

Wireless Networks

Series Editor

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

The purpose of Springer's Wireless Networks book series is to establish the state of the art and set the course for future research and development in wireless communication networks. The scope of this series includes not only all aspects of wireless networks (including cellular networks, WiFi, sensor networks, and vehicular networks), but related areas such as cloud computing and big data. The series serves as a central source of references for wireless networks research and development. It aims to publish thorough and cohesive overviews on specific topics in wireless networks, as well as works that are larger in scope than survey articles and that contain more detailed background information. The series also provides coverage of advanced and timely topics worthy of monographs, contributed volumes, textbooks and handbooks.

**** Indexing: Wireless Networks is indexed in EBSCO databases and DPLB ****

More information about this series at <http://www.springer.com/series/14180>

Jie Gao • Mushu Li • Weihua Zhuang

Connectivity and Edge Computing in IoT: Customized Designs and AI-based Solutions



Springer

Jie Gao
Department of Electrical and Computer
Engineering
Marquette University
Milwaukee, WI, USA

Mushu Li
Department of Electrical and Computer
Engineering
University of Waterloo
Waterloo, ON, Canada

Weihua Zhuang
Department of Electrical and Computer
Engineering
University of Waterloo
Waterloo, ON, Canada

ISSN 2366-1186

ISSN 2366-1445 (electronic)

Wireless Networks

ISBN 978-3-030-88742-1

ISBN 978-3-030-88743-8 (eBook)

<https://doi.org/10.1007/978-3-030-88743-8>

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2021

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 Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

The Internet of Things (IoT) is revolutionizing the world and impacting the daily lives of billions of people. Supporting use cases for households, manufacturers, transportation, agriculture, healthcare, and much more, IoT carries many potentials and expectations for prospering human society. Technologically, we are at an early stage of IoT development, aiming at connecting tens of billions of devices to make homes, communities, factories, farms, and everywhere else smart and automated. Tremendous efforts are necessary to advance IoT research and development.

Two cornerstones of IoT are data collection/exchange and data analysis. The former demands connectivity solutions, while the latter requires computing solutions. Due to the broad scope of IoT and the drastically different characteristics and requirements of IoT use cases, no “one-size-fits-all” design can meet the expectations of all use cases. Therefore, customizing connectivity or computing solutions for specific use cases is challenging yet essential. There are many system features and performance measures to consider in the customization, such as connection link density, resource overhead, transmission and computation delay, service reliability, energy efficiency, and device mobility, and making proper trade-offs among them is critical.

Accounting for all performance metrics and making optimal trade-offs can yield high complexity. Correspondingly, artificial intelligence (AI) solutions, such as neural networks and reinforcement learning, can become useful. Powered by AI methods, connectivity or computing solutions can learn from experience to handle the complexity, assuming that sufficient data are available for training. Specifically, AI can play various roles in IoT, including data traffic load prediction, access control, and computation task scheduling, to name a few.

In this book, we focus on connectivity and edge computing in IoT and present our designs for four representative IoT use cases, i.e., smart factory, rural IoT, Internet of vehicles, and mobile virtual reality. We thoroughly review the existing research in this field, including many works published in recent years. Then, through innovative designs, we demonstrate the necessity and potential of customizing solutions based on the use cases. In addition, we exploit AI methods to empower our solutions. The four research works included in this book serve a collective objective:

enabling on-demand data collection and/or analysis for IoT use cases, especially in resource-limited IoT systems. We hope that this book will inspire further research on connectivity and edge computing in the field of IoT.

Milwaukee, WI, USA

Jie Gao

Waterloo, ON, Canada

Mushu Li

Waterloo, ON, Canada

Weihua Zhuang

July 2021

Acknowledgements

The authors would like to thank Professor Xuemin (Sherman) Shen at the University of Waterloo, the Editor of the *Wireless Networks* series, for his support in publishing this book and his comments and suggestions on its technical content.

