

Peter Adam Hoehner

# Visible Light Communications

Solutions Manual



HANSER

Hoeher

**Visible Light Communications  
Solutions Manual**



Peter Adam Hoeher

# Visible Light Communications

Solutions Manual

Hanser Publishers, Munich

HANSER  
Hanser Publications, Cincinnati

**The Author:**

Prof. Dr. Peter A. Hoeher,

Fellow of the IEEE, is a Full Professor of electrical and information engineering at Kiel University, Kiel, Germany

Distributed in the Americas by:

Hanser Publications

6915 Valley Avenue, Cincinnati, Ohio 45244-3029, USA

Fax: (513) 527-8801

Phone: (513) 527-8977

[www.hanserpublications.com](http://www.hanserpublications.com)

Distributed in all other countries by:

Carl Hanser Verlag

Postfach 86 04 20, 81631 München, Germany

Fax: +49 (89) 98 48 09

[www.hanser-fachbuch.de](http://www.hanser-fachbuch.de)

The use of general descriptive names, trademarks, etc., in this publication, even if the former are not especially identified, is not to be taken as a sign that such names, as understood by the Trade Marks and Merchandise Marks Act, may accordingly be used freely by anyone. While the advice and information in this book are believed to be true and accurate at the date of going to press, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

The final determination of the suitability of any information for the use contemplated for a given application remains the sole responsibility of the user.

All rights reserved. No part of this book may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying or by any information storage and retrieval system, without permission in writing from the publisher.

© Carl Hanser Verlag, Munich 2020

Editor: Dipl.-Ing. Natalia Silakova-Herzberg

Production management: Anne Kurth

Cover design: Max Kostopoulos

Cover concept: Marc Müller-Bremer, [www.rebranding.de](http://www.rebranding.de), Munich, Germany

Typesetting: Peter Adam Hoeher, Heikendorf, Germany

Printed in Germany

E-Book-ISBN            978-3-446-46303-5

# Preface

This solutions manual complements the textbook

*Visible Light Communications: Theoretical and Practical Foundations*,

Munich: Carl Hanser Verlag, 2019, ISBN: 978-3-446-46206-9,

E-Book: ISBN: 978-3-446-46172-7.

## ■ Disclaimer

Although the solutions manual has been prepared carefully, typographical errors and mistakes are possible. The author is responsible for any flaw. Feedback by email to

VLC-book@web.de

is welcome.

Kiel, Germany, September 2019

Peter Adam Hoeher

# Table of Contents

|          |                                                       |           |
|----------|-------------------------------------------------------|-----------|
| <b>1</b> | <b>Introduction .....</b>                             | <b>1</b>  |
| 1.1      | Historical OWC Applications .....                     | 1         |
| 1.2      | OWC Applications .....                                | 1         |
| 1.3      | Advantages of VLC .....                               | 2         |
| 1.4      | Technical Problems of VLC .....                       | 3         |
| 1.5      | Latency of VLC .....                                  | 4         |
| 1.6      | VLC Applications.....                                 | 4         |
| 1.7      | Camera-Based VLC .....                                | 6         |
| <b>2</b> | <b>Fundamentals of Illumination Engineering .....</b> | <b>7</b>  |
| 2.1      | Electromagnetic Pollution .....                       | 7         |
| 2.2      | Daylight Harvesting .....                             | 8         |
| 2.3      | CIE 1931 XYZ, RGB, and HSV Color Spaces .....         | 8         |
| 2.4      | CIE 1931 xy Chromaticity Diagram, Part I .....        | 10        |
| 2.5      | CIE 1931 xy Chromaticity Diagram, Part II .....       | 12        |
| 2.6      | Eye Sensitivity Function .....                        | 14        |
| 2.7      | Color Blindness .....                                 | 15        |
| 2.8      | Efficiency Measures of Light Sources .....            | 16        |
| <b>3</b> | <b>VLC and IR/UV Channel Modeling.....</b>            | <b>18</b> |
| 3.1      | Generalized Lambertian Source .....                   | 18        |
| 3.2      | Line-of-Sight Channel Modeling .....                  | 19        |
| 3.3      | Non-Line-of-Sight Channel Modeling .....              | 20        |
| 3.4      | Optical Underwater Channel Modeling .....             | 20        |
| 3.5      | Crest Factor for Intensity Modulation.....            | 21        |
| 3.6      | Shot Noise, Thermal Noise, and Dark Current .....     | 22        |
| 3.7      | Signal-to-Noise Ratio of OWC Systems .....            | 23        |

