Communication Networks and Service Management in the Era of Artificial Intelligence and Machine Learning

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Edited by Nur Zincir-Heywood, Marco Mellia, and Yixin Diao

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Nur Zincir-Heywood received the PhD in Computer Science and Engineering in 1998. She is a full professor at the Faculty of Computer Science, Dalhousie University, Canada, where she directs the NIMS Research Lab on Network Information Management and Security. Her research interests include machine learning and artificial intelligence for cyber security, network, systems, and information analysis, topics on which she has published over 200 fully reviewed papers. She is a recipient of several best paper awards as well as the supervisor for the recipient of the IFIP/IEEE IM 2013 Best PhD Dissertation Award in Network Management. She is the co-editor of the book "Recent Advances in Computational Intelligence in Defense and Security" and co-author of the book "Nature-inspired Cyber Security and Resiliency: Fundamentals, Techniques, and Applications." She is an Associate Editor of the IEEE Transactions on Network and Service Management and Wiley's International Journal of Network Management. She has been a co-organizer for the IEEE/IFIP International Workshop on Analytics for Network and Service Management since 2016. She served as Technical Program Co-chair for the IEEE Symposium on Computational Intelligence for Security and Defence Applications in 2011, International Conference on Network Traffic Measurement and Analysis in 2018, International Conference on Network and Service Management in 2019, and she served as General Co-chair for the International Conference on Network and Service Management in 2020. Professor Zincir-Heywood's research record was recognized with the title of Dalhousie University Research Professor in 2021.

Marco Mellia graduated with PhD in Electronic and Telecommunication Engineering in 2001. He is a full professor at Politecnico di Torino, Italy, where he coordinates the SmartData@PoliTO center on Big Data, Machine Learning and Data Science. In 2002, he visited the Sprint Advanced Technology Laboratories in Burlingame, CA, working at the IP Monitoring Project (IPMON). In 2011, 2012, and 2013, he collaborated with Narus Inc. in Sunnyvale, CA, working on traffic monitoring and cyber-security system design. In 2015 and 2016, he visited Cisco

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Yixin Diao received the PhD degree in electrical engineering from Ohio State University, Columbus, OH, USA. He is currently a Director of Data Science and Analytics at PebblePost, New York, NY, USA. Prior to that, he was a Research Staff Member at IBM T. J. Watson Research Center, Yorktown Heights, NY, USA. He has published more than 80 papers and filed over 50 patents in systems and services management. He is the co-author of the book "Feedback Control of Computing Systems" and the co-editor of the book "Maximizing Management Performance and Quality with Service Analytics." He was a recipient of several Best Paper Awards from the IEEE/IFIP Network Operations and Management Symposium, the IFAC Engineering Applications of Artificial Intelligence, and the IEEE International Conference on Services Computing. He served as Program Co-chair for the International Conference on Network and Service Management in 2010, the IFIP/IEEE International Symposium on Integrated Network Management in 2013, and the IEEE International Conference on Cloud and Autonomic Computing in 2016 and served as General Co-chair for the International Conference on Network and Service Management in 2019. He is an Associate Editor of the IEEE Transactions on Network and Service Management and the Journal of Network and Systems Management. He is a Fellow of IEEE.

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Preface

Advances in artificial intelligence and machine learning algorithms provide endless possibilities in many different science and engineering disciplines including computer communication networks. Research is therefore needed to understand and improve the potential and suitability of artificial intelligence and machine learning in general for communications and networking technologies and research, but also in particular systems and networks operations and management. Approaches and techniques such as artificial intelligence, data mining, statistical analysis, and machine learning are promising mechanisms to harness the immense stream of operational data in order to improve the management and security of IT systems and networks. This will not only provide deeper understanding and better decision-making based on largely collected and available operational data but will also present opportunities for improving data analysis algorithms and methods on aspects such as accuracy, scalability, and generalization.

This book will focus on recent, emerging approaches, and technical solutions that can exploit artificial intelligence, machine learning, and big data analytics for communications networks and service management solutions. In this context, the book is intended to be a reference book for information and communications technology educators, engineers, and professionals, in terms of presenting a picture of the current landscape and discussing the opportunities and challenges of this field for the future. It is not intended as a textbook. Having said this, it can be used as a reference text for related graduate courses or high-level undergraduate courses on topic.

This book is composed of three parts and 13 chapters that provide an in-depth review of current landscape, opportunities, challenges, and improvements created by the artificial intelligence and machine learning techniques for network and service management.

The first part, Introduction, gives a general overview of the network and service management research as well as the artificial intelligence and machine learning techniques.

