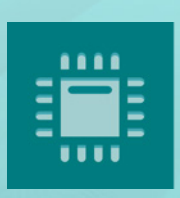

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Green, Energy-Efficient and Sustainable Networks

Edited by
Josip Lorincz, Antonio Capone, Luca Chiaraviglio and Jinsong Wu

Printed Edition of the Special Issue Published in *Sensors*

www.mdpi.com/journal/sensors

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Special Issue Editors

Josip Lorincz
Antonio Capone
Luca Chiaraviglio
Jinsong Wu

MDPI • Basel • Beijing • Wuhan • Barcelona • Belgrade

Special Issue Editors
Josip Lorincz
University of Split
Croatia

Antonio Capone
Politecnico di Milano
Italy

Luca Chiaraviglio
University of Rome Tor Vergata
Italy

Jinsong Wu
Universidad de Chile
Chile

Editorial Office
MDPI
St. Alban-Anlage 66
4052 Basel, Switzerland

This is a reprint of articles from the Special Issue published online in the open access journal *Sensors* (ISSN 1424-8220) from 2018 to 2019 (available at: https://www.mdpi.com/journal/sensors/special_issues/green_energy_efficient_sustainable_networks).

For citation purposes, cite each article independently as indicated on the article page online and as indicated below:

LastName, A.A.; LastName, B.B.; LastName, C.C. Article Title. *Journal Name* **Year**, *Article Number*, Page Range.

ISBN 978-3-03928-038-4 (Pbk)
ISBN 978-3-03928-039-1 (PDF)

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Contents

About the Special Issue Editors . . . . . **vii**

Preface to "Green, Energy-Efficient and Sustainable Networks" . . . . . **ix**

Josip Lorincz, Antonio Capone and Jinsong Wu
Greener, Energy-Efficient and Sustainable Networks: State-Of-The-Art and New Trends
Reprinted from: *Sensors* **2019**, *19*, 4864, doi:10.3390/s19224864 . . . . . **1**

Paris Charalampou and Efstathios D. Sykas
An SDN Focused Approach for Energy Aware Traffic Engineering in Data Centers
Reprinted from: *Sensors* **2019**, *19*, 3980, doi:10.3390/s19183980 . . . . . **30**

Carlos Cruz, Esther Palomar, Ignacio Bravo and Alfredo Gardel
Towards Sustainable Energy-Efficient Communities Based on a Scheduling Algorithm
Reprinted from: *Sensors* **2019**, *19*, 3973, doi:10.3390/s19183973 . . . . . **45**

Songlin Chen, Hong Wen, Jinsong Wu, Aidong Xu, Yixin Jiang, Huanhuan Song and Yi Chen
Radio Frequency Fingerprint-Based Intelligent Mobile Edge Computing for Internet of Things Authentication
Reprinted from: *Sensors* **2019**, *19*, 3610, doi:10.3390/s19163610 . . . . . **71**

Hammad Hassan, Irfan Ahmed, Rizwan Ahmad, Hedi Khammari, Ghulam Bhatti, Waqas Ahmed and Muhammad Mahtab Alam
A Machine Learning Approach to Achieving Energy Efficiency in Relay-Assisted LTE-A Downlink System
Reprinted from: *Sensors* **2019**, *19*, 3461, doi:10.3390/s19163461 . . . . . **86**

Tran Manh Hoang, Nguyen Le Van, Ba Cao Nguyen and Le The Dung
On the Performance of Energy Harvesting Non-Orthogonal Multiple Access Relaying System with Imperfect Channel State Information over Rayleigh Fading Channels
Reprinted from: *Sensors* **2019**, *19*, 3327, doi:10.3390/s19153327 . . . . . **111**

Md. Mohaimenul Hossain, Jean-Philippe Georges, Eric Rondeau and Thierry Divoux
Energy, Carbon and Renewable Energy: Candidate Metrics for Green-Aware Routing?
Reprinted from: *Sensors* **2019**, *19*, 2901, doi:10.3390/s19132901 . . . . . **129**

Xianghua Xu, Lu Chen and Zongmao Cheng
Optimizing Charging Efficiency and Maintaining Sensor Network Perpetually in Mobile Directional Charging
Reprinted from: *Sensors* **2019**, *19*, 2657, doi:10.3390/s19122657 . . . . . **151**

