

# LOW ELECTROMAGNETIC FIELD EXPOSURE WIRELESS DEVICES

FUNDAMENTALS AND RECENT ADVANCES

EDITED BY

**MASOOD UR REHMAN**

**MUHAMMAD ALI JAMSHED**



  
IEEE PRESS

WILEY

# Table of Contents

[Cover](#)

[Title Page](#)

[Copyright](#)

[Dedication](#)

[Editor Biography](#)

[List of Contributors](#)

[Preface](#)

[1 Electromagnetic Field Exposure: Fundamentals and Key Practices](#)

[1.1 Introduction](#)

[1.2 EMF Metric and Evaluation Framework](#)

[1.3 Application of Metric for Setting Guidelines/Limits and Reducing Exposure](#)

[1.4 Conclusion](#)

[References](#)

[2 Exposure to Electromagnetic Fields Emitted from Wireless Devices: Mechanisms and Assessment Methods](#)

[2.1 Fundamentals of EMF Interactions with the Human Body](#)

[2.2 Physical Models to Represent the Interaction of EMFs with Biological Tissue](#)

[2.3 Dosimetry Concepts](#)

[2.4 Dosimetry Methodology](#)

[2.5 Numerical Dosimetry at the Radiofrequency and Microwave Regions](#)

[References](#)

## 3 Numerical Exposure Assessments of Communication Systems at Higher Frequencies

### 3.1 Introduction

### 3.2 Exposure Configuration

### 3.3 Plane Wave Exposure Assessment of E-field Absorption Within the Skin Using SAR as a Function of Frequency

### 3.4 Plane Wave Exposure Assessment of E-field Absorption Within Multi-layer Model Using SAR as a Function of Frequency

### 3.5 Plane Wave Exposure Assessment of E-field Absorption Within the Eye Using SAR as a Function of Frequency

### 3.6 Chapter Summary

### Appendix 3.A

### References

## 4 Age Dependent Exposure Estimation Using Numerical Methods

### 4.1 Introduction

### 4.2 Numerical Human Models

### 4.3 Age-Dependent Tissue Properties

### 4.4 Numerical Validation

### 4.5 Chapter Summary

### Appendix 4.A

### References

## 5 Antenna Design Considerations for Low SAR Mobile Terminals

### 5.1 Introduction

### 5.2 SAR Reduction and Dual Coupling of Antenna

### 5.3 Coupling Manipulation Simulation Campaign

[5.4 SAR Analysis and Surface Current](#)

[5.5 Resilience to Different Head Use Cases](#)

[5.6 Analysis of MIMO Performance in Data Mode](#)

[5.7 Conclusion](#)

[References](#)

[6 MIMO Antennas with Coupling Manipulation for Low SAR Devices](#)

[6.1 Introduction](#)

[6.2 Working Principle and Antenna Geometry](#)

[6.3 Antenna Measurements](#)

[6.4 Efficiency and SAR Analysis](#)

[6.5 Conclusion](#)

[References](#)

[7 Reinforcement Learning and Device-to-Device Communication for Low EMF Exposure](#)

[7.1 Introduction](#)

[7.2 Background](#)

[7.3 Related Works](#)

[7.4 System Model, Problem Formulation, and Proposed RL-ID2D](#)

[7.5 Performance Evaluation](#)

[7.6 Conclusion](#)

[References](#)

[8 Unsupervised Learning Based Resource Allocation for Low EMF NOMA Systems](#)

[8.1 Introduction](#)

[8.2 EMF-Aware PD-NOMA Framework](#)

[8.3 Machine Learning Based User Grouping/Subcarrier Allocation](#)

[8.4 Power Assignment](#)

[8.5 Numerical Analysis](#)

[8.6 Conclusion](#)

[References](#)

[9 Emission-Aware Resource Optimization for Backscatter-Enabled NOMA Networks](#)

[9.1 Introduction](#)

[9.2 System Model](#)

[9.3 Proposed Solution](#)

[9.4 Performance Evaluation](#)

[9.5 Conclusion](#)

[References](#)

[10 Road Ahead for Low EMF User Proximity Devices](#)

[10.1 Introduction](#)

[10.2 Perception and Physiological Impact of EMF](#)

