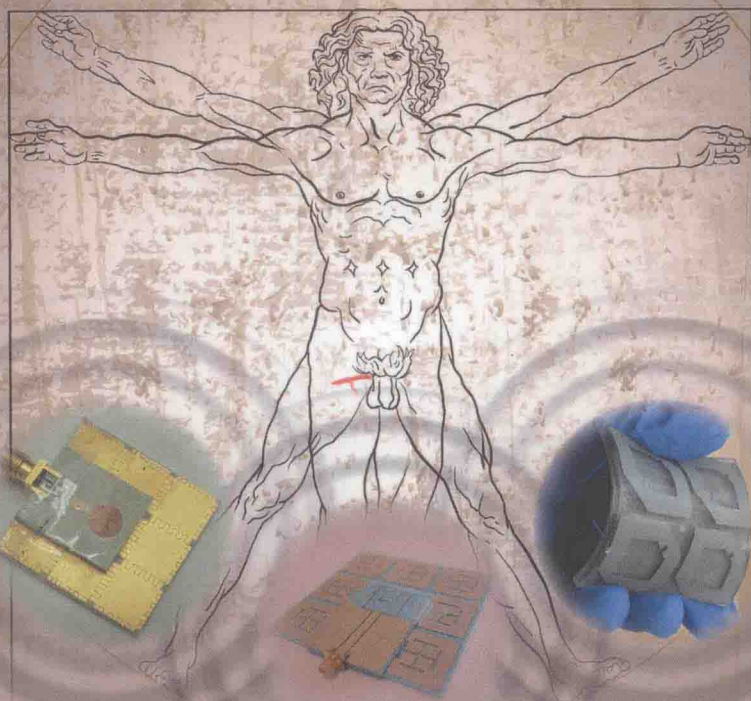


EDITED BY
DOUGLAS H. WERNER AND ZHI HAO JIANG

Electromagnetics of Body Area Networks

Antennas, Propagation, and RF Systems




IEEE PRESS

WILEY

ELECTROMAGNETICS OF BODY-AREA NETWORKS

**Antennas, Propagation,
and RF Systems**

Edited by

**DOUGLAS H. WERNER
ZHI HAO JIANG**


IEEE PRESS

WILEY

Copyright © 2016 by The Institute of Electrical and Electronics Engineers, Inc.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey. All rights reserved.
Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at <http://www.wiley.com/go/permission>.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at www.wiley.com.

Library of Congress Cataloging-in-Publication Data is available.

ISBN: 978-1-119-02946-5

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

LIST OF CONTRIBUTORS

Kush Agarwal, Department of Electrical and Computer Engineering, National University of Singapore, Singapore

Sara Amendola, Department of Civil Engineering and Informatics, University of Rome Tor Vergata, Rome, Italy

Joonsung Bae, Department of Electrical Engineering, Korea Advanced Institute of Science and Technology, Daejeon, Republic of Korea

Nacer Chahat, NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

Zhi Ning Chen, Institute for Infocomm Research, A*STAR, Singapore, and Department of Electrical and Computer Engineering, National University of Singapore, Singapore

ChristianENZ, Integrated Circuits Laboratory (ICLAB), IMT Institute, École Polytechnique Fédérale de Lausanne, Neuchâtel, Switzerland

Yong-Xin Guo, Department of Electrical and Computer Engineering, National University of Singapore, Singapore

Anda Guraliuc, Institute of Electronics and Telecommunications of Rennes, UMR CNRS 6164, University of Rennes 1, Rennes, France

Yang Hao, School of Electronic Engineering and Computer Science, Queen Mary University of London, London, UK