|          |                                                                         |           |
|----------|-------------------------------------------------------------------------|-----------|
| <b>4</b> | <b>Modulation Schemes for Optical Wireless Communications .....</b>     | <b>24</b> |
| 4.1      | Intensity Modulation with Direct Detection .....                        | 24        |
| 4.2      | Linear Modulation Schemes .....                                         | 25        |
| 4.3      | On-Off Keying .....                                                     | 26        |
| 4.4      | Amplitude Shift Keying .....                                            | 27        |
| 4.5      | Pulse Position Modulation .....                                         | 28        |
| 4.6      | Carrierless Amplitude and Phase Modulation .....                        | 29        |
| 4.7      | Color-Domain Modulation Schemes .....                                   | 30        |
| 4.8      | Multi-Carrier Modulation Schemes .....                                  | 31        |
| 4.9      | Code-Division Multiplexing .....                                        | 32        |
| 4.10     | Superposition Modulation .....                                          | 33        |
| 4.11     | Optical Camera Communication .....                                      | 33        |
| <b>5</b> | <b>Optical Multiple-Input Multiple-Output (MIMO) Techniques .....</b>   | <b>34</b> |
| 5.1      | Optical MIMO Channel Modeling .....                                     | 34        |
| 5.2      | Optical Space-Time Block Codes .....                                    | 35        |
| 5.3      | Spatial Diversity .....                                                 | 35        |
| 5.4      | Spatial Optical Multi-Carrier Modulation .....                          | 36        |
| 5.5      | Superposition Modulation .....                                          | 37        |
| 5.6      | Interference-Avoidance Modulation Techniques .....                      | 38        |
| 5.7      | Optical Camera Communication .....                                      | 39        |
| <b>6</b> | <b>OWC Standardization .....</b>                                        | <b>40</b> |
| 6.1      | Infrared Standardization .....                                          | 40        |
| 6.2      | Current Standardization Efforts .....                                   | 41        |
| 6.3      | Flicker Mitigation and Dimming Assistance .....                         | 41        |
| 6.4      | Color Shift Keying .....                                                | 43        |
| <b>7</b> | <b>Software-Defined Radio Concept and its Applications in OWC .....</b> | <b>46</b> |
| 7.1      | Software-Defined Radio Concept .....                                    | 46        |
| 7.2      | Strengths and Weaknesses of the Software-Defined Radio Concept .....    | 46        |
| 7.3      | Adaptive, Cognitive, and Intelligent Radio .....                        | 47        |
| 7.4      | Hardware-Friendly Modulation Schemes .....                              | 48        |
| 7.5      | Hardware Platforms for OWC Applications .....                           | 48        |
| <b>8</b> | <b>Photonic Devices and High-Speed Amplifiers .....</b>                 | <b>50</b> |
| 8.1      | DC and AC Behavior of III-V LEDs .....                                  | 50        |
| 8.2      | Organic LEDs .....                                                      | 51        |
| 8.3      | Micro-LEDs and Laser Diodes .....                                       | 51        |

|           |                                                                      |           |
|-----------|----------------------------------------------------------------------|-----------|
| 8.4       | Silicon Photodiodes .....                                            | 52        |
| 8.5       | Noise-Equivalent Power of a Photodiode.....                          | 53        |
| 8.6       | Equivalent Circuit Model of a Photodetector .....                    | 54        |
| 8.7       | Operational Amplifiers .....                                         | 54        |
| <b>9</b>  | <b>Circuit Design Rules for OWC Transmitters and Receivers .....</b> | <b>58</b> |
| 9.1       | Elementary LED Driver .....                                          | 58        |
| 9.2       | Constant-Current Source .....                                        | 59        |
| 9.3       | Buck Converter .....                                                 | 60        |
| 9.4       | Multi-String LED Driver.....                                         | 61        |
| 9.5       | Basic Design Criteria for LED Drivers .....                          | 62        |
| 9.6       | Transimpedance Amplifier .....                                       | 62        |
| 9.7       | Ambient Light Compensation .....                                     | 63        |
| <b>10</b> | <b>Selected VLC and FSO Applications .....</b>                       | <b>66</b> |
| 10.1      | Light Fidelity.....                                                  | 66        |
| 10.2      | Optical Underwater Communication .....                               | 68        |
| 10.3      | Wireless Ethernet .....                                              | 69        |
| 10.4      | Optical Relaying.....                                                | 71        |
| 10.5      | Hybrid Microwave/Free-Space Optical Communication .....              | 72        |
| <b>11</b> | <b>Optical Rangefinding and Visible Light Positioning.....</b>       | <b>74</b> |
| 11.1      | Distance Estimation by Runtime Measurements .....                    | 74        |
| 11.2      | Distance Estimation by Triangulation .....                           | 77        |
| 11.3      | Time-of-Arrival Localization .....                                   | 78        |
| 11.4      | Time-Difference-of-Arrival Localization .....                        | 78        |
| 11.5      | Angle-of-Arrival Localization .....                                  | 79        |
| 11.6      | Hybrid Localization .....                                            | 80        |