by the papers that make reference to it. My research on Google Scholar has found Haykin cited more than 800 times. **Appendix 1010-C** presents citations from February 2004 to June 2005 to demonstrate early usage. The earliest citing documents were published in February and September 2004, further demonstrating that Haykin was available at least as early as December 2004.

5. Summary of Haykin

50. Taken together, the date stamp of "APR 05 2004" on the Library of Congress copy of Haykin (**Ex. 1010**), the bibliographic record (**Appendix 1010-A**), the MARC record (**Appendix 1010-B**), and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that Haykin (**Ex. 1010**) would have been cataloged and discoverable by the public at the online catalog of the Library of Congress by August 2003 when the CIP cataloging record was created, and the physical copy would have been available for public access by December 24, 2004, at the latest, which would be three months after the physical copy was sent to the processing unit. The citation history of Haykin shows the earliest citing documents to Haykin were published in February and September 2004, further demonstrating the availability of Haykin in 2004.

C. Ex. 1011 (Yang)

1. Authentication

51. **Ex. 1011** is a true and correct copy of "Reducing the computations of the SVD array given by Brent and Luk," ("Yang"), by B. Yang and J. F. Bohme, in *Advanced Algorithms and Architectures for Signal Processing IV* (Proceedings SPIE Vol. 1152), pp. 92-102 (November 1989), that I obtained from Linda Hall Library. When I was asked to prepare this declaration, I searched WorldCat by the title of this book for records, and the search results informed me that Linda Hall Library held this title. I then searched the Linda Hall Library online catalog for records and the search results confirmed the holdings information. I then asked the Document Delivery Service of the Linda Hall Library to provide me with a scanned copy of Yang and the front matter of *Advanced Algorithms and Architectures for Signal Processing* IV. I received the scanned pages on February 3, 2020.

52. Page 1 of **Ex. 1011** is the first page of **Yang** that shows the authors and title of this article, and the running title at the bottom indicates the article was published in "SPIE Vol. 1152 Advanced Algorithms and Architectures for Signal Processing IV (1989)." Page 12 of **Ex. 1011** is the cover of *Advanced Algorithms and Architectures for Signal Processing IV* that shows "Franklin T. Luk" as the chair/editor, and "8-10 August 1989 San Diego, California" as the conference whose proceedings are represented by this title. The cover also identifies this publication as "Proceedings SPIE—The International Society for Optical Engineering" and shows the volume number is "1152." Page 13 of **Ex. 1011** is the title page that shows the same information as the cover, and also shows that the conference was sponsored by "SPIE—The International Society for Optical Engineering" and this volume was published by SPIE. Page 14 of **Ex. 1011** (internal page iii) is the table of contents that shows "Reducing the computations of the singular value decomposition array given by Brent and Luk" by B. Yang and J. F. Böhme was presented in Session 2 "Numerical Techniques" as item "1152-09" and the article begins on page 92 of the volume. The upper left corner of the table of contents page shows a hand-written date of "1-23-90," which, according to the librarian at the Linda Hall Library, is the date when this monograph was added to the collection, and the bottom of this page shows a stamp of "LINDA HALL LIBRARY KANSAS CITY, MO." Page 15 of **Ex. 1011** is the copyright page that shows a "1989" copyright date with "The Society of Photo-Optical Instrumentation Engineers" as the copyright holder. The copyright page also shows "0-8194-01889" as the ISBN (International Standard Book Number) and "89-43265" as the Library of Congress Catalog Card No. of this publication. This page also shows a hand-written call number assigned to this publication: TK5102.5 .A313 1989.

2. Linda Hall Library Records

53. **Appendix 1011-A** is a true and correct copy of the bibliographic record for *Advanced Algorithms and Architectures for Signal Processing IV* that contains Yang. I retrieved the record from the online catalog of the Linda Hall Library by searching for the title for records. I personally located, identified and obtained this bibliographic record, which experts in my field would reasonably rely upon when forming their opinion. As indicated earlier, conference proceedings can be cataloged as monographs if the conferences have distinctive titles and users are likely to search for them as monographs. Proceedings of conferences that take place at regular intervals tend to be cataloged as serials to speed up the cataloging process and make newly published proceedings available to users quickly. In this case, the bibliographic record (**Appendix 1011-A**) shows that "Advanced algorithms and architectures for signal processing IV" was cataloged as a monograph by the Linda Hall Library.

54. The bibliographic record has a link for "Staff view," which brings up the MARC record for *Advanced Algorithms and Architectures for Signal Processing IV* that contains Yang (**Appendix 1011-B**). This is the type of record experts in my field would reasonably rely upon when forming their opinion.

55. The title field of the bibliographic record (**Appendix 1011-A**) and

Field 245 of the MARC record (**Appendix 1011-B**) show that "Advanced algorithms and architectures for signal processing IV" is the title that represents a conference held from "8-10 August 1989, San Diego, California." Subfield c of Field 245 of the MARC record (**Appendix 1011-B**) shows the responsible parties are "Franklin T. Luk, chair/editor; sponsored by SPIE—the International Society for Optical Engineering; cooperating organizations, Applied Optics Laboratory/New Mexico State University … [et al.]." The Imprint field of the bibliographic record (**Appendix 1011-A**) and Field 260 of the MARC record (**Appendix 1011-B**) show that SPIE of Bellingham, Washington published this volume of proceedings with a copyright date of 1989. Field 010 of the MARC record shows the Library of Congress card number of this publication is "89043265" and Field 020 shows the 10-digit ISBN of this publication is "0819401889." The Series field of the bibliographic record and Field 490 and Field 830 of the MARC record show that this publication is volume 1152 of the "Proceedings of SPIE—the International Society for Optical Engineering" series. The title, authors, publisher, copyright date, LCCN, ISBN, and series information match the information contained in **Ex. 1011**.

56. The first six digits of Field 008 of the MARC record (**Appendix 1011-B**) show that the record was created on "900103" (*i.e.*, January 3, 1990). Subfield a of Field 040 shows that "SCT" was the creator of the original record, and subfield d shows that "LHL" used the SCT record to create a copy cataloging record. According to the Directory of OCLC Members (https://www.oclc.org/en/contacts/libraries.html), "SCT" is the OCLC symbol for the US Air Force, Institute of Technology in Wright Patterson AFB, Ohio, and LHL is the OCLC symbol for Linda Hall Library. The holdings information area shows the book is in the "Open Stacks" of the Linda Hall Library, its call number is "TK5102.5 .A313 1989" and the status of the book is "Not Charged" (meaning available to users). Field 035 of the MARC record shows the record has an OCLC number of "20841365," which means the record is available to OCLC members for copy cataloging and interlibrary loan purposes, and also available for searching on WorldCat, the free web portal to more than 10,000 library collections around the world.

57. Field 246 of the MARC record (**Appendix 1011-B**) shows that a variant title is provided for users to discover this title by "Optical & optoelectronic applied science & engineering." A general note in Field 500 explains that "Conference 1152 … was part of a five-conference program on Signal and Image Processing and Storage held at SPIE's 33rd Annual International Symposium on Optical & Optoelectronic Applied Science & Engineering, 6-11 August 1989, San Diego, Calif." The editor, the sponsor, and the first cooperating organization are included as additional access points in Field 700 and Fields 710 for users to discover this publication.

58. Field 090 of the MARC record (**Appendix 1011-B**) shows this monograph has a Library of Congress Classification (LCC) number of "TK5102.5," which is the class number for the "general special" sub-category in the "Telecommunications" category. Users interested in the topic represented by the LCC number could search it as a keyword in the online catalog of the Linda Hall Library to retrieve materials that have been assigned the same classification number. The subjects of this book are also represented in the 650 fields by three Library of Congress subject headings, "Signal processing," "Algorithms," and "Computer architecture" and these subject headings are followed by a form subdivision "Congresses" (encoded in subfield "v") to indicate these topics were covered at a conference.

59. This MARC record (**Appendix 1011-B**) shows that *Advanced Algorithms and Architectures for Signal Processing IV* that contains Yang is a book that has been made searchable in the online catalog of the Linda Hall Library, and users interested in the topics of the book can find it by the LCC number and by subject terms assigned to it. Users can also find this book by its title, variant title, the editor, sponsoring and cooperating organizations, and ISBN.

60. Based on the hand-written date on the table of contents of **Ex. 1011**, the bibliographic record (**Appendix 1011-A**), the MARC record (**Appendix 1011-B**), and my understanding of the ordinary and customary cataloging and processing practices of libraries, it is my opinion that *Advanced Algorithms and Architectures for Signal Processing IV* that contains Yang was cataloged by the Linda Hall Library as a monograph, using the original MARC record created by the US Air Force, Institute of Technology on "900103" (*i.e.*, January 3, 1990) and the monograph was added to the Linda Hall Library collection on "1-23-90" (*i.e.*, January 23, 1990). Since most academic and research libraries make newly cataloged monographs available to the public soon after the cataloging work is completed, usually within a week, it is my opinion that *Advanced Algorithms and Architectures for Signal Processing IV* that contains Yang would have become available to the public at the Linda Hall Library by January 30, 1990.

3. US Air Force, Institute of Technology Library Records

61. To verify the record creation date of the original MARC record, I personally identified, located, and obtained the bibliographic record (**Appendix 1011-C**) and MARC record (**Appendix 1011-D**) for *Advanced Algorithms and Architectures for Signal Processing IV* that contains Yang from the online catalog of the D'Azzo Research Library of the US Air Force, Institute of Technology at https://w95020.eos-intl.net/W95020/OPAC/Index.aspx for this declaration. This is the type of record experts in my field would reasonably rely upon when forming their opinion.

62. The bibliographic record (**Appendix 1011-C**) shows that one copy of *Advanced Algorithms and Architectures for Signal Processing IV* is held by the D'Azzo Research Library, its item ID number is "0117100369182" and it is a "circulating item" with a call number of "SPIE 1152." The Library's MARC record (**Appendix 1011-D**) confirms in Field 008 that the original record was created on "900103" (*i.e.*, January 3, 1990) and Field 040 subfield a and subfield c show that "SCT," which is the OCLC symbol for the US Air Force, Institute of Technology Library, created the original record. Because the Linda Hall Library MARC record is based on the SCT MARC record, the two records have the same data for Library of Congress card number (Field 010), ISBN (Field 020), main title (Field 245), publisher (Field 260) and series information (Fields 490 and 830). Differences between these two records are that the SCT MARC record lists the OCLC number ("20841365") in Field 001, while the Linda Hall Library MARC record lists it in Field 035; the SCT MARC record uses the series numbering of "SPIE 1152" as the call number while the Linda Hall Library record uses a call number that is based on the Library of Congress Classification number, "TK5102.5." The SCT MARC record spells out the name of the publisher, while the Linda Hall Library record uses "SPIE", and the SCT MARC record does not provide a variant title in Field 246 or uses the first cooperating organization as an additional access point in Field 710.

63. Based on the bibliographic record (**Appendix 1011-A**) and MARC record (**Appendix 1011-B**) for *Advanced Algorithms and Architectures for Signal Processing IV* and my understanding of the ordinary and customary cataloging and processing practices of libraries, it is my opinion that *Advanced Algorithms and Architectures for Signal Processing IV* that contains Yang was first cataloged by the US Air Force Institute of Technology Library on January 3, 1990, and soon after the physical copy was made available to users at that library. The original record became available to OCLC members for cataloging and interlibrary loan purposes, and also became searchable on WorldCat for the general public. On January 23, 1990 the Linda Hall Library used the original MARC record from the US Air Force Institute of Technology Library to create their copy cataloging record and add the monograph to their collection. In most academic libraries a newly cataloged book becomes available for the public soon after the cataloging record is completed, usually within a week. It is therefore my opinion that the physical copy of *Advanced Algorithms and Architectures for Signal Processing IV* (including Yang contained therein) would have been available for public access by January 30, 1990.

4. Actual Usage Records

64. Actual usage of a publication is reflected by the papers that make reference to it. The citation history on Google Scholar shows Yang has been cited at least 16 times. **Appendix 1011-E** presents select citations from 1990 to 1992 to demonstrate early usage. The earliest citing document is an IEEE conference article published in September 1990 that further demonstrates the availability of Yang in 1990.

5. Summary on Yang

65. Taken together, the "900103" record creation date of the MARC record from the US Air Force Institute of Technology Library (**Appendix 1011-D**), the "1-23-90" hand-written add date for the Linda Hall Library collection (**Ex. 1011**), the Linda Hall Library bibliographic record (**Appendix 1011-A**), their MARC record (**Appendix 1011-C**), and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that *Advanced Algorithms and Architectures for Signal Processing IV*, which containsYang, would have been available for public access by January 10, 1990 at the US Air Force Institute of Technology Library, and by January 30, 1990 at the Linda Hall Library. Citation history of Yang shows that the earliest citing article to Yang was published in September 1990, further supporting my opinion that *Advanced Algorithms and Architectures for Signal Processing IV* (including Yang contained therein) was publicly available in 1990.

D. Ex. 1013 (Sadrabadi)

1. Authentication

66. **Ex. 1013** is a true and correct copy of "A new method of channel feedback quantization for high data rate MIMO systems" ("Sadrabadi"), by Sadrabadi et al., in *GLOBECOM'04, IEEE Global Telecommunications Conference*, *2004*, Vol. 1, pp. 91-95, that I obtained from the Institute of Electrical and Electronics Engineering (IEEE), the publisher of the proceedings. When I was asked to prepare this declaration, I searched the IEEE Xplore Digital Library for records for "A new method of channel feedback quantization for high data rate MIMO systems" because this article is an IEEE publication. The search result shows an IEEE record for Sadrabadi at https://ieeexplore.ieee.org/document/1377919. I then used the PDF link to purchase the article from IEEE.

67. Page 1 of **Ex. 1013** is the first page of Sadrabadi that shows "A new method of channel feedback quantization for high data rate MIMO systems" as the title, and "Mehdi Ansari Sadrabadi, Amir K. Khandani and Farshad Lahouti" as the authors. The bottom of this page shows Sadrabadi has a "2004" copyright date with IEEE as the copyright holder. It also shows Sadrabadi appears in "IEEE Communications Society Globecom 2004," which has an ISBN number of "0-7803-8794-5." Sadrabadi begins on page 91 and ends on page 95, including one figure and 20 references.

68. **Appendix 1013-A** is the IEEE record for Sadrabadi that I personally located, identified and obtained from the IEEE Xplore Digital Library. The record shows the title, authors, and abstract of Sadrabadi. It also shows that Sadrabadi was published in "IEEE Global Telecommunications Conference, 2004. GLOBECOM '04" and the print ISBN for this publication is "0-7803-8794-5." The IEEE record also shows that GLOBECOM '04 took place from "29 Nov.-3 Dec. 2004" in Dallas, Texas, USA. The Date Added to IEEE Xplore field shows the IEEE record for Sadrabadi was added on "17 January 2005" and the DOI (digital object identifier) of Sadrabadi is "10.1109/GLOCOM.2004.1377919."

2. Library of Congress Copy of Sadrabadi

69. **Appendix 1013-B** is a true and correct copy of "A new method of channel feedback quantization for high data rate MIMO systems," ("Sadrabadi"), by Sadrabadi et al., in *GLOBECOM'04, IEEE Global Telecommunications Conference, 2004*, Vol. 1, pp. 91-95, that I obtained from the Library of Congress. When I was asked to prepare this declaration, I searched WorldCat by the article for records, and the search results informed me that Library of Congress held *IEEE Global Telecommunications Conference* that contains Sadrabadi. I then searched the Library of Congress online catalog for records and the search results confirmed the holdings information, showing that the Library of Congress has cataloged *Globecom IEEE Global Telecommunications Conference* as a serial. The "Item Availability" area of the library records shows the call number of this serial is "TK5101.A1 I145a" and the Library of Congress holdings begin with volume 1 of 2003. This area also indicates users can request conference proceedings of this serial at the "Jefferson or Adams Building Reading Rooms." I requested access to volume 1 of the 2004 conference proceedings, and received the volume at the Science and Technology Reading Room in the Adams Building on February 6, 2020.

70. **Appendix 1013-B** is a true and correct copy of Sadrabadi that I produced while the volume containing Sadrabadi was in my personal possession at the Library of Congress. **Appendix 1013-B** includes the front matter of volume 1 of *GLOBECOM '04 IEEE Global Telecommunications Conference* (the cover, title page, copyright page, table of contents), the spine, back cover, and the Sadrabadi article. Page 1 of **Appendix 1013-B** is the cover that shows "GLOBECOM '04 IEEE Global Telecommunications Conference" as the title, identifies this volume as "volume 1," and shows the conference took place on "29 November – 3 December 2004" in Dallas Texas. It also shows IEEE and IEEE Communications Society as contributing organizations. Page 2 of **Appendix 1013-B** is the title page that is identical to the cover page. Page 3 of **Appendix 1013-B** is the copyright page that shows a date stamp of "LIBRARY OF CONGRESS JAN 25 2005

COPYRIGHT OFFICE" and a copyright date of "2004" with the Institute of Electrical and Electronics Engineers, Inc. as the copyright holder. The copyright page also shows that the IEEE Catalog Numbers for the softbound copy is "04CH37615" and the number for the CD-ROM is "04CH37615C." The ISBN for the softbound copy is "0-7803-8794-5" and the ISBN for the CD-ROM is "0-7803-8795-3." The bottom of the page shows a hand-written number of "2004209774," which has the appearance of a Library of Congress Control Number. Page 4 of **Appendix 1013-B** is the table of contents that shows that Sadrabadi is included in the "CT05: MIMO" session as "CT05-4" (internal page xvi), and the article begins on page 91 and ends on page 95. Page 14 of **Appendix 1013-B** is the first page of Sadrabadi that shows the title, authors, and the text of this article. The bottom of the page shows "IEEE Communications Society Globecom 2004" as the publication that contains Sadrabadi, and the ISBN of this publication is "0-7803-8794-5." I have closely compared the IEEE copy of Sadrabadi (**Ex. 1013**) with the Library of Congress copy of Sadrabadi (**Appendix 1013-B**) and found them to contain the same Sadrabadi article. The main differences are that the Library of Congress copy has a date stamp of "Jan 25 2005" on the copyright page and includes the front matter, spine, and back cover of the volume containing Sadrabadi.

3. Library of Congress Records

71. **Appendix 1013-C** is a true and correct copy of the bibliographic record for *Globecom* by IEEE Global Telecommunications Conference whose 2004 Conference contains Sadrabadi. I personally identified, located, and obtained this record from the online catalog of the Library of Congress for this declaration. This is the type of record experts in my field would reasonably rely upon when forming their opinion. The bibliographic record (**Appendix 1013-C**) shows that the Library of Congress has cataloged this title as a "Periodical or Newspaper" (*i.e.*, serial), the author is the meeting name, "IEEE Global Telecommunications Conference" and the main title is "Globecom." The record also shows IEEE of Piscataway, New Jersey, has published and held the copyright of Globecom since 2003. The ISSN field shows "1930-529X" as the number assigned to this serial. The Publication History field shows the serial began publication in 2003 and "ceased in 2011." The meeting name, title, publisher, and copyright date match the information contained in **Appendix 1013-B**. The "Item Availability" area shows that the call number of this serial is "TK5105.A1 I145a," that the Library of Congress holds conference proceedings from 2003 to 2011, and that users can request access to this serial at the "Jefferson or Adams Building Reading Rooms."

72. **Appendix 1013-D** is a true and correct copy of the MARC record for *Globecom* by IEEE Global Telecommunications Conference. I personally identified, located, and obtained this record from the online catalog of the Library of Congress for this declaration. This is the type of record experts in my field would reasonably rely upon when forming their opinion.

73. The first six digits of Field 008 show the MARC record (**Appendix 1013-D**) was created on “040416” (*i.e.*, April 16, 2004), and the “d20032011” code following these digits indicates the serial began publication in 2003 and ceased publication in 2011. Subfield a of Field 040 shows “DLC” is the creator of the serial record. “DLC” is the OCLC symbol for the Library of Congress, according to the Directory of OCLC Members (https://www.oclc.org/en/contacts/libraries.html). Field 042 shows the record was authenticated by “pcc” (the Program for Cooperative Cataloging) and “ndsp” (the National Data Serial Program). Field 362 shows the serial began in 2003 and Field 310 shows the publication frequency is “Annual.”

74. Field 050 of the MARC record (**Appendix 1013-D**) shows this serial has a Library of Congress Classification (LCC) number of “TK5101.A1,” which is the class number for “periodicals, societies, congresses, etc.” in the “Telecommunication” category. Field 082 shows the book has a Dewey Decimal Classification (DDC) number of “621.382,” which is the class number for the “communications engineering” category. Users interested in the topic represented by the LCC number or the DDC number could search it as a keyword in the Library of Congress catalog to retrieve materials that have been assigned the same classification number. The subjects of this book are also represented in the 650 fields by three Library of Congress subject headings--"Telecommunication," "Data transmission systems," and "Information networks"--and these main headings are followed by a form subdivision "Congresses" (encoded in subfield v) to indicate the serial covers these topics discussed in conferences.

75. This MARC record (**Appendix 1013-D**) shows that *Globecom*, the serial, existed from 2003 to 2011, and was made searchable in the online catalog of the Library of Congress. Users interested in the topics of this serial can find the serial by the LCC and DDC numbers and by subject terms assigned to it. Users can also find this serial by its title, the conference name, and the ISSN.

4. Library of Congress Date Stamp

76. The copyright page of the Library of Congress copy of Sadrabadi (**Appendix 1013-B**) shows a date stamp of "LIBRARY OF CONGRESS JAN 25 2005 COPYRIGHT OFFICE." The stamp has the appearance and distinctive characteristics of a typical check-in date stamp utilized by libraries to indicate the date a particular publication was received by the library. As I noted above, it is ordinary and regular practice for a library to maintain intake records, including date stamping serial issues during the check-in process, updating the holdings record and making a newly received serial issue available to the public in the library shortly after the library receives and date stamps the issue, usually within a week after serial check in. In this case, it is my understanding that the Library of Congress received *Globecom '04* and date stamped it on January 25, 2005, and shortly thereafter, would have made the volumes of this conference accessible for the public as early as January 25, 2005, and no later than February 25, 2005 which would be one month after serial check-in was completed.

77. Based on the information above, it is my opinion that *Globecom* by IEEE Global Telecommunications Conference is cataloged as a serial by the Library of Congress, and made searchable in their online catalog since April 2004. The library records show the Library of Congress holds proceedings of the conference from 2003 to 2011, and members of the public with an interest in the topics covered by the serial would be able to search for it by the subject headings and classification numbers assigned to it, in addition to title, meeting names, and ISSN. The date stamp on the copyright page of the Library of Congress copy (**Appendix 1013-B**) shows that volume 1 of the 2004 conference was received on January 25, 2005, and the volume would have been accessible to the public as early as January 25, 2005, and no later than February 25, 2005, which would be one month after serial check-in was completed.

5. Linda Hall Library Records

78. As discussed earlier, libraries may choose to catalog conference proceedings as monographs or serials. The Library of Congress copy of Sadrabadi (**Appendix 1013-B**) and records show a serial treatment of *Globecom*. My research on WorldCat for "A new method of channel feedback quantization for high data rate MIMO systems" found that some libraries catalog *Globecom '04* as a monograph. WorldCat records for *Globecom '04* show that Linda Hall Library holds a copy, so I searched the online catalog of the Linda Hall Library and the records confirmed the holdings. **Appendix 1013-E** is a true and correct copy of the bibliographic record for *Globecom '04*. I retrieved the record from the online catalog of the Linda Hall Library after searching for "2004 IEEE global telecommunications." I personally located, identified and obtained this bibliographic record, which experts in my field would reasonably rely upon when forming their opinion.

79. As indicated earlier, conference proceedings can be cataloged as monographs if the conferences have distinctive titles and themes, and users are likely to search for them as monographs. Proceedings of conferences that take place at regular intervals tend to be cataloged as serials to speed up the cataloging time and make newly published proceedings available to users quickly. In this case, the bibliographic record (**Appendix 1013-E**) shows that the Linda Hall

Library has cataloged "GLOBECOM '04 : IEEE Global Telecommunications Conference" as a monograph.