Run-Fa Liao, Hong Wen, Jinsong Wu, Fei Pan, Aidong Xu, Yixin Jiang,Feiyi Xie and Minggui Cao
Deep-Learning-Based Physical Layer Authentication for Industrial Wireless Sensor Networks
Reprinted from: *Sensors* **2019**, *19*, 2440, doi:10.3390/s19112440 . . . . . **175**

Zelalem Legese Hailemariam, Yuan-Cheng Lai, Yen-Hung Chen, Yu-Hsueh Wu and Arthur Chang
Social-Aware Peer Discovery for Energy Harvesting-Based Device-To-Device Communications
Reprinted from: *Sensors* **2019**, *19*, 2304, doi:10.3390/s19102304 . . . . . **192**

Yanzan Sun, Han Xu, Shunqing Zhang, Yating Wu, Tao Wang, Yong Fang, Shugong Xu
Joint Optimization of Interference Coordination Parameters and Base-Station Density for Energy-Efficient Heterogeneous Networks
Reprinted from: *Sensors* **2019**, *19*, 2154, doi:10.3390/s19092154 . . . . . **213**

Yi Chen, Hong Wen, Jinsong Wu, Huanhuan Song, Aidong Xu, Yixin Jiang, Tengyue Zhang and Zhen Wang
Clustering Based Physical-Layer Authentication in Edge Computing Systems with Asymmetric Resources
Reprinted from: *Sensors* **2019**, *19*, 1926, doi:10.3390/s19081926 . . . . . **237**

Xiaolei Liu, Xiaojiang Du, Xiaosong Zhang, Qingxin Zhu, Hao Wang and Mohsen Guizani
Adversarial Samples on Android Malware Detection Systems for IoT Systems
Reprinted from: *Sensors* **2019**, *19*, 974, doi:10.3390/s19040974 . . . . . **257**

Ran Li, Xiaomeng Duan and Yanling Li
Measurement Structures of Image Compressive Sensing for Green Internet of Things (IoT)
Reprinted from: *Sensors* **2019**, *19*, 102, doi:10.3390/s19010102 . . . . . **272**

Pablo Fondo Ferreiro, Miguel Rodríguez Pérez, Manuel FernándezVeiga and Sergio Herrería Alonso
Matching SDN and Legacy Networking Hardware for Energy Efficiency and Bounded Delay
Reprinted from: *Sensors* **2018**, *18*, 3915, doi:10.3390/s18113915 . . . . . **288**

Seung-Woo Ko and Seong-Lyun Kim
Impact of Node Speed on Energy-Constrained Opportunistic Internet-of-Things with Wireless Power Transfer
Reprinted from: *Sensors* **2018**, *18*, 2398, doi:10.3390/s18072398 . . . . . **311**

Le Van Nguyen, Ba Cao Nguyen, Xuan Nam Tran and Le The Dung
Closed-Form Expression for the Symbol Error Probability in Full-Duplex Spatial Modulation Relay System and Its Application in Optimal Power Allocation
Reprinted from: *Sensors* **2019**, *19*, 5390, doi:10.3390/s19245390 . . . . . **333**

Muhammad Usama, Melike Erol-Kantarci
A Survey on Recent Trends and Open Issues in Energy Efficiency of 5G
Reprinted from: *Sensors* **2019**, *19*, 3126, doi:10.3390/s19143126 . . . . . **345**

About the Special Issue Editors

Josip Lorincz received a B.Sc. (M.S. equivalent) and Ph.D. degree in telecommunications engineering and computer science from the University of Split, Croatia in 2002 and 2010, respectively. In 2003 he joined the Department of Electronics and computing at FESB – Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Croatia where he currently works as an associate professor. In 2009/2010 academic year, he was a visiting researcher at the Department of electronics, informatics and bioengineering of the Politecnico di Milano, Milan, Italy. As a project leader or researcher, he participated in more than twenty scientific and professional projects funded by EU, public or private sector. He is founder and co-chair of the Symposium on Green Networking and Computing, organized in the frame of International Conference on Software, Telecommunications and Computer Networks (SoftCOM). He also serves as the technical program committee member for many international scientific conferences and reviewer for top scientific journals. He was awarded as an outstanding young researcher by the Croatian Academy of Engineering in 2013. His current research interests include energy-efficient wireless and wired networks, optimization in telecommunications, advanced design, the management and analyses of computer heterogeneous networks, and performance evolution of routing protocols. He has authored more than 40 research papers published in different scientific conferences and journals. He is a senior IEEE member, senior ACM member, and the first president of the Croatian ACM chapter. Since 2004, he has owned Cisco CCNA, CCAI, and BCMSN certificates.

