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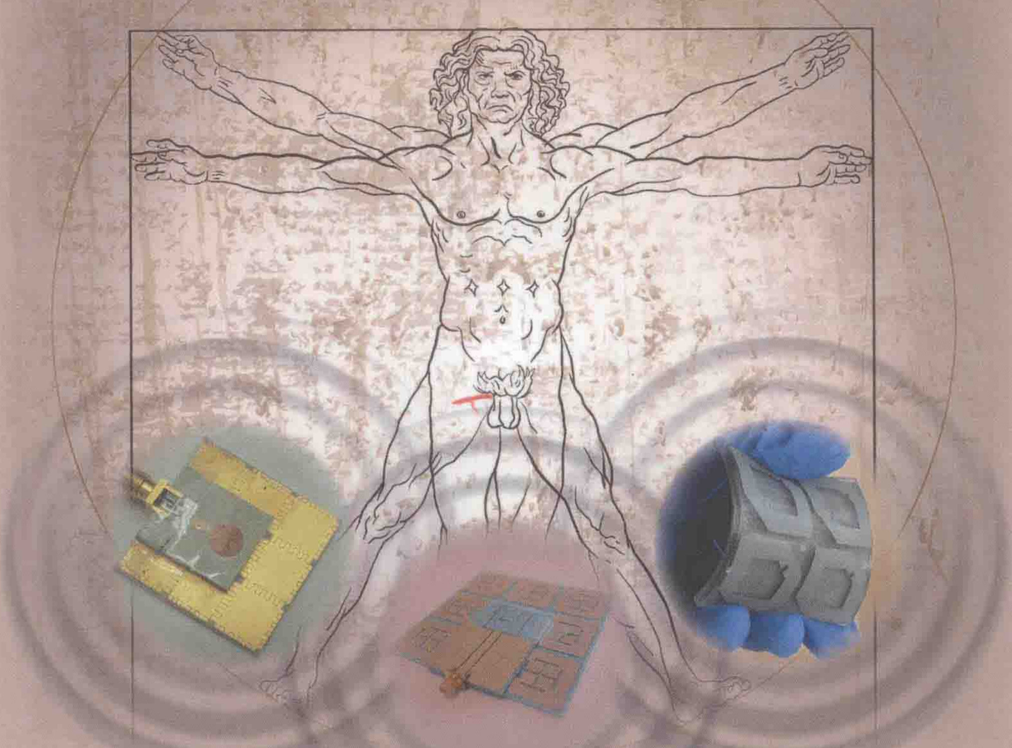
DOUGLAS H. WERNER AND ZHI HAO JIANG

Electromagnetics of Body Area Networks

Antennas, Propagation, and RF Systems



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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, microfludic-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.

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