80. The bibliographic record has a link for "Staff view," which brings up the MARC record for "GLOBECOM '04 : IEEE Global Telecommunications Conference" (**Appendix 1013-F**). This is the type of record experts in my field would reasonably rely upon when forming their opinion.

81. The title field of the bibliographic record (**Appendix 1013-E**) and Field 245 of the MARC record (**Appendix 1013-F**) show "GLOBECOM '04 : IEEE Global Telecommunications Conference" is the main title, the conference took place on "29-November-3 December, 2004, Dallas Texas" and IEEE and IEEE Communications Society are sponsors. Field 111 shows the authorized form of the meeting name as the author of this publication. The Imprint field of the bibliographic record (**Appendix 1013-E**) and Field 260 of the MARC record (**Appendix 1013-F**) show that IEEE of Piscataway, New Jersey, published the 2004 conference proceedings with a copyright date of 2004. The 020 fields of the MARC record show the 10-digit and 13-digit ISBNs of the softbound and CD-ROM copies of this publication. The author, title, publisher, publication year, and ISBNs of this MARC record match the information contained in the Library of Congress copy of Sadrabadi (**Appendix 1013-B**).

82. The first six digits of Field 008 show the MARC record was created on "050113" (*i.e.*, January 13, 2005), and subfield a of Field 040 shows "LHL" is the record creator. "LHL" is the OCLC symbol of the Linda Hall Library, according to the Directory of OCLC Members (https://www.oclc.org/en/contacts/libraries.html). The MARC record shows that three variant titles are provided in the 246 fields to enable users to discover this publication. Field 300 shows this publication consists of six volumes. A 500 general note field shows the IEEE Catalog Numbers for the softbound and CD-ROM copies, and the numbers match the numbers on the copyright page of **Appendix 1013-B**. The sponsors, IEEE and IEEE Communications Society, are included in the MARC record as additional access points in Fields 710 to help users discover this publication.

83. Field 090 of the MARC record (**Appendix 1013-F**) shows this monograph has a Library of Congress Classification (LCC) number of "TK5101," which is the class number for "general works" in the "Telecommunication" category. Users interested in the topic represented by the LCC number could search it as a keyword in the online catalog of the Linda Hall Library to retrieve materials that have been assigned the same classification number. The subjects of this book are also represented in the 650 fields by five Library of Congress subject headings--"Telecommunication," "Data transmission systems," Computer networks," "Broadband communication systems," and "Artificial satellites in telecommunication"—and all five subject headings are followed by a form subdivision "Congresses" (encoded in subfield "v") to indicate these topics were covered at a conference. In addition, Field 035 shows the record's OCLC number is "57414143," meaning the record is available to OCLC members for copy cataloging and interlibrary loan purposes, and also available for searching on WorldCat, a free web portal to more than 10,000 library collections worldwide. is "0819401889."

84. This MARC record (**Appendix 1013-F**) shows that *GLOBECOM '04 IEEE Global Telecommunications Conference* whose volume 1 contains Sadrabadi is a book that has been made searchable in the online catalog of the Linda Hall Library, and users interested in the topics of the book can find it by the LCC and by subject terms assigned to it. Users can also find this book by its title, variant title, the sponsoring organizations, and ISBNs.

85. Based on the IEEE record (**Appendix 1013-A**), the date stamp on the Library of Congress copy of Sadrabadi (**Appendix 1013-B**), the record creation date of the MARC record from the Linda Hall Library (**Appendix 13-F**), and my understanding of the ordinary and customary cataloging and processing practices of libraries, it is my opinion that *GLOBECOM '04 IEEE Global*

Telecommunications Conference whose volume 1 contains Sadrabadi was cataloged by the Linda Hall Library as a monograph on January 13, 2005; the Sadrabadi record was added to the IEEE Xplore Digital Library on January 17, 2005; and the Library of Congress received and date stamped *GLOBECOM '04 IEEE Global Telecommunications Conference* whose volume 1 on January 25, 2005. Since most academic and research libraries make newly cataloged monographs available to the public soon after the cataloging work is completed, usually within a week, it is my opinion that *GLOBECOM '04 IEEE Global Telecommunications Conference* would have become available to the public at the Linda Hall Library by January 20, 2005. The IEEE record for Sadrabadi was added to the IEEE Xplore Digital Library on January 17, 2005, and would have been freely searchable in the IEEE Xplore Digital Library since that date, making it very easy for users to discover Sadrabadi. The Library of Congress treats *Globecom* as a serial, and *Globecom '04* was date stamped and checked in on January 25, 2005. Most academic libraries make newly checked-in serial issues available soon after serial check-in is completed, usually within a week. The physical copy of *Globecom '04* therefore would have become available for public access by February 1, 2005.

6. Actual Usage Records

86. Actual usage of a publication is reflected by the papers that make reference to it. The citation history on Google Scholar shows Sadrabadi has been cited at least 24 times, including once in 2005. The earliest citing document was published in March 2005: Dharamdial, N., & Adve, R. S. (2005, March). Efficient feedback for precoder design in single-and multi-user MIMO systems. In *Proceedings of the 39th Conference on Information Sciences and Systems (CISS'05)*. This early citation further support my opinion that *Globecom '04* that contains Sadrabadi was publicly available by March 2005.

7. Summary on Sadrabadi

87. Taken together, the "17 January 2005" add date in the IEEE record for Sadrabadi (**Appendix 1013-A**), the "050113" (*i.e.*, January 13, 2005) record creation date in the Linda Hall Library MARC record (**Appendix 1013-F**), and the date stamp on the Library of Congress copy of Sadrabadi (**Appendix 1013-B**) and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that *Globecom '04* became publicly accessible after the Linda Hall Library cataloged it as a monograph on January 13, 2005. Since more academic and research libraries make newly cataloged monographs available to users soon after the cataloging work is completed, usually within a week, the physical copy of *Globecom '04* would have been available to the public by January 20, 2005. The IEEE record for Sadrabadi was added to the IEEE Xplore Digital Library on January 17, 2005, making it possible for users to discover Sadrabadi from that day on. The Library of Congress copy of *Globecom ’04* was date stamped on January 25, 2005, so the physical copy would have been available by February 1, 2005. If workload was very heavy at the time, the physical copy would have been available to the public by February 25, 2005, which would be one month after serial check-in was completed. Citation history shows the earliest citation was published in March 2005, further demonstrating public accessibility of *Globecom ’04* (and Sadrabadi contained therein) by March 2005.

V. CONCLUSION

88. I hereby declare that all statements made herein on 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.

Dated: February 19, 2020 By: Ingrid Hsieh-Yee

Ingrid Hsieh-Yee, Ph.D.

APPENDIX A

Ingrid Hsieh-Yee

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Education

Ph.D. Library and Information Studies, University of Wisconsin-Madison
Minors: Sociology and Psychology

M.A. Library and Information Studies, University of Wisconsin-Madison.

M.A. Comparative Literature, University of Wisconsin-Madison.

B.A. Foreign Languages and Literature, National Taiwan University.

Work Experience

Professor, School/Dept. of Library and Information Science, Catholic University of America, 2004- (Assistant Professor, 1990-1996; Associate Professor, 1997-2004)

Co-Chair, Dept. of Library and Information Science, Catholic University of America, June 2015-August 2016.

Acting Dean, School of Library and Information Science, Catholic University of America, January 2010-June 2012.

Cataloger, Dept. of Legislative Reference Library, Annapolis, Maryland, 1989-1990.

Lecturer, School of Library and Information Studies, University of Wisconsin-Madison, 1988.

Teaching Assistant, School of Library and Information Studies, University of Wisconsin-Madison, 1986-1988.

Cataloger, Health Sciences Library, University of Wisconsin-Madison, 1984-1986.

Areas of Teaching and Research Interests

Information Organization and Access; Metadata; Cataloging & Classification; Information Architecture; Information Retrieval; Digital Collections; Scholarly Communication; Information

Behavior; Health Informatics; Human Computer Interaction; Usability Studies

Grants & Honors

Cultural Heritage Information Management Project. IMLS grant. Amount: $498,741. Period: Aug. 2012 to July 2015. Co-PI with Dr. Youngok Choi.

D.C. Health Information Technology (HIT4): Building Capacity & Providing Access in Our Nation's Capital. Dept. of Labor H2B Training Grant. Grant amount: $4,175,500. Grant period: Nov. 2011 to Dec. 2015. Partner with the Metropolitan School of Professional Studies of the Catholic University of America, Children's National Medical Center, D.C. Department of Employment Services, Holy Cross Hospital, Howard University, Center for Urban Progress, Providence Hospital, and Sibley Memorial Hospital.

Capital Health Careers Project. Department of Labor Healthcare Sector and Other High Growth and Emerging Industries Grant. Grant amount: $4,953,999. Grant period: March 2010 – February 2013. Awarded to a group of healthcare organizations and educational institutions in Washington, D.C. Providence Health Foundation of Providence Hospital (Lead institution). Part of the grant supported the development of a Master's degree program in Information Technology with a concentration in Health Information Technology offered by the School of Library and Information Science.

The Washington D.C. School Librarians Project. IMLS grant. Grant amount: $412,660. Grant period: Aug. 2007 – June 2011. The School partnered with the District of Columbia Public Schools (DCPS) and the District of Columbia Library Association to educate and mentor school media specialists for the DCPS system. PI, Jan. 2010 to June 2011.

SIG Member of the Year, American Society for Information Science and Technology (2009).

Most Outstanding Paper of *OCLC Systems & Services* (2001).

ALISE Research Grant (2001).

Most Outstanding Paper of *OCLC Systems & Services* (2000).

Research Grant from ERIC (1999-2000).

Best Research Paper Award; Association for Library and Information Science Education (1998).

Research Grants, Catholic University of America. 1991, 1992, 1993, 1996, 1998, 1999, 2004, 2005, 2006, 2007, 2013-14.

Cooperative Faculty Research Grant, Consortium of Universities in the Washington Metropolitan Area (1993-1994).

Cooperative Research Grant, Council on Library Resources (1993-1994).

Journal of the American Society for Information Science Best Paper Award (1993).

ASIS/ISI Information Science Doctoral Dissertation Scholarship (1989).

HEA Title IIB Fellowship (Dept. of Education) (1989)

Chinese-American Librarians Association Scholarship (1987).

Beta Phi Mu (1985).

Vilas Fellowship, University of Wisconsin-Madison. 1984

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Hsieh-Yee, I. (February, 2017) *Research Data Management: New Competencies and Opportunities for Information Professionals*. Presented at the 9th Bridging the Spectrum Symposium, Washington, D.C.

Hsieh-Yee, I. and Lawton, P. (February, 2017) *Enhancing Catholic Portal Searches with User Terms and LCSH*. Presented at the 9th Bridging the Spectrum Symposium, Washington, D.C.

Hsieh-Yee, I. (2016, October) *Visualizing Data for Information*. Presented at the 2016 Virginia Library Association Conference, Hot Springs, VA.

Hsieh-Yee, I. (2016, August) *Religious Materials Toolbox for Archivists: Solutions to Problems Facing the Profession*. Presented at Archives * Records 2016, Atlanta, GA.

Hsieh-Yee, I. and Lawton, P. (2016, March) *Enhancing Retrieval of Catholic Materials with LCSH Knowledge Structure*. Presented at the 2016 Catholic Library Association Conference, San Diego, CA.

Fagan-Fry, J. and Hsieh-Yee, I. (2016, February) *Approaches to Digital Scholarship at Top Universities around the World: Scholarly Publishing in the Digital Age.* Presented at the 8th Bridging the Spectrum Symposium, Washington, D.C.

Hsieh-Yee and Fagan-Fry, J. (2016, January) *Innovative Services for Digital Scholarship at Top 100 Research Libraries of the World*. Poster presented at the 2016 Annual Conference of the Association for Library and Information Science Education, Boston, Mass.

Hsieh-Yee, I. and Lawton, P. (2015, June). *Crowdsourcing terms for CRRA portal themes.* Poster presented at the third CRRA symposium and annual meeting, Bringing the created toward the Creator: Liturgical art and design since Vatican II. Catholic Theological Union, Chicago, Illinois.

Hsieh-Yee, I. and Lawton, P. (2015, February). *Crowdsourcing terms for thematic exploration in the Catholic Portal.* Poster presented at the 7th Annual Bridging the Spectrum Symposium, Washington, D.C.

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Wise, M., Cylke, K., and Hsieh-Yee, I. (2009, January). *Digital Talking Books: Meeting the Needs of the Blind and the Handicapped*. Paper presented at the Bridging the Spectrum Symposium, Catholic University of America, Washington, D.C.

Hsieh-Yee, I. (2009, January). *User Expectations of MERIC*. Presented at the Information Organization Competencies for the 21st Century Discussion Session of the 2009 Conference of the Association for Library and Information Science Education, Denver, Colorado.

Choi, Y., and Hsieh-Yee, I. (2008,November). *Subject Access for Images in an OPAC.* Annual Meeting of the American Society for Information Science and Technology, Columbus, Ohio. (Also co-organized a panel on Retrieving and Using Visual Resources: Challenges and Opportunities for Research and Education.)

Hsieh-Yee, I. (2008, June). *Educating Cataloging Professionals in a Changing Information Environment*. National Taiwan University, Taipei, Taiwan.

Vellucci, S. L., Moen, W.E., Hsieh-Yee, I., Marson, B., and Wisser, K. (2008, January) *Building a Metadata Education and Research Community through MERIC (Metadata Education and Research Information Commons): Demo and Stakeholder Input*. A panel presented at the 2008 Conference of the Association for Library and Information Science Education, Philadelphia, Pennsylvania.

Hsieh-Yee, I., Choi,Y. and Kules, B. (2007, October). *Searching for Books and Images in OPAC: Effects of LCSH, TOC and Subject Domains.* A poster presented at the American Society for Information Science and Technology Annual Meeting, Milwaukee, Wisconsin.

Hsieh-Yee, I. and Coogan, J. (2007, August) *Google Scholar vs. Academic Search Premier: A Comparative Analysis.* Presented to the Faculty and Staff of the University of the District of Columbia.

Hsieh-Yee, I. and Coogan, J. (2007, June). *Google Scholar vs. Academic Search Premier: A Comparative Analysis*. Presented to the Washington Research Library Consortium Community, Catholic University of America, Washington, D.C.

Hsieh-Yee, I., Choi, Y., and Kules, B.. (2007, June). *What Users Need for Subject Access: Table of Contents or Subject Headings?* A poster presented at the 2007 American Library Association Annual Conference, Washington, D.C., June 2007.

Choi, Y., Hsieh-Yee, I., and Kules, B. (2007, June). *Retrieval Effectiveness of TOC and LCSH.* A paper presented at the Joint Conference on Digital Libraries 2007, Vancouver, Canada.

Vellucci, S. L., Hsieh-Yee, I., and Moen, W.E. (2007, May). *If We Build It, Will They Come? Building a Community of Practice for Metadata Stakeholders.* A poster presented at the Rutgers University Research Day, Bridgeton, New Jersey.

Hsieh-Yee, I. (2007, May). *Federated Searching: User Experience & Perceptions.* International Conference on Information Organization & Retrieval, National Taiwan University, Taipei, Taiwan.

Hsieh-Yee, I. (2007, May). *Search Performance of Google Scholar and Academic Search Premier.* International Conference on Information Organization & Retrieval, National Taiwan University, Taipei, Taiwan.

Hsieh-Yee, I. (2007, May) *MERIC: Building a Digital Commons for Metadata Education & Research.* International Conference on Information Organization & Retrieval, National Taiwan University, Taipei, Taiwan.

Hsieh-Yee, I., and Coogan, J. (2007, March/April). *A Comparative Analysis of Google Scholar and Academic Search Premier.* Poster presented at the Association of College & Research Libraries 13th National Conference, Baltimore, Maryland.

Vellucci, S. L. and Hsieh-Yee, I. (2007, March/April) *They Didn't Teach Me That in Library School! Building a Digital Teaching Commons to Enhance Metadata Teaching, Learning and Research*. On-site presentation and Webcast by Elluminate. A contributed paper presented at the Association of College & Research Libraries 13th National Conference, Baltimore, Maryland. The acceptance rate for contributed paper was 20%. This paper was one of 10 conference papers chosen for live webcast during the conference.

Moen, W., Hsieh-Yee, I. and Vellucci, S.L. (2007, January) *A DSpace Foundation for a Teaching & Research Commons: The Metadata Education and Research Information Commons.* A poster session presented at the Open Repositories Conference 2007, San Antonio, Texas.

Tang, R., Hsieh-Yee, I., and Zhang, S. (2006, November) *User Perception of MetaLib Combined Search*. Paper presented at the Annual Meeting of the American Society for Information Science and Technology, Austin, Texas, Nov. 2006.

Hsieh-Yee, I. (2006, November). *Federated Searching: User Perceptions, System Design, and Library Instructions.* Paper presented at the Annual Meeting of the American Society for Information Science and Technology, Austin, Texas. (Panel organizer, moderator, presenter).

Hsieh-Yee, I. (2006, November). *Building a Digital Teaching Commons to Enhance Teaching and Learning: The MERIC Experience and Challenges.* Paper presented at the Annual Meeting of the American Society for Information Science and Technology, Austin, Texas. (Panel organizer, moderator, presenter)

Hsieh-Yee, I. (2006, September). *Search Performance of Google Scholar and Academic Search Premier.* Paper presented at the ERIC Publishers Meeting, Washington, D.C.

Hsieh-Yee, I., Zhang, S., and Rong Tang, R. (2006, June). *User Perceptions of a Federated Search System*. Poster presented at Joint Conference on Digital Libraries, Chapel Hill, North Carolina.

Hsieh-Yee, I. and Zhang, S. (2006, June). *Preparing Users for Federated Search: Implications of a MetaLib User Perceptions Study.* Paper presented at the 2006 Ex Libris User Groups of North America Conference, Knoxville, Tennessee.

Hsieh-Yee, I. (2006, January). *MERIC Organizations and Navigation*. Paper presented at the 2006 ALISE Annual Conference, San Antonio, Texas.

Hsieh-Yee, I. (2006, January). *Metadata and Cataloging Education: Recommended Competencies.* Paper presented at the 2006 ALISE Annual Conference, San Antonio, Texas.

Hsieh-Yee, I. (2005, November). *Digital Library Evaluation: Progress & Next Steps.* Presentation at the Annual Meeting of the American Society for Information Science & Technology, Charlotte, North Carolina.

Hsieh-Yee, I. (2005, August). *Providing Access to Digital Content: Issues for DL Managers.* Presentation at MDK12 Digital Library Steering Committee Meeting, Columbia, Maryland.

Hsieh-Yee, I. (2005, April). *Enhancing Teaching and Learning: The Role of School Library Media Specialists.* Presentation at Meeting of the Baltimore County Public School System School Media Specialists, Baltimore, Maryland.

Hsieh-Yee, I. (2005, January). *Subject Access and Users: Insights & Inspirations from Marcia J. Bates.* Paper presented at the Historical Perspectives SIG, 2005 Conference of the Association for Library and Information Science Education, Boston, Massachusetts.

Hsieh-Yee, I. (2005, January). *Electronic Resource Management: Practice, Employer Expectations, & CE Interests.* Paper presented at Technical Services Education SIG, 2005 Conference of the Association for Library and Information Science Education, Boston, Massachusetts.

Hsieh-Yee, I. (2004, October). *Library Professionals for the Digital Age: Competencies & Preparation.* Paper presented at Bibliographic Access Management Team meeting, Library of Congress, Washington, D.C.

Hsieh-Yee, I. (2004, January). *Cataloging and metadata expertise for the digital era.* Presented at Preparing 21st Century Cataloging and Metadata Professionals: A Workshop for Educators and Trainers, San Diego and sponsored by ALCTS, ALISE, LC, and OCLC.

Hsieh-Yee, I. (2004, January). *Educating catalogers for the digital era.* Paper presented at the Technical Services SIG, 2004 Conference of the Association for Library and Information Science Education, San Diego.

Hsieh-Yee, I. (2003, July). *Cataloging Education for the 21st Century.* A presentation at the Library of Congress, Washington, D.C.

Hsieh-Yee, I. (2002, January) *Metadata Education and Research Priorities: A Delphi Study of*

Metadata Experts. Presentation at the 2002 Conference of the Association for Library and Information Science Education, New Orleans.

Hsieh-Yee, I. (2001, November). *A Delphi Study of Metadata: Preliminary Findings.* Poster session at the 2001 Annual Meeting of the American Society for Information Science & Technology, Washington, D.C.

Hsieh-Yee, I. (2001, June). *Resources on Asian American Children: Analysis of Retrieval by Search Engines and WorldCat.* Presentation at the National Conference on Asian Pacific American Librarians, San Francisco.

Hsieh-Yee, I. (2001, January). *Delphi Study on Metadata: Project Design.* Presentation at Research Awards Session, Association for Library & Information Science Education, Washington, D.C.

Hsieh-Yee, I. (2000, May). *Web Search Behavior Research: Progress and Implications.* Presentation at the Symposium on Evaluating Library and Information Science Research, University of Wisconsin-Madison, Madison, Wisconsin.

Hsieh-Yee, I. (2000, March). *ERIC User Services: Evaluation in a Decentralized Environment.* Presentation at the National ERIC Joint Directors/Technical Meeting, Arlington, Virginia.

Hsieh-Yee, I. (2000, January). *Enhancing Learning with Web Technology.* Presentation at Faculty Conversations, Catholic University of America, Washington, D.C.

Hsieh-Yee, I. (2000, January). *From Surrogates to Objects: CUA's Approaches to Organizing Electronic Resources.* Paper presentation at the Annual Conference of the Association for Library and Information Science Education, San Antonio, Texas.

Yee, P., and Hsieh-Yee, I. (1997, November). *Individual Differences in Search Behavior on the WWW.* A poster session presented at the 38th Annual Meeting of the Psychonomic Society, Philadelphia, Pennsylvania.

Hsieh-Yee, I. (1997, April). *Research + Marketing + Preparation = Job!* Presented at the "Workshop on Resume and Interview Techniques," Special Libraries Association, Student Chapter, Catholic University of America, Washington, D.C.

Hsieh-Yee, I. (1997, February). *Creating CyberCatalogers: Education and Training.* Presentation at ALA's Midwinter Meeting, Washington, D.C.

Hsieh-Yee, I. (1997, February). *Search Tactics of Web Users in Searching for Texts, Graphics, Known Items and Subjects: A Search Simulation Study.* Presented at the Conference of the Association for Library and Information Science Education, Washington, D.C.

Hsieh-Yee, Ingrid. "Beginning Your Special Library/Information Center Career." Presented at SLA's "Career Day," Jan. 11, 1997, Catholic University of America.

Hsieh-Yee, I. (1996, September). *The Roles of Library and Information Scientists in Managing Electronic Information.* Presentation at Hamilton College, Clinton, New York.

Hsieh-Yee, I. (1996, May). *The Future of Cataloging as a Profession.* Presented at "The Cataloging Forum, Library of Congress, Washington, D.C.

Hsieh-Yee, I. (1994, October). *The Impact of the Internet on OPACs.* Presented at the Third Workshop on User Interfaces for OPACs, Library of Congress, Washington, D.C.

Reports

Hsieh-Yee, I., with Knowledge Management Competencies and Performance Action Group of the Federal Knowledge Management Initiative. "From Knowledge Management Competencies to Improved Organizational Performance." April 9, 2009.

Hsieh-Yee, I., with Knowledge Practices Action Group of the Federal Knowledge Management Initiative. "KM Practice in Government Agencies: Findings and Recommendations." April 9, 2009.

Hsieh-Yee, I. "Delphi Study on Metadata." 2001. Three quarterly reports submitted to the Association for Library and Information Science Education.