Aravind Prasad Heragu, Semtech Neuchâtel Sàrl, Neuchâtel, Switzerland

- Koichi Ito**, Center for Frontier Medical Engineering, Chiba University, Chiba-shi, Japan
- Zhi Hao Jiang**, Department of Electrical Engineering, Pennsylvania State University, University Park, PA, USA
- John Kimionis**, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA
- Gianluca Lazzi**, Department of Electrical and Computer Engineering, University of Utah, Salt Lake City, UT, USA
- Gaetano Marrocco**, Department of Civil Engineering and Informatics, University of Rome Tor Vergata, Rome, Italy
- Max O. Munoz**, School of Electronic Engineering and Computer Science, Queen Mary University of London, London, UK
- Cecilia Occhiuzzi**, Department of Civil Engineering and Informatics, University of Rome Tor Vergata, Rome, Italy
- Xianming Qing**, Institute for Infocomm Research, A*STAR, Singapore
- Yahya Rahmat-Samii**, Department of Electrical Engineering, University of California, Los Angeles, CA, USA
- Harish Rajagopalan**, Department of Electrical Engineering, University of California, Los Angeles, CA, USA
- Anil K. RamRakhyani**, Department of Electrical and Computer Engineering, University of Utah, Salt Lake City, UT, USA
- Hendrik Rogier**, Department of Information Technology, Ghent University, Ghent, Belgium, and iMinds, Ghent, Belgium
- Ronan Sauleau**, Institute of Electronics and Telecommunications of Rennes, UMR CNRS 6164, University of Rennes 1, Rennes, France
- Terence Shie Ping See**, Institute for Infocomm Research, A*STAR, Singapore
- Ping Jack Soh**, Advanced Communication Engineering Centre, School of Computer and Communication Engineering, Universiti Malaysia Perlis, Arau, Perlis, Malaysia
- Adrian Tang**, NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
- Manos (Emmanouil) M. Tentzeris**, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA
- Raghavasimhan Thirunarayanan**, Integrated Circuits Laboratory (ICLAB), IMT Institute, École Polytechnique Fédérale de Lausanne, Neuchâtel, Switzerland

Patrick Van Torre, Department of Information Technology, Ghent University, Ghent, Belgium, and iMinds, Ghent, Belgium

Guido Valerio, Laboratoire d'Electronique et Electromagnétisme, Sorbonne Universités – Université Pierre et Marie Curie, Paris, France

Luigi Vallozzi, Department of Information Technology, Ghent University, Ghent, Belgium, and iMinds, Ghent, Belgium

Guy A. E. Vandenbosch, ESAT-TELEMIC Research Division, Department of Electrical Engineering, KU Leuven, Leuven, Belgium

Douglas H. Werner, Department of Electrical Engineering, Pennsylvania State University, University Park, PA, USA

Hoi-Jun Yoo, Department of Electrical Engineering, Korea Advanced Institute of Science and Technology, Daejeon, Republic of Korea

Taiwei Yue, Department of Electrical Engineering, Pennsylvania State University, University Park, PA, USA

Maxim Zhadobov, Institute of Electronics and Telecommunications of Rennes, UMR CNRS 6164, University of Rennes 1, Rennes, France

PREFACE

The subject of this book is the burgeoning area of research and development on the electromagnetic aspects of body area networks (BANs) including antennas and propagation, as well as the associated RF systems and sensor technology. BANs, sometimes also referred to as body sensor networks or body-centric networks, are wireless communication networks of wearable devices that transmit information within, on, near, or around the human body. In these systems, distributed wearable and/or implanted sensors are required to communicate with either other on-body computing devices such as smart phones, watches or glasses, or more distant off-body systems like wireless routers. In such a network, the sensors are responsible for collecting various critical physiological signals and/or environmental parameters, and effectively relaying this data to a smart wearable processing unit. The smart wearable processing unit, which is capable of storing the data temporarily and performing fundamental signal processing, is primarily used to communicate with a wireless router or a smart phone such that the data can then be sent via internet to a remote center (e.g., the cloud) for further processing and analysis by specialists. These wearable devices are either implanted within or placed in extremely close proximity to the body, which leads to a number of unconventional challenges for wireless system and RF designers. Over the past few years, the field of BAN electromagnetics has witnessed tremendous advancements in many of its associated sub-areas, which have jointly enabled systems with revolutionary functionalities for a wide variety of applications including health monitoring, patient tracking, physiotherapy, wearable computing, battlefield survival, the Internet of Things (IoT), and so on. As such, BAN technology holds great promise for revolutionizing many aspects of the daily life of human beings.