Antonio Capone is Full Professor at Politecnico di Milano (Technical University of Milan), where he is the Dean of the School of Industrial and Information Engineering, Director of the Advanced Network Technologies Laboratory (ANTLab), and a member of the strategic agenda team POLIMI 2040. His expertise is on networking and his main research activities include radio resource management in wireless networks, traffic management in software-defined networks, network planning, and optimization. On these topics, he has published more than 250 peer-reviewed papers. He serves on the Technical Program Committee of major conferences in networking, he is an editor of *IEEE Trans. on Mobile Computing, and Computer Communications* (Elsevier), and he was editor of *ACM/IEEE Trans. on Networking and Computer Network*s (Elsevier). He is a fellow of the IEEE.

Luca Chiaraviglio is Associate Professor at the University of Rome Tor Vergata (Italy). He holds a Ph.D. in Telecommunication and Electronics Engineering, obtained from Polytechnic of Turin (Italy). He has spent research periods at Boston University (USA), INRIA Sophia Antipolis (France), Auckland University of Technology (New Zealand), and ETECSA S.A. (Cuba). Luca has co-authored over 130 publications in international journals, books, and conferences, and he has collaborated with more than 200 authors. He participates in the TPC of top-leading conferences, including IEEE INFOCOM, IEEE GLOBECOM, IEEE ICC, IEEE VTC, and IEEE GlobalSIP. He is also a member of the organizing committee of different conferences, such as ECOC, IEEE LANMAN, and 5G-Italy. He was the general chair of the IEEE ICCCS 2019 conference. Moreover, he is on the Editorial Board of IEEE Communications Magazine, IEEE Access and IEEE Transactions on Green Communications and Networking. He is currently a member of the H2020 LOCUS project. He has been involved in the H2020 5G-EVE, H2020 Superfluidity, FP7 Trend, FP7 EcoNet, and FP7 Bone European projects. During 2018–2019, he was the coordinator of the national project BRIGHT: Bringing 5G Connectivity

in Rural and Low-Income Areas. Luca has received the Best Paper Award at the IEEE VTC and ICIN conferences. Some of his papers are listed as Best Readings on Green Communications by IEEE. Moreover, he has been recognized as an author in the top 1% most highly cited papers in the ICT field worldwide. His papers "Optimal Energy Savings in Cellular Access Networks" and "Reducing Power Consumption in Backbone Networks" are the most cited papers from all IEEE ICC conferences and IEEE ICC workshops in the period 2009–2018 (Source: Scopus). He is also an IEEE Senior Member and a founding member of the IEEE Communications Society Technical Subcommittee on Green Communications and Computing.

Jinsong Wu received a Ph.D. from Department of Electrical and Computer Engineering at Queen's University, Canada. He is the Vice-Chair, Technical Activities, IEEE Environmental Engineering Initiative, a pan-IEEE effort under IEEE Technical Activities Board (TAB). He was the Founder and Founding Chair of IEEE Technical Committee on Green Communications and Computing (TCGCC). He is also the co-founder and founding Vice-Chair of IEEE Technical Committee on Big Data (TCBD). He won both the 2017 and 2019 IEEE System Journal Best Paper Awards. His co-authored paper won the 2018 IEEE TCGCC Best Magazine Paper Award. He received IEEE Green Communications and Computing Technical Committee 2017 Excellent Services Award for Excellent Technical Leadership and Services in the Green Communications and Computing Community. He was the leading editor and co-author of the comprehensive book, entitled *Green Communications: Theoretical Fundamentals, Algorithms, and Applications*, published by CRC Press in September 2012. He is a current IEEE Senior Member.

Preface to "Green, Energy-Efficient and Sustainable Networks"

Over the last decades, information and communication technology (ICT) has radically changed many fields of living, with a significant improvement to people's lives. However, the benefits introduced by the development and the usage of ICT systems have consequences and new challenges have arisen regarding sustainability and practices that are environmentally acceptable. More specifically, ICT systems and infrastructures have constantly increased their power consumption and environmental footprint. This is primarily reflected in huge amounts of energy consumption and greenhouse gas (GHG) emissions of overall ICTs, with an additional contribution to the pollution of ICT system elements during their production and disposal phase.