Hsieh-Yee, I. "College Students' Information Channels: Patterns of Use and Possible Factors in Channel Selection." 1995. Submitted to the Catholic University of America.

Hsieh-Yee, I. "The Information-Seeking Patterns of Scholars and Their Use of an Online Information System." 1994. Submitted to the Council on Library Resources.

Book Reviews

Review of *The Measurement and Evaluation of Library Services*, by Sharon L. Baker and F. Wilfrid Lancaster. *Information Processing and Management* 30 (1994): 450-52.

Review of *Subject Access to Films and Videos, by Sheila S. Intner and William E. Studwell; and Cataloging Unpublished Nonprint Materials*, by Verna Urbanski with Bao Chu Chang and Bernard L. Karon. *Information Processing and Management* 30 (1994): 449-50.

Review of *Automated Information Retrieval in Libraries: A Management Handbook*, by Vicki Anders. *Journal of Library and Information Science* 19 (1993): 98-100.

Review of *Full Text Databases*, by Carol Tenopir and Jung Soon Ro. *Information Processing and Management* 28 (1992): 667-68.

Review of *Descriptive Cataloging for the AACR2R And USMARC: A How-to-Do It Workbook*, by Larry Millsap and Terry Ellen Ferl. *Information Processing and Management* 28 (1992): 809-11.

Review of *MARC Manual: Understanding and Using MARC Records*, by Deborah J. Byrne. *Information Processing and Management* 28 (1992): 537-38.

Service

Professional Associations and Societies

- Library of Congress. RDA Training Program for the Profession. Co-authored with Tim Carlton. 2013-2014.
- 2014 Digital Preservation Outreach & Education Survey. Contributed to the design of the survey, 2014.
- National Digital Stewardship Alliance. Outreach Committee. 2011-2014.
- National Digital Stewardship Residency Program. Advisory Group, 2012-2013.
- FEDLINK Health Information Technology Advisory Council, 2011-2015.
- 2012 Joint Conference on Digital Libraries. Program Planning Committee, Pre-Conference Proposals Review Committee, 2012
- Catholic Research Resources Alliance. Five-Year Strategic Plan Task Force, 2011-2012
- Institute of Museum and Library Services. Grant reviewer. 2004, 2005, 2010.

- Association for Library and Information Science Education.
  * ALISE Bodan Wynar Research Paper Award Committee, 2015, 2016, 2017
  * ALISE Eugene Garfield Dissertation Award Competition, Jury, 2013, 2014
  * ALISE Research Grant Competition Committee. Chair, 2012
  * Pratt-Severn Faculty Innovation Award. Chair, 2009, 2010
  * ALISE Doctoral Poster Jury, 2012
  * "Information Organization Competencies for the 21st Century" Discussion session leader. 2009 Conference of the Association for Library and Information Science Education.
  * Assisted Technical Services SIG Convener in organizing a program, ""Building a Metadata Education and Research Community through MERIC (Metadata Education and Research Information Commons): Demo and Stakeholder Input" for the 2008 ALISE conference.
  * Association for Library Collections and Technical Services/Association for Library and Information Science Education (ALCTS/ALISE) Metadata Education and Research Information Center (MERIC) Advisory Board, Co-Chair (with Sherry Vellucci), 2005-2007. Chair, 2008-2009 (leading the effort to build MERIC, a repository and collaborative space for metadata educators, practitioners, and researchers)

* Technical Services SIG, Convener, 2004-2005. Organized a program on "Electronic Resources Management: Current Practices, Employer Expectations, and Teaching Strategies" for the 2005 conference in Boston, Massachusetts.
* Technical Services SIG, Convener, 2003-2004. Organized a program on "Organizing Information with Metadata: Desired Competencies and Teaching Innovations" for the 2004 conference.
* Technical Services SIG, Convener, 1999-2000. Organized a program on "Teaching the Organization of Electronic Resources" for the 2000 conference.
* Curriculum SIG, Co-convener (with Sibyl Moses), 1996-97. Organized a program on "Government Information Policy" for the 1997 conference.

- American Society for Information Science & Technology.
  * Reviewer, Conference program panel submissions and poster submissions, 2005, 2006, 2007, 2009, 2011, 2012, 2013, 2014, 2015, 2016, 2017
  * Nomination Committee, 2009-2011
  * Information Science Education Special Interest Group. American Society for Information Science and Technology. Chair-Elect, 2007-2008. Chair 2008-2009.
  * Committee on Information Science Education. 1999-2006.
  * Committee on Information Science Education. Organizing Committee for an orientation program for students at ASIS annual meetings, 1999-2001
  * Committee on Information Science Education. Sub-committee on Student Welfare (focusing on issues related to master's education), 1998-2001
  * SIG ED. Organizing Committee for the "Seminar on Research and Career Development" for junior researchers. 1995-96 (chair), 1997-2001
  * ISI Doctoral Dissertation Proposal Scholarship Jury, 1997; 2001, 2002
  * Pratt-Severn Best Student Research Paper Award Jury. Chair. 1997
  * 1998 Midyear Meeting (referee of contributed papers), 1997
  * Organizer and moderator of the ASIS Doctoral Forum and the Doctoral Research Seminar 1994-1995
  * SIG Human Computer Interaction. Chair-Elect, Chair, 1993-1995
  * Doctoral Forum Award Jury, 1995
  * Best Student Paper Award Jury, 1995

- American Library Association.
  * Committee on Accreditation, External Review Panelist, 2009- (site visiting team 2013-2014; site visiting team 2016-2017)
  * Association for Library Collections and Technical Services Task Force on Competencies and Education for a Career in Cataloging, member, 2008-2009
  * Facilitator for "What They Don't Teach in Library School: Competencies, Education and Employer Expectations for a Career in Cataloging," an Association for Library Collections and Technical Services Preconference, June 22, 2007 in Washington, D.C. Also a local liaison for bringing this program to the Catholic University of America.
  * Facilitator for a discussion on "Effect of Electronic Resources on Technical Services" at ALA's Midwinter Meeting held in Feb. 1997 in Washington, D.C.

* International Relations Committee, Subcommittee Task Force for IFLA and China, 1994-1997

- Virginia Association of School Librarians. Scholarships and Awards Committee. 2010-2012

- Federal Knowledge Management Initiative, Knowledge Management Practices Action Group. Member. 2009 (leading the effort to build a knowledge management repository)
- Federal Knowledge Management Initiative, Knowledge Management Competencies & Learning Action Group. Member. 2009 (developing an action plan for helping government knowledge workers and government agencies to develop knowledge management competencies)
- National Center for Education Statistics. Technical Review Panel. 2008.
- External evaluator for a case of promotion to full professorship. University of Tennessee. 2008.
- National Information Standards Organization (NISO). Advisory Board, Revision of "IMLS Framework of Guidance for Building Good Digital Collections," 2004, 2007.
- Library of Congress, Bibliographic Control of Web Resources: A Library of Congress Action Plan. Principal Investigator of Action Item 5.1, focusing on cataloging and metadata education for students and new librarians, 2002-2003. (worked with the Association for Library Collections and Technical Services, Education Task Force)

- Chinese American Librarians Association
  * Chinese American Librarians Association Outstanding Library Leadership Award in Memory of Dr. Margaret Chang Fung, Award Committee, 2016-2017
  * Achievement Award Jury, 2000-2001
  * CALA Goal 2000 Task Force, 1997
  * Scholarship Committee, 1995, 1996-1997 (chair)
  * Board of Directors, 1994-1997
  * Publication Committee, 1993-1995
  * International Relations Committee, 1993-1996

- Sailor^{SM} Assessment Advisory Group (An impact study of Sailor, Maryland's Public Information Network), 1995

- Editorial boards
  Journal of Library and Information Science. Editorial Board, 2012-
  Chinese American Librarians Association, *Occasional Papers Series*. Editorial Board, 2009-2016.
  Library Quarterly. Editorial Board, 2003-2008
  Bulletin of the Medical Library Association, 1994-97
  Newsletter editor for the Chinese American Librarians Association, 1989-92

- Referee for the following journals
  Information Processing and Management

Journal of Digital Information
Journal of Education for Library and Information Science
Journal of Information Science
Journal of Library & Information Science
Journal of Library Metadata
Journal of the American Society for Information Science & Technology
Library and Information Science Research
Library Quarterly

- Expert reviewer, “Digital Library” course, Evaluation module, University of North Carolina, Chapel Hill, 2007-2008.
- Expert reviewer, “Information Organization” course, University of Michigan, Ann Arbor. 2007.

Catholic University of America

- School of Arts & Sciences, Academic Senate representative, 2017-2020
- School of Arts & Sciences, Committee on Appointments and Promotions, 2015-2019
- School of Arts & Sciences, Academic Council, 2015-2016.
- School of Arts & Sciences, Ordinary Professor Group, 2013-
- Doctoral Dissertation Defense Committee, Chair, Dept. of Psychology, 2016, 2017, 2018
- Doctoral Dissertation Defense Committee, Chair, Dept. of Education, 2014, 2015, 2017
- President’s Administrative Council, 2010-2012
- Deans’ Council, 2010-2012
- Academic Leadership Group, 2010-2012
- Academic Senate, 2003-2012
- Academic Senate, Committee on Committees and Rules, 2009-2012
- Academic Senate, Committee on Appointments and Promotions, 2005-2008
- Graduate Board, 2010-2012
- CUA Scholarly Communication Project Team, Member (2007), Chair, 2008-2009
- Academic Senate Library Committee, Interim Chair (2007), Member, 2008-2012
- Doctoral Dissertation Defense Committee, Chair, School of Nursing, 2006, 2008
- Dean Search Committee, 1992-1994, 1998-1999, 2002-2003, 2006-2007
- Fulbright Review Panel, 2006
- Academic Senate Committee on Computing, 1995-2003
- CUA Service Learning Advisory Board, 2001-2002
- CUA Faculty Conversations on Enhancing Teaching and Learning through Technology, Planning Group, 1999-2001
- CUA Initiative on Technology and Teaching, 1998-2001

Dept. of Library and Information Science

- Symposium and Colloquium Committee, fall 2016-May 2018, Chair, May 2018-

- Admissions Committee, 2007-2009, Chair 2010-2012, Member 2013-2015, Member 2018-
- Accreditation presentation, Chair, June 2015-August 2016
- Interim Co-Chair, June 2015-August 2016.
- Appointments and Promotions Committee, 1991-
- Blended/OWL Learning Committee, spring 2016-2018
- Scholarship and Awards Committee, fall 2016-
- Technology Committee, fall 2016-2017
- Comprehensive examination editor, 2016-2017, reader (every year since 1990)
- LIS Advisory Board, 2015-2016 (chair); fall 2016- May 2018 (member)
- Committee on Planning and Assessment, 2015-2016 (chair)
- Senior Faculty Committee, 2014-2016.
- Accreditation Steering Committee, 2014-2016 (Chair, 2015-2016)
- Accreditation Students Standard Committee, co-chair, 2014-2016
- Accreditation Mission, Goals, and Objectives Standard Committee, co-chair, 2014-2016
- Accreditation Curriculum Standard, member 2014-2-16
- Accreditation Administration and Finance Standard, member 2014-2016
- Cultural Heritage Information Management Project (IMLS-funded), Co-PI, 2012-2015
- Cultural Heritage Information Management Forum (scheduled for June 2015), Co-Organizer, 2013-2015
- Health Information Technology Interim Review Committee, 2015 (chair)
- Health Sciences Librarianship Advisory Group, 2015- (chair)
- Comprehensive examination editors, 2013-2014, 2016-2017
- National Digital Stewardship Alliance liaison, 2011-2014
- Advisory Board, Chair 2010-2012
- Academic Honesty Committee, Chair, 2008-2012
- Blended Learning Committee, 2010-2012
- Colloquium Committee, 2010-2012
- Comprehensive Examination Administration, 2010-2012
- Cultural Heritage Information Management Advisory Committee, 2010-2012 (chair), 2013-
- Curriculum Committee, 1991-2003, 2007-2009, Chair 2010-2012, member 2013-
- Curriculum Subcommittee on Comprehensive Examination, Chair 2009-2012
- Health Information Technology Advisory Board, Chair 2010-2012. Member 2013-
- Health Sciences Advisory Committee, 2009, Chair 2010-2012. Member 2013-
- HIT Expert Forum, Chair 2012. Member 2013-
- Health Information Technology Student Group Advisor, 2011-2012
- State Council for Higher Education of Virginia, SLIS Representative, 2010-2012
- Symposium Planning Committee, 2010-2012
- Website Management Team, Chair, 2010-2012
- Urban School Librarianship Project (IMLS-Funded), PI, 2007-2011 (chair, 2010-11)
- Failing Grades Committee, 1995-1997 (chair), 2000-2001 (chair), 2004-2005 (chair), 2007 (chair)-2011

- Faculty Search Committee, 1994-1998, 2002-2004, 2006 (chair), Fall 2007-2009, Chair fall 2009-2012
- Recruitment Committee, Chair 2010-2012
- Strategic Planning Committee, Chair 2010-2012
- Technology Committee, 2010-2012
- Accreditation Advisory Committee, 2007-2009
- Accreditation Coordinating Committee, 2007-2009
- Accreditation Steering Committee, 2007-2009
- SLIS Advisory Group, 2007-2009
- Accreditation Curriculum Standard Committee, Co-chair, 2007-2009
- Accreditation Faculty Standard Committee, Co-chair, 2007-2009
- LSC 551 Information Organization Review Team, Co-chair, 2008-2009, 2015-2016.
- Curriculum Subcommittee on Portfolios, 2009
- LSC 555 Information Systems in Libraries and Information Centers Review Team, contributor, 2008-2009
- Redesign of LSC 730 Use and Users of Libraries and Information. 2009-
- Development of a metadata institute that was taught as LSC 715 Organization of Internet Resources in 2008. The institute is being revised and will be offered in 2010 under a new course title.
- Development of lesson plans, assignments, and evaluation rubrics for LSC 606, Cataloging and Classification, for the School's NCATE accreditation. 2008
- Howard and Mathilde Rovelstad Scholarship Committee, Chair, 2004-2007
- Assistant Dean Search Committee, Chair, Fall 2007
- Liaison to the Association for Library Collections and Technical Services to bring its preconference program, Cataloging Education and Employer Expectations, to CUA during the 2007 American Library Association Annual Meeting in Washington, D.C.
- Organizer of the colloquium presentation and reception for Tamar Sadeh of Ex Libris on PRIMO June 2007
- Practicum review and design (work with potential supervisors, such as the American Indian Museum internship description revision) 2006-
- Comprehensive examinations (edits, proctoring, and grading), 1990-
- SLIS Web site redesign: Comments and suggestions. Fall 2007
- Conducted surveys of current students and alumni in preparation for the 2005 re-accreditation, 2004-2005
- Student advisement, 1990-
- Technology Committee, 1992-1999 (chair, 1996-1998), 2002-2003 (member)
- Colloquia Committee 1997-1999, 2002-2003.
- Advisor of the CUA Student Chapter of the American Society for Information Science and Technology, 2002-2003
- Visiting Professor Search Committee, 1999, 2000, 2001
- Leader, Participation in the CORC experiment, 1999-2000
- Advisor of the Special Libraries Association Student Chapter, 1993-1999; the group was recognized for outstanding leadership by SLA in 1999.

- COA planning Committee, Task Force on Electronic Presentation of SLIS Reports (team leader) 1997-1998
- COA Planning Committee, Subcommittee on Technology 1996-1998
- NLM practicum coordinator, 1997-1998
- Computer Literacy Workshops: Assisted with the development and evaluation of the workshops, 1996-1998
- Leader, Participation in the InterCat project, 1995-1997

APPENDIX B

MARC 21 Reference Materials

Part VII:

A Summary of Commonly Used MARC 21 Fields

This is a summary of the MARC 21 tags used most frequently by libraries in entering their own bibliographic records. For full listings of all MARC 21 tags, indicators, and subfield codes, see *MARC 21 Format for Bibliographic Data*.

In the explanations on these pages:

Tags -- The tags (3-digit numbers) are followed by the names of the fields they represent. In this summary, and in the *MARC 21 Format for Bibliographic Data*, if a tag can appear more than once in one bibliographic record, it is labeled repeatable (R). If it can only be used once, it is labeled non-repeatable (NR). For example, a catalog record can have several subjects, so the tags for subject added entries (6XX) are labeled repeatable (R).

Indicators -- The use of indicators is explained in fields where they are used. Indicators are one-digit numbers. Beginning with the 010 field, in every field -- following the tag -- are two character positions, one for Indicator 1 and one for Indicator 2. The indicators are not actually defined in all fields, however. And it is possible that a 2nd indicator will be used, while the 1st indicator remains undefined (or vice versa). When an indicator is undefined, the character position will be represented by the character # (for blank space).

Subfield codes -- All the data in each field (beginning with the 010 field) is divided into subfields, each of which is preceded by a delimiter-subfield code combination. The most common subfield codes used with each tag are shown. Each subfield code is preceded by the character $, signifying a delimiter. The name of the subfield follows the code.

In general, every field MUST have a subfield 'a' (**$a**). One exception that is often seen is in Field 020 (ISBN), when the ISBN information (subfield **$a**) is unavailable but the price (subfield **$c**) is known. Some subfields are repeatable. In this summary, repeatability is noted for only the more common repeatable subfields.

Examples: Examples follow the explanation for each field. For clarity, one space has been placed between the tag and the first indicator, one space has been placed between the second indicator and the first delimiter- subfield code, and one space has been inserted between the delimiter-subfield code and the subfield data.

010 Library of Congress Control Number -- (LCCN)
(NR, or Not Repeatable

Indicators undefined.
Subfield used most often:
$a -- Library of Congress control number

```
Example:    010 ##  $a ###86000988#
```

020 International Standard Book Number -- (ISBN)
(R, or Repeatable)

Indicators undefined.
Subfields used most often:
$a -- International Standard Book Number
$c -- Terms of availability (often a price)
$z -- Cancelled/invalid ISBN (R)

```
Example:    020 ##  $a 0877547637
```

040 Cataloging source -- (NR)

Indicators undefined.
Subfields used most often:
$a -- Original cataloging agency
$c -- Transcribing agency
$d -- Modifying agency (R)

```
Example:    040 ## $a DLC
                   $c DLC
                   $d gwhs
```

100 Main entry -- Personal name -- (primary author)
(NR; there can be only one main entry)

Indicator 1: Type of personal name entry element
- 0 -- Forename
- 1 -- Surname (this is the most common form)
- 3 -- Family name

Indicator 2 undefined.
Indicator 2 became obsolete in 1990. Older records may display 0 or 1

Subfields used most often:
- **$a** -- Personal name
- **$b** -- Numeration
- **$c** -- Titles and other words associated with a name (R)
- **$q** -- Fuller form of name
- **$d** -- Dates associated with a name (generally, year of birth)

```
Example:    100 1# $a Gregory, Ruth W.
                   $q (Ruth Wilhelme),
                   $d 1910-
```

130 Main entry -- Uniform title -- (NR)

Indicator 1: Nonfiling characters
- 0-9 -- Number of nonfiling characters present (for initial articles, including spaces)

Indicator 2 undefined.
Indicator 2 became obsolete in 1990. (See 100 above.)

Subfields used most often:
- **$a** -- Uniform title
- **$p** -- Name of part/section of a work (R)
- **$l** -- Language of a work
- **$s** -- Version
- **$f** -- Date of a work

```
Example:    130 0# $a Bible.
                   $p O.T.
                   $p Psalms.
```

240 Uniform title (NR)

Indicator 1: Uniform title printed or displayed
- 0 -- Not printed or displayed
- 1 -- Printed or displayed (most common)

Indicator 2: Nonfiling characters

0-9 -- Number of nonfiling characters present (for initial articles, including spaces)

Subfields used most often:

$a -- Uniform title
$l -- Language of a work
$f -- Date of a work

```
Example:    240 10 $a Ile mystérieuse.
                   $l English.
                   $f 1978
```

245 Title Statement (NR)

Indicator 1: Title added entry

(Should the title be indexed as a title added entry?)

0 -- No title added entry

(indicates a title main entry; i.e. no author is given)

1 -- Title added entry

(the proper indicator when an author given in 1XX; the most common situation)

Indicator 2: Nonfiling characters

0-9 -- Number of nonfiling characters present, including spaces; usually set at zero, except when the title begins with an article; e.g., for *The robe*, the second indicator would be set to 4. The letters *T*, *h*, *e*, and the space following them are then ignored in alphabetizing titles. The record will be automatically filed under "*r*" -- for *Robe*.

Subfields used most often:

$a -- Title proper
$h -- Medium (often used for non-book media)
$p -- Name of part/section of a work (R)
$b -- Reminder of title (subtitles, etc.)
$c -- Remainder of title page transcription/Statement of responsibility

```
Example:    245 14 $a The DNA story :
                   $b a documentary history of gene
                      cloning /
                   $c James D. Watson, John Tooze.
```

246 Varying form of title (R)

Indicator 1: Note/title added entry controller
1 -- Note, title added entry
3 -- No note, title added entry
Indicator 2: Type of title
-- No information provided
0 -- Portion of title
1 -- Parallel title
4 -- Cover title
8 -- Spine title
Subfield used most often:
$a -- Title proper

```
Example:    246 3# $a Four corners power review
```

250 Edition statement (NR)

Indicators undefined.
Subfield used most often:
$a -- Edition statement

```
Example:    250 ## $a 6th ed.
```

260 Publication, distribution, etc. (Imprint) (R)

Indicator 1: Sequence of publishing statements
-- No information provided
Indicator 2: Undefined
Subfields used most often:
$a -- Place of publication, distribution, etc. (R)
$b -- Name of publisher, distributor, etc. (R)
$c -- Date of publication, distribution, etc. (R)

```
Example:    260 ## $a New York :
                   $b Chelsea House,
                   $c 1986.
```

300 Physical description (R)

Indicators undefined.
Subfields used most often:

$a -- Extent (number of pages) (R)
$b -- Other physical details (usually illustration information)
$c -- Dimensions (cm.) (R)
$e -- Accompanying material (for example, "teacher's guide" or "manual")

```
Example:    300 ## $a 139 p. :
                   $b ill. ;
                   $c 24 cm.
```

440 Series statement / Added entry--Title

This field was made obsolete in 2008 to simplify the series statement. See 490 and 830.

490 Series statement (No added entry is traced from field) (R)

Indicator 1: Specifies whether series is traced (whether an 8XX tag is also present)

0 -- Series not traced
1 -- Series traced (8XX is in record)

Indicator 2 undefined.
Subfield used most often:

$a -- Series statement (R)
$v -- Volume number (R)

```
Example:    490 1# $a Colonial American craftsmen
```

500 General note (R)

Indicators undefined.
Subfield used most often:

$a -- General note (Used when no specialized note field has been defined for the information. Examples: Notes regarding the index; the source of the title; variations in title; descriptions of the nature, form, or scope of the item.)

```
Example:    500 ##  $a Includes index.
```

504 Bibliography, etc. note (R)

Indicators undefined.
Subfield used most often:
$a -- Bibliography, etc. note

```
Example:    504 ## $a Includes bibliographical
                  references.
```

505 Formatted contents note (R)

Indicator 1: Type of contents note
0 -- Complete contents
1 -- Incomplete contents (used with multivolume set when some volumes are not yet published)
2 -- Partial contents
Indicator 2: Level of content designation
-- Basic
Subfield used most often:
$a -- Formatted contents note

```
Example:    505 0# $a Pride and prejudice -- Emma
                  -- Northanger Abbey.
```

520 Summary, etc. note (R)

Indicator 1: Display constant controller
-- Summary
1 -- Review
2 -- Scope and content
3 -- Abstract
Indicator 2 undefined
Subfields used most often
$a -- Summary, abstract, or annotation
$b -- Expansion of summary note

```
Example:    520 ## $a This basic guide to parliamentary
                  procedure tells how to conduct
                  and participate in a meeting
                  properly.
```

600 Subject added entry -- Personal name (R)

Indicator 1: Type of personal name entry element
- 0 -- Forename
- 1 -- Surname (this is the most common form)
- 3 -- Family name

Indicator 2: Subject heading system/thesaurus (identifies the specific list or file which was used)
- 0 -- Library of Congress Subject Headings
- 1 -- LC subject headings for children's literature
- 2 -- Medical Subject Headings
- 3 -- National Agricultural Library subject authority file
- 4 -- Source not specified
- 5 -- Canadian Subject Headings
- 6 -- Répertoire de vedettes-matière
- 7 -- Source specified in subfield $2

(Note regarding Sears subject headings: The MARC 21 format does not provide an assigned indicator for Sears subject headings. Therefore, an indicator of 7 is used, and the MARC defined code "sears" is placed in subfield $2.)