The main goal of this book is to provide an overview of the many recent and significant accomplishments regarding the various electromagnetic topics related to BAN systems. In this book, a comprehensive treatment of the field has been

compiled from a group of leading scholars and researchers throughout the world on subjects ranging from the fundamental theoretical principles and new technological advancements to the state-of-the-art device design and demonstration examples encompassing a wide range of related sub-areas. In particular, topics that will be covered include recent developments on novel wearable and implantable antenna concepts and designs, advanced wireless propagation models for on-body, in-body (or through-body), and off-body modes, efficient numerical human body modeling techniques, artificial phantom synthesis and fabrication, as well as low-power RF systems and related sensor technology. Newly emerging flexible materials and fabrication methodologies are also highlighted for the key role they play as enabling technologies for wearable and implantable devices. Moreover, an in-depth discussion of wearable and implantable RF transmitter/receiver design and implementation using low-power integrated circuits has also been included, providing a valuable perspective on BANs from the systems viewpoint. Throughout the book, a plethora of application examples have been included, encompassing wireless capsule endoscopy, physiological data acquisition, wireless implantable neuroprobe microsystems for motor prosthetics, retina prosthetics, medical compliance sensing, temperature sensing, wearable wireless energy harvesting, fire-fighter tracking, exposimeters, security and identification, and others. These topics have been carefully selected for their transformational impact on the next generation of BAN systems and beyond. Each chapter was contributed by an internationally recognized author or group of authors covering the latest research results. We hope that this book will be an indispensable resource for graduate students and researchers in academia as well as professionals in the consumer electronics and telecommunication industries.

This book contains 14 invited chapters contributed by leading experts in the field of electromagnetics of BANs. A brief summary of each chapter is provided as follows. Chapter 1 discusses the materials, design, fabrication, and characterization methods for textile wearable antennas. Various antenna performance evaluation techniques are reviewed, including numerical simulations based on the HUGO human body model, specific absorption rate measurements using a DASY-4 system, and antenna efficiency measurements using a reverberation chamber. Chapter 2 introduces several new antenna designs for off-body communications that provide more compact form factors and/or multiple functionalities, including metasurface-enabled linear-polarized antennas and circularly polarized integrated filtering antennas. The performance of these antennas is evaluated numerically and experimentally when mounted on different positions of a human body. Chapter 3 presents several novel wearable antenna designs for on-body communications based on miniaturized Yagi-Uda antennas backed by artificial magnetic conducting ground planes. Numerical and experimental evaluations of antenna prototypes fabricated using flexible latex substrate materials are reported. Chapter 4 presents the design and characterization methodologies of implantable antennas operating at different frequency bands. These antenna examples are exploited for applications including wireless capsule endoscopy diagnostics, medical compliance sensing, and patient monitoring. Chapter 5 considers the basic characteristics of wearable antennas and their associated wave propagation over a wide frequency range from 3 MHz to 3 GHz. The impacts of human body movement and the surrounding environment on the antenna properties

as well as wave propagation are investigated. Chapter 6 presents a study of the channel properties for through-body communication modes excited using different basic antenna structures. In addition, more advanced implantable antenna designs for wireless capsule endoscopy and wireless implantable neuroprobe microsystems as well as the corresponding experimental results are presented. Chapter 7 discusses the use of phantoms, wearable antenna design, and the associated material and fabrication considerations important for millimeter wave applications. Several wearable antennas are demonstrated at the 60 GHz band, which are used to study the channel properties of on-body propagation modes. Chapter 8 investigates the multiple-in multiple-out (MIMO) channel characteristics in a BAN for off-body communications. The design and experimental results for active wearable antennas are also presented, which demonstrate a scenario for MIMO off-body communication between fire fighters. Chapter 9 reviews the performance of antennas when they are mounted on the human body and proposes epidermal antennas for radio frequency identification (RFID) applications. By exploiting the epidermal membranes, devices that perform wireless measurement of body temperature and which monitor fluid change at the skin interface are demonstrated. Chapter 10 provides an overview of inkjet printing technology for implementing wearable devices including antennas, sensors, microfluidic-tunable filters, and RF receivers. A specific example is included, which achieves wireless energy harvesting at an ultra-high frequency band. Chapter 11 presents the concepts and system design of wearable RF integrated circuits. In particular, a BAN system is demonstrated that includes an energy efficient dual-band wearable hub receiver, a compact implantable temperature sensor node, and a wearable electrocardiogram sensor node. Chapter 12 proposes the use of MEMS thin-film bulk acoustic resonators for ultra low power wearable and implantable chips that can be employed in a BAN system. Moreover, the design and implementation of a transmitter and a receiver in the ISM band are presented. Chapter 13 describes different non-invasive RF technologies that have the potential for remote monitoring of vital signs. To this end, the received signal strength-based method, continuous wave method, and the wideband pulse radar method are explained in detail. Chapter 14 discusses the various methods of supplying power for implantable and wearable devices including non-regenerative and regenerative approaches. In addition, a methodology to achieve simultaneous power/data telemetry for BAN devices is proposed, including an illustrative example for a retinal prosthesis.