[10.3 EMF Exposure Evaluation Metric and Regulations: A Future Perspective](#)

[10.4 Conclusion](#)

[References](#)

[Index](#)

[End User License Agreement](#)

## **List of Tables**

Chapter 2

[Table 2.1 Frequency characterization of the main biological tissue relaxati...](#)

[Table 2.2 A comparison of the current numerical and experimental electromag...](#)

## Chapter 4

[Table 4.1 Body water \(kg\) for young and elderly men, and elderly women from...](#)

[Table 4.2 Human age predictions using animals weight \[2, 10, 18\].](#)

[Table 4.3 Parameters for age-dependent generalized expression \(ID: Interver...](#)

[Table 4.4 Comparison between measured animal \[2\] permittivity and conductiv...](#)

[Table 4.5 Cole-Cole parameters for the dielectric properties of human tissu...](#)

[Table 4.A.1 Dielectric properties of 40 different tissue types assigned to N...](#)

[Table 4.A.2 Dielectric properties of 38 different tissue types assigned to N...](#)

[Table 4.A.3 Dielectric properties of 75 different tissue types of Eartha at](#)

## Chapter 5

[Table 5.1 Adjusted values of  \$L\_p\$  for each  \$d\$  .](#)

[Table 5.2 Comparison of UT metrics with  \$d = 17\$  . mm and  \$d = 62\$  mm at 2.4 GHz. Simulated...](#)

## Chapter 6

[Table 6.1 Changes in SAR \(10g \(W/Kg\)\) value for scenarios when DGS is eithe...](#)

[Table 6.2 Changes in overall antenna efficiency in \(dB\).](#)

## Chapter 7

[Table 7.1 Simulation parameters](#)

## Chapter 8

[Table 8.1 Notations with definitions used throughout the chapter.](#)

[Table 8.2 Default simulation parameters.](#)

# List of Illustrations

## Chapter 1

[Figure 1.1 Common EMF exposure sources generally present in the environment ...](#)

[Figure 1.2 Antenna field areas are depicted \[26\].](#)

[Figure 1.3 The most often used metrics for assessing EMF exposure \[9\].](#)

[Figure 1.4 A typical SAR measuring setup is depicted.](#)

[Figure 1.5 An overview of PD measurement.](#)

## Chapter 2

[Figure 2.1 An illustration of the effects of the applied electric field \(E\) ...](#)

[Figure 2.2 Flowchart showing the basic IEEE procedure for peak SAR numerical...](#)

[Figure 2.3 A valid setup for the SAR averaging volumes. Based on IEC/IEEE In...](#)

[Figure 2.4 Assignment of SAR values for each tissue sub-volume. Based on IEC...](#)

[Figure 2.5 Schematic diagram of the probe field measurement within liquid ph...](#)

[Figure 2.6 Schematic diagram of the thermographic measurement set-up.](#)

[Figure 2.7 Computation procedure for computing the EM, SAR, and thermal dist...](#)

[Figure 2.8 Operation of the FDTD program. \\* The FDTD solver iteration chart ...](#)

[Figure 2.9 A Flow chart showing the computation steps of the main FDTD progr...](#)

[Figure 2.10 The file structure for \(a\) model voxel configurations; and \(b\) t...](#)

[Figure 2.11 Plots of the normalized analytically assessed SAR patterns along...](#)

[Figure 2.12 Plots of the normalized FDTD-computed SAR patterns along the maj...](#)

[Figure 2.13 Plots of the normalized analytically assessed SAR patterns along...](#)

[Figure 2.14 Plots of the normalized FDTD-computed SAR patterns along the maj...](#)

[Figure 2.15 Plots of the normalized FDTD-computed SAR patterns along the maj...](#)

## Chapter 3

[Figure 3.1 Plane wave exposure configuration of \(a\). Single-layer skin-equiva...](#)

[Figure 3.2 3D view of HHECM, where all dimensions are in mm.](#)

[Figure 3.3 Sub-volume dimensions of HHECM; where “d” is the variable distanc...](#)

[Figure 3.4 Comparison of SAR values of dry- and wet-skin HHECM with its sub-...](#)

[Figure 3.5 Comparison of SAR values of dry- and wet-skin HHECM with its sub-...](#)