Not surprisingly, such a noteworthy increase in energy consumption and GHG emissions will continue to rise due to the increase in the number of users/devices/types of ICT services, which will be coupled with the proliferation of high transmission capacity demands, mainly due to bandwidth-hungry applications and massive implementation of the Internet of Everything (IoE) technologies. In order to satisfy the detrimental economic and social demands and expectations, estimations show that the energy consumption of ICT is going to increase with an exponential trend. Although the contribution of ICT systems to global energy consumption and GHG emissions cannot be completely eliminated, these contributions should be maximally reduced, in order to limit the exponential increase of energy consumption and GHG emission trends. To face this challenge, improved or completely new algorithms, tools, platforms, methodologies, paradigms, systems, and energy models must be devised and practically implemented. Hence, greener and energy-efficient networks and ICT systems should be designed on all layers, by targeting an increase of energy efficiency, a decrease of GHG emissions, better re-use of resources, and large-scale adoption of sustainable materials and renewable energy sources. However, accomplishing this task is extremely challenging, due to the fact that it requires the combined effort of different stakeholders, e.g., from industry, academia, governments, and national and international organizations.

Additionally, sustainable networks and ICT systems refer to concepts that consider a set of programs, procedures, attitudes, and policies based on which ICT systems and corresponding elements will be implemented, used, and disposed of. Sustainable networks and ICT systems have a key role in developing the digitalized world, since technologies for the connected world have to assure the sustainability requests of new solutions and paradigms. Sustainable networks and ICT systems can be achieved only if a holistic approach in life-cycle management is targeted. This process includes structuring, developing, implementing, and disposing of ICT systems and corresponding elements, with a minimal or even without an environmental impact. Hence, sustainability is a topic of increasing importance in modern society, with a primary objective dedicated to achieving the technological, economic, social, and environmental sustainability of ICT systems and networks.

Despite such ever-growing interests in improving the energy-efficiency of ICT systems, the research on greener, energy-efficient, and sustainable networking and computing in many fields and on different levels requires improved or novel solutions and some fundamental problems are still open or are even in its infancy. Hence, green, energy-efficient, and sustainable networks are and will continue to be very relevant academic, industrial, economic, and social topics. However, recent advances in communication networks and systems have created new opportunities for the implementation of energy-efficient techniques that can be successfully built into ICT systems. This

book, Green, Energy-Efficient and Sustainable Networks, focuses on all aspects of the research and development related to these areas. The book contains the outcomes of the Special Issue on "Green, Energy-Efficient and Sustainable Networks" of the Sensors journal published by MDPI (Multidisciplinary Digital Publishing Institute). Eighteen high-quality works have been collected and reproduced in this book, demonstrating significant achievements in the field. Among published scientific papers, one paper is an editorial and one paper is a review, while the remaining 16 works are research articles.

Published papers are self-contained peer-review scientific works. The editorial paper gives an introduction to the problem of ICT energy consumption and greenhouse-gas-emissions, presenting the state of the art and future trends in terms of improving the energy-efficiency of wireless networks and data centers as the major energy consumers in the ICT sector. In addition, the published articles aim to improve energy efficiency in the fields of software-defined networking (SDN), Internet of things (IoT), machine learning, authentication, energy harvesting, wireless relay systems, routing metrics, wireless sensor networks (WSNs), the device to device (D2D) communications, heterogeneous wireless networks (HetNets), and image sensing. The last paper is a review that gives a detailed overview of the energy-efficiency improvements and methods for the implementation of fifth-generation (5G) networks and beyond.

More than 80 different authors from both academia and industry backgrounds have contributed to this book. Therefore, this book can serve as a source of information for industrial, teaching, and/or research and development activities. Hence, the book gives insights and solutions for a range of problems in the field of obtaining greener, energy-efficient, and sustainable networks and it lays the foundation for solving new challenges and achieving future advances. The book editors would like to thank all authors who have submitted their articles and all reviewers for their valuable work dedicated to giving an expert review for submitted papers. Moreover, the book editors are grateful to all those involved in the publication of this book for their invaluable support, including the editors of Sensors and the team of people involved in editing the Sensors journal Special Issue on "Green, Energy-Efficient and Sustainable Networks."

We sincerely hope that this book will be a valuable source of information, presenting recent advances in different fields related to greening and improving the energy-efficiency and sustainability of those information and communication technologies particularly addressed in this book.

Josip Lorincz, Antonio Capone, Luca Chiaraviglio, Jinsong Wu
Special Issue Editors

MDPI
St. Alban-Anlage 66
4052 Basel
Switzerland
Tel. +41 61 683 77 34
Fax +41 61 302 89 18
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ISBN 978-3-03928-039-1