We are indebted to the authors of the 14 chapters for their outstanding contributions to this book, each reporting on cutting-edge research in the field. The cooperation of the contributing authors during the course of the book preparation as well as their dedication to delivering a high-quality product is deeply appreciated. We would also like to gratefully acknowledge the editorial assistance provided by Jeremy A. Bossard, Kenneth L. Morgan, Zachary C. Morgan, and John A. Easum of the Pennsylvania State University Computational Electromagnetics and Antenna Research Lab.

DOUGLAS H. WERNER
ZHI HAO JIANG

ACKNOWLEDGMENTS

Ping Jack Soh and Guy A. E. Vandenbosch would like to acknowledge Ms. Nor Farahiyah Mohd Aun of Universiti Malaysia Perlis for her contributions to Chapter 1. The work in Chapter 1 is also supported in part by the Malaysian Ministry of Higher Education, COST IC1102 VISTA – Versatile Integrated and Signal-Aware Technologies for Antennas Short Term Scientific Mission (STSM) and the FP7 CARE (Coordinating Antenna Research in Europe) Secondment Programme. The work reported in Chapter 2, contributed by Zhi Hao Jiang, Taiwei Yue, and Douglas H. Werner, was supported by the National Science Foundation ASSIST Nanosystems ERC under Award EEC-1160483. The work summarized in Chapter 3, contributed by Kush Agarwal and Yong-Xin Guo, was supported in part by the National Research Foundation, Prime Minister’s Office, Singapore, under Grant NRF-CRP8-2011-01, and in part by the National Natural Science Foundation of China under Grant 61372012. Koichi Ito would like to acknowledge Dr. Nozomi Haga of Gunma University, Dr. Masaharu Takahashi and Dr. Kazuyuki Saito of Chiba University, for their contributions to Chapter 5. Finally, the work reported in Chapter 7 was partly supported by the European Union Seventh Framework Program under the grant no 619563 (MiWaveS project) and by Labex CominLabs under the French National Research Agency program “Investing for the Future” ANR-10-LABX-07-01 (ResCor/BoWi project). The editors would also like to thank Jeremy A. Bossard and Mario Pantoja for providing ideas and assistance during the preparation of the cover art for this book. The sample shown in the photograph on the front book cover of the flexible artificial metasurface for wearable antenna applications was fabricated by Prof. Yong Zhu and Zheng Cui at North Carolina State University.

CONTENTS

List of Contributors	xv
Preface	xix
Acknowledgments	xxiii
1 Textile Antennas for Body Area Networks: Design Strategies and Evaluation Methods	1
<i>Ping Jack Soh and Guy A. E. Vandenbosch</i>	
1.1 Introduction, 1	
1.2 Textile Materials and Antenna Fabrication Procedure, 2	
1.2.1 Conductive Textiles/Foils, 2	
1.2.2 Non-conductive Textiles, 3	
1.2.3 Textile Antenna Fabrication Procedure Using Commercial Textiles, 4	
1.3 Design Strategies and Evaluation Methods, 5	
1.3.1 Antenna Simulation and Evaluation in Free Space, 5	
1.3.2 On-Body Co-simulations and Experimental Evaluations, 6	
1.3.3 Deformation Study, 9	
1.3.4 Antenna Efficiency Evaluation, 11	
1.3.5 Specific Absorption Rate Evaluation, 15	
1.3.6 Aging and Varying Environmental Conditions, 18	
1.4 Conclusion, 20	
References, 21	