Subfields used most often:
- **$a** -- Personal name (surname and forename)
- **$b** -- Numeration
- **$c** -- Titles and other words associated with a name (R)
- **$q** -- Fuller form of name
- **$d** -- Dates associated with a name (generally, year of birth)
- **$t** -- Title of a work
- **$v** -- Form subdivision (R)
- **$x** -- General subdivision (R)
- **$y** -- Chronological subdivision (R)
- **$z** -- Geographic subdivision (R)
- **$2** -- Source of heading or term (used with 2nd indicator of 7)

```
Example:    600 10 $a Shakespeare, William,
                   $d 1564-1616
                   $x Comedies
                   $x Stage history.
```

```
Example:    600 10 $a Shakespeare, William,
                   $d 1564-1616
                   $x Knowledge
```

```
                 $z Rome
                 $v Congresses.
```

Notice that subfields $v, $x, and $z in the 600 field are repeatable. Subfields $v, $x, $y, and $z do not have to be in alphabetical order. They will be in the order prescribed by the instructions given by the subject heading system.

610 Subject added entry -- Corporate name (R)

Indicator 1: Type of corporate name entry element
- 0 -- Inverted name (not used with AACR2)
- 1 -- Jurisdiction name
- 2 -- Name in direct order

Indicator 2: Subject heading system/thesaurus.
- See indicator 2 under 600

Subfields used most often:
- **$a** -- Corporate name or jurisdiction name as entry element
- **$b** -- Subordinate unit (R)
- **$v** -- Form subdivision (R)
- **$x** -- General subdivision (R)
- **$y** -- Chronological subdivision (R)
- **$z** -- Geographic subdivision (R)
- **$2** -- Source of heading or term (used with 2nd indicator of 7)

```
Example:    610 10 $a United States.
                   $b Army Air Forces
                   $v Biography.
```

650 Subject added entry -- Topical term (Most subject headings fit here.) (R)

Indicator 1: Level of subject
- # -- No information provided

Indicator 2: Subject heading system/thesaurus
(identifies the specific list or file which was used)
- 0 -- Library of Congress Subject Headings
- 1 -- LC subject headings for children's literature
- 2 -- Medical Subject Headings
- 3 -- National Agricultural Library subject authority file
- 4 -- Source not specified
- 5 -- Canadian Subject Headings
- 6 -- Répertoire de vedettes-matière
- 7 -- Source specified in subfield $2

Note regarding Sears subject headings: The MARC 21 format does not provide an assigned indicator for Sears subject headings. Therefore, an indicator of 7 is used, and the MARC defined code "sears" is placed in subfield $2.)

Subfields used most often:
$a -- Topical term
$v -- Form subdivision (R)
$x -- General subdivision (R)
$y -- Chronological subdivision (R)
$z -- Geographic subdivision (R)
$2 -- Source of heading or term used with 2nd indicator of 7)

```
Example:    650 #0 $a Theater
                   $z United States
                   $v Biography
                   $v Dictionaries.
```

Notice that subfields $v, $x, and $z in the 650 field are repeatable. Subfields $v, $x, $y, and $z do not have to be in alphabetical order. They will be in the order prescribed by the instructions given by the subject heading system.

651 Subject added entry -- Geographic name (R)

Indicator 1: undefined.
Indicator 2: Subject heading system/thesaurus.
See indicator 2 under 600
Subfields used most often:
$a -- Geographic name
$v -- Form subdivision (R)
$x -- General subdivision (R)
$y -- Chronological subdivision (R)
$z -- Geographic subdivision (R)
$2 -- Source of heading or term (used with 2nd indicator of 7)

```
Example:    651 #0 $a United States
                   $x History
                   $v Chronology.
```

Notice that subfields $v, $x, and $z in the 651 field are repeatable. Subfields $v, $x, $y, and $z do not have to be in alphabetical order. They will be in the order prescribed by the instructions given by the subject heading system.

700 Added entry -- Personal name (R)

Indicator 1: Type of personal name entry element
- 0 -- Forename
- 1 -- Surname (this is the most common form)
- 3 -- Family name

Indicator 2: Type of added entry
- # -- No information provided (most common; co-authors, editors, etc.)
- 2 -- Analytical entry (The values for Indicator 2 changed in 1994 with Format Integration, and older records may display additional values. An analytical entry involves an author/title of an item contained in a work.)

Subfields used most often:
- **$a** -- Personal name
- **$b** -- Numeration
- **$c** -- Titles and other words associated with a name (R)
- **$q** -- Fuller form of name
- **$d** -- Dates associated with a name (generally, year of birth)
- **$e** -- Relator term (such as ill.) (R)
- **$4** -- Relator code (R)

Example: `700 1# $a Baldridge, Letitia.`

710 Added entry -- Corporate name (R)

Indicator 1: Type of corporate name entry element
- 0 -- Inverted name (not used with AACR2)
- 1 -- Jurisdiction name
- 2 -- Name in direct order

Indicator 2: Type of added entry.
See Indicator 2 under 700
- # -- No information provided
- 2 -- Analytical entry

Subfields used most often:
- **$a** -- Corporate name or jurisdiction name as entry element
- **$b** -- Subordinate unit (R)

Example: `710 2# $a Sunburst Communications (Firm)`

740 Added entry -- Uncontrolled related/analytical title (R)

Indicator 1: Nonfiling characters

0-9 -- Number of nonfiling characters present (for initial articles, including spaces)

*Indicator 2:*Type of added entry. See Indicator 2 under 700

-- No information provided

2 -- Analytical entry

(This field was redefined in 1994 with Format Integration. Prior to 1994, the field was also used for variant titles, such as a different wording on a spine title. In records created since Format Integration, those variant tiles appear in a 246 field.)

Subfield used most often:

$a -- Title

```
Example:    740 02 $a Uncle Vanya.
```

800 Series added entry -- Personal name (R)

Indicator 1: Type of personal name entry element

0 -- Forename

1 -- Surname

3 -- Family name

Indicator 2 undefined.

Subfields used most often:

$a -- Personal name

$b -- Numeration

$c -- Titles and other words associated with a name (R)

$q -- Fuller form of name

$d -- Dates associated with a name (generally, year of birth)

$t -- Title of a work (the series)

$v -- Volume number

```
Example:    800 1# $a Fisher, Leonard Everett.
                   $t Colonial American craftsmen.
```

830 Series added entry -- Uniform title (R)

Indicator 1 undefined.

Indicator 2: Nonfiling characters

0-9 -- Number of nonfiling characters present (for initial articles, including spaces)

Subfield used most often:

$a -- Uniform title

$v -- Volume number

```
    Example:    830 #0 $a Railroads of America (Macmillan)
```

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Part VIII:

A List of Other Fields Often Seen in MARC Records

001	Control number
003	Control number identifier
005	Date and time of latest transaction
006	Fixed-length data elements -- additional material characteristics
007	Physical description fixed field
008	Fixed length data elements (See Part X)
022	International Standard Serial Number (ISSN)
037	Source of acquisition
041	Language code
043	Geographic area code
050	Library of Congress call number
060	National Library of Medicine call number
082	Dewey Decimal classification number (the one recommended by the Library of Congress; locally-assigned call numbers may appear elsewhere)
110	Main entry -- Corporate name (less frequent under AACR2 rules)
256	Computer file characteristics
263	Projected publication date (indicates a CIP -- Cataloging in Publication -- record)
306	Playing time
508	Creation/production credits note
510	Citation/references note (review sources)
511	Participant or performer note
521	Target audience note (first indicator: 0 = reading grade level, 1 = interest age level, 2 = interest grade level, 3 = special audience characteristics, 4 = motivation interest level)
530	Additional physical form available note
538	System details note
586	Awards note
656	Index term -- Occupation
730	Added entry -- Uniform title
852	Location

856 Electronic location and access
9XX Reserved for local use. (They are used by vendors, systems, or individual libraries to exchange additional data)

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Part IX:

The Leader

There are 24 positions in the Leader, numbered from 00 to 23. For fuller explanation, see the *MARC 21 Format for Bibliographic Data*.

00-04 Record length (calculated by the computer for each record)
05 Record status
- a = increase in encoding level
- c = corrected or revised
- d = deleted
- n = new
- p = increase in encoding from prepublication (previous CIP)

06 Type of record
- a = language material
- c = printed music
- d = manuscript music
- e = cartographic material
- f = manuscript cartographic material
- g = projected medium
- i = nonmusical sound recording
- j = musical sound recording
- k = 2-dimensional nonprojectable graphic
- m = computer file
- o = kit
- p = mixed materials
- r = 3-dimensional artifact or naturally occurring object
- t = manuscript language material

07 Bibliographic level
- a = monographic component part
- b = serial component part
- c = collection
- d = subunit
- i = integrating resource
- m = monograph/item
- s = serial

08 Type of control
- # = no specified type
- a = archival

09 Character coding scheme
# = MARC-8
a = UCS/Unicode
10 Indicator count (always "2")
11 Subfield code count (always "2")
12-16 Base address of data (calculated by the computer for each record)
17 Encoding level
# = full level
1 = full level, material not examined
2 = less-than-full level, material not examined
3 = abbreviated level
4 = core level
5 = partial (preliminary) level
7 = minimal level
8 = prepublication level (CIP)
u = unknown
z = not applicable
18 Descriptive cataloging form
# = non-ISBD
a = AACR2
i = ISBD
u = unknown
19 Multipart resource record level
# = Not specified or not applicable
a = Set
b = Part with independent title
c = Part with dependent title
20 Length of the length-of-field portion (always "4")
21 Length of the starting-character-position portion (always "5")
22 Length of the implementation-defined portion (always "0")
23 Undefined (always "0")

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Part X:

Field 008 for Books

Field 008 is used for Fixed Length Data Elements ("Fixed Field Codes"). There are 40 character positions in field 008, numbered from 00-39. Undefined positions must contain either a blank (#) or a fill character (|). Positions 00-17 and 35-39 are defined the same way for all media.

The information shown here for positions 18-34 applies only to books. For explanation of all the positions below and for positions 18-34 for other media, see the *MARC 21 Format* *for Bibliographic Data*.

Note that field 008 has no indicators or subfield codes.

00-05 Date entered on file (YYMMDD), where Y=year, M=month, and D=day
06 Type of date/publication status:
- b = no dates given; B.C. date involved
- e = detailed date
- s = single known date/probable date
- m = multiple dates
- r = reprint/reissue date (Date 1) and original date (Date 2)
- n = dates unknown
- q = questionable date
- t = publication date and copyright date
- | = no attempt to code

07-10 Date 1/beginning date of publication
11-14 Date 2/ending date of publication

Date fields contain the year(s) of publication. The type of date(s) in these elements are specified in fixed field element 06: Type of date/publication status. (For further details, see the field 008 description in the *MARC 21 Format for Bibliographic Data*.)

15-17 Place of publication, production, or execution
For example:
- pk# = Pakistan
- cau = California (US)

(For a full list of codes used in these positions, see the *MARC Code List for Countries*.)

18-21 Illustrations (up to 4 codes):
- # = no illustrations
- a = illustrations
- b = maps
- c = portraits
- d = charts
- e = plans
- f = plates
- g = music
- h = facsimiles
- i = coats of arms
- j = genealogical tables
- k = forms
- l = samples
- m = phonodisc, phonowire, etc.
- o = photographs
- p = illuminations
- | = no attempt to code

22	Target audience:	
	# =	unknown or not specified
	a =	preschool
	b =	primary
	c =	pre-adolescent
	d =	adolescent
	e =	adult
	f =	specialized
	g =	general
	j =	juvenile
	| =	no attempt to code
23	Form of item:	
	# =	none of the following
	a =	microfilm
	b =	microfiche
	c =	microopaque
	d =	large print
	f =	braille
	r =	regular print reproduction
	s =	electronic
	| =	no attempt to code
24-27	Nature of contents (up to 4):	
	# =	no specified nature of contents
	a =	abstracts/summaries
	b =	bibliographies (is one or contains one)
	c =	catalogs
	d =	dictionaries
	e =	encyclopedias
	f =	handbooks
	g =	legal articles
	i =	indexes
	j =	patent document
	k =	discographies
	l =	legislation
	m =	theses
	n =	surveys of literature
	o =	reviews
	p =	programmed texts
	q =	filmographies
	r =	directories
	s =	statistics
	t =	technical reports
	u =	standards/specifications
	v =	legal cases and notes
	w =	law reports and digests
	z =	treaties
	| =	no attempt to code

28 Government publication:
# = not a government publication
i = international intergovernmental
f = federal/national
a = autonomous or semi-autonomous component
s = state, provincial, territorial, dependent, etc.
m = multistate
c = multilocal
l = local
z = other type of government publication
o = government publication -- level undetermined
u = unknown if item is government publication
| = no attempt to code

29 Conference publication:
0 = not a conference publication
1 = conference publication
| = no attempt to code

30 Festschrift:
0 = not a festschrift
1 = festschrift
| = no attempt to code

31 Index:
0 = no index
1 = index present
| = no attempt to code

32 Undefined (since 1990) (Earlier records may contain the values 0 or 1)
= Undefined
| = no attempt to code

33 Literary form:
0 = not fiction (not further specified)
1 = fiction (not further specified)
c = comic strips
d = dramas
e = essays
f = novels
h = humor, satires, etc.
i = letters
j = short stories
m = mixed forms
p = poetry
s = speeches
u = unknown
| = no attempt to code

34 Biography:
# = no biographical material
a = autobiography
b = individual biography

c = collective biography
d = contains biographical information
| = no attempt to code

35-37 Language:
A three-letter code. For example: eng fre ger spa rus ita

(For a full list of codes used in these positions, see the *MARC Code List for Languages*.)

38 Modified record:
# = not modified
x = missing characters (because of characters unavailable in MARC character set)
s = shortened
d = "dashed-on" information omitted
r = completely romanized/printed cards in script
o = completely romanized/printed cards romanized
| = no attempt to code

39 Cataloging source:
# = national bibliographic agency
c = cooperative cataloging program
d = other sources
u = unknown
| = no attempt to code

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Library of Congress
Library of Congress Help Desk (10/27/2009)

Declaration of Dr. Ingrid Hsieh-Yee
U.S. Patent No. 8,416,862

APPENDIX 1008-A

Conferences > 2004 EEE Wireless Communica

An efficient feedback method for MIMO systems with slowly time-varying channels

Publisher: IEEE

<< Resu ts   Next >

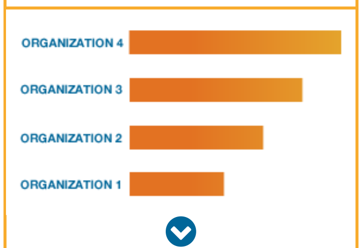
2 Author(s)   June Chu Roh ; B D Rao   **View All Authors**

Abstract

Abstract: The capac ty of a mu t p e- nput mu t p e-output (MIMO) channe can be mproved f the transm tter has a know edge of the channe . In th s paper, we propose an effic ent ... **View more**

Metadata

Abstract:
The capac ty of a mu t p e- nput mu t p e-output (MIMO) channe can be mproved f the transm tter has a know edge of the channe . In th s paper, we propose an effic ent and pract ca feedback method based on parameter zat on and quant zat on of channe parameters. The spat a   nformat on of the channe at the transm tter, wh ch s represented as a matr x w th orthonorma co umns, has a geometr ca structure. In parameter zat on, the geometr ca structure s exp o ted to extract a set of parameters that has a one-to-one mapp ng to the or g na matr x. In s ow y t me-vary ng channe s, the parameters are a so found to he smooth y chang ng n t me. We emp oy adapt ve de ta modu at on to quant ze and feed back each parameter. The resu ts show that the proposed feedback scheme has a channe track ng feature and ach eves a capac ty very c ose to the perfect feedback case w th a reasonab e feedback rate.



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DOI: 10.1109/WCNC.2004.1311282

Publisher: IEEE

Conference Location: At anta, GA, USA, USA

Contents

I. Introduction

Mu t p e transm t and rece ve antenna system s cons dered as a strong cand date for future w re ess systems because of potent a   mprovement n channe capac ty and   nk performance. A mu t p e antenna channe prov des d fferent capac t es under d fferent channe state nformat on (CSI) assumpt ons. The two common CSI assumpt ons are) comp ete CSIT (channe state nformat on at the transm tter) where perfect channe   nformat on s known to both the transm tter and the rece ver, e.g., [1], [2]; and   ) no CSIT where perfect channe   nformat on s ava ab e on y at the rece ver, e.g., [1]. The former case, of course, prov des a h gher channe capac ty than the atter, but the ga n comes at an expense of the transm tter s perfect know edge of MIMO channe . However, s nce n many app cat ons the channe   nformat on s prov ded to the transm tter through a ded cated feedback channe , t s a most mposs b e for the transm tter to have perfect nformat on n t me-vary ng channe s. Many prev ous stud es cons dered the above two extreme CSIT assumpt ons, and there are on y a few stud es dea ng w th how to feed back the MIMO channe   nformat on. Some researchers have worked on feedback of channe   nformat on n vector form, for examp e, for mu t p e- nput s ng e-output (MISO) channe s [3] and for the pr nc pa e gen-mode of MIMO channe s [4]. Onggosanus and Dabak [5] stud ed feedback of matr x channe   nformat on for MIMO channe s. They ntroduced a feedback scheme where among a set of un tary matr ces for the channe spat a   nformat on, an ndex of the matr x m n m z ng error probab   ty s fed back to the transm tter.

Authors

Figures

References

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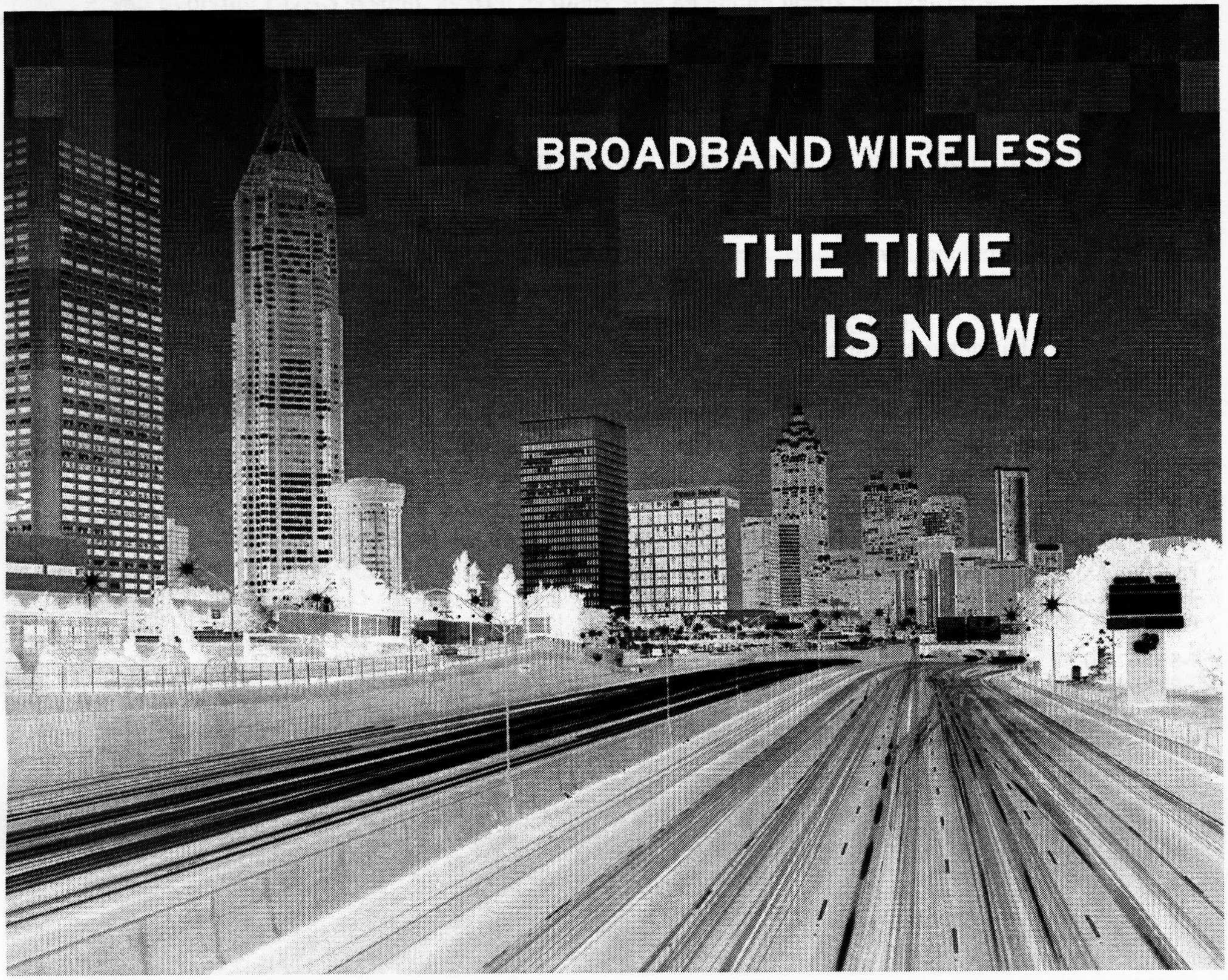
APPENDIX 1008-B

2004 IEEE Wireless Communications and Networking Conference

WCNC 2004

Volume Two



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Letter from the Technical Program Committee Chair

Organizing a program for a major conference, which WCNC has become, is always a challenge. This year it was especially challenging because of the large number (almost 1100) of technical paper submissions, about 50% more than last year; the first-time use of the EDAS papers processing system; and a heavier than expected proportion of papers addressing questions in the physical and medium access levels. The Technical Program Committee (TPC) had to quickly enlarge and learn how to cope with the powerful but still evolving EDAS system, as well as many special author needs and concerns.

I am grateful to many colleagues on the TPC who handled heavy paper processing loads, and particularly to Laurie Cuthbert, Halim Yanikomeroglu, Dejan Djonin and Zeljko Blazek, who served as co-TPC chairs or representatives of co-TPC chairs for the major tracks. The conference is also indebted to a large number of industrious reviewers whose work made it possible to converge on a set of about 470 papers. Many good-quality papers had to be rejected in this difficult and imperfect process. I want to thank the authors of both accepted and rejected papers for their efforts, and encourage all of them to come back with new submissions next year.

My TPC colleagues and I believe that we have an outstanding program that addresses many of the "hottest" and most pressing issues facing researchers, developers, and service providers in the wireless industry. It is remarkable that progress continues to be made on using the wireless medium more efficiently and with better performance, and the community of contributors presenting the papers in WCNC 2004 are the people generating that progress. We hope and expect that the value you, the attendee and in many cases an author as well, get from this conference will be substantial and will further accelerate technical progress and the development of a stronger wireless industry.