[Figure 3.6 Comparison of SAR values of dry- and wet-skin HHECM with its sub-...](#)

[Figure 3.7 Comparison of SAR values of dry- and wet-skin HHECM with its sub-...](#)

[Figure 3.8 E-field absorption within the dry-skin from surface to 50 mm deep...](#)

[Figure 3.9 E-field absorption within the wet-skin from surface to 50 mm deep...](#)

[Figure 3.10 Dimensions of multi-layer HHECM; The outer, middle and inner cub...](#)

[Figure 3.11 Comparison of SAR values of dry-skin and multi-layer HHECM with ...](#)

[Figure 3.12 Comparison of SAR values of dry-skin and multi-layer HHECM with ...](#)

[Figure 3.13 Comparison of SAR values of dry-skin and multi-layer box phantom...](#)

[Figure 3.14 Comparison of SAR values of dry-skin and multi-layer box phantom...](#)

[Figure 3.15 E-field absorption within the multi-layer model \(dry-skin, fat, ...](#)

[Figure 3.16 Comparison of maximum penetration depth of EM waves within dry- ...](#)

[Figure 3.17 HHECM composition with its dimensions.](#)

[Figure 3.18 Comparison of SAR values of HHECM and multi-layer model \(size no...](#)

[Figure 3.19 Comparison of maximum SAR values between HHECM and multi-layer m...](#)

[Figure 3.20 E-field absorption within the eye from surface to 50 mm deep ins...](#)

[Figure 3.21 Maximum penetration depth of EM waves within eye from the surfac...](#)

[Figure 3.A.1 Debye model fitted permittivity values of dry- and wet-skin, fa...](#)

[Figure 3.A.2 Debye model fitted conductivity values of dry- and wet-skin, fa...](#)

[Figure 3.A.3 Comparison of SAR values of dry-skin equivalent HHECM with its ...](#)

[Figure 3.A.4 Comparison of SAR values of dry-skin equivalent HHECM with its ...](#)

[Figure 3.A.5 Comparison of SAR values of dry-skin equivalent HHECM with its ...](#)

[Figure 3.A.6 Comparison of SAR values of dry-skin equivalent HHECM with its ...](#)

[Figure 3.A.7 Comparison of SAR values of dry-skin HHECM with its sub-volume ...](#)

[Figure 3.A.8 Comparison of SAR values of HHECM and multi-layer model \(size n...](#)

[Figure 3.A.9 Comparison of SAR values of HHECM and multi-layer model \(size n...](#)

[Figure 3.A.10 Comparison of SAR values of HHECM and multi-layer model \(size ...](#)

[Figure 3.A.11 Comparison of SAR values of HHECM and multi-layer model \(size ...](#)

[Figure 3.A.12 Comparison of SAR values of HHECM and multi-layer model \(size ...](#)

[Figure 3.A.13 Comparison of SAR values of HHECM and multi-layer model \(size ...](#)

[Figure 4.1 Volume rendered images of the female model; \(a\) The outside surfa...](#)

[Figure 4.2 Volume rendered images of the male model; \(a\) The outside surface...](#)

[Figure 4.3 Volume rendered images of the female child model; \(a\) The outside...](#)

[Figure 4.4 Permittivity of Fat at \*\*1 GHz\*\*.](#)

[Figure 4.5 Conductivity of Fat at \*\*1 GHz\*\*.](#)

[Figure 4.6 Comparison between age-dependent properties of fat tissue with on...](#)

[Figure 4.7 Age-dependent fitted values for relaxation parameters of the Cole...](#)

[Figure 4.8 Plots of the normalized FIT-computed SAR patterns along the major...](#)

[Figure 4.A.1 Comparison between age-dependent properties of bone marrow 30% ...](#)

[Figure 4.A.2 Comparison between age-dependent properties of bone marrow 50% ...](#)

[Figure 4.A.3 Comparison between age-dependent properties of cornea tissue wi...](#)

[Figure 4.A.4 Comparison between age-dependent properties of dura tissue with...](#)

[Figure 4.A.5 Comparison between age-dependent properties of gray matter tiss...](#)

[Figure 4.A.6 Age-dependent properties of intervertebral disc centre. Due to ...](#)

[Figure 4.A.7 Comparison between age-dependent properties of intervertebral d...](#)