2	Metamaterial-Enabled and Microwave Circuit Integrated Wearable Antennas for Off-Body Communications	27
	<i>Zhi Hao Jiang, Taiwei Yue, and Douglas H. Werner</i>	
2.1	Introduction, 27	
2.2	A Metasurface-Enabled Compact Wearable Antenna, 29	
2.2.1	Antenna Design, 29	
2.2.2	Radiation Mechanism, 31	
2.2.3	Free-Space Experiments, 34	
2.2.4	Bandwidth Extended Design, 34	
2.3	Microwave Circuit Integrated Wearable Filtering Antennas, 37	
2.3.1	Narrowband CP Filtering Antenna Synthesis, 37	
2.3.2	Wideband CP Filtering Antenna Synthesis, 41	
2.3.3	Free-Space Experiments, 46	
2.4	Investigation of Performance for Wearable Applications, 47	
2.4.1	Metasurface-Enabled Antenna, 47	
2.4.2	Narrowband CP Filtering Antenna, 49	
2.4.3	Wideband CP Filtering Antenna, 52	
2.5	Conclusion, 55	
	References, 55	
3	AMC-Backed Flexible Near-Endfire Wearable Antennas for On-Body Communications	61
	<i>Kush Agarwal and Yong-Xin Guo</i>	
3.1	Introduction, 61	
3.2	AMC-Backed Near-Endfire Antenna for On-Body Communications, 64	
3.2.1	Bidirectional Yagi Antenna for Endfire Radiation, 65	
3.2.2	Near-Endfire Yagi Antenna Backed by Single-Layered AMC, 65	
3.2.3	Near-Endfire Yagi Antenna Backed by Double-Layered AMC, 67	
3.3	Fabricating the Antenna Configurations on Flexible Latex Substrate, 68	
3.4	Investigation of Antenna Performances in Free Space, 69	
3.4.1	Return Loss, 70	
3.4.2	Gain, 70	
3.4.3	Radiation Patterns, 71	
3.5	Investigation of Antenna Performances on Voxel Model, 72	
3.5.1	Frequency Detuning, 72	
3.5.2	Specific Absorption Rate and Antenna Efficiency, 74	
3.5.3	Radiation Patterns, 74	
3.6	Antenna Performance Under Bending Deformation, 76	
3.7	Measurement Results, 79	
3.7.1	Return Loss Measurements, 80	
3.7.2	Radiation Pattern Measurements, 81	
3.7.3	Gain Measurements, 83	
3.8	Conclusion, 84	
	References, 85	

4 Novel Antenna Designs and Characterization Methodologies for Medical Diagnostics and Sensing 87

Harish Rajagopalan and Yahya Rahmat-Samii

- 4.1 Introduction, 87
 - 4.1.1 Antennas for Implantable Devices: Operating Frequency-Based Classification, 91
 - 4.1.2 Methodologies for Numerical Simulations and Characterizations, 95
- 4.2 Ingestible Antenna Design at WMTS Band: Wireless Capsule Endoscopy Diagnostics, 97
 - 4.2.1 Ingestible Antenna Design: Conformal Meandered Offset Dipole Antenna, 100
 - 4.2.2 Link Budget and SAR Comparison for Different Ingestible Antenna Designs, 101
 - 4.2.3 An Adaptive Antenna System with Frequency Reconfigurability Using Wireless Power Transfer Technology, 105
- 4.3 Ingestible Antenna Design at ISM Band: Medical Compliance Sensing, 110
 - 4.3.1 Tuning Parameters and Impedance Control, 114
 - 4.3.2 Potential Batch Fabrication Process, 115
- 4.4 On-Body Antenna at UHF Band: RFID Tag for Patient Monitoring, 117
 - 4.4.1 Simplified Circuit Model for Planar Fat-Type Folded Dipole Bio-tag, 119
 - 4.4.2 Tag Characterizations on Human Body in Terms of Impedance and Radiation Pattern, 121
 - 4.4.3 Read Range Measurements, 124
- 4.5 Future Outlook, 126
 - 4.5.1 A Brain–Machine Interface System, 127
 - 4.5.2 A Diagnostic Capsule System with Nano-Biosensors, 128
- 4.6 Conclusion, 129
- References, 130

5 Basic Performance Characteristics of Wearable Antennas Over a Wide Frequency Range 135

Koichi Ito

- 5.1 Introduction, 135
- 5.2 Frequency Dependence of Communication Channels Between Wearable Antennas Mounted on the Human Body, 136
 - 5.2.1 Calculation Models, 136
 - 5.2.2 Electric Field Distributions, 139
 - 5.2.3 Received Open Voltage and Ideal Power Transmission Efficiency, 140

- 5.3 Influences of Surrounding Environment and Body Movement, 142
 - 5.3.1 Influence of a Floor and a Wall, 142
 - 5.3.2 Influence of Body Movement, 143
- 5.4 Practical Applications, 149
 - 5.4.1 Wall-Mounted ID Tag System, 149
 - 5.4.2 Human Vital Data Acquisition System Using a Dual-Mode Antenna, 152
- 5.5 Conclusion, 156
- References, 156

