

SPRINGER BRIEFS IN COMPUTER SCIENCE

Guoming Tang  
Deke Guo  
Kui Wu

# GreenEdge: New Perspectives to Energy Management and Supply in Mobile Edge Computing

 Springer

# SpringerBriefs in Computer Science

## Series Editors

Stan Zdonik, Brown University, Providence, RI, USA

Shashi Shekhar, University of Minnesota, Minneapolis, MN, USA

Xindong Wu, University of Vermont, Burlington, VT, USA

Lakhmi C. Jain, University of South Australia, Adelaide, SA, Australia

David Padua, University of Illinois Urbana-Champaign, Urbana, IL, USA

Xuemin Sherman Shen, University of Waterloo, Waterloo, ON, Canada

Borko Furht, Florida Atlantic University, Boca Raton, FL, USA

V. S. Subrahmanian, University of Maryland, College Park, MD, USA

Martial Hebert, Carnegie Mellon University, Pittsburgh, PA, USA

Katsushi Ikeuchi, University of Tokyo, Tokyo, Japan

Bruno Siciliano, Università di Napoli Federico II, Napoli, Italy

Sushil Jajodia, George Mason University, Fairfax, VA, USA

Newton Lee, Institute for Education, Research and Scholarships, Los Angeles, CA, USA

SpringerBriefs present concise summaries of cutting-edge research and practical applications across a wide spectrum of fields. Featuring compact volumes of 50 to 125 pages, the series covers a range of content from professional to academic.

Typical topics might include:

- A timely report of state-of-the art analytical techniques
- A bridge between new research results, as published in journal articles, and a contextual literature review
- A snapshot of a hot or emerging topic
- An in-depth case study or clinical example
- A presentation of core concepts that students must understand in order to make independent contributions

Briefs allow authors to present their ideas and readers to absorb them with minimal time investment. Briefs will be published as part of Springer's eBook collection, with millions of users worldwide. In addition, Briefs will be available for individual print and electronic purchase. Briefs are characterized by fast, global electronic dissemination, standard publishing contracts, easy-to-use manuscript preparation and formatting guidelines, and expedited production schedules. We aim for publication 8–12 weeks after acceptance. Both solicited and unsolicited manuscripts are considered for publication in this series.

\*\*Indexing: This series is indexed in Scopus, Ei-Compendex, and zbMATH \*\*

Guoming Tang • Deke Guo • Kui Wu

# GreenEdge: New Perspectives to Energy Management and Supply in Mobile Edge Computing

The First Book on Green Edge Computing

 Springer

Guoming Tang   
Department of Broadband Communication  
Peng Cheng Laboratory  
Shenzhen, China

Deke Guo  
College of Systems Engineering  
National University of Defense Technology  
Changsha, Hunan, China

Kui Wu  
Department of Computer Science  
University of Victoria  
Victoria, BC, Canada

ISSN 2191-5768                      ISSN 2191-5776 (electronic)  
SpringerBriefs in Computer Science  
ISBN 978-981-16-9689-3              ISBN 978-981-16-9690-9 (eBook)  
<https://doi.org/10.1007/978-981-16-9690-9>

© The Author(s), under exclusive license to Springer Nature Singapore Pte Ltd. 2022

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.  
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

# Preface

The 5G technology has been commercialized worldwide and is expected to provide superior performance with enhanced mobile broadband, ultra-low latency transmission, and massive IoT connections. Meanwhile, the edge computing paradigm gets popular to provide distributed computing and storage resources in proximity to the users (at the network edge). Compared with cloud computing, edge computing has the advantage of conducting latency-critical tasks by having them executed closer to end users. As edge services and applications prosper, 5G and edge computing will be tightly coupled and continuously promote each other forward. Embracing this trend, however, mobile users, infrastructure providers, and service providers are all faced with the energy dilemma. From the user side, battery-powered mobile devices are much constrained by battery life, whereas mobile platforms and apps nowadays are usually power-hungry. From the infrastructure and service provider side, the energy cost of edge facilities, particularly 5G base stations and edge datacenters, accounts for a large proportion of operating expenses and has become a huge burden.