[Figure 4.A.8 Comparison between age-dependent properties of long bone tissue...](#)

[Figure 4.A.9 Comparison between age-dependent properties of skin tissue with...](#)

[Figure 4.A.10 Comparison between age-dependent properties of skull tissue wi...](#)

[Figure 4.A.11 Comparison between age-dependent properties of spinal cord tis...](#)

[Figure 4.A.12 Comparison between age-dependent properties of tongue tissue w...](#)

[Figure 4.A.13 Comparison between age-dependent properties of white matter ti...](#)

## Chapter 5

[Figure 5.1 A traditional PIFA illustration arranged in a two-element MIMO la...](#)

[Figure 5.2 Simulated  \$S\_{21}\$  and  \$S\_{11}\$  of a two-element MIMOPIFA arrangement, position...](#)

[Figure 5.3 Following the IEEE guidelines and aligning UE with the homogeneou...](#)

[Figure 5.4 Variation of the overall efficiency and the SAR for a sphere with...](#)

[Figure 5.5 SAR and overall efficiency are varied by adjusting the difference...](#)

[Figure 5.6 Current distribution comparison of various PIFA configurations al...](#)

[Figure 5.7 Cross section comparison of SAR of various PIFA configurations al...](#)

[Figure 5.8 Cross section comparison of SAR of various PIFA configurations al...](#)

[Figure 5.9 SAR vs. phase angle variations between elements of PIFA for a fix...](#)

[Figure 5.10 The variation of SAR vs. phase angle between elements with fixed...](#)

[Figure 5.11 An SAR penetration comparison aligned with voxel model using a h...](#)

[Figure 5.12 Prototype of the UE with \(a\)  \$d = 17\$  mm and \(b\)  \$d = 62\$  mm.](#)

[Figure 5.13 Comparison of simulated and measured S-parameters for the UE wit...](#)

## Chapter 6

[Figure 6.1 The proposed two element MIMO-enabled dual band rim antenna's geo...](#)

[Figure 6.2 Surface current plots simulated \(a\) 2.1 GHz \(b\) 4.3 GHz.](#)

[Figure 6.3 Surface current graphs simulated at 2.1 GHz and 4.3 GHz for scena...](#)

[Figure 6.4 An example of a CMA study of a shattered metallic rim. \(a\) Ground...](#)

[Figure 6.5 Prototype of \(a\) DGS ON configuration \(b\) DGS OFF configuration o...](#)

[Figure 6.6 S-parameters simulation vs. measurement.](#)

[Figure 6.7 Far-field radiation pattern simulation vs. measurement \(a\) Azimut...](#)

[Figure 6.8 An example of a voxel model used to investigate the influence of](#)

[Figure 6.9 Demonstration of the influence of hand and LCD on the antenna des...](#)

## Chapter 7

[Figure 7.1 \(a\) NB-IoT deployment modes, \(b\) NB-IoT frame structure.](#)

[Figure 7.2 Few use cases of D2D communication.](#)

[Figure 7.3 D2D communication relay scenarios.](#)

[Figure 7.4 Distributed direct discovery process.](#)

[Figure 7.5 Narrowband-D2D system model.](#)

[Figure 7.6 The agent-environment interaction in a Markov decision process us...](#)

[Figure 7.7 Cumulative  \$Q\$ -value vs. steps.](#)

[Figure 7.8 EDR vs. steps.](#)

[Figure 7.9 EDR vs. QL parameters.](#)

[Figure 7.10 EDR vs. transmission power.](#)

[Figure 7.11 EDR vs D2D transmission range.](#)

[Figure 7.12 Average E2E delay vs. distance.](#)

[Figure 7.13 Average E2E delay vs number of cellular relays.](#)

[Figure 7.14 Comparison of RL-ID2D with opportunistic and deterministic model...](#)

[Figure 7.15 Comparison of RL-ID2D with opportunistic and deterministic model...](#)

## Chapter 8

[Figure 8.1 An illustration of a single cell system with multiple users.....](#)

[Figure 8.2  \$F\$ -test statistic in 8.11 as a function of  \$M\$  for  \$K = 100\$ ,  \$N = 1\$ , and  \$T = 1\$  .....](#)

