PROCEEDINGS OF SPIE

SPIDigitalLibrary.org/conference-proceedings-of-spie

Front Matter: Volume 7814

, "Front Matter: Volume 7814," Proc. SPIE 7814, Free-Space Laser Communications X, 781401 (20 September 2010); doi: 10.1117/12.876294

SPIE.

Event: SPIE Optical Engineering + Applications, 2010, San Diego, California, United States

PROCEEDINGS OF SPIE

Free-Space Laser Communications X

**Arun K. Majumdar
Christopher C. Davis**
Editors

**2–3 August 2010
San Diego, California, United States**

Sponsored and Published by
SPIE

Volume 7814

Proceedings of SPIE, 0277-786X, v. 7814

SPIE is an international society advancing an interdisciplinary approach to the science and application of light.

The papers included in this volume were part of the technical conference cited on the cover and title page. Papers were selected and subject to review by the editors and conference program committee. Some conference presentations may not be available for publication. The papers published in these proceedings reflect the work and thoughts of the authors and are published herein as submitted. The publisher is not responsible for the validity of the information or for any outcomes resulting from reliance thereon.

Please use the following format to cite material from this book:

Author(s), "Title of Paper," in *Free-Space Laser Communications X*, edited by Arun K. Majumdar, Christopher C. Davis, Proceedings of SPIE Vol. 7814 (SPIE, Bellingham, WA, 2010) Article CID Number.

ISSN 0277-786X

ISBN 9780819483102

Published by

SPIE

P.O. Box 10, Bellingham, Washington 98227-0010 USA

Telephone +1 360 676 3290 (Pacific Time) · Fax +1 360 647 1445

SPIE.org

Copyright © 2010, Society of Photo-Optical Instrumentation Engineers

Copying of material in this book for internal or personal use, or for the internal or personal use of specific clients, beyond the fair use provisions granted by the U.S. Copyright Law is authorized by SPIE subject to payment of copying fees. The Transactional Reporting Service base fee for this volume is \$18.00 per article (or portion thereof), which should be paid directly to the Copyright Clearance Center (CCC), 222 Rosewood Drive, Danvers, MA 01923. Payment may also be made electronically through CCC Online at copyright.com. Other copying for republication, resale, advertising or promotion, or any form of systematic or multiple reproduction of any material in this book is prohibited except with permission in writing from the publisher. The CCC fee code is 0277-786X/10/\$18.00.

Printed in the United States of America.

Publication of record for individual papers is online in the SPIE Digital Library.

SPIE
Digital Library

SPIDigitalLibrary.org

Paper Numbering: Proceedings of SPIE follow an e-First publication model, with papers published first online and then in print and on CD-ROM. Papers are published as they are submitted and meet publication criteria. A unique, consistent, permanent citation identifier (CID) number is assigned to each article at the time of the first publication. Utilization of CIDs allows articles to be fully citable as soon they are published online, and connects the same identifier to all online, print, and electronic versions of the publication. SPIE uses a six-digit CID article numbering system in which:

- The first four digits correspond to the SPIE volume number.
- The last two digits indicate publication order within the volume using a Base 36 numbering system employing both numerals and letters. These two-number sets start with 00, 01, 02, 03, 04, 05, 06, 07, 08, 09, 0A, 0B ... 0Z, followed by 10-1Z, 20-2Z, etc.

The CID number appears on each page of the manuscript. The complete citation is used on the first page, and an abbreviated version on subsequent pages. Numbers in the index correspond to the last two digits of the six-digit CID number.

Contents

vii	Conference Committee
ix	Introduction

SESSION 1 FSO SYSTEM PERFORMANCE

7814 02	Performance of a 10 Gbps QoS-based buffer in a FSO/RF IP network (Invited Paper) [7814-01] R. Peach, G. Burdge, F. Reitberger, C. Visone, M. Oyler, C. Jensen, J. Sonnenberg, Harris Corp. (United States)
7814 03	Pointing performance of an aircraft-to-ground optical communications link [7814-02] M. W. Regehr, A. Biswas, J. M. Kovalik, M. W. Wright, Jet Propulsion Lab. (United States)
7814 04	Non-line-of-sight link performance study for indoor visible light communication systems [7814-03] Z. Dong, K. Cui, G. Chen, Z. Xu, Univ. of California, Riverside (United States)
7814 05	Molecular inspired models for prediction and control of directional FSO/RF wireless networks [7814-04] J. Llorca, S. D. Milner, C. C. Davis, Univ. of Maryland, College Park (United States)
7814 06	Wireless optical network for a home network [7814-05] O. Bouchet, P. Porcon, France Télécom, Cesson-Sévigné (France); J. W. Walewski, S. Nerreter, Siemens AG (Germany); K.-D. Langer, L. Fernández, J. Vučić, Fraunhofer-HHL (Germany); T. Kamalakis, G. Ntogiari, I. Neokosmidis, Univ. of Athens (Greece); E. Gueutier, Apside (France)