In this book, we introduce our recent work tackling the energy issues in mobile edge computing. We name the constellation of work **GreenEdge**. Unlike traditional approaches, solutions, and frameworks, we deal with energy management and supply problems from totally new perspectives. For mobile users, (i) we investigate their low-battery anxiety through a large-scale user survey and quantify their anxiety degree and video watching behavior concerning the battery status; and (ii) by leveraging the quantified low-battery anxiety model, we further develop a low-power video streaming solution at the network edge to save mobile devices' energy and alleviate users' low-battery anxiety. For edge infrastructure and service operators, (i) we devise an optimal backup power deployment framework to cut down the backup battery cost in 5G networks; (ii) we investigate the cost-saving potential of transforming the backup batteries to a distributed battery energy storage

system; and (iii) we design an integrated renewable energy supply architecture and a software-defined power supply mechanism to pursue net-zero edge datacenters in the future edge computing environment.

Shenzhen, China  
Changsha, China  
Victoria, BC, Canada

Guoming Tang  
Deke Guo  
Kui Wu

# Contents

<b>1</b>	<b>Introduction</b>	1
1.1	When 5G Meets Edge Computing	1
1.2	The Energy Dilemma	2
1.3	Key Problems and Contributions	3
1.4	Content Organization	4
<b>2</b>	<b>Investigating Low-Battery Anxiety of Mobile Users</b>	7
2.1	Introduction	7
2.2	Related Work	9
2.3	A Survey Over 2000+ Mobile Users	10
2.4	Quantification of Low-Battery Anxiety	11
2.4.1	Extraction of LBA Curve	11
2.4.2	Observations and Analysis	12
2.4.3	Lessons Learnt from LBA Quantification	15
2.5	Impacts of LBA on Video Watching	15
2.5.1	Extraction of Video Abandoning Likelihood Curve	15
2.5.2	Observations and Analysis	16
2.5.3	Advice for Video Streaming Services	19
2.6	Ethics	19
2.7	Conclusion	19
<b>3</b>	<b>User Energy and LBA Aware Mobile Video Streaming</b>	21
3.1	Introduction	21
3.2	Background and Related Work	24
3.2.1	Background of Low-Battery Anxiety	24
3.2.2	Background of Display Power Saving	24
3.2.3	Work Related to This Work	25
3.3	LBA Survey and Modelling	26
3.3.1	Data Collection	26
3.3.2	LBA Curve Extraction	27
3.3.3	Insights on LBA Alleviation	28



3.4	LPVS: Low-Power Video Streaming	28
3.4.1	Scenario Overview	28
3.4.2	Models for Power Consumption in Video Streaming	30
3.4.3	Models for Energy Status and Low-Battery Anxiety	31
3.4.4	Video Streaming Capacity at the Edge	32
3.4.5	Joint Optimization for Energy Saving and Anxiety Reduction	32
3.5	Solution Methodology	33
3.5.1	The Difficulties	33
3.5.2	Information Compacting	33
3.5.3	A Two-Phase Heuristic for Joint Optimization	35
3.5.4	Determine $\gamma_n$ with Bayesian Inference	36
3.6	LBA Model Updating	38
3.6.1	Analysis of LBA Heterogeneity	38
3.6.2	Local LBA Model Updating	38
3.7	Implementations	40
3.7.1	Real-World Video Streaming Traces	40
3.7.2	LPVS Emulation and Setups	41
3.8	Performance Evaluations	43
3.8.1	LPVS with Sufficient Edge Resource	43
3.8.2	LPVS with Limited Edge Resource	44
3.8.3	Impact of LPVS on Low-Battery Users	45
3.8.4	LPVS with Updated LBA Models	46
3.8.5	Overhead of LPVS and Impact on Other QoE Metrics	47
3.9	Conclusion	48
<b>4</b>	<b>Optimal Backup Power Allocation for 5G Base Stations</b>	<b>51</b>
4.1	Introduction	51
4.1.1	Spatial Dimension	52
4.1.2	Temporal Dimension	53
4.2	Related Work	53
4.3	BS Power Measurements and Observations	54
4.3.1	Power Consumption of 4G and 5G BSs	54
4.3.2	Power Consumption of 5G BS Major Components	55
4.3.3	Multiplexing Gain with Backup Power Sharing	55
4.4	System Model	57
4.4.1	Scenario Overview	58
4.4.2	Traffic Load and Power Demand	59
4.5	Optimal Backup Power Allocation	59
4.5.1	Analysis of Power Outages and Network Failure	59
4.5.2	Condition of Network Reliability	61
4.5.3	Backup Power Deployment Constraints	62
4.5.4	Backup Power Allocation Optimization	62