[Figure 8.3 The comparison of total EMF uplink exposure vs. the target number...](#)

[Figure 8.4 The comparison of total EMF uplink exposure vs. varying the numbe...](#)

[Figure 8.5 The comparison of total EMF uplink exposure vs. varying the time ...](#)

[Figure 8.6 The comparison of total EMF uplink exposure vs. varying the targe...](#)

[Figure 8.7 Illustration of SAR testing positions \(a\) Cheek position, \(b\) Til...](#)

[Figure 8.8 Comparison of total uplink exposure with target number of bits fo...](#)

## Chapter 9

[Figure 9.1 Illustration of the system model.](#)

[Figure 9.2 Silhouette values vs.  \$C\$  for  \$O = 1\$ ,  \$U = 100\$ , and  \$\hat{T} = 1\$ .](#)

[Figure 9.3 Comparing combined uplink EMF against a variation in the bits for...](#)

[Figure 9.4 Comparing combined uplink EMF against a variation in the number o...](#)

## Chapter 10

[Figure 10.1 Exposure reduction scenario using MIMO antennas.](#)

**IEEE Press**  
445 Hoes Lane  
Piscataway, NJ 08854

**IEEE Press Editorial Board**  
Sarah Spurgeon, *Editor in Chief*

Jón Atli  
Benediktsson

Anjan Bose

Adam Drobot

Peter (Yong) Lia

Andreas  
Molisch

Saeid  
Nahavandi

Jeffrey Reed

Thomas  
Robertazzi

Diomidis  
Spinellis

Ahmet Murat  
Tekalp

# **Low Electromagnetic Field Exposure Wireless Devices**

## **Fundamentals and Recent Advances**

*Edited by*

*Masood Ur Rehman*

University of Glasgow, Glasgow, UK

*Muhammad Ali Jamshed*

University of Glasgow, Glasgow, UK



Copyright © 2023 by The Institute of Electrical and Electronics Engineers, Inc.  
All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.  
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](http://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. Further, readers should be aware that websites listed in this work may have changed or disappeared between when this work was written and when it is read. Neither the publisher nor authors 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](http://www.wiley.com).

*Library of Congress Cataloging-in-Publication Data Applied for:*  
Hardback ISBN: 9781119909163

Cover Design: Wiley  
Cover Image: © whiteMocca/Shutterstock

*I dedicate this effort to my parents, Khalil Ur Rehman and  
Ilfaz Begum;  
my siblings, Habib, Waheed, Tahera;  
my wife, Faiza;  
and my son, Musaab.*

*Masood Ur Rehman*

*I dedicate this effort to my parents, Jamshed Iqbal and  
Nuzhut Jamshed;  
my siblings, Laiba, Maliha, Mariam;  
and my wife, Aqsa Tariq.*

*Muhammad Ali Jamshed*

## **Editor Biography**

**Masood Ur Rehman** received a B.Sc. degree in electronics and telecommunication engineering from the University of Engineering and Technology, Lahore, Pakistan, in 2004 and a M.Sc. and Ph.D. degrees in electronic engineering from Queen Mary University of London, London, UK, in 2006 and 2010, respectively. He worked at Queen Mary University of London as a Postdoctoral Research Assistant until 2012 before joining the Centre for Wireless Research at the University of Bedfordshire as a Lecturer. He served briefly at the University of Essex, UK and then moved to the James Watt School of Engineering at the University of Glasgow, UK in the capacity of an Assistant Professor. His research interests include compact antenna design, radiowave propagation and channel characterization, satellite navigation system antennas in cluttered environment, electromagnetic wave interaction with human body, body-centric wireless networks and sensors, remote health care technology, mmWave and nano-communications for body-centric networks, and D2D/H2H communications. He has worked on a number of projects supported by industrial partners and research councils. He has contributed to a patent and authored/co-authored 4 books, 7 book chapters, and more than 120 technical articles in leading journals and peer reviewed conferences. Dr. Ur Rehman is a fellow of the Higher Education Academy, UK, a member of the IET and part of the technical program committees and organizing committees of several international conferences, workshops, and special sessions. He is acting as an Associate Editor of the IEEE Access and IET Electronics Letters and Lead Guest Editor of numerous special issues

of renowned journals. He also serves as a reviewer for book publishers, IEEE conferences, and leading journals.