With best regards,

Steve Weinstein
Technical Program Chair
WCNC 2004

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An Efficient Feedback Method for MIMO Systems with Slowly Time-Varying Channels

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Abstract— **The capacity of a multiple-input multiple-output (MIMO) channel can be improved if the transmitter has knowledge of channel. In this paper, we propose an efficient and practical feedback method based on parameterization and quantization of channel parameters. The spatial information of channel at transmitter, which is represented as a matrix with orthonormal columns, has a geometrical structure. In parameterization, the geometrical structure is exploited to extract a set of parameters that has a one-to-one mapping to the original matrix. In slowly time-varying channels, the parameters are also found to be smoothly changing in time. We employ adaptive Delta modulation to quantize and feed back each parameter. The results show that the proposed feedback scheme has a channel tracking feature and achieves a capacity very close to the perfect feedback case with a reasonable feedback rate.**

I. Introduction

Multiple transmit and receive antenna system is considered as a strong candidate for future wireless systems because of potential improvement in channel capacity and link performance. A multiple antenna channel provides different capacities under different channel state information (CSI) assumptions. The two common CSI assumptions are i) *complete CSIT* (channel state information at the transmitter) where perfect channel information is known to both the transmitter and the receiver, e.g., [1], [2]; and ii) *no CSIT* where perfect channel information is available only at the receiver, e.g., [1]. The former case, of course, provides a higher channel capacity than the latter, but the gain comes at an expense of the transmitter's perfect knowledge of MIMO channel. However, since in many applications the channel information is provided to the transmitter through a dedicated feedback channel, it is almost impossible for the transmitter to have perfect information in time-varying channels. Many previous studies considered the above two extreme CSIT assumptions, and there are only a few studies dealing with how to feed back the MIMO channel information. Some researchers have worked on feedback of channel information in vector form, for example, for multiple-input single-output (MISO) channels [3] and for the principal eigen-mode of MIMO channels [4]. Onggosanusi and Dabak [5] studied feedback of matrix channel information for MIMO channels. They introduced a feedback scheme where among a set of unitary matrices for the channel spatial information, an index of the matrix minimizing error probability is fed back to the transmitter.

The purpose of this paper is to provide a general framework for quantization of MIMO channel information and to develop a practical feedback method for slowly time-varying channels. The CSIT consists of the spatial information of channel and the power allocation over spatial channels. We first focus on quantization of the spatial information which can be represented as a matrix with orthonormal columns (a unitary matrix is an example). We notice a geometrical structure in the matrix. For example, the columns of a $t \times t$ unitary matrix $V = [v_1, \dots, v_t]$ are all on the unit-norm sphere $\mathcal{S}_t \subset \mathbb{C}^t$ and mutually orthogonal, i.e., $v_1 \in \mathcal{S}_t$, $v_2 \in (\mathcal{S}_t \cap v_1^\perp)$, $v_3 \in (\mathcal{S}_t \cap v_1^\perp \cap v_2^\perp)$, and so on, where $v_i^\perp$ is the orthogonal complement of the space spanned by v_i. In this paper, the geometrical structure is exploited in quantizing the spatial information. In particular, from the matrix with orthonormal columns, we extract a set of essential parameters that has a one-to-one mapping to the original matrix. The number of parameters equals the degree of freedom in the matrix. Then, instead of quantizing the original matrix, the parameters are quantized and fed back to the transmitter, and an approximate (quantized) version of spatial information is reconstructed at the transmitter. Although jointly quantizing the parameters (vector quantization) could be better choice, this paper considers quantizing each parameter independently (scalar coding) because of its low complexity. More specifically, adaptive Delta modulation (ADM) [6] is employed from an observation that, in slowly time-varying channels, the extracted parameters are also smoothly changing. ADM is a practical low-rate scalar coding scheme that can track time-varying channels efficiently.

We use the following notations. $A^\dagger$ and A^T indicate the conjugate transpose and the transpose of matrix A, respectively. I_n is the $n \times n$ identity matrix and $0_{m,n}$ means the $m \times n$ zero matrix. $\mathrm{diag}(a_1, \dots, a_n)$ is a square diagonal matrix with $a_1, \dots, a_n$ along the diagonal. The 2-norm of vector v is denoted by $\|v\|$. $E[\cdot]$ represents the expectation operator, and $\mathcal{CN}(\mu, \Sigma)$ is circularly symmetric complex Gaussian random vector with mean μ and covariance Σ.

II. System Model and Mutual Information

A. Channel Model

We consider a multiple antenna system with t antennas at the transmitter and r at the receiver. Assuming slow flat-fading, the MIMO channel is modeled by the channel matrix $H \in$

$\mathbb{C}^{r \times t}$. That is, the channel input $x \in \mathbb{C}^t$ and the channel output $y \in \mathbb{C}^r$ have the following relationship:

$$y = Hx + \eta \tag{1}$$

where $\eta \in \mathbb{C}^r$ is the additive white Gaussian noise vector distributed by $\mathcal{CN}(0_{r,1}, I_r)$. We denote the rank of H by m. And, the singular value decomposition (SVD) of H is given by $H = U_H \Sigma_H V_H^\dagger$, where $U_H \in \mathbb{C}^{r \times r}$ and $V_H \in \mathbb{C}^{t \times t}$ are unitary matrices and $\Sigma_H \in \mathbb{R}^{r \times t}$ contains the singular values $\sigma_1 \geq \ldots \geq \sigma_m > 0$ of H. We impose a constraint on the transmit power by $E[x^\dagger x] \leq P_T$.

We assume that in all cases perfect CSI is known to the receiver. And, the first n $(0 \leq n \leq m)$ columns of V_H are to be quantized and fed back to the transmitter as channel *spatial* information. When we consider perfect feedback, i.e., no quantization error, this setting includes the two extreme cases: i) $n = m$ is the case that the transmitter has same spatial information as in the *complete CSIT* case; and ii) $n = 0$ accounts for no spatial information at the transmitter as in the *no CSIT* case. And, when $0 < n < m$, it corresponds to *partial CSIT* of [7], [8]. For notational convenience, let us define $V = [v_1, \ldots, v_n]$ where v_i is the i-th column vector of V_H.

The CSIT consists of the spatial information of channel and the power allocation information. The matrix V conveys the spatial information that is needed at the transmitter. In [7], we discussed a multiple-antenna system concept in which the optimal power allocation is calculated at the receiver and provided to the transmitter as additional CSI. The power allocation information is represented by a real vector $\gamma = [\gamma_i]$ where $\sum_i \gamma_i = 1$ and $0 \leq \gamma_i \leq 1$.

B. Feedback System Model

This subsection describes a feedback system model for time-varying MIMO channels that accounts for the discrepancy between the real channel and the CSI at the transmitter. It will be used in performance evaluation in Section V. Figure 1 depicts the block-fading model and the frame structure of the feedback system model. We assume that the channel matrix is not changing during a time block, which will be called *channel block* (with length T_C). The channel matrix at k-th channel block is denoted by $H[k]$, and $V[k]$ and $\gamma[k]$ are the corresponding CSI. The quantized version of the CSI ($\hat{V}[k]$ and $\hat{\gamma}[k]$ in the figure) is provided to the transmitter at a *feedback rate* of R_F times per second via an error-free feedback channel. The time frame between two consequent channel updates is called *feedback frame* (with length $T_F = 1/R_F$). For simplicity, we assume there are M (an integer) channel blocks in a feedback frame, i.e., $T_F = MT_C$. In addition, in order to model composite delay, e.g., due to processing and propagation, we introduce an integer parameter D: at the starting point of each frame, the CSI corresponding to the D previous channel block is available at the transmitter. Figure 1 is an example when $D = 1$. The CSIT is used in transmission during the frame before the next update arrives.

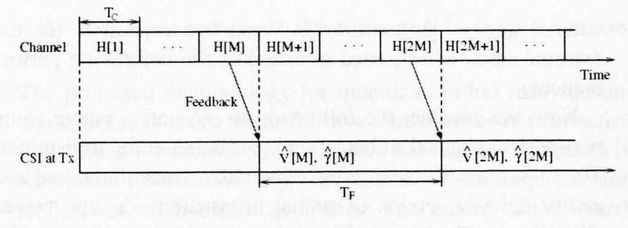

Fig. 1. Feedback system model (when $D = 1$).

C. Mutual Information and Capacity

Among many possible measures for evaluating the performance of the feedback method, we consider mutual information as performance measure in this paper. When the transmit signal x is distributed by $\mathcal{CN}(0_{t,1}, \Phi_x)$, the mutual information for a given channel realization H is given by $I(x;y) = \log\det(I_r + H\Phi_x H^\dagger)$ [1]. Since the covariance matrix Φ_x is a Hermitian positive semidefinite matrix, it can be decomposed as $\Phi_x = W\Phi W^\dagger$ with a unitary matrix $W \in \mathbb{C}^{t \times t}$ and a diagonal matrix $\Phi = \mathrm{diag}(P_1, \ldots, P_t), P_i \geq 0$. From this, we notice that it is equivalent to transmitting $x = Ws, s \in \mathbb{C}^t$ with $E[ss^\dagger] = \Phi$ over channel H, i.e., an equivalent channel is

$$y = HWs + \eta. \tag{2}$$

This point of view is useful because each column of W can be interpreted as the beamforming vector for the corresponding symbol in s. And, in some cases, W and Φ can be adjusted by using the spatial and the power allocation information available at the transmitter. Let us define $\gamma = [\gamma_1, \ldots, \gamma_t]$, where $\gamma_i \in [0, 1]$ and $\sum_i \gamma_i = 1$, which is referred as power allocation information by setting $\gamma_i = P_i/P_T$, i.e., $\Phi(\gamma) = P_T \,\mathrm{diag}(\gamma_1, \ldots, \gamma_t)$. And, we denote the mutual information $I(s;y)$ of the channel (2) when the transmitter uses beamforming matrix W and power allocation γ by

$$\begin{aligned}\Psi(W, \gamma) &= \log\det(I + HW\Phi(\gamma)W^\dagger H^\dagger) \\ &= \log\det(I + V_H^\dagger W\Phi(\gamma)W^\dagger V_H \Sigma^2).\end{aligned}$$

When the transmitter has perfect knowledge of channel (as in *complete CSIT* case), W is set to V_H. Then, the mutual information is written as $I(s;y) = \Psi(V_H, \gamma) = \sum_{i=1}^m \log(1 + P_i\lambda_i)$, where $\lambda_i = \sigma_i^2$. With water-filling to maximize $I(s;y)$, we have the channel capacity

$$C_{\text{Full}} = \sum_{i=1}^m [\log(\nu\lambda_i)]^+ \tag{3}$$

where $[a]^+$ is defined as $\max\{a, 0\}$ and ν is the water-filling level satisfying the power constraint $\sum_{i=1}^m [\nu - \lambda_i^{-1}]^+ = P_T$. When we denote the optimum power allocation information by γ_{wf}, we can write $C_{\text{Full}} = \Psi(V_H, \gamma_{\text{wf}})$. On the other hand, when no information about channel is available at the transmitter (as in *no CSIT* case), the capacity is given by

$$C_{\text{None}} = \Psi(I_t, \gamma_{\text{unif}}) = \sum_{i=1}^m \log\left(1 + \frac{P_T}{t}\lambda_i\right) \tag{4}$$

where $\gamma_{\text{unif}} = [1/t, \ldots, 1/t]$. These two capacities for the extreme cases will be used as references in comparing performances.

Now, we consider the following two scenarios where some non-perfect channel information is available at the transmitter. The first case is when the transmitter uses the quantized and/or delayed version of spatial information $\hat{V}_H$ and power allocation information $\hat{\gamma}$. Then, the mutual information can be written as

$$I_{\hat{V}_H, \hat{\gamma}} = \Psi(\hat{V}_H, \hat{\gamma}). \tag{5}$$

Note that the subscripts in mutual information and capacity notations indicate the CSIT. The second case is when the transmitter has only spatial information $\hat{V}_H$ and no power allocation information. In this case, one easy choice of power allocation is uniform allocation. Then, the mutual information is given by

$$I_{\hat{V}_H} = \Psi(\hat{V}_H, \gamma_{\text{unif}}) = \sum_{i=1}^{m} \log\left(1 + \frac{P_T}{t}\lambda_i(H_{\text{eq}}H_{\text{eq}}^\dagger)\right) \tag{6}$$

where $H_{\text{eq}} = H\hat{V}_H$ and $\lambda_i(H_{\text{eq}}H_{\text{eq}}^\dagger)$ is the i-th largest eigenvalue of $H_{\text{eq}}H_{\text{eq}}^\dagger$.

We expect that channel feedback has more gain when $t > r$ [7]. In this case, since the rank of channel $m < t$, we need to feedback only first m columns of V_H, i.e., $V = [v_1, \ldots, v_m]$ $(n = m)$. And, if $\hat{V}$ is reasonably close to V, the optimum power allocation will has nearly zeros in the last $t - m$ entries in γ. Therefore, when only spatial information $\hat{V}$ is available at the transmitter, a reasonable uniform power allocation is $\gamma = [1/m, \ldots, 1/m, 0, \ldots, 0]$.

III. Parameterization of Channel Information

In this section, we focus on how to extract essential parameters from the spatial information denoted by V. Since the columns in spatial information V are geometrically structured, the degree of freedom in the matrix is much smaller than the number of real-number entries in the matrix. The degree of freedom in $V \in \mathbb{C}^{t\times n}$ can be expressed as

$$N = 2t \cdot n - n - 2\binom{n}{2} = 2tn - n^2 \text{ (real numbers)} \tag{7}$$

where the first term is the number of real-number entries in the matrix, and second term accounts for reductions from unit-norm property of each column, and third term from orthogonality in each pair of columns. For example, a $t \times t$ unitary matrix has $2t^2$ real-number entries, but its degree of freedom is only t^2. Furthermore, one phase in each column can be made fixed (e.g., the first row has all nonnegative real numbers), which gives n additional reductions. Then,

$$N = (2t-1)n - n^2 \text{ (real numbers)} \tag{8}$$

Now, we want to extract a set of essential parameters that has a one-to-one mapping to the matrix V. There are several possible ways such as using Givens rotations or Householder reflections. In this paper, we propose a parameterization method using Givens rotations in which the number of parameters is equal to (8), the degree of freedom in the matrix.

Theorem 1 (Parameterization): A matrix $V \in \mathbb{C}^{t\times n}(t \geq n)$ with orthonormal columns can be decomposed as

$$V = \left[\prod_{k=1}^{n} D_k(\phi_{k,k}, \ldots, \phi_{k,t}) \prod_{l=1}^{t-k} G_{t-l,t-l+1}(\theta_{k,l})\right] \tilde{I} \tag{9}$$

where t dimensional diagonal matrix

$$D_k(\phi_{k,k}, \ldots, \phi_{k,t}) = \text{diag}(1_{k-1}, e^{j\phi_{k,k}}, \ldots, e^{j\phi_{k,t}})$$

1_{k-1} is $(k-1)$ 1's; and $G_{p-1,p}(\theta)$ is the Givens matrix which operates in the $(p-1, p)$ coordinate plane of the form

$$G_{p-1,p}(\theta) = \begin{bmatrix} I_{p-2} & & & \\ & c & -s & \\ & s & c & \\ & & & I_{t-p} \end{bmatrix}, \tag{10}$$

$c = \cos\theta$ and $s = \sin\theta$; and $t \times n$ matrix $\tilde{I} = [I_n, 0_{n,t-n}]^T$.

Let us explain the above parameterization procedure with an example. Consider 4×3 matrix V with orthonormal columns.

$$\begin{bmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{bmatrix} \xrightarrow{D_1^\dagger} \begin{bmatrix} |\times| & \times & \times \\ |\times| & \times & \times \\ |\times| & \times & \times \\ |\times| & \times & \times \end{bmatrix} \xrightarrow{G_{3,4}^\dagger, G_{2,3}^\dagger, G_{1,2}^\dagger} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \\ 0 & \times & \times \end{bmatrix} \xrightarrow{D_2^\dagger}$$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & |\times| & \times \\ 0 & |\times| & \times \\ 0 & |\times| & \times \end{bmatrix} \xrightarrow{G_{3,4}^\dagger, G_{2,3}^\dagger} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \times \\ 0 & 0 & \times \end{bmatrix} \xrightarrow{D_3^\dagger} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & |\times| \\ 0 & 0 & |\times| \end{bmatrix} \xrightarrow{G_{3,4}^\dagger} \tilde{I}$$

where $|\times|$ represents the magnitude of a particular element. The procedure is similar to the QR decomposition using Givens matrices. In the first step, we want to make all the entries in the first column under the first component all zeros. To do that, we first extract the phases from the first column by pre-multiplying V by $D_1^\dagger$ to have a real-valued column, and then apply a series of Givens matrices with appropriate parameters to make all entries under the $(1,1)$ element zeros. Since the Givens rotation preserves the length of vector, the $(1,1)$ element becomes 1. At the same time, all the entries in the first row except the $(1,1)$ element also become zeros because of the orthogonality between columns. We carry out similar procedures on the remaining columns sequentially, and then finally we have a diagonal matrix $\tilde{I}$. Since a Givens matrix is an orthogonal matrix, the matrix V can be factored as

$$\begin{aligned} V = {} & D_1(\phi_{1,1}, \ldots, \phi_{1,4})\, G_{3,4}(\theta_{1,1})\, G_{2,3}(\theta_{1,2})\, G_{1,2}(\theta_{1,3}) \\ & \cdot D_2(\phi_{2,2}, \phi_{2,3}, \phi_{2,4})\, G_{3,4}(\theta_{2,1})\, G_{2,3}(\theta_{2,2}) \\ & \cdot D_3(\phi_{3,3}, \phi_{3,4})\, G_{3,4}(\theta_{3,1})\, \tilde{I}. \end{aligned}$$

Therefore, once we have a set of parameters, the phases $\{\phi_{k,l}\}$ and the rotation angles $\{\theta_{k,l}\}$, the original matrix V can be exactly reconstructed.

Now, we will show that the number of parameters obtained by the proposed parameterization is equal to the degree of freedom in V with the following with the following Lemma and Theorem.

Lemma 1: Define as $\tilde{V}$ the resulting matrix after applying D_1 and the first l Givens rotations $G_{t-q,t-q+1}^\dagger(\theta_{1,q})$, $q =$

$1,\dots,l$, in the procedure for the first column. Then, the $(t-l,p)$ element of $\hat{V}$ is given by

$$\hat{V}[t-l,p] = \begin{cases} \|v_1^{(l+1)}\| & \text{if } p=1, \\ \frac{(v_1^{(l+1)})^\dagger v_p^{(l+1)}}{\|v_1^{(l+1)}\|} & \text{if } p=2,\dots,n \end{cases} \quad (11)$$

where $v_i^{(l+1)}$ is a vector defined as the last $l+1$ elements in the i-th column v_i, i.e., $v_i^{(l+1)} = [v_{t-l,i}, v_{t-l+1,i}, \dots, v_{t,i}]^T$.

Proof: This can be proved by induction. ∎

Theorem 2: In the matrix factorization of Theorem 1, if orthonormal column matrix V has real-valued elements in the first row with alternating signs as $+-+-\dots$, then the first parameter of D_k is zero, i.e., $\phi_{k,k}=0$ for all k. Therefore, the number of parameters is $(2t-1)n-n^2$, which is the degree of freedom in V.

Proof: This can be proved by using Lemma 1 and orthogonality between two columns of V. After applying $D_1^\dagger$ and $t-1$ Givens matrices $G_{t-l,t-l+1}^\dagger(\theta_{1,l})$, $l=1,\dots,t-1$, it can be shown that the resulting matrix is given by

$$G_{1,2}^\dagger \cdots G_{t-1,t}^\dagger D_1^\dagger V = \begin{bmatrix} 1 & 0_{1,n-1} \\ 0_{t-1,1} & V' \end{bmatrix} \quad (12)$$

and V' is a $(t-1)\times(n-1)$ matrix with orthonormal columns that has same structure as V, i.e., alternating signs in the first row. Therefore, in a sequential way we can prove the first phase parameter of D_k is zero for all k. From this, we have n less parameters than (7), which results in the final conclusion. ∎

Now we find the distribution of the parameters and establish their independence, a property useful for quantization purposes.

Theorem 3 (Statistics of Parameters): When the channel matrix H has *i.i.d.* $\mathcal{CN}(0,1)$ entries, then all the parameters from Theorem 1 are statistically independent. Moreover, the phase $\phi_{k,j}$ is uniformly distributed over $(-\pi,\pi]$ for all k and j, and the rotational angle $\theta_{k,l}$ has probability density

$$p(\theta_{k,l}) = 2l\sin^{2l-1}\theta_{k,l}\cos\theta_{k,l}, \quad 0 \le \theta_{k,l} < \frac{\pi}{2}. \quad (13)$$

Proof: The theorem can be proved using techniques for calculating the distribution of transformed random vector/matrix similar to [9, Ch. 1–3]. Details are omitted due to space limitations. ∎

The parameterization for power allocation information $\gamma = [\gamma_1,\dots,\gamma_t]$, $\sum_{i=1}^t \gamma_i = 1$ is rather simple. We can see that γ has $t-1$ of degree of freedom. And, the parameters can be simply the first $t-1$ elements, $[\gamma_1,\dots,\gamma_{t-1}]$. Then, from the constraint, the last one is determined as $\gamma_t = 1-\sum_{i=1}^{t-1}\gamma_i$.

IV. Quantization in Parameter Domain

The overall strategy for quantization is depicted in Figure 2 and summarized below.

1) From the spatial information V, extract a set of parameters Θ (*Parameterization*): $\Theta = \mathcal{T}(V)$.
2) Quantize the parameters Θ and feed back the quantized parameters $\hat{\Theta}$ (*Quantization*): $\hat{\Theta} = \mathcal{Q}(\Theta)$.
3) Reconstruct the spatial information $\hat{V}$ from $\hat{\Theta}$ (*Reconstruction*): $\hat{V} = \mathcal{T}^{-1}(\hat{\Theta})$.

The proposed methodology for quantization has many advantages. Some of them are as follows. The number of parameters to quantize is minimal since it equals the degree of freedom in the spatial information. The parameters, which are phases and angles, are all bounded quantities. The reconstructed matrix $\hat{V}$ has the same geometrical structure as V, i.e., $\hat{V}^\dagger\hat{V} = I_n$. In addition, the methodology is general and can be applied to any multiple antenna scenario: MISO systems (when $n=1$) and MIMO systems with partial feedback (when $1<n<m$) as well as MIMO systems with full feedback ($n=m$).

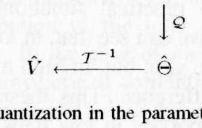

Fig. 2. Quantization in the parameter domain.

One can apply some vector quantization (VQ) method to quantize the parameters. But, complexity issues and tracking requirement motivate us to consider employing scalar quantization. Moreover, the independence of the parameters, Theorem 3, indicates that the overall loss is minimal. More specifically, adaptive Delta modulation (ADM) [6, ch. 8] is used to quantize each parameter. In slowly time-varying channels, the parameters are also slowly and continuously changing most of the time. The encoder of ADM consists of a simple accumulator and a one-bit quantizer. Basically, it quantizes the difference between the newly incoming sample and the previous quantized sample. For a parameter θ,

$$\hat{\theta}[k] = \hat{\theta}[k-1] \pm \Delta[k]. \quad (14)$$

And the step-size $\Delta[k]$ of the one-bit quantizer is adaptively changing to better track the dynamics of the signal. The ADM with one-bit memory [6] is an example. The step-size is increased if the consequent two encoded bits are same, and decreased otherwise, that is,

$$\Delta[k] = \begin{cases} M_1\,\Delta[k-1], & \text{if } c[k]=c[k-1] \\ M_2\,\Delta[k-1], & \text{if } c[k]\neq c[k-1] \end{cases} \quad (15)$$

where $\Delta[k]$ and $c[k]$ is the step-size and the encoded bit for the k-th sample; and $M_1>1$ and $0<M_2<1$, usually $M_2 = 1/M_1$. Compared to VQ, ADM has considerably lower complexity. And it is a low-rate scalar quantization scheme (as low as one bit per parameter). Another important advantage is that ADM has inherently a channel tracking feature for slowly time-varying channels.