- 4.6 Experimental Evaluations ..... 63
  - 4.6.1 Experiment Setup ..... 63
  - 4.6.2 Results and Analysis ..... 63
- 4.7 Conclusion ..... 65
- 5 Reusing Backup Batteries for Power Demand Reshaping in 5G ..... 67**
  - 5.1 Introduction ..... 67
  - 5.2 System Models ..... 69
    - 5.2.1 Scenario Overview ..... 69
    - 5.2.2 BS Power Supply and Demand ..... 70
    - 5.2.3 Battery Specification ..... 71
  - 5.3 Power Demand Reshaping via BESS Scheduling ..... 71
    - 5.3.1 Energy Cost with BESS ..... 72
    - 5.3.2 Battery Degradation Cost ..... 73
    - 5.3.3 Optimal BESS Operation Scheduling ..... 74
    - 5.3.4 Problem Analysis ..... 75
  - 5.4 A DRL-Based Approach to Distributed BESS Scheduling ..... 77
    - 5.4.1 DRL Based BESS Scheduling: Components and Concepts ..... 77
    - 5.4.2 Reward Function Design ..... 78
    - 5.4.3 Learning Process Design ..... 78
  - 5.5 Experimental Evaluations ..... 81
    - 5.5.1 Experiment Setup ..... 81
    - 5.5.2 General Performance at Cost Reduction with BESS ..... 83
    - 5.5.3 Case Studies of DRL-Based BESS Scheduling ..... 85
    - 5.5.4 ROIs of Different BESS Deployments ..... 86
  - 5.6 Related Work ..... 87
    - 5.6.1 General System Peak Power Shaving with BESS ..... 87
    - 5.6.2 DC Peak Power Shaving with Centralized BESS ..... 88
    - 5.6.3 DC Peak Power Shaving with Distributed BESS ..... 88
  - 5.7 Conclusion ..... 89
- 6 Software-Defined Power Supply to Geo-Distributed Edge DCs ..... 91**
  - 6.1 Introduction ..... 91
  - 6.2 Architecture of Software-Defined Power Supply (SDPS) ..... 92
    - 6.2.1 Motivation and Design Rationales ..... 93
    - 6.2.2 Architecture Design ..... 93
  - 6.3 Two-Phase Optimization in Software-Defined Power Supply ..... 95
    - 6.3.1 System Model ..... 95
    - 6.3.2 Phase-I: Constructing Green Cells ..... 96
    - 6.3.3 Phase-II: BESS Discharging/Charging Operations ..... 97
  - 6.4 Experimental Evaluations ..... 99
    - 6.4.1 Experiments Setup ..... 99
    - 6.4.2 Performance Comparison ..... 99
  - 6.5 Conclusion ..... 101

<b>7 Conclusions and Future Work</b> .....	103
7.1 Conclusions .....	103
7.2 Future Work .....	103
<b>A Questionnaire of LBA Survey and Collected Answers</b> .....	105
<b>Bibliography</b> .....	109