**Muhammad Ali Jamshed** received a Ph.D. degree from the University of Surrey, Guildford, UK, in 2021. He is endorsed by Royal Academy of Engineering under exceptional talent category. He was nominated for Departmental Prize for Excellence in Research in 2019 at the University of Surrey. He served briefly as Wireless Research Engineer at BriteYellow Ltd., UK, and then moved to James Watt School of Engineering, University of Glasgow, as a Post-Doctoral Research Assistant. He has authored/co-authored 2 book chapters and more than 37 technical articles in leading journals and peer reviewed conferences. His main research interests include EMF exposure reduction, low SAR antennas for mobile handsets, machine learning for wireless communication, Backscatter communication, and wireless sensor networks. He served as a Reviewer, TPC, and the Session Chair, at many well-known conferences, i.e. ICC, WCNC, VTC, GlobeCom etc., and other scientific workshops.

# List of Contributors

## ***Yasir Alfadhl***

School of Electronic Engineering and Computer  
Science

Queen Mary University of London

London

UK

## ***Tim W.C. Brown***

Institute of Communication Systems (ICS)

Home of 5G and 6G Innovation Centre, University of  
Surrey

Guildford

UK

## ***Xiaodong Chen***

School of Electronic Engineering and Computer  
Science

Queen Mary University of London

London

UK

## ***Fabien Héliot***

Institute of Communication Systems (ICS)  
Home of 5G and 6G Innovation Centre, University of  
Surrey  
Guildford  
UK

***Muhammad Ali Imran***

James Watt School of Engineering  
University of Glasgow  
Glasgow  
UK

***Muhammad Ali Jamshed***

James Watt School of Engineering  
University of Glasgow  
Glasgow  
UK

***Wali Ullah Khan***

Interdisciplinary Center for Security Reliability and  
Trust (SnT)  
University of Luxembourg  
Luxembourg City  
Luxembourg

***Sung Won Kim***

Department of Information and Communication  
Engineering

Yeungnam University

Gyeongsan-si

South Korea

***Ali Nauman***

Department of Information and Communication  
Engineering

Yeungnam University

Gyeongsan-si

South Korea

***Haris Pervaiz***

School of Computing and Communications

Lancaster University

Lancaster

UK

***Muhammad Rifaqat Ali Qureshi***

School of Electronic Engineering and Computer  
Science

Queen Mary University of London

London

UK

***Masood Ur Rehman***

James Watt School of Engineering

University of Glasgow

Glasgow

UK

## **Preface**

The past decade has seen a huge upsurge in the demand of wireless devices that are expected to cross the 29.4 billion mark by 2030. This increase is fueled by the advances in wearables, portables, flexible electronics, and other wireless technologies facilitating communication, transportation, and navigation needs of billions of users around the world in the wake of Internet of Things and 5G/6G. These rising numbers, along with ever-growing data requirements, necessitate a growth in the capacity of wireless communication networks by almost 1000 times. Part of this capacity enhancement will be made possible by increasing the number of access points (APs). These developments are ultimately resulting in added electromagnetic field (EMF) exposure sources in the environment.

EMF exposure has been deemed prone to inflict adverse health and safety effects on the users. The World Health Organization (WHO) has classified these EMF radiations as possibly carcinogenic to humans and has an ongoing project to assess potential health effects of exposure to EMF in the general and working population. The Federal Communications Commission (FCC) and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) have, therefore, imposed strict safety standards for device operation. Consequently, EMF exposure characterization warranting strict adherence to these safety regulations is a vital design parameter for wireless devices to ensure the safety of the users.