V. Numerical Results

We have performed simulations to investigate the performance of the proposed feedback method, especially in slowly time-varying MIMO channels. The components of the channel matrix are *i.i.d.* discrete-time random processes and each process models Rayleigh fading channel gain. The simulated channel has the Doppler frequency $f_D = 7.4$ Hz, which corresponds to a mobility of 4 km/h at carrier frequency of 2 GHz. As for the frame structure of Section II-B, we considered the case of $M = 4$ and $D = 1$.

Figure 3 shows the cumulative distribution of mutual information with different CSIT assumptions and various transmit power, $P_T = -10, 0, 10, 20$ dB, with the feedback rate $R_F = 500$ per second ($t = 4$ and $r = 2$). C_{Full} and C_{None} are calculated from (3) and (4), respectively. Note that the CSIT for C_{Full} is perfect, that is, it involves neither quantization error nor channel tracking error. The performances of the proposed feedback method are shown as $C_{\hat{V},\hat{\gamma}}$ and $C_{\hat{V}}$, which are calculated according to (5) and (6), respectively. These include the effect of quantization error and delay; therefore, they reflect more practical situations of feedback systems. From the results, we can see that, in low transmit power range, the two have some gap; but, in high transmit power range, the two have little difference. This means that power allocation information is important in low transmit power range, which can be understood from the water-filling argument. That is, when transmit power is low, the optimum transmission scheme is using only a few spatial channels that have high channel gains. Note that the feedback rate is corresponding to 5.5 kbps (for $C_{\hat{V},\hat{\gamma}}$) and 5 kbps (for $C_{\hat{V}}$) of feedback bit-rate since we have 10 parameters for V and one for γ, and ADM encodes each parameter into one bit at each feedback instant.

Figure 4 shows the results when the feedback rate is increased to $R_F = 1000$ per second, which corresponds to 11/10 kbps. We can see that the performances become much closer to C_{Full}. This can be explained as follows. By increasing the feedback rate, the quantization error is reduced, since in ADM encoding the variations between the adjacent samples are reduced. Also the channel tracking error due to delay is lessened with increasing the feedback rate.

VI. Conclusion

We proposed a general framework for quantization of MIMO channel information, which involves parameterization of orthonormal column matrix and quantization of parameters. We introduced a new parameterization method that uses Givens rotations and that provides minimal number of parameters. The distributions of the parameters were found and the independence between them was shown. In slowly time-varying channels, the extracted parameters are also slowly and continuously changing in time. This motivated employing adaptive Delta modulation in quantizing the parameters. The adaptive Delta modulation is a simple and practical quantization method that has a channel tracking feature for slowly time-varying channels. The proposed feedback scheme requires $(2t-1)n - n^2$ bits to feedback $V \in \mathbb{C}^{t\times n}$. With the proposed feedback method, a performance close to the perfect feedback case can be achieved with a reasonable feedback rate.

Acknowledgment

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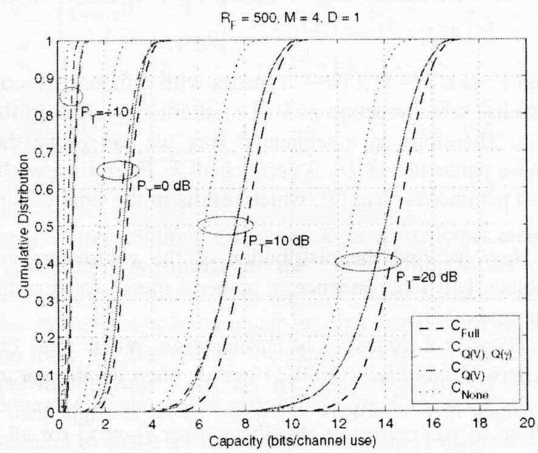

Fig. 3. Cumulative distribution of capacities when $R_F = 500$/sec ($t = 4$ and $r = 2$). $Q(V) = \hat{V}$ and $Q(\gamma) = \hat{\gamma}$.

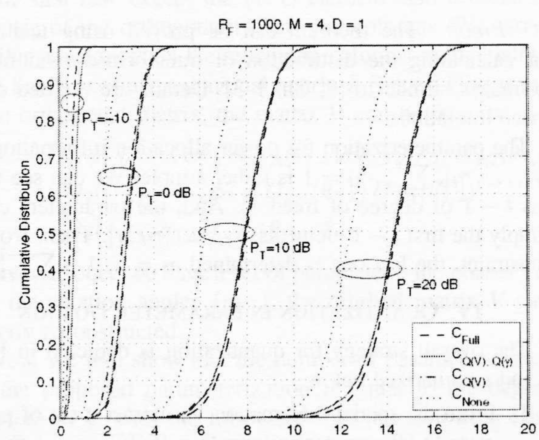

Fig. 4. Cumulative distribution of capacities when $R_F = 1000$/sec ($t = 4$ and $r = 2$).

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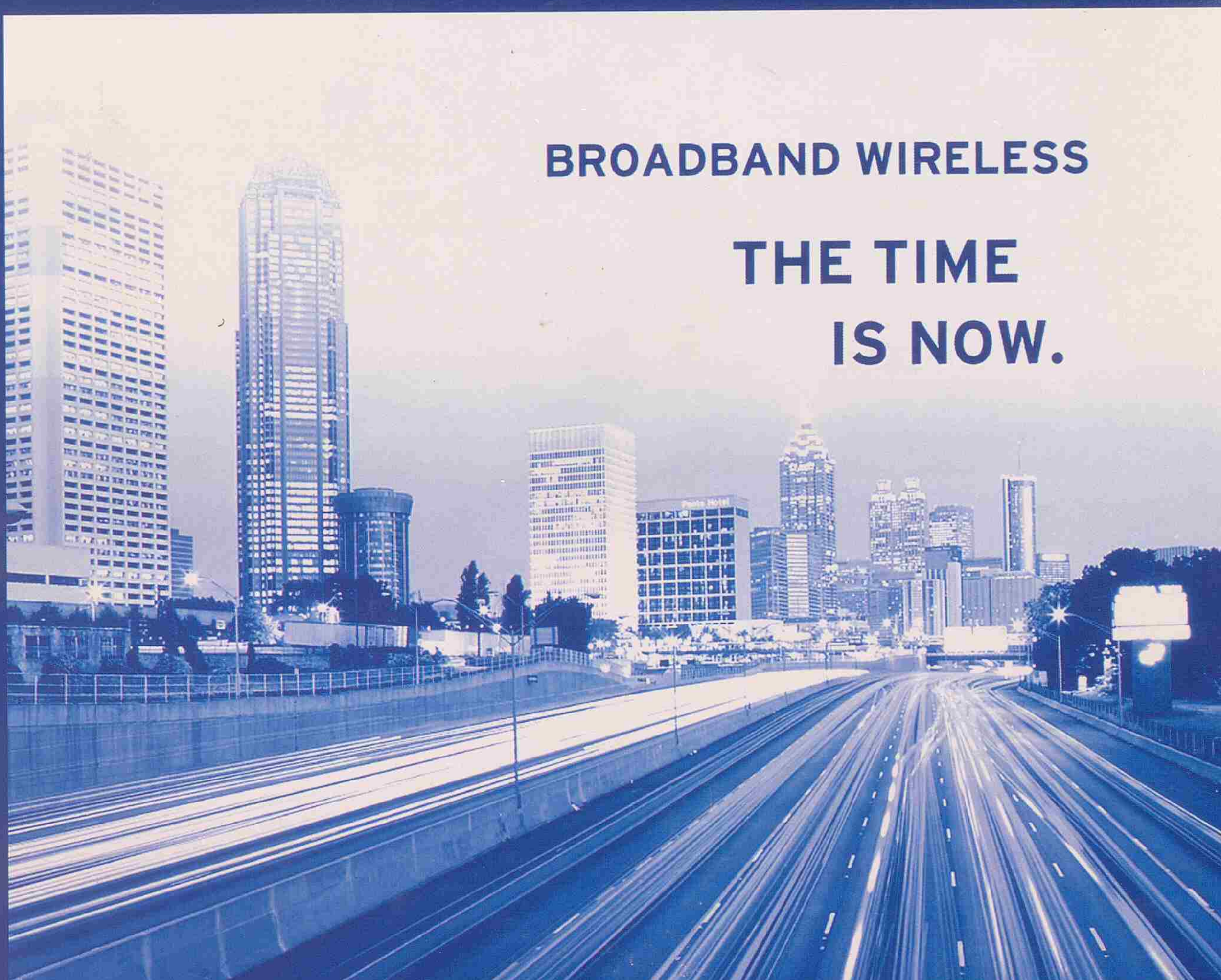

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An Efficient Feedback Method for MIMO Systems with Slowly Time-Varying Channels

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***Abstract*— The capacity of a multiple-input multiple-output (MIMO) channel can be improved if the transmitter has knowledge of channel. In this paper, we propose an efficient and practical feedback method based on parameterization and quantization of channel parameters. The spatial information of channel at transmitter, which is represented as a matrix with orthonormal columns, has a geometrical structure. In parameterization, the geometrical structure is exploited to extract a set of parameters that has a one-to-one mapping to the original matrix. In slowly time-varying channels, the parameters are also found to be smoothly changing in time. We employ adaptive Delta modulation to quantize and feed back each parameter. The results show that the proposed feedback scheme has a channel tracking feature and achieves a capacity very close to the perfect feedback case with a reasonable feedback rate.**

I. Introduction

Multiple transmit and receive antenna system is considered as a strong candidate for future wireless systems because of potential improvement in channel capacity and link performance. A multiple antenna channel provides different capacities under different channel state information (CSI) assumptions. The two common CSI assumptions are i) *complete CSIT* (channel state information at the transmitter) where perfect channel information is known to both the transmitter and the receiver, e.g., [1], [2]; and ii) *no CSIT* where perfect channel information is available only at the receiver, e.g., [1]. The former case, of course, provides a higher channel capacity than the latter, but the gain comes at an expense of the transmitter's perfect knowledge of MIMO channel. However, since in many applications the channel information is provided to the transmitter through a dedicated feedback channel, it is almost impossible for the transmitter to have perfect information in time-varying channels. Many previous studies considered the above two extreme CSIT assumptions, and there are only a few studies dealing with how to feed back the MIMO channel information. Some researchers have worked on feedback of channel information in vector form, for example, for multiple-input single-output (MISO) channels [3] and for the principal eigen-mode of MIMO channels [4]. Onggosanusi and Dabak [5] studied feedback of matrix channel information for MIMO channels. They introduced a feedback scheme where among a set of unitary matrices for the channel spatial information, an index of the matrix minimizing error probability is fed back to the transmitter.

The purpose of this paper is to provide a general framework for quantization of MIMO channel information and to develop a practical feedback method for slowly time-varying channels. The CSIT consists of the spatial information of channel and the power allocation over spatial channels. We first focus on quantization of the spatial information which can be represented as a matrix with orthonormal columns (a unitary matrix is an example). We notice a geometrical structure in the matrix. For example, the columns of a $t \times t$ unitary matrix $V = [v_1, \ldots, v_t]$ are all on the unit-norm sphere $\mathcal{S}_t \subset \mathbb{C}^t$ and mutually orthogonal, i.e., $v_1 \in \mathcal{S}_t$, $v_2 \in (\mathcal{S}_t \cap v_1^{\perp})$, $v_3 \in (\mathcal{S}_t \cap v_1^{\perp} \cap v_2^{\perp})$, and so on, where $v_i^{\perp}$ is the orthogonal complement of the space spanned by v_i. In this paper, the geometrical structure is exploited in quantizing the spatial information. In particular, from the matrix with orthonormal columns, we extract a set of essential parameters that has a one-to-one mapping to the original matrix. The number of parameters equals the degree of freedom in the matrix. Then, instead of quantizing the original matrix, the parameters are quantized and fed back to the transmitter, and an approximate (quantized) version of spatial information is reconstructed at the transmitter. Although jointly quantizing the parameters (vector quantization) could be better choice, this paper considers quantizing each parameter independently (scalar coding) because of its low complexity. More specifically, adaptive Delta modulation (ADM) [6] is employed from an observation that, in slowly time-varying channels, the extracted parameters are also smoothly changing. ADM is a practical low-rate scalar coding scheme that can track time-varying channels efficiently.

We use the following notations. $A^{\dagger}$ and A^T indicate the conjugate transpose and the transpose of matrix A, respectively. I_n is the $n \times n$ identity matrix and $0_{m,n}$ means the $m \times n$ zero matrix. $\text{diag}(a_1, \ldots, a_n)$ is a square diagonal matrix with $a_1, \ldots, a_n$ along the diagonal. The 2-norm of vector v is denoted by $\|v\|$. $E[\cdot]$ represents the expectation operator, and $\mathcal{CN}(\mu, \Sigma)$ is circularly symmetric complex Gaussian random vector with mean μ and covariance Σ.

II. System Model and Mutual Information

A. Channel Model

We consider a multiple antenna system with t antennas at the transmitter and r at the receiver. Assuming slow flat-fading, the MIMO channel is modeled by the channel matrix $H \in$

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$\mathbb{C}^{r\times t}$. That is, the channel input $x \in \mathbb{C}^t$ and the channel output $y \in \mathbb{C}^r$ have the following relationship:

$$y = Hx + \eta \tag{1}$$

where $\eta \in \mathbb{C}^r$ is the additive white Gaussian noise vector distributed by $\mathcal{CN}(0_{r,1}, I_r)$. We denote the rank of H by m. And, the singular value decomposition (SVD) of H is given by $H = U_H \Sigma_H V_H^\dagger$, where $U_H \in \mathbb{C}^{r\times r}$ and $V_H \in \mathbb{C}^{t\times t}$ are unitary matrices and $\Sigma_H \in \mathbb{R}^{r\times t}$ contains the singular values $\sigma_1 \geq \ldots \geq \sigma_m > 0$ of H. We impose a constraint on the transmit power by $E[x^\dagger x] \leq P_T$.

We assume that in all cases perfect CSI is known to the receiver. And, the first n ($0 \leq n \leq m$) columns of V_H are to be quantized and fed back to the transmitter as channel *spatial* information. When we consider perfect feedback, i.e., no quantization error, this setting includes the two extreme cases: i) $n = m$ is the case that the transmitter has same spatial information as in the *complete CSIT* case; and ii) $n = 0$ accounts for no spatial information at the transmitter as in the *no CSIT* case. And, when $0 < n < m$, it corresponds to *partial CSIT* of [7], [8]. For notational convenience, let us define $V = [v_1, \ldots, v_n]$ where v_i is the i-th column vector of V_H.

The CSIT consists of the spatial information of channel and the power allocation information. The matrix V conveys the spatial information that is needed at the transmitter. In [7], we discussed a multiple-antenna system concept in which the optimal power allocation is calculated at the receiver and provided to the transmitter as additional CSI. The power allocation information is represented by a real vector $\gamma = [\gamma_i]$ where $\sum_i \gamma_i = 1$ and $0 \leq \gamma_i \leq 1$.

B. Feedback System Model

This subsection describes a feedback system model for time-varying MIMO channels that accounts for the discrepancy between the real channel and the CSI at the transmitter. It will be used in performance evaluation in Section V. Figure 1 depicts the block-fading model and the frame structure of the feedback system model. We assume that the channel matrix is not changing during a time block, which will be called *channel block* (with length T_C). The channel matrix at k-th channel block is denoted by $H[k]$, and $V[k]$ and $\gamma[k]$ are the corresponding CSI. The quantized version of the CSI ($\hat{V}[k]$ and $\hat{\gamma}[k]$ in the figure) is provided to the transmitter at a *feedback rate* of R_F times per second via an error-free feedback channel. The time frame between two consequent channel updates is called *feedback frame* (with length $T_F = 1/R_F$). For simplicity, we assume there are M (an integer) channel blocks in a feedback frame, i.e., $T_F = MT_C$. In addition, in order to model composite delay, e.g., due to processing and propagation, we introduce an integer parameter D: at the starting point of each frame, the CSI corresponding to the D previous channel block is available at the transmitter. Figure 1 is an example when $D = 1$. The CSIT is used in transmission during the frame before the next update arrives.

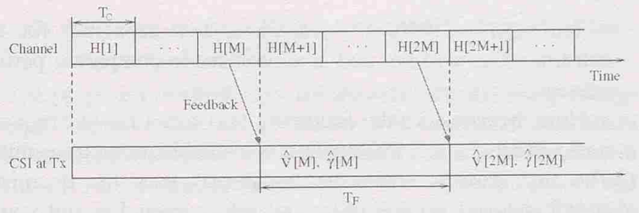

Fig. 1. Feedback system model (when $D = 1$).

C. Mutual Information and Capacity

Among many possible measures for evaluating the performance of the feedback method, we consider mutual information as performance measure in this paper. When the transmit signal x is distributed by $\mathcal{CN}(0_{t,1}, \Phi_x)$, the mutual information for a given channel realization H is given by $I(x;y) = \log\det(I_r + H\Phi_x H^\dagger)$ [1]. Since the covariance matrix Φ_x is a Hermitian positive semidefinite matrix, it can be decomposed as $\Phi_x = W\Phi W^\dagger$ with a unitary matrix $W \in \mathbb{C}^{t\times t}$ and a diagonal matrix $\Phi = \mathrm{diag}(P_1, \ldots, P_t)$, $P_i \geq 0$. From this, we notice that it is equivalent to transmitting $x = Ws, s \in \mathbb{C}^t$ with $E[ss^\dagger] = \Phi$ over channel H, i.e., an equivalent channel is

$$y = HWs + \eta. \tag{2}$$

This point of view is useful because each column of W can be interpreted as the beamforming vector for the corresponding symbol in s. And, in some cases, W and Φ can be adjusted by using the spatial and the power allocation information available at the transmitter. Let us define $\gamma = [\gamma_1, \ldots, \gamma_t]$, where $\gamma_i \in [0, 1]$ and $\sum_i \gamma_i = 1$, which is referred as power allocation information by setting $\gamma_i = P_i/P_T$, i.e., $\Phi(\gamma) = P_T \,\mathrm{diag}(\gamma_1, \ldots, \gamma_t)$. And, we denote the mutual information $I(s;y)$ of the channel (2) when the transmitter uses beamforming matrix W and power allocation γ by

$$\begin{aligned}\Psi(W,\gamma) &= \log\det(I + HW\Phi(\gamma)W^\dagger H^\dagger)\\ &= \log\det(I + V_H^\dagger W\Phi(\gamma)W^\dagger V_H \Sigma^2).\end{aligned}$$

When the transmitter has perfect knowledge of channel (as in *complete CSIT* case), W is set to V_H. Then, the mutual information is written as $I(s;y) = \Psi(V_H, \gamma) = \sum_{i=1}^m \log(1 + P_i\lambda_i)$, where $\lambda_i = \sigma_i^2$. With water-filling to maximize $I(s;y)$, we have the channel capacity

$$C_{\text{Full}} = \sum_{i=1}^{m} [\log(\nu\lambda_i)]^+ \tag{3}$$

where $[a]^+$ is defined as $\max\{a, 0\}$ and ν is the water-filling level satisfying the power constraint $\sum_{i=1}^m [\nu - \lambda_i^{-1}]^+ = P_T$. When we denote the optimum power allocation information by γ_{wf}, we can write $C_{\text{Full}} = \Psi(V_H, \gamma_{\text{wf}})$. On the other hand, when no information about channel is available at the transmitter (as in *no CSIT* case), the capacity is given by

$$C_{\text{None}} = \Psi(I_t, \gamma_{\text{unif}}) = \sum_{i=1}^{m} \log\left(1 + \frac{P_T}{t}\lambda_i\right) \tag{4}$$

where $\gamma_{\text{unif}} = [1/t, \ldots, 1/t]$. These two capacities for the extreme cases will be used as references in comparing performances.

Now, we consider the following two scenarios where some non-perfect channel information is available at the transmitter. The first case is when the transmitter uses the quantized and/or delayed version of spatial information $\hat{V}_H$ and power allocation information $\hat{\gamma}$. Then, the mutual information can be written as

$$I_{\hat{V}_H,\hat{\gamma}} = \Psi(\hat{V}_H, \hat{\gamma}). \tag{5}$$

Note that the subscripts in mutual information and capacity notations indicate the CSIT. The second case is when the transmitter has only spatial information $\hat{V}_H$ and no power allocation information. In this case, one easy choice of power allocation is uniform allocation. Then, the mutual information is given by

$$I_{\hat{V}_H} = \Psi(\hat{V}_H, \gamma_{\text{unif}}) = \sum_{i=1}^{m} \log\left(1 + \frac{P_T}{t}\lambda_i(H_{\text{eq}}H_{\text{eq}}^{\dagger})\right) \tag{6}$$

where $H_{\text{eq}} = H\hat{V}_H$ and $\lambda_i(H_{\text{eq}}H_{\text{eq}}^{\dagger})$ is the i-th largest eigenvalue of $H_{\text{eq}}H_{\text{eq}}^{\dagger}$.

We expect that channel feedback has more gain when $t > r$ [7]. In this case, since the rank of channel $m < t$, we need to feedback only first m columns of V_H, i.e., $V = [v_1, \ldots, v_m]$ $(n = m)$. And, if $\hat{V}$ is reasonably close to V, the optimum power allocation will has nearly zeros in the last $t - m$ entries in γ. Therefore, when only spatial information $\hat{V}$ is available at the transmitter, a reasonable uniform power allocation is $\gamma = [1/m, \ldots, 1/m, 0, \ldots, 0]$.

III. Parameterization of Channel Information

In this section, we focus on how to extract essential parameters from the spatial information denoted by V. Since the columns in spatial information V are geometrically structured, the degree of freedom in the matrix is much smaller than the number of real-number entries in the matrix. The degree of freedom in $V \in \mathbb{C}^{t \times n}$ can be expressed as

$$N = 2t \cdot n - n - 2\binom{n}{2} = 2tn - n^2 \text{ (real numbers)} \tag{7}$$

where the first term is the number of real-number entries in the matrix, and second term accounts for reductions from unit-norm property of each column, and third term from orthogonality in each pair of columns. For example, a $t \times t$ unitary matrix has $2t^2$ real-number entries, but its degree of freedom is only t^2. Furthermore, one phase in each column can be made fixed (e.g., the first row has all nonnegative real numbers), which gives n additional reductions. Then,

$$N = (2t-1)n - n^2 \text{ (real numbers)} \tag{8}$$

Now, we want to extract a set of essential parameters that has a one-to-one mapping to the matrix V. There are several possible ways such as using Givens rotations or Householder reflections. In this paper, we propose a parameterization method using Givens rotations in which the number of parameters is equal to (8), the degree of freedom in the matrix.

Theorem 1 (Parameterization): A matrix $V \in \mathbb{C}^{t \times n}(t \geq n)$ with orthonormal columns can be decomposed as

$$V = \left[\prod_{k=1}^{n} D_k(\phi_{k,k}, \ldots, \phi_{k,t}) \prod_{l=1}^{t-k} G_{t-l,t-l+1}(\theta_{k,l})\right] \tilde{I} \tag{9}$$

where t dimensional diagonal matrix

$$D_k(\phi_{k,k}, \ldots, \phi_{k,t}) = \text{diag}(1_{k-1}, e^{j\phi_{k,k}}, \ldots, e^{j\phi_{k,t}})$$

1_{k-1} is $(k-1)$ 1's; and $G_{p-1,p}(\theta)$ is the Givens matrix which operates in the $(p-1, p)$ coordinate plane of the form

$$G_{p-1,p}(\theta) = \begin{bmatrix} I_{p-2} & & & \\ & c & -s & \\ & s & c & \\ & & & I_{t-p} \end{bmatrix}, \tag{10}$$

$c = \cos\theta$ and $s = \sin\theta$; and $t \times n$ matrix $\tilde{I} = [I_n, 0_{n,t-n}]^T$.