SESSION 2 INDOOR OPTICAL WIRELESS AND NON-LINE-OF-SIGHT FSO COMMUNICATION

7814 07	Experimental demonstration of non-line-of-sight ultraviolet communication channel characteristics [7814-06] G. Chen, Z. Xu, Univ. of California, Riverside (United States); B. M. Sadler, U.S. Army Research Lab. (United States)
7814 08	Gigabit class high-speed indoor optical wireless: system design, challenges and results [7814-07] D. O'Brien, Univ. of Oxford (United Kingdom); H. Le Minh, Northumbria Univ. (United Kingdom); G. Faulkner, Univ. of Oxford (United Kingdom); M. Wolf, L. Grobe, J. Li, Technische Univ. Ilmenau (Germany); O. Bouchet, France Telecom R&D (France)
7814 09	Performance of non-line-of-sight ultraviolet communication receiver in ISI channel [7814-08] L. Wang, Q. He, Z. Xu, Univ. of California, Riverside (United States); B. M. Sadler, U.S. Army Research Lab. (United States)

- 7814 0A **Energy scavenging sensors for ultra-low power sensor networks** [7814-09]
D. C. O'Brien, J. J. Liu, G. E. Faulkner, P. Vachiramon, S. Collins, S. J. Elston, Univ. of Oxford (United Kingdom)

SESSION 3 FADE MITIGATION, CODING, AND NETWORKING

- 7814 0C **Aperture averaging in a laser Gaussian beam: simulations and experiments** [7814-12]
R. Barrios, F. Dios, J. Reolons, A. Rodriguez, Univ. Politècnica de Catalunya (Spain)
- 7814 0D **Performance measures in acousto-optic chaotic signal encryption system subject to parametric variations and additive noise** [7814-13]
M. R. Chatterjee, Univ. of Dayton (United States); A. K. Ghosh, The Univ. of Oklahoma, Tulsa (United States); M. A. Al-Saedi, Univ. of Dayton (United States)
- 7814 0E **Free space optical sensor network for short-range applications** [7814-14]
N. Agrawal, S. D. Milner, C. C. Davis, Univ. of Maryland, College Park (United States)

SESSION 4 OPTICAL TURBULENCE CHARACTERIZATION AND BEAM PROPAGATION I

- 7814 0H **Turbulence strength and temporal correlation in a terrestrial laser communication link** [7814-16]
J. A. Anguita, J. E. Cisternas, Univ. de Los Andes (Chile)
- 7814 0I **Coupling turbulence-distorted wave front to fiber: wave propagation theory perspective** [7814-17]
M. Charnotskii, Zel Technologies, LLC (United States) and NOAA/Earth System Research Lab. (United States)
- 7814 0J **Portable daytime differential image motion sensor for atmospheric turbulence characterization** [7814-18]
M. Belen'kii, T. Brinkley, D. Bruns, L. DiRuscio, H. Runyeon, V. Rye, L. Angell, Trex Enterprises Corp. (United States); D. Haddock, S. Hammel, M. Lasher, Space and Naval Warfare Systems Command (United States)
- 7814 0K **Comparing the Log-Normal and Gamma-Gamma model to experimental probability density functions of aperture averaging data** [7814-19]
D. T. Wayne, R. L. Phillips, L. C. Andrews, T. Leclerc, P. Sauer, Univ. of Central Florida (United States); J. Stryjewski, Computer Sciences Corp. (United States)

SESSION 5 OPTICAL TURBULENCE CHARACTERIZATION AND BEAM PROPAGATION II

- 7814 0O **Channel estimation for free-space optical communications: preliminary experimental results and analysis** [7814-23]
C. N. Reinhardt, Y. Kuga, J. Ritcey, A. Ishimaru, Univ. of Washington (United States); S. Hammel, D. Tsintikidis, Space and Naval Warfare Systems Ctr., San Diego (United States)