The current developments and expected future growth of the wireless systems are also mounting concerns regarding users' safety and possible health consequences of EMF

## ***k***

Karush-Kuhn-Tucker (KKT) conditions [200](#)

## ***l***

Lagrangian [200](#), [220](#)

Licensed spectrum [157](#)

Long term evolution (LTE) [49](#), [121](#)

Low power wide area (LPWA) [151](#)

## ***m***

Machine learning (ML) [153](#), [189](#), [199](#), [214](#)

clustering [189](#), [190](#), [196](#), [197](#), [199](#), [218](#)

elbow method [197](#), [215](#), [218](#)

F-test [190](#), [197](#), [199](#), [215](#), [218](#)

K-means [189](#), [190](#), [196](#), [197](#), [199](#), [214](#), [218](#)

k-medoids [214](#), [218](#), [223](#)

Silhouette analysis [214](#), [215](#), [218](#), [220](#), [223](#)

Mass density [7](#), [8](#), [31](#), [67](#), [194](#)

Metamaterials [115](#), [135](#)

MmWave [227-229](#), [232](#), [233](#)

Monte Carlo (MC) [161](#)

Multiple-input multiple-output (MIMO) [115](#), [135](#), [192](#)

envelope cross correlation (ECC) [135](#)

## ***n***

Narrowband internet of things (NB-IoT) [155](#)  
Noise power density [175](#), [191](#)  
Non-orthogonal multiple access (NOMA) [188](#), [213](#)  
    code-domain NOMA (CD-NOMA) [188](#), [213](#)  
    power domain-NOMA (PD-NOMA) [188](#), [213](#)

## ***o***

Orthogonal frequency division multiplexed (OFDM) [155](#)

## ***p***

Parasitic elements [115](#)  
Perfectly matched layer (PML) [39](#)  
Power allocation [189](#), [191](#), [192](#), [196](#), [200](#), [201](#), [215](#), [218](#),  
[221](#)  
    Newton-Raphson [200](#)  
    Secant [200](#)  
    waterfilling [201](#)  
Proximity-based service (ProSe) [157](#)

## ***q***

Q-learning [162](#), [168](#), [174](#)  
    accumulated reward [168](#), [177](#)  
    policy [161](#), [162](#), [168](#), [170](#), [171](#), [176](#)  
    Q-value [162](#), [168](#), [170](#), [173](#), [176](#)  
Quadrature phase shift keying (QPSK) [157](#)  
Quality of service (QoS) [4](#), [188](#), [214](#), [233](#)

## ***r***

- Radiation pattern [141](#)
  - normalized radiation patterns [141](#)
  - omnidirectional [141](#)
- Radio access technologies (RATs) [9](#)
- Radio frequency (RF) [7](#), [49](#), [214](#), [228](#)
- Random waypoint model (RWP) [164](#)
- Rayleigh channel [164](#)
- Rayleigh fading [189](#), [202](#), [218](#), [221](#)
- Reference signal received quality (RSRQ) [166](#)
- Reinforcement learning (RL) [153](#), [160](#)
- Relative phase [11](#), [115](#)–[117](#), [122](#), [126](#), [127](#), [130](#), [132](#)

## ***s***

- Spectral efficiency [141](#), [153](#), [163](#), [188](#), [189](#), [196](#), [200](#), [203](#), [213](#), [220](#), [222](#), [229](#)
- Successive interference cancellation (SIC) [190](#), [214](#)

## ***t***

- Temporal difference (TD) [161](#)
- Theory of characteristic mode (TCM) [139](#)
  - characteristic mode (CM) [139](#)
  - modal significance (MS) [139](#)
- 3rd Generation partnership project (3GPP) [152](#), [154](#), [155](#), [157](#), [160](#), [166](#), [174](#)
- Time-division multiple access (TDMA) [188](#)

Total body water (TBW) [81](#)

## ***u***

Ultra-massive machine type communication (umMTC) [151](#)

Uplink communication [152](#), [202](#), [204](#)

User equipment (UE) [115](#), [135](#)

cellular UE (CUE) [163](#), [164](#)

data mode [130](#)

earpiece [116](#), [119](#), [120](#), [123](#), [126](#), [127](#), [130](#), [132](#)

metal-rimmed [135](#)

Smartphone [118](#), [130](#), [132](#), [135](#), [136](#)

talk position [11](#), [116](#), [123](#), [127](#), [132](#), [146](#)

tilt position [191](#), [206](#), [208](#)

user proximity wireless devices (UPWDs) [213](#)

user terminal (UT) [187](#)

## ***v***

Voxels [33](#), [34](#), [40](#), [42](#), [44](#), [77-80](#), [97](#)

## ***w***

Wi-Fi [19](#), [95](#)

Wireless local area network (WLAN) [13](#)

World Health Organization (WHO) [19](#), [187](#), [213](#), [225](#)