Let us explain the above parameterization procedure with an example. Consider 4×3 matrix V with orthonormal columns.

$$\begin{bmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{bmatrix} \xrightarrow{D_1^{\dagger}} \begin{bmatrix} |\times| & \times & \times \\ |\times| & \times & \times \\ |\times| & \times & \times \\ |\times| & \times & \times \end{bmatrix} \xrightarrow{G_{3,4}^{\dagger} \cdot G_{2,3}^{\dagger} \cdot G_{1,2}^{\dagger}} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \\ 0 & \times & \times \end{bmatrix} \xrightarrow{D_2^{\dagger}}$$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & |\times| & \times \\ 0 & |\times| & \times \\ 0 & |\times| & \times \end{bmatrix} \xrightarrow{G_{3,4}^{\dagger} \cdot G_{2,3}^{\dagger}} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \times \\ 0 & 0 & \times \end{bmatrix} \xrightarrow{D_3^{\dagger}} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & |\times| \\ 0 & 0 & |\times| \end{bmatrix} \xrightarrow{G_{3,4}^{\dagger}} \tilde{I}$$

where $|\times|$ represents the magnitude of a particular element. The procedure is similar to the QR decomposition using Givens matrices. In the first step, we want to make all the entries in the first column under the first component all zeros. To do that, we first extract the phases from the first column by pre-multiplying V by $D_1^{\dagger}$ to have a real-valued column, and then apply a series of Givens matrices with appropriate parameters to make all entries under the $(1,1)$ element zeros. Since the Givens rotation preserves the length of vector, the $(1,1)$ element becomes 1. At the same time, all the entries in the first row except the $(1,1)$ element also become zeros because of the orthogonality between columns. We carry out similar procedures on the remaining columns sequentially, and then finally we have a diagonal matrix $\tilde{I}$. Since a Givens matrix is an orthogonal matrix, the matrix V can be factored as

$$\begin{aligned} V = {} & D_1(\phi_{1,1}, \ldots, \phi_{1,4})\, G_{3,4}(\theta_{1,1})\, G_{2,3}(\theta_{1,2})\, G_{1,2}(\theta_{1,3}) \\ & \cdot D_2(\phi_{2,2}, \phi_{2,3}, \phi_{2,4})\, G_{3,4}(\theta_{2,1})\, G_{2,3}(\theta_{2,2}) \\ & \cdot D_3(\phi_{3,3}, \phi_{3,4})\, G_{3,4}(\theta_{3,1})\, \tilde{I}. \end{aligned}$$

Therefore, once we have a set of parameters, the phases $\{\phi_{k,l}\}$ and the rotation angles $\{\theta_{k,l}\}$, the original matrix V can be exactly reconstructed.

Now, we will show that the number of parameters obtained by the proposed parameterization is equal to the degree of freedom in V with the following with the following Lemma and Theorem.

Lemma 1: Define as $\tilde{V}$ the resulting matrix after applying D_1 and the first l Givens rotations $G_{t-q,t-q+1}^{\dagger}(\theta_{1,q})$, $q =$

$1,\ldots,l$, in the procedure for the first column. Then, the $(t-l,p)$ element of $\hat{V}$ is given by

$$\hat{V}[t-l,p] = \begin{cases} \|v_1^{(l+1)}\| & \text{if } p=1, \\ \frac{(v_1^{(l+1)})^\dagger v_p^{(l+1)}}{\|v_1^{(l+1)}\|} & \text{if } p=2,\ldots,n \end{cases} \tag{11}$$

where $v_i^{(l+1)}$ is a vector defined as the last $l+1$ elements in the i-th column v_i, i.e., $v_i^{(l+1)} = [v_{t-l,i}, v_{t-l+1,i}, \ldots, v_{t,i}]^T$.

Proof: This can be proved by induction. ■

Theorem 2: In the matrix factorization of Theorem 1, if orthonormal column matrix V has real-valued elements in the first row with alternating signs as $+-+-\ldots$, then the first parameter of D_k is zero, i.e., $\phi_{k,k}=0$ for all k. Therefore, the number of parameters is $(2t-1)n-n^2$, which is the degree of freedom in V.

Proof: This can be proved by using Lemma 1 and orthogonality between two columns of V. After applying $D_1^\dagger$ and $t-1$ Givens matrices $G_{t-l,t-l+1}^\dagger(\theta_{1,l})$, $l=1,\ldots,t-1$, it can be shown that the resulting matrix is given by

$$G_{1,2}^\dagger \ldots G_{t-1,t}^\dagger D_1^\dagger V = \begin{bmatrix} 1 & 0_{1,n-1} \\ 0_{t-1,1} & V' \end{bmatrix}, \tag{12}$$

and V' is a $(t-1)\times(n-1)$ matrix with orthonormal columns that has same structure as V, i.e., alternating signs in the first row. Therefore, in a sequential way we can prove the first phase parameter of D_k is zero for all k. From this, we have n less parameters than (7), which results in the final conclusion. ■

Now we find the distribution of the parameters and establish their independence, a property useful for quantization purposes.

Theorem 3 (Statistics of Parameters): When the channel matrix H has *i.i.d.* $\mathcal{CN}(0,1)$ entries, then all the parameters from Theorem 1 are statistically independent. Moreover, the phase $\phi_{k,j}$ is uniformly distributed over $(-\pi,\pi]$ for all k and j, and the rotational angle $\theta_{k,l}$ has probability density

$$p(\theta_{k,l}) = 2l\sin^{2l-1}\theta_{k,l}\cos\theta_{k,l}, \quad 0 \le \theta_{k,l} < \frac{\pi}{2}. \tag{13}$$

Proof: The theorem can be proved using techniques for calculating the distribution of transformed random vector/matrix similar to [9, Ch. 1–3]. Details are omitted due to space limitations. ■

The parameterization for power allocation information $\gamma = [\gamma_1,\ldots,\gamma_t]$, $\sum_{i=1}^t \gamma_i = 1$ is rather simple. We can see that γ has $t-1$ of degree of freedom. And, the parameters can be simply the first $t-1$ elements, $[\gamma_1,\ldots,\gamma_{t-1}]$. Then, from the constraint, the last one is determined as $\gamma_t = 1-\sum_{i=1}^{t-1}\gamma_i$.

IV. Quantization in Parameter Domain

The overall strategy for quantization is depicted in Figure 2 and summarized below.

1) From the spatial information V, extract a set of parameters Θ (*Parameterization*): $\Theta = \mathcal{T}(V)$.
2) Quantize the parameters Θ and feed back the quantized parameters $\hat\Theta$ (*Quantization*): $\hat\Theta = \mathcal{Q}(\Theta)$.
3) Reconstruct the spatial information $\hat V$ from $\hat\Theta$ (*Reconstruction*): $\hat V = \mathcal{T}^{-1}(\hat\Theta)$.

The proposed methodology for quantization has many advantages. Some of them are as follows. The number of parameters to quantize is minimal since it equals the degree of freedom in the spatial information. The parameters, which are phases and angles, are all bounded quantities. The reconstructed matrix $\hat V$ has the same geometrical structure as V, i.e., $\hat V^\dagger \hat V = I_n$. In addition, the methodology is general and can be applied to any multiple antenna scenario: MISO systems (when $n=1$) and MIMO systems with partial feedback (when $1<n<m$) as well as MIMO systems with full feedback ($n=m$).

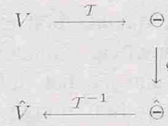

Fig. 2. Quantization in the parameter domain.

One can apply some vector quantization (VQ) method to quantize the parameters. But, complexity issues and tracking requirement motivate us to consider employing scalar quantization. Moreover, the independence of the parameters, Theorem 3, indicates that the overall loss is minimal. More specifically, adaptive Delta modulation (ADM) [6, ch. 8] is used to quantize each parameter. In slowly time-varying channels, the parameters are also slowly and continuously changing most of the time. The encoder of ADM consists of a simple accumulator and a one-bit quantizer. Basically, it quantizes the difference between the newly incoming sample and the previous quantized sample. For a parameter θ,

$$\hat\theta[k] = \hat\theta[k-1] \pm \Delta[k]. \tag{14}$$

And the step-size $\Delta[k]$ of the one-bit quantizer is adaptively changing to better track the dynamics of the signal. The ADM with one-bit memory [6] is an example. The step-size is increased if the consequent two encoded bits are same, and decreased otherwise, that is,

$$\Delta[k] = \begin{cases} M_1\Delta[k-1], & \text{if } c[k]=c[k-1] \\ M_2\Delta[k-1], & \text{if } c[k]\ne c[k-1] \end{cases} \tag{15}$$

where $\Delta[k]$ and $c[k]$ is the step-size and the encoded bit for the k-th sample; and $M_1>1$ and $0<M_2<1$, usually $M_2 = 1/M_1$. Compared to VQ, ADM has considerably lower complexity. And it is a low-rate scalar quantization scheme (as low as one bit per parameter). Another important advantage is that ADM has inherently a channel tracking feature for slowly time-varying channels.

V. Numerical Results

We have performed simulations to investigate the performance of the proposed feedback method, especially in slowly time-varying MIMO channels. The components of the channel matrix are *i.i.d.* discrete-time random processes and each process models Rayleigh fading channel gain. The simulated

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channel has the Doppler frequency $f_D = 7.4$ Hz, which corresponds to a mobility of 4 km/h at carrier frequency of 2 GHz. As for the frame structure of Section II-B, we considered the case of $M = 4$ and $D = 1$.

Figure 3 shows the cumulative distribution of mutual information with different CSIT assumptions and various transmit power, $P_T = -10, 0, 10, 20$ dB, with the feedback rate $R_F =$ 500 per second ($t = 4$ and $r = 2$). C_{Full} and C_{None} are calculated from (3) and (4), respectively. Note that the CSIT for C_{Full} is perfect, that is, it involves neither quantization error nor channel tracking error. The performances of the proposed feedback method are shown as $C_{\hat{V},\hat{\gamma}}$ and $C_{\hat{V}}$, which are calculated according to (5) and (6), respectively. These include the effect of quantization error and delay; therefore, they reflect more practical situations of feedback systems. From the results, we can see that, in low transmit power range, the two have some gap; but, in high transmit power range, the two have little difference. This means that power allocation information is important in low transmit power range, which can be understood from the water-filling argument. That is, when transmit power is low, the optimum transmission scheme is using only a few spatial channels that have high channel gains. Note that the feedback rate is corresponding to 5.5 kbps (for $C_{\hat{V},\hat{\gamma}}$) and 5 kbps (for $C_{\hat{V}}$) of feedback bit-rate since we have 10 parameters for V and one for γ, and ADM encodes each parameter into one bit at each feedback instant.

Figure 4 shows the results when the feedback rate is increased to $R_F = 1000$ per second, which corresponds to 11/10 kbps. We can see that the performances become much closer to C_{Full}. This can be explained as follows. By increasing the feedback rate, the quantization error is reduced, since in ADM encoding the variations between the adjacent samples are reduced. Also the channel tracking error due to delay is lessened with increasing the feedback rate.

VI. Conclusion

We proposed a general framework for quantization of MIMO channel information, which involves parameterization of orthonormal column matrix and quantization of parameters. We introduced a new parameterization method that uses Givens rotations and that provides minimal number of parameters. The distributions of the parameters were found and the independence between them was shown. In slowly time-varying channels, the extracted parameters are also slowly and continuously changing in time. This motivated employing adaptive Delta modulation in quantizing the parameters. The adaptive Delta modulation is a simple and practical quantization method that has a channel tracking feature for slowly time-varying channels. The proposed feedback scheme requires $(2t-1)n - n^2$ bits to feedback $V \in \mathbb{C}^{t \times n}$. With the proposed feedback method, a performance close to the perfect feedback case can be achieved with a reasonable feedback rate.

Acknowledgment

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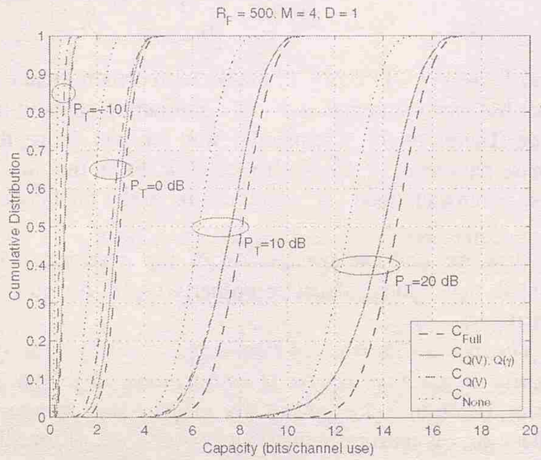

Fig. 3. Cumulative distribution of capacities when $R_F = 500$/sec ($t = 4$ and $r = 2$). $Q(V) = \hat{V}$ and $Q(\gamma) = \hat{\gamma}$.

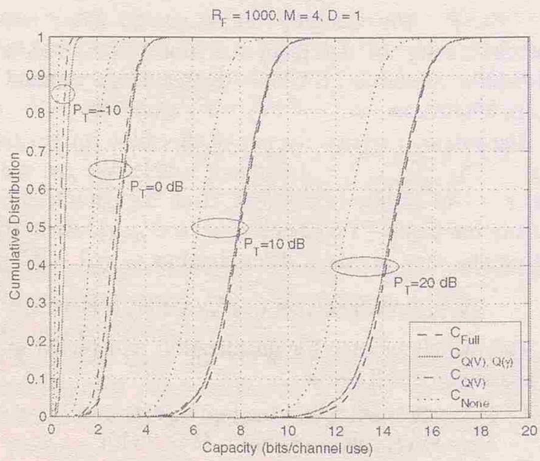

Fig. 4. Cumulative distribution of capacities when $R_F = 1000$/sec ($t = 4$ and $r = 2$).

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APPENDIX 1011-E

Appendix 1011-E

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Delosme, J. M. (1990, September). Bit-level systolic algorithm for the symmetric eigenvalue problem. In *[1990] Proceedings of the International Conference on Application Specific Array Processors* (pp. 770-781). IEEE.

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APPENDIX 1013-A

A new method of channel feedback quantization for high data rate MIMO systems

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3 Author(s) M.A. Sadrabadi ; A.K. Khandani ; F. Lahouti **View All Authors**

Abstract

Abstract:
In this work, we study a multiple-input multiple-output wireless system, where the channel state information is partially available at the transmitter through a feedback link. Based on singular value decomposition, the MIMO channel is split into independent subchannels, which allows separate, and therefore, efficient decoding of the transmitted data signal. Effective feedback of the required spatial channel information entails efficient quantization/encoding of a Haar unitary matrix. The parameter reduction of an n /spl times/ n unitary matrix to its n/sup 2/ - n basic parameters is performed through Givens decomposition. We prove that Givens matrices of a Haar unitary matrix are statistically independent. Subsequently, we derive the probability distribution function (PDF) of the corresponding matrix elements. Based on these analyses, an efficient quantization scheme is proposed. The performance evaluation is provided for a scenario where the rates allocated to each independent channel are selected according to its corresponding gain. The results indicate a significant performance improvement compared to the performance of MIMO systems without feedback at the cost of a very low-rate feedback link.

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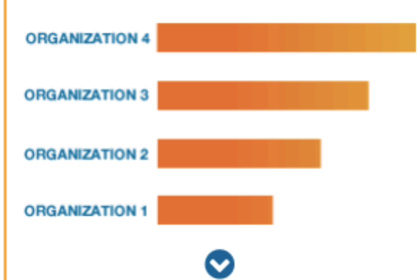

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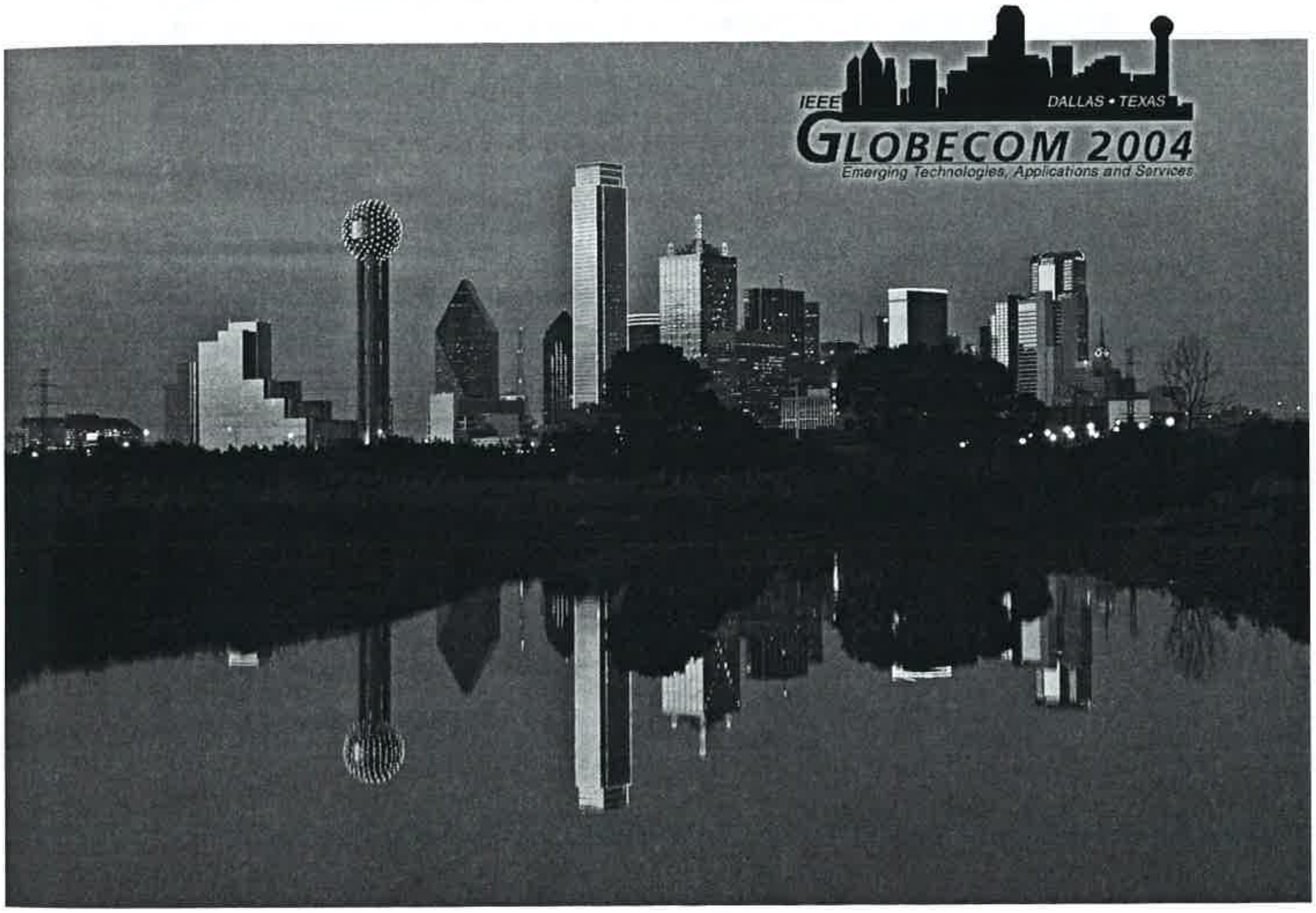

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A New Method of Channel Feedback Quantization for High Data Rate MIMO Systems

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Abstract—**In this work, we study a Multiple-Input Multiple-Output wireless system, where the channel state information is partially available at the transmitter through a feedback link. Based on Singular Value Decomposition, the MIMO channel is split into independent subchannels, which allows separate, and therefore, efficient decoding of the transmitted data signal. Effective feedback of the required spatial channel information entails efficient quantization/encoding of a Haar unitary matrix. The parameter reduction of an $n \times n$ unitary matrix to its $n^2 - n$ basic parameters is performed through Givens decomposition. We prove that Givens matrices of a Haar unitary matrix are statistically independent. Subsequently, we derive the probability distribution function (PDF) of the corresponding matrix elements. Based on these analyses, an efficient quantization scheme is proposed. The performance evaluation is provided for a scenario where the rates allocated to each independent channel are selected according to its corresponding gain. The results indicate a significant performance improvement compared to the performance of MIMO systems without feedback at the cost of a very low-rate feedback link.**

I. Introduction

Multiple-Input Multiple-Output (MIMO) communication systems have received considerable attention in response to the increasing requirements of high spectral efficiency in wireless communications. In fact, the capacity of MIMO systems equipped with M_t transmit and M_r receive antennas scales up almost linearly with the minimum of M_t and M_r in flat Rayleigh fading environments [1] [2].

In recent years, researchers have examined the transmission strategies for MIMO systems, in which the transmitter and/or the receiver have full or partial knowledge of the Channel State Information (CSI). In [3], it has been shown that the achievable bit rate when perfect CSI is available both at the transmitter and the receiver is significantly higher than that when CSI is only available at the receiver. Due to practical restrictions such as an imperfect channel estimation and a limited feedback data rate, CSI is not perfect at the transmitter. However, unlike the single antenna systems, where exploiting CSI at the transmitter does not significantly enhance the capacity, in multiple antenna systems, the capacity is substantially improved through even partial CSI [4].

When CSI is available at the transmitter of a Multiple-Input Single-Output (MISO) system, beamforming can be used to exploit transmit diversity through spatial match filtering. In the context of MISO systems, several quantization schemes have been suggested to feed back instantaneous CSI to the transmitter. A simple and effective scheme has been suggested for a 3G wireless standard [5]. In [6] the authors have designed a codebook of beamformer vectors with the objective of minimizing the outage probability. Similar works, titled in single-substream precoding, have been reported in [7] [8], where the codebook design criterion is derived to maximize the received Signal to Noise Ratio (SNR).

For MIMO systems, the problem of quantizing CSI is more involved than for MISO systems. In [9] a precoder is combined with space-time encoder. The precoder is designed so as to reduce an upper bound on the worst pairwise codeword error probability conditioned on imperfect CSI at the transmitter. In [10], by assuming the availability of partial CSI at the transmitter of a MIMO system, a criterion has been presented to design a precoder based on the capacity maximization. However, [10] has not provided a practical approach to design such a precoder when the number of receive antennas is more than one. In this paper, we present a technique to address the need for a practical feedback scheme for a MIMO system (as opposed to a MISO). After we accomplished this work [11], we became aware of a similar work in quantizing the spatial information of the channel [12]. Specifically, the authors in [12] have come up with the same idea of using Givens rotations to reduce the number of parameters which need to be quantized. They use the time-dependency of the corresponding parameters of adjacent frames in slowly time-varying channels and employ a differential quantization for each parameter. However, in this work, we quantize the parameters of the channel's spatial information frame by frame. The quantization design and optimum bit allocation among the quantizers are accomplished based on the interference measure we define in Section III.

Consider the situation in which a MIMO channel is split into several independent subchannels by means of Singular Value Decomposition (SVD) based on the CSI at the transmitter and the receiver. This allows independent decoding of the subchannels and results in a low decoding complexity. In general, the optimum Maximum Likelihood (ML) decoding in a MIMO system without feedback is equivalent to a lattice decoding problem, which incurs significant complexity. Lower complexity decoding algorithms can be devised by the proper design of a transmit strategy, e.g., the Bell Labs Layered

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Space Time system [1]. However, this is achieved at the cost of degraded performance [13] [14]. This indicates that, in addition to the gain in the SNR performance, a reduction in the decoding complexity is another important advantage of a closed loop MIMO system based on the SVD.

In this work, the modulation format is selected to match the subchannel SNR on each subchannel. In this scheme, the spatial information of the channel and the constellation index of each subchannel is needed at the transmitter. We develop an algorithm to quantize the spatial information of the channel, based on minimizing the interference between the subchannels. The rate allocation strategy is determined at the receiver and fed back to the transmitter by using an efficient low rate approach.

The system model is described in Section II. In Section III, the parametrization and statistics of the right singular matrix of a Gaussian matrix is discussed. The feedback design is developed according to these properties, and the decoding strategy at the receiver. In Section IV, feedback scheme for transferring the rate information of each subchannel is discussed. In Section V, the simulation results are presented. Section VI concludes the paper.