- 7814 OP **Field measurements and comparisons to simulations of high energy laser propagation and off-axis scatter** [7814-24]
S. T. Fiorino, R. M. Randall, R. J. Bartell, J. D. Haiducek, M. F. Spencer, S. J. Cusumano, Air Force Institute of Technology (United States)
- 7814 OQ **Estimating turbulence in images** [7814-25]
M. van Iersel, A. M. J. van Eijk, TNO Defence, Security and Safety (Netherlands)
- 7814 OR **Gaussian beam propagation in maritime atmospheric turbulence: long term beam spread and beam wander analysis** [7814-26]
I. Toselli, B. Agrawal, Naval Postgraduate School (United States); S. Restaino, Naval Research Lab. (United States)

SESSION 6 COMPONENTS AND SYSTEM DESIGN AND ANALYSIS I

- 7814 OS **Coherent beam combining and optical space-time division multiple access** [7814-27]
W. Miniscalco, Raytheon Co. (United States); S. A. Lane, Air Force Research Lab. (United States); K. Fisher, S. Waite, M. Howlett, I. Smith, Raytheon Co. (United States)
- 7814 OT **Beam queuing for aeronautical free space optical networks** [7814-28]
K. Karras, D. Marinos, P. Kouros, Technological Educational Institute of Piraeus (Greece)
- 7814 OU **Free-space optics based sensor network design using angle-diversity photodiode arrays** [7814-29]
A. K. Ghosh, S. Kunta, P. Verma, R. C. Huck, The Univ. of Oklahoma, Tulsa (United States)
- 7814 OV **Evaluating M-ary PSK multiple-subcarrier modulation over FSO links using aperture averaging** [7814-30]
C. Ben Naila, A. Bekkali, K. Kazaura, K. Wakamori, M. Matsumoto, Waseda Univ. (Japan)

SESSION 7 COMPONENTS AND SYSTEM DESIGN AND ANALYSIS II

- 7814 OY **Air-to-ground lasercom system demonstration design overview and results summary** [7814-33]
F. G. Walther, S. Michael, R. R. Parenti, J. A. Taylor, MIT Lincoln Lab. (United States)
- 7814 OZ **Comparisons of C_n^2 measurements and power-in-fiber data from two long-path free-space optical communication experiments** [7814-34]
R. R. Parenti, S. Michael, J. M. Roth, T. M. Yarnall, MIT Lincoln Lab. (United States)

POSTER SESSION

- 7814 10 **Control loop analysis of the complex axis in satellite laser communications** [7814-35]
W. Lu, L. Liu, J. Sun, Y. Zhou, Y. Wu, Shanghai Institute of Optics and Fine Mechanics (China)
- 7814 11 **Design and fabrication of optical 90° hybrid by birefringent crystals for coherent receiver in free-space optical communication system** [7814-36]
Y. Zhi, Y. Zhou, J. Sun, L. Liu, Shanghai Institute of Optics and Fine Mechanics (China)
- 7814 12 **Self-homodyne interferometric detection in 2×4 optical hybrid for free-space optical communication** [7814-37]
Y. Zhi, Y. Zhou, J. Sun, A. Yan, Z. Luan, L. Liu, Shanghai Institute of Optics and Fine Mechanics (China)
- 7814 14 **Propagation study of 850nm/58 GHz hybrid municipal system** [7814-39]
O. Wilfert, Brno Univ. of Technology (Czech Republic); V. Kvicera, Czech Metrology Institute (Czech Republic); Z. Kolka, Brno Univ. of Technology (Czech Republic); M. Grabner, Czech Metrology Institute (Czech Republic); O. Fiser, Institute of Atmospheric Physics (Czech Republic)
- 7814 15 **On decoding (31, 16, 7) quadratic residue code up to its error correcting capacity with bit-error probability estimates** [7814-40]
T.-C. Lin, P.-Y. Shih, W.-K. Su, T.-K. Truong, I-Shou Univ. (Taiwan)

Author Index

Conference Committee

Program Track Chairs

Stephen M. Hammel, Space and Naval Warfare Systems Center,
San Diego (United States)

Alexander M. J. van Eijk, TNO Defense, Security and Safety
(Netherlands)

Conference Chairs

Arun K. Majumdar, Naval Air Warfare Center (United States)

Christopher C. Davis, University of Maryland, College Park (United
States)

Program Committee

Larry C. Andrews, University of Central Florida (United States)

Shlomi Arnon, Ben-Gurion University of the Negev (Israel)

Mikhail S. Belen'kii, Trex Enterprises Corporation (United States)

Don M. Boroson, MIT Lincoln Laboratory (United States)

Naresh Chand, BAE Systems (United States)