We would also like to thank Professor Lian Zhao at the Ryerson University for her helpful discussions on the research presented in Chaps. 3 and 4.

In addition, we thank Dr. Xu Li, Professor Nan Cheng, and Conghao Zhou, who participated in the research discussed in Chaps. 2, 4, and 5, respectively.

We appreciate valuable discussions with the members of the Broadband Communications Research (BBCR) Lab at the University of Waterloo.

Special thanks to Susan Lagerstrom-Fife, Senior Editor at Springer New York, and Shina Harshavardhan, Project Coordinator for Springer Nature for their help during the preparation of this monograph.

Contents

1	Introduction	1
1.1	The Era of Internet of Things	1
1.2	Connectivity in IoT	3
1.3	Edge Computing in IoT	4
1.4	AI in IoT	5
1.5	Scope and Organization of This Book	6
	References	7
2	Industrial Internet of Things: Smart Factory	11
2.1	Industrial IoT Networks	11
2.2	Connectivity Requirements of Smart Factory	13
2.2.1	Application-Specific Requirements	13
2.2.2	Related Standards	14
2.2.3	Potential Non-Link-Layer Solutions	16
2.2.4	Link-Layer Solutions: Recent Research Efforts	16
2.3	Protocol Design for Smart Factory	18
2.3.1	Networking Scenario	18
2.3.2	Mini-Slot Based Carrier Sensing (MsCS)	20
2.3.3	Synchronization Sensing (SyncCS)	23
2.3.4	Differentiated Assignment Cycles	25
2.3.5	Superimposed Mini-slot Assignment (SMsA)	26
2.3.6	Downlink Control	27
2.4	Performance Analysis	28
2.4.1	Delay Performance with No Buffer	29
2.4.2	Delay Performance with Buffer	30
2.4.3	Slot Idle Probability	31
2.4.4	Impact of SyncCS	32
2.4.5	Impact of SMsA	33
2.5	Scheduling and AI-Assisted Protocol Parameter Selection	34
2.5.1	Background	34
2.5.2	The Considered Scheduling Problem	36

2.5.3	Device Assignment	38
2.5.4	AI-Assisted Protocol Parameter Selection.....	43
2.6	Numerical Results.....	46
2.6.1	Mini-Slot Delay with MsCS, SyncCS, and SMsA	46
2.6.2	Performance of the Device Assignment Algorithms	51
2.6.3	DNN-Assisted Scheduling	54
2.7	Summary	56
	References	57
3	UAV-Assisted Edge Computing: Rural IoT Applications.....	63
3.1	Background on UAV-Assisted Edge Computing	63
3.2	Connectivity Requirements of UAV-Assisted MEC for Rural IoT ...	65
3.2.1	Network Constraints	65
3.2.2	State-of-the-Art Solutions	66
3.3	Multi-Resource Allocation for UAV-Assisted Edge Computing.....	66
3.3.1	Network Model	67
3.3.2	Communication Model	68
3.3.3	Computing Model	69
3.3.4	Energy Consumption Model	70
3.3.5	Problem Formulation	72
3.3.6	Optimization Algorithm for UAV-Assisted Edge Computing	72
3.3.7	Proactive Trajectory Design Based on Spatial Distribution Estimation	81
3.4	Numerical Results.....	83
3.5	Summary	90
	References	90
4	Collaborative Computing for Internet of Vehicles	93
4.1	Background on Internet of Vehicles	93
4.2	Connectivity Challenges for MEC	94
4.2.1	Server Selection for Computing Offloading	95
4.2.2	Service Migration	95
4.2.3	Cooperative Computing	96
4.3	Computing Task Partition and Scheduling for Edge Computing	97
4.3.1	Collaborative Edge Computing Framework	97
4.3.2	Service Delay	99
4.3.3	Service Failure Penalty	102
4.3.4	Problem Formulation	103
4.3.5	Task Partition and Scheduling.....	104
4.4	AI-Assisted Collaborative Computing Approach	108
4.5	Performance Evaluation	112
4.5.1	Task Partition and Scheduling Algorithm	113
4.5.2	AI-Based Collaborative Computing Approach.....	114
4.6	Summary	119
	References	119