II. System Model

We consider an independent and identically distributed block fading channel model. For a multiple transmit antenna system with M_t transmit and M_r receive antennas, the model leads to the following complex baseband representation of the received signal:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}, \tag{1}$$

where $\mathbf{x}$ is the $M_t \times 1$ vector of the transmitted symbols, $\mathbf{H}$ is the $M_r \times M_t$ channel matrix, $\mathbf{n}$ is the $M_r \times 1$ zero mean Gaussian noise vector with the autocorrelation $\sigma^2\mathbf{I}$ where $\mathbf{I}$ is the identity matrix, and $\mathbf{y}$ is the received signal. The power constraint of the transmitted signal is defined as $E(\mathbf{x}\mathbf{x}^*) = \mathcal{E}\mathbf{I}$, where E represents the expectation and $(.)^*$ is the hermitian of $(.)$. The elements of the channel matrix $\mathbf{H}$ are circularly symmetric complex Gaussian distributed with zero mean and unit variance.

The SVD of matrix $\mathbf{H}$ is defined as [15]

$$\mathbf{H} = \mathbf{V}\mathbf{\Lambda}\mathbf{U}^*, \tag{2}$$

where $\mathbf{V}$ and $\mathbf{U}$ are the unitary matrices, and $\mathbf{\Lambda}$ is a diagonal matrix. If $\mathbf{U}$ is available at the transmitter and the transmitted signal is prefiltered by $\mathbf{U}$, then the received signal is given by

$$\begin{aligned}\mathbf{y} &= \mathbf{H}\mathbf{U}\mathbf{x} + \mathbf{n}\\ &= \mathbf{V}\mathbf{\Lambda}\mathbf{x} + \mathbf{n}.\end{aligned} \tag{3}$$

The receiver filters the received vector $\mathbf{y}$ by $\mathbf{V}^*$,

$$\mathbf{r} = \mathbf{V}^*\mathbf{y} = \mathbf{\Lambda}\mathbf{x} + \mathbf{n}. \tag{4}$$

Therefore, a MIMO channel with M_t transmit antennas and M_r receive antennas is transformed to 'rank $\mathbf{H}$' parallel subchannels. This transformation substantially reduces the decoding complexity. In the transition from (3) to (4), we take advantage of the fact that the elements of $\mathbf{n}$ are statistically independent, and rotating $\mathbf{n}$ by the unitary matrix $\mathbf{V}^*$ does not change the distribution of the noise.

As it can be seen in (4), the subchannels provide different gains corresponding to $\mathbf{\Lambda}$. We consider a case in which data is transmitted and received separately in each subchannel with different rates and with equal energy. It can be shown that the use of equal energy maximizes the rate under the assumption of continuous approximation for a cubical shaping region (subject to a constraint on total energy). This method involves the allocation of an appropriate data rate to each subchannel, while a certain target error rate on each subchannel is met. By this assumption, the transmitter requires the rate information of each subchannel, in addition to the right singular matrix of the channel.

III. Feedback Design:Channel Singular Matrix Quantization

In the scenario described above, the transmitter needs to know the right singular matrix of the channel. We assume that a noiseless feedback link from the receiver to the transmitter is available. By the SVD of $\mathbf{H}$ at the receiver, the unitary matrix $\mathbf{U}$ is computed, quantized and sent to the transmitter.

If we assume the quantization error $\mathbf{\Delta U}$ for $\mathbf{U}$, the received signal is

$$\mathbf{r} = \mathbf{\Lambda}\mathbf{x} + \mathbf{\Lambda}\mathbf{U}^*\mathbf{\Delta U}\mathbf{x} + \mathbf{n}. \tag{5}$$

The quantization scheme is based on minimizing the interference between the parallel subchannels, since the receiver strategy is to detect the data in each subchannel independently. The variance of the interference signal is expressed as follows:

$$\begin{aligned}E(\|\mathbf{\Lambda}\mathbf{U}^*\mathbf{\Delta U}\mathbf{x}\|^2) &= E\mathrm{Tr}(\mathbf{\Lambda}\mathbf{U}^*\mathbf{\Delta U}\mathbf{x}\mathbf{x}^*\mathbf{\Delta U}^*\mathbf{U}\mathbf{\Lambda})\\ &= \lambda E\mathrm{Tr}(\mathbf{\Delta U}\mathbf{\Delta U}^*\mathbf{x}\mathbf{x}^*)\\ &= \lambda\mathcal{E}E\mathrm{Tr}(\|\mathbf{\Delta U}\|^2),\end{aligned} \tag{6}$$

where $E(\mathbf{\Lambda}^2) = \lambda\mathbf{I}$, $E(\mathbf{x}\mathbf{x}^*) = \mathcal{E}\mathbf{I}$ and Tr denotes the trace function. In (6), we use the property that the singular values of a Gaussian matrix are independent from the corresponding singular vectors [16], and also the equality $\mathrm{Tr}(\mathbf{AB}) = \mathrm{Tr}(\mathbf{BA})$. As a result, minimizing the mean of the interference power leads to the minimization of the Frobenius norm of $\mathbf{\Delta U}$. In order to minimize the interference, the unitary matrix $\mathbf{U}$ should be quantized, based on minimizing the expression in (6). In the following, we examine the statistical properties of the underlying unitary matrices.

A. Statistics of Singular Matrices of a Random Gaussian Matrix

In most analytic studies of MIMO systems, the channel between the transmitter and the receiver is assumed to be Rayleigh fading. This indicates that the entries of the channel matrix are statistically independent and identically distributed, and have a complex Gaussian distribution with a zero mean. We are interested in the probability distribution of the singular matrices[1] of the mentioned channel matrix in the space of

[1]The probability distribution of a matrix is the joint PDF of its elements.

$M(n)$, namely the group of $n \times n$ unitary matrices. It is known that such a random unitary matrix takes its values uniformly from $M(n)$ in the sense of the following property [17].

Theorem 1 *Let us assume that* $\mathbf{U}$ *is a singular matrix of a random Gaussian matrix. For all* $\mathbf{V} \in M(n)$, *the distribution of* $\mathbf{U}$ *and* $\mathbf{VU}$ *are the same.*

Such a distribution is called the Haar distribution and the corresponding unitary matrices are called Haar unitary matrices [17]. We refer to this property as the right invariance property.

A complex $n \times n$ matrix can be described by $2n^2$ real parameters. However, the definition of a unitary matrix implies there is a dependency between these parameters. The number of equations describing this dependency for an $n \times n$ unitary matrix is $n + 2\binom{n}{2}$ (as the norm of each column is unit and every two columns are orthogonal to each other). Therefore, a unitary matrix $\mathbf{U}$ has $n^2 = 2n^2 - (n + 2\binom{n}{2})$ independent parameters. Here, for the purpose of matrix decomposition using SVD, n out of n^2 parameters are also redundant, since SVD can be performed such that the diagonal elements of $\mathbf{U}$ in (2) are set to be real. Several different approaches such as the Cayley transform, Householder reflection, and Givens rotations can be used to parameterize a complex $n \times n$ unitary matrix $\mathbf{U}$ in its $n^2 - n$ real parameters [15].

In this work, we consider the matrix decomposition using Givens matrices. Besides their ability to decompose the unitary matrix to the minimum number of parameters, the resulting parameters are statistically independent (Theorem 2). The independence property facilitates the quantization procedure.

A complex unitary matrix $\mathbf{U}$ can be decomposed in terms of the products of Givens matrices [15], i.e.,

$$\mathbf{U} = \prod_{k=1}^{n-1} \prod_{i=k+1}^{n} \mathbf{G}(k, i), \tag{7}$$

where each $\mathbf{G}(k,i)$ is an $n \times n$ unitary matrix with two parameters, c, and, s. Parameter c is in the position (k,k) and (i,i), s is in (k,i) and $-s^*$ is in (i,k), $k < i$. The other diagonal elements of the matrix $\mathbf{G}(k,i)$ are 1 and the remaining elements are zero. Since $\mathbf{G}(k,i)$ is a unitary matrix, then $|c|^2 + |s|^2 = 1$. In this work, we can assume that c is real since the SVD operation allows $\mathbf{U}$ to be multiplied by an arbitrary diagonal unitary matrix

In the following, the statistical properties of Givens matrices corresponding to a Haar unitary matrix $\mathbf{U}$ is derived. This will be later used to determine the quantization strategy. The key point of the codebook design for a Haar unitary matrix is the following result[2].

Theorem 2 *Let us assume that* $\mathbf{U}$ *is an* $n \times n$ *unitary matrix with a Haar distribution which is decomposed into Givens matrices as in (7). The set of Givens matrices* $\{\mathbf{G}(k,i)\}$ *for* $1 \le k < i \le n$ *are statistically independent of each other. Moreover, the PDF of the elements of* $\mathbf{G}(k,i)$ *is*

$$p_{k,i}(c, \angle s) = p_{k,i}(c)p(\angle s) = \frac{i-k}{\pi} c^{2(i-k)-1}, \quad 0 \le c \le 1, \quad \angle s \in [-\pi, \pi]. \tag{8}$$

The proof is omitted because of the limited space. See [11] for the details.

B. Quantization of Unitary Matrices

Based on the criterion presented for the quantizer design in (6), the distortion measure of the quantizer for matrix $\mathbf{U}$ is defined as follows:

$$D(U) = \frac{1}{2} E\mathrm{Tr}(\|\mathbf{U} - \widehat{\mathbf{U}}\|^2). \tag{9}$$

Substituting (7) in (9), we derive the first order approximation of $D(U)$ as follows:

$$D(U) \simeq \sum_{k=1}^{n-1} \sum_{i=k+1}^{n} D(G(k,i)), \tag{10}$$

where $D(G)$ is defined as follows:

$$D(G) = \frac{1}{2} E\mathrm{Tr}(\|\mathbf{G} - \widehat{\mathbf{G}}\|^2), \tag{11}$$

and $\widehat{\mathbf{G}}$ is the quantized version of $\mathbf{G}$. In the following, we use

$$\mathbf{G} = \begin{pmatrix} c & s \\ -s^* & c \end{pmatrix} \tag{12}$$

to refer to the non-trivial part of a Givens matrix.

1) Method A: The basic parameters of the Givens matrix, named c and $\theta = \angle s$, are quantized as $\widehat{c}$ and $\widehat{\theta}$, independently. The transmitter uses $\widehat{c}$ and $\widehat{\theta}$ to construct $\widehat{\mathbf{G}}$ as follows:

$$\widehat{\mathbf{G}} = \begin{pmatrix} \widehat{c} & |\widehat{s}|e^{j\widehat{\theta}} \\ -|\widehat{s}|e^{-j\widehat{\theta}} & \widehat{c} \end{pmatrix}, \tag{13}$$

where $|\widehat{s}| = \sqrt{1 - \widehat{c}^2}$. According to the construction scheme in (13) , $\widehat{\mathbf{G}}$ is also unitary. It can be easily demonstrated that the first order approximation of $D(G)$ is

$$D(G) \simeq E\left(\frac{(c - \widehat{c})^2}{1 - c^2}\right) + E(1 - c^2)E(\theta - \widehat{\theta})^2. \tag{14}$$

We apply (8) to simplify the following expression,

$$E(1 - c_{k,i}^2) = \frac{1}{2(i-k)+1}. \tag{15}$$

By applying (10) and (14), and (15), we write,

$$D(U) \simeq \sum_{k=1}^{n-1} \sum_{i=k+1}^{n} E\left(\frac{(c_{k,i} - \widehat{c}_{k,i})^2}{1 - c_{k,i}^2}\right) + \frac{1}{2(i-k)+1} E(\theta_{k,i} - \widehat{\theta}_{k,i})^2. \tag{16}$$

We design Linde-Buzo-Gray (LBG) quantizers for different $c_{k,i}$ and $\theta_{k,i}$ to minimize

$$E\left(\frac{(c_{k,i} - \widehat{c}_{k,i})^2}{1 - c_{k,i}^2}\right),$$

[2] As we mentioned earlier, after we accomplished this work, we became aware of [12] which independently proves a similar result.

and,

$$E(\theta_{k,i}-\widehat{\theta}_{k,i})^2,$$

respectively.

We utilize dynamic programming to find the optimum allocation of bits among the quantizers. We use a trellis diagram with $B+1$ states and n^2-n stages to allocate B bits to the quantizers of the independent parameters $c_{k,i}$ and $\theta_{k,i}$, $1 \leq i < k \leq n$ of the $n \times n$ unitary matrix. The lth state in jth stage corresponds to the distortion caused by the jth parameter using $l-1$ bits. In the trellis diagram, each branch represents the difference between the number of bits corresponding to the two ending states on the branch. The search through the trellis determines the path with minimum overall distortion and the corresponding number of bits for each parameter.

2) Method B: In this method, we quantize each Givens matrix as a unit and define a new parameterization for this purpose. The non-trivial part of a Givens matrix can be shown as follows:

$$\mathbf{G}=\begin{pmatrix} \cos(\eta) & e^{j\theta}\sin(\eta) \\ -e^{-j\theta}\sin(\eta) & \cos(\eta) \end{pmatrix}, \tag{17}$$

where $0 \leq \theta \leq 2\pi$ and $0 \leq \eta \leq \pi$. The distortion measure for $\mathbf{G}$, relative to a reference matrix with parameters η_0 and θ_0, is

$$D_0(G)=1-E(\cos(\eta)\cos(\eta_0)+\sin(\eta)\sin(\eta_0)\cos(\theta-\theta_0)). \tag{18}$$

We use the LBG algorithm to determine the regions and centroids of the two-dimensional quantizers corresponding to various (η,θ). The distortion function is

$$D=\sum_{m=1}^{M}\int_{R_m} D_m(G)p(\eta,\theta)d\eta d\theta, \tag{19}$$

where R_m is the mth quantization region and M is the number of quantization partitions. The centroid (η_m,θ_m) is determined iteratively by minimizing the distortion function in the region R_m,

$$\theta_m=\tan^{-1}(\frac{\varsigma_m}{\gamma_m}), \tag{20}$$

$$\eta_m=\tan^{-1}\left(\frac{\sqrt{\varsigma_m^2+\gamma_m^2}}{\int_{R_m}\cos^{l+1}(\eta)\sin(\eta)d\eta d\theta}\right), \tag{21}$$

where

$$\gamma_m=\int_{R_m}\cos^{l}(\eta)\sin^2(\eta)\cos(\theta)d\eta d\theta, \tag{22}$$

and,

$$\varsigma_m=\int_{R_m}\cos^{l}(\eta)\sin^2(\eta)\sin(\theta)d\eta d\theta, \tag{23}$$

and $l=2(i-k)-1$, in the case of quantizing $\mathbf{G}(k,i)$ in (7). By applying the above algorithm, we design codebooks of the matrices for different rates. In this method, a trellis diagram with the same structure as method A trellis diagram is used for optimum bit allocation. The trellis diagram contains $\frac{n^2-n}{2}$ stages, each corresponds to a Givens component of an $n \times n$ unitary matrix, and $B+1$ states (B is the number of bits). The lth state in jth stage corresponds to the distortion caused by the jth Givens matrix using $l-1$ bits.

IV. Feedback Design: Encoding of Rate Allocation Information

Besides the quantized right singular matrix of the channel that is fed back to the transmitter, information pertaining the rate that will be allocated to each subchannel is also fed back. This indicates a set of M_t indices from a set of N_R predetermined rates, e.g., the different modulation schemes. Obviously, the total rate is bounded, and since we can perform the SVD of the channel matrix so that the singular values become ordered, the M_t indices correspond to an ordered set of increasing positive integers (rates). To encode this information, we can use a trellis diagram with N_R states and M_t stages. The states correspond to the set of possible rates in an increasing fashion, and there is a branch from each state to another state in the next stage, only if the entering state is located at the same or at a lower level position. Each path in the trellis then corresponds to a set of subchannel rates, whose index is chosen by the receiver and fed back to the transmitter. The trellis structure exploits the ordering property of the rates, and therefore, allows their efficient coding at a rate of [18]

$$R_{rate}=\left\lceil \log_2\binom{M_t+N_R-1}{N_R-1}\right\rceil. \tag{24}$$

The complexity of this algorithm is very low and is, in fact, proportional to the number of states. Similar structures have been used to address the points of a block-based trellis quantizer in [18], or a pyramid vector quantizer in [19].

V. Performance Evaluation

In this section, we present the performance results of the system, described in Section II. We assume that the precoding is performed by the quantized version of the right singular matrix of the channel by applying the quantization methods presented in Section III-B. For the different subchannels, we use different modulation schemes. The process of selecting the appropriate modulation scheme for each subchannel is accomplished at the receiver. We restrict the system to transmit data with the power $\frac{\mathcal{E}}{M_t}$ on each transmit antenna. It means that the power is equally distributed among data symbols, since we use an orthonormal precoder. Therefore the rate is maximized based on continuous approximation concept. At the receiver, the channel state information and the instantaneous quantization noise power is assumed to be available. For each subchannel, the probability of error is computed for different modulation schemes. The receiver selects a modulation scheme for each subchannel that achieves the target Bit Error Rate (BER) of the system and sends the indices of the corresponding modulation schemes to the transmitter through the feedback channel that was described in Section IV. The received SNR at the kth subchannel is,

$$SNR_k=\frac{\mathcal{E}\lambda_k^2}{M_t(\sigma^2+\widehat{\sigma}_k^2)}, \tag{25}$$

where $\widehat{\sigma}_k^2$ is the corresponding quantization noise variance of the kth subchannel. We consider a set of QAM modulation formats. At the receiver, the rate r_k of kth subchannel is computed as follows,

$$\max_{P(SNR_k)\leq P_b} r_k, \tag{26}$$

where P_b is the target BER of the system and $P(SNR)$, the BER function of the modulation scheme with rate r, is [20]

$$P(SNR) \approx \frac{4}{r} Q\left(\sqrt{\frac{3r SNR}{2^r - 1}}\right), \tag{27}$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{x^2}{2}} dx$.

The SVD and Givens decomposition are performed at the receiver. The number of computations required by the SVD and Givens decomposition for an $n \times n$ matrix are $21n^3$ and $3n^2(n-1)$ flops, respectively [15].

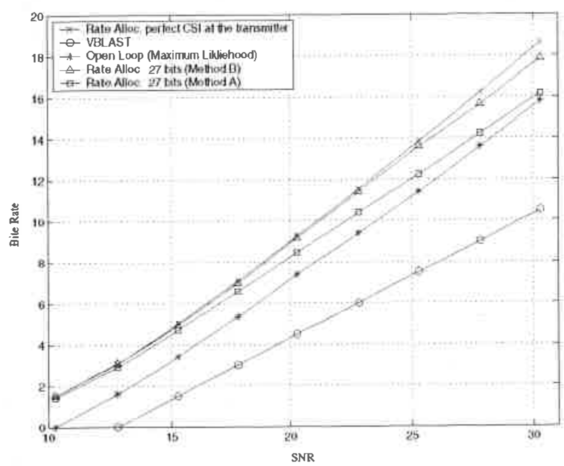

Fig. 1. The average bit rate for different schemes where $M_t = 3$ and $M_r = 3$. The target BER$= 5 \times 10^{-3}$.

Figure 1 shows the average bit rate versus SNR for different MIMO systems with $M_t = 3$ and $M_r = 3$ at the target BER$= 5 \times 10^{-3}$. We use 8 bits for the feedback of the right singular matrix. The modulation schemes we use are QAMs with bit rates between 1 and 7, inclusively, and then $N_R = 8$. We use 6 bits for the feedback of the rate allocation vector in each transmission block (the number of bits is derived by applying (24)). The two quantization methods presented in Section III-B are compared. Method B outperforms method A at the cost of complexity. The average bit rate of a 3×3 MIMO system with ML decoding is depicted. It can be seen that the performance gain, compared to the gain of the ML decoding of the open loop system is noticeable. For example, at the bit rate= 10 the system has a 3 dB improvement in comparison to the optimum open loop system. We also compare the performance of this system with that of a V-BLAST system which is proposed as a solution to overcome the complexity problem. Figure 1 displays a significant improvement in comparison to the V-BLAST at the price of the feedback. The performance of the system, if perfect channel information is available at the transmitter, is also depicted.

VI. Conclusion

In this work, we have presented efficient methods for the channel information quantization in a high data rate MIMO system. We have developed efficient algorithms for the quantization of the underlying unitary matrices. Also, we have presented a low rate indexing of rate allocation information. The simulation results show a significant improvement compared to MIMO systems without feedback at the cost of a very low-rate feedback link.

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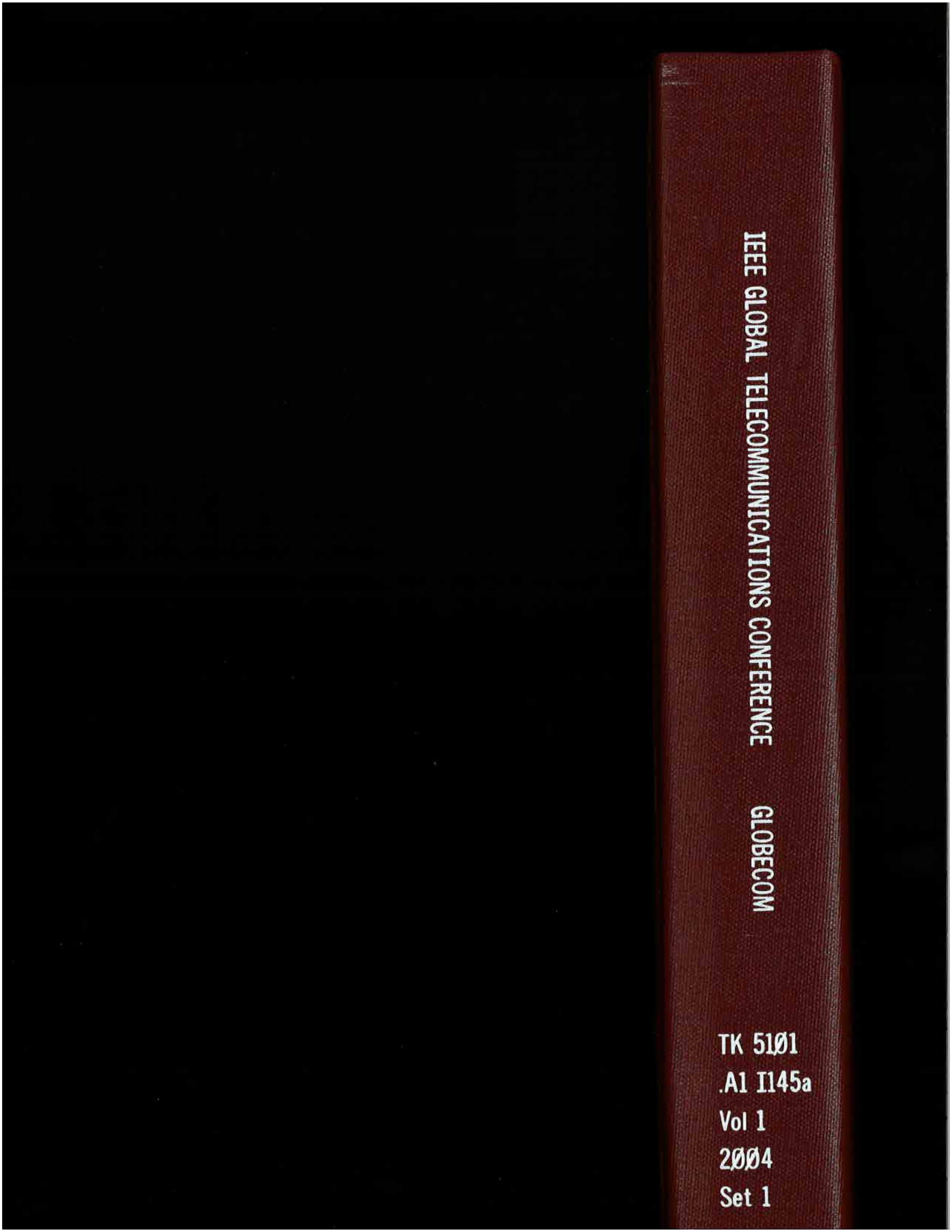
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