Bernhard Eppe, DLR Standort Oberpfaffenhofen (Germany)

G. Charmaine Gilbreath, Naval Research Laboratory (United States)

Stephen M. Hammel, Space and Naval Warfare Systems Center, San
Diego (United States)

Hennes Henniger, DLR Standort Oberpfaffenhofen (Germany)

Stuart D. Milner, University of Maryland, College Park (United States)

Michela Muñoz Fernández, Jet Propulsion Laboratory (United States)

Dominic C. O'Brien, University of Oxford (United Kingdom)

Jacobus M. Oschmann, Jr., Ball Corporation (United States)

Ronald R. Parenti, MIT Lincoln Laboratory (United States)

Narasimha S. Prasad, NASA Langley Research Center (United States)

William S. Rabinovich, Naval Research Laboratory (United States)

Marcos Reyes Garcia-Talavera, Instituto de Astrofísica de Canarias
(Spain)

Michael C. Roggemann, Michigan Technological University (United
States) and Pacific Defense Solutions (United States)

Larry B. Stotts, Defense Advanced Research Projects Agency (United
States)

Alexander M. J. van Eijk, TNO Defence, Security and Safety
(Netherlands)

Session Chairs

- 1 FSO System Performance
Arun K. Majumdar, Naval Air Warfare Center (United States)
Christopher C. Davis, University of Maryland, College Park (United States)
- 2 Indoor Optical Wireless and Non-Line-of-Sight FSO Communication
Dominic C. O'Brien, University of Oxford (United Kingdom)
Arun K. Majumdar, Naval Air Warfare Center (United States)
- 3 Fade Mitigation, Coding, and Networking
Michael C. Roggemann, Michigan Technological University (United States) and Pacific Defense Solutions (United States)
Aleksandr V. Sergeev, Michigan Technological University (United States)
- 4 Optical Turbulence Characterization and Beam Propagation I
Stephen M. Hammel, Space and Naval Warfare Systems Center, San Diego (United States)
Mikhail S. Belen'kii, Trex Enterprises Corporation (United States)
- 5 Optical Turbulence Characterization and Beam Propagation II
Alexander M. J. van Eijk, TNO Defence, Security and Safety (Netherlands)
Christopher C. Davis, University of Maryland, College Park (United States)
- 6 Components and System Design and Analysis I
Frederick G. Walther, MIT Lincoln Laboratory (United States)
Arun K. Majumdar, Naval Air Warfare Center (United States)
- 7 Components and System Design and Analysis II
Anjan K. Ghosh, The University of Oklahoma, Tulsa (United States)
Chedlia Ben Naila, Waseda University (Japan)

Introduction

This volume contains the papers submitted and accepted as full manuscripts following presentation at the Free-Space Laser Communications X conference. The papers in this volume also include papers that deal with imaging through the turbulent atmosphere, especially in the marine layer. Free space optical (FSO) communication is now a mature field, but many exciting fundamental and technological challenges remain to improve its performance in a range of scenarios. The data rates provided by FSO links continue to increase in both long and short range applications. The performance of communication networks containing such links in addition to directional and omnidirectional RF connections continues, however, to present research challenges. Military applications of FSO technology, including the simultaneous use of directional RF communication links involving long range links, with mobile and airborne platforms, remains an area of active research and development. Very long range terrestrial links through the atmosphere can experience severe scintillation caused by atmospheric turbulence, which presents significant challenges in beam pointing and leads to deep fades. Some questions remain regarding how much the performance of FSO links through atmospheric turbulence can be improved with adaptive optics, and how these improvements depend on the length of the link. The performance of free space links can also be improved by forward error correction, interleaving, and packet-level correction codes. Clever transceiver implementations, new beam profiles, and the right modulation schemes can also improve link performance. Non-line-of-sight links using solar blind UV radiation scattered from transmitter to receiver open interesting communication scenarios. There continues to be great interest in modeling the optical channel through the atmosphere for both low and high power lasers. All these issues are addressed in papers published in this volume.

The use of FSO communications in indoor spaces for secure communications and sensor networking over short ranges is attracting attention as a non-interfering alternative to RF communications, and several papers address this important area of research and development. A number of papers describe novel transceiver and sub-system designs for FSO communications, both terrestrial and from ground to space. At a fundamental level, several papers address measurements of the effects of the atmosphere on propagating beam waves, where atmospheric properties can be measured, and correlated with theoretical models describing phenomena such as obscuration, beam wander, scintillation and image motion.

Arun K. Majumdar
Christopher C. Davis