6 Implanted Antennas and RF Transmission in Through-Body Communications

159

Terence Shie Ping See, Zhi Ning Chen, and Xianming Qing

- 6.1 Introduction, 159
- 6.2 Antennas for Wireless Capsule Endoscopy, 162
 - 6.2.1 RF Transmission Characterization, 162
 - 6.2.2 Channel Characterization, 168
 - 6.2.3 Antenna Designs, 174
 - 6.2.4 System Integration, 183
- 6.3 Antennas in Wireless Implantable Neuroprobe Microsystem for Motor Prosthesis, 187
 - 6.3.1 Antenna Configuration on Head, 187
 - 6.3.2 Antenna Designs at 434 MHz Band, 187
 - 6.3.3 Antenna Designs at 4 GHz Band, 192
 - 6.3.4 Primate Demonstration, 199
- 6.4 Conclusion, 201
- References, 201

7 Antennas, Phantoms, and Body-Centric Propagation at Millimeter-Waves

205

Nacer Chahat, Adrian Tang, Anda Guraliuc, Maxim Zhadobov, Ronan Sauleau, and Guido Valerio

- 7.1 Introduction, 205
- 7.2 Human Body Modeling and Exposure Guidelines, 207
 - 7.2.1 From Microwaves to Millimeter-Waves, 207
 - 7.2.2 Dielectric Properties and Measurement Techniques for Phantoms and Human Tissues at Millimeter-Waves, 211
 - 7.2.3 Numerical and Experimental Phantoms at Millimeter-Waves, 213
 - 7.2.4 Exposure Limits and Guidelines, 218
- 7.3 Antennas For Off-Body Communications at Millimeter-Waves, 222
 - 7.3.1 From Microwaves to Millimeter-Waves, 222
 - 7.3.2 Antenna Requirements for Off-Body Communications, 225

- 7.3.3 Study of the Interaction with the Human Body of a Patch Antenna Array, 225
- 7.3.4 Textile Antennas, 227
- 7.4 Antenna and Propagation for On-Body Propagation, 231
 - 7.4.1 State-of-the-Art, 231
 - 7.4.2 On-Body Antennas, 233
 - 7.4.3 Theoretical Analysis of On-Body Propagation, 235
 - 7.4.4 On-Body Channel Measurements, 241
 - 7.4.5 On-Body to Off-Body Propagation Scenario, 244
 - 7.4.6 A Challenge to Overcome: Transceivers for Wearable Devices at Millimeter-Waves, 247
- 7.5 Conclusion, 248
- References, 249

8 Wearable Active Antenna Modules for Energy-Efficient Reliable Off-Body Communication Systems 261

Patrick Van Torre, Luigi Vallozzi, and Hendrik Rogier

- 8.1 Introduction, 261
- 8.2 Diversity and MIMO Techniques for Off-Body Wireless Channels, 264
 - 8.2.1 The Indoor Off-Body Radio Propagation Channel, 264
 - 8.2.2 Diversity and MIMO Systems, 265
 - 8.2.3 Signal Processing Techniques in Diversity and MIMO Systems, 266
- 8.3 Active Wearable Antennas: Efficient Design and Implementation, 269
 - 8.3.1 Full-Wave/Circuit Co-design Paradigm for Energy-Efficient Active Antennas in Professional Garments, 270
- 8.4 Body-Centric MIMO Channels, 273
 - 8.4.1 Off-Body Stochastic Modeling, 273
 - 8.4.2 Off-Body Deterministic Modeling, 280
 - 8.4.3 Spatial Modulation, 289
- 8.5 Applications, 295
 - 8.5.1 Wearable Distributed Sensor Network, 295
 - 8.5.2 Distributed Exposimeter, 304
- 8.6 Conclusions, 311
- References, 313

9 More Than Wearable: Epidermal Antennas for Tracking and Sensing 319

Sara Amendola, Cecilia Occhiuzzi, and Gaetano Marrocco

- 9.1 Introduction, 319
- 9.2 RFID Technology, 321
- 9.3 Radiation Performance of Epidermal Antennas, 322
 - 9.3.1 Efficiency and Gain versus Antenna Size, 324