5	Edge-Assisted Mobile VR	123
5.1	Background on Mobile Virtual Reality	123
5.2	Caching and Computing Requirements of Mobile VR	124
5.2.1	Mobile VR Video Formats	125
5.2.2	Edge Caching for Mobile VR	125
5.2.3	Edge Computing for Mobile VR	126
5.3	Mobile VR Video Caching and Delivery Model	127
5.3.1	Network Model	127
5.3.2	Content Distribution Model	128
5.3.3	Content Popularity Model	130
5.3.4	Research Objective	130
5.4	Content Caching for Mobile VR	131
5.4.1	Adaptive Field-of-View Video Chunks	132
5.4.2	Content Placement on an Edge Cache	135
5.4.3	Placement Scheme for Video Chunks in a VS	139
5.4.4	Placement Scheme for Video Chunks of Multiple VSs	142
5.4.5	Numerical Results	146
5.5	AI-Assisted Mobile VR Video Delivery	148
5.5.1	Content Distribution	149
5.5.2	Intelligent Content Distribution Framework	150
5.5.3	WI-based Delivery Scheduling	152
5.5.4	Reinforcement Learning Assisted Content Distribution	153
5.5.5	Neural Network Structure	154
5.5.6	Numerical Results	157
5.6	Summary	159
	References	160
6	Conclusions	163
6.1	Summary of the Research	163
6.2	Discussion of Future Directions	165
	Index	167

Acronyms

3GPP	Third generation partnership project
5G	Fifth generation
5G NR	5G new radio
AC	Actor-critic
AD	Access delay
AD-F	Access delay counted in frames
ADMM	Alternating direction method of multipliers
AI	Artificial intelligence
AP	Access point
BFoV	Base field-of-view
BS	Base station
CNN	Convolutional neural network
CSMA	Carrier-sense multiple access
DCF	Distributed coordination function
DDPG	Deep deterministic policy gradient
DNN	Deep neural network
DQN	Deep Q network
DRL	Deep reinforcement learning
EDT	Early data transmission
EFoV	Extended field-of-view
eMBB	Enhanced mobile broadband
ET	Enhanced tile
FoV	Field-of-view
HMD	Head-mounted device
HP	High priority
IIoT	Industrial Internet of Things
IoT	Internet of Things
IoV	Internet of Vehicles
IT	Information technology
LoRa	Long range
LP	Low priority

LPWA	Low-power wide-area
LSTM	Long short-term memory
LTE	Long-term evolution
LTE-M	Long-term evolution for machine-type communications
M2M	Machine-to-machine
MAC	Medium access control
MDP	Markov decision process
mMTC	Massive machine-type communications
mmWave	Millimeter-wave
MsCS	Mini-slot based carrier sensing
MSE	Mean squared error
MTC	Machine-type communication
NB-IoT	Narrowband IoT
NOMA	Non-orthogonal multiple access
QoE	Quality of experience
QoS	Quality of service
RACH	Random access channel
RAW	Restricted access window
RMAB	Restless multi-armed bandit
RP	Regular priority
RSU	Roadside unit
SCA	Successive convex approximation
SOC	Second order cone
SMsA	Superimposed mini-slot assignment
SyncCS	Synchronization carrier sensing
TDMA	Time-division multiple access
TPSA	Task partition and scheduling algorithm
TTI	Transmission time interval
UAV	Unmanned aerial vehicle
URLLC	Ultra-reliable low-latency communications
V2I	Vehicle-to-infrastructure
V2X	Vehicle-to-everything
VR	Virtual reality
VS	Video segment
WI	Whittle index
WLAN	Wireless local area network