9.3.2	Gain versus the Trace Width, 326
9.3.3	Radiation Performance versus the Trace Conductivity, 326
9.3.4	Radiation Performance versus the Spacing From the Skin, 327
9.4	Performance of Epidermal RFID Dual-Loop Tag, 328
9.4.1	Tag Layout, 329
9.4.2	Prototype and On-Skin Performance, 330
9.4.3	On-Skin Retuning, 332
9.5	Special (Functionalized) Epidermal Membranes, 335
9.5.1	Scaffold Membranes: Poli(ϵ -Caprolactone), 336
9.5.2	Hydrogel Membranes, 338
9.6	Sensing Applications, 341
9.6.1	Epidermal RF Thermometer, 341
9.6.2	Smart-Plaster for Wound Healing, 342
9.7	Conclusion, 347
	References, 348

10 Inkjet-Printed Smart Skins and Wirelessly-Powered Sensors for Wearable Applications 351

John Kimionis and Manos (Emmanouil) M. Tentzeris

10.1	Introduction, 351
10.2	Multilayer Inkjet Printing—Conductors and Dielectrics, 352
10.3	Multilayer Inkjet Printing—Antenna Examples, 354
10.4	Inkjet-Printed Sensors, 356
10.5	Conductive Polymer-Based Sensors, 357
10.6	Carbon Nanomaterial-Based Sensors, 358
10.7	Inkjet-Printed Microfluidics, 360
10.8	Wireless Energy Harvesting for Wearables, 364
10.9	Microwave Receiver Design, 364
10.10	Circuit Fabrication with Inkjet-Printed Masking, 365
10.11	Input Power Estimation and RF-DC Conversion Circuit Design, 366
10.12	RF-DC Conversion Efficiency Measurement and Prototype Operation Tests, 368
10.13	Conclusion, 371
	References, 371

11 Circuits and Systems for Wireless Body Area Network 375

Joonsung Bae and Hoi-Jun Yoo

11.1	Introduction, 375
11.2	MBAN System Concept, 377
11.2.1	System Overview, 377
11.2.2	Crystal-Less Sensor Nodes, 379
11.3	Energy-Efficient MBAN Hub Design, 381
11.3.1	Concurrent Dual-Band Operation, 381
11.3.2	Dual-Band Hub Transceiver, 383

- 11.4 Compact Sensor Node Designs, 389
 - 11.4.1 Implantable Sensor Node Transceiver, 389
 - 11.4.2 Wearable Sensor Node Transceiver, 394
- 11.5 System Implementation, 400
- 11.6 Conclusion, 401
- References, 402

12 Ultra Low-Power MEMS-Based Radios for WBAN **405**

*Raghavasimhan Thirunarayanan, Aravind Prasad Heragu,
and Christian Enz*

- 12.1 Introduction to Body Area Networks, 405
- 12.2 WBAN Requirements, 406
- 12.3 Limitations of Conventional Radios for WBAN Systems, 407
- 12.4 Comparison Metrics for ULP Radios, 408
- 12.5 MEMS Resonators—A Solution to Bulky Crystals, 411
 - 12.5.1 BAW Resonators, 411
- 12.6 FBAR-Based Radios, 413
- 12.7 FBAR-Based TX Architecture, 413
 - 12.7.1 FBAR DCO, 414
 - 12.7.2 Phase Switching Divider, 416
 - 12.7.3 Mixer, Power Amplifier Stage, and Digital Baseband, 416
- 12.8 Transmitter Measurement Results, 418
- 12.9 Summary of the FBAR-Based TX, 424
- 12.10 Receiver Architecture, 424
 - 12.10.1 Frequency Synthesis: The Integer- N Approach, 425
 - 12.10.2 FBAR-Based RF Front-End, 428
 - 12.10.3 Quadrature Sub-Sampling Mixer, 437
 - 12.10.4 Receiver Measurement Results, 440
- 12.11 Summary of the FBAR-Based RX, 443
- 12.12 Conclusion, 443
- References, 443

13 Exploring Physiological Features from On-Body Radio Channels **447**

Max O. Munoz and Yang Hao

- 13.1 Introduction, 447
- 13.2 Physiological Information Parameters, 449
- 13.3 Methods for Non-Invasive Physiological Detection, 449
 - 13.3.1 Received Signal Strength-Based Methods, 451
 - 13.3.2 Continuous-Wave (CW) Methods, 457
 - 13.3.3 Wide Band Pulsed Radar Method, 464
- 13.4 Discussion and Conclusion, 466
- References, 468