Chapter 1, Overview of Network and Service Management, outlines the field of network and service management that involve the setup, configuration, administration, and management of networks and associated services to ensure that network resources are effectively made available to customers and consumed as efficiently as possible by applications.

Chapter 2, Overview of Artificial Intelligence and Machine Learning, overviews the AI/ML algorithms that are most commonly used in the network and service management field, and discusses the strategic areas within network and services management that evidence growing interest of the community in developing cutting edge AI/ML solutions.

The second part of the book, Management Models and Frameworks, is dedicated to important management models and frameworks such as virtualized networks, 5G networks, and fog computing.

Chapter 3, Managing Virtualized Networks and Services with Machine Learning, exposes the state-of-the-art research that leverages Artificial Intelligence and Machine Learning to address complex problems in deploying and managing virtualized networks and services. It also delineates open, prominent research challenges and opportunities to realize automated management of virtualized networks and services.

Chapter 4, Self-Managed 5G Networks, discusses the main challenges that must be faced to successful develop 5G systems, focusing particularly on radio access networks, optical networks, data plane management, network slicing, and service orchestration, and highlights autonomous data-driven network management and federation among administrative domains that are critical for the development of 5G-and-beyond systems.

Chapter 5, AI in 5G Networks: Challenges and Use Cases, covers three representative case studies including QoE assessment, deployment of virtualized network functions, and slice management. It further points out general and use case-specific requirements and challenges and derives guidelines for network operators who plan to deploy such mechanisms.

Chapter 6, Machine Learning for Resource Allocation in Mobile Broadband Networks, provides an in-depth review of the existing machine learning techniques that have been applied to wireless networks in the context of wireless spectrum and power allocations, user scheduling, and user association.

Chapter 7, Reinforcement Learning for Service Function Chain Allocation in Fog Computing, explores the use of reinforcement learning as an efficient and scalable solution for service function chaining, especially given the dynamic

behavior of the network and the need for efficient scheduling strategies, as compared to the state-of-the-art integer linear programming-based implementations.

The third part of the book, Management Functions and Applications, is focused on vital management function and applications including performance management, security management, and Blockchain applications.

Chapter 8, Designing Algorithms for Data-Driven Network Management and Control: State-of-the-Art and Challenges, provides an overview of approaches that use machine learning and artificial intelligence to learn from problem solution pairs to improve network algorithms. It discusses the applicability for different use cases and identifies research challenges within those use cases.

Chapter 9, AI-Driven Performance Management in Data-Intensive Applications, overviews recurring performance management activities for data-intensive applications and examines the role that AI and machine learning are playing in enhancing configuration optimization, performance anomaly detection, load forecasting, and auto-scaling of software systems.

Chapter 10, Datacenter Traffic Optimization with Deep Reinforcement Learning, develops a two-level deep reinforcement learning system as a scalable end-to-end traffic optimization system that can collect network information, learn from past decisions, and perform actions to achieve operator-defined goals.

Chapter 11, The New Abnormal: Network Anomalies in the AI Era, summarizes recent developments on how AI algorithms bring new possibilities for anomaly detection, and discusses new representation learning techniques such as Generative Artificial Networks and Autoencoders, and new techniques such as reinforcement learning that can be used to improve models learned with machine learning algorithms.

Chapter 12, Automated Orchestration of Security Chains Driven by Process Learning, describes an automated orchestration methodology for security chains in order to secure connected devices and their applications and illustrates how it could be used for protecting Android devices by relying on software-defined networks.

Chapter 13, Architectures for Blockchain-IoT Integration, focuses on defining and determining measures and criteria to be met for an efficient Blockchain and Internet-of-Things integration. It discusses the integration incentives and suitable use cases, as well as the dedicated metrics for scalability, security, and energy efficiency.

New York

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Acronyms

5G	Fifth generation standard for broadband cellular networks
6G	Sixth generation standard for broadband cellular networks
AD	Administrative Domain
AE	Auto Encoder
AF	Application Function
AI	Artificial Intelligence
ANN	Artificial Neural Networks
API	Application Programming Interface
AP	Access Point
ARQ	Automatic Repeat reQuest
AS	Autonomous System
ASIC	Application-Specific Integrated Circuit
AWS	Amazon Web Services
BC	Blockchain
BGP	Border Gateway Protocol
BNG	Broadband Network Gateway
C/S	Client-Server
CNN	Convolutional Neural Networks
CDN	Content Distribution Network
ConvLSTM	Convolutional Long-Short Term Memory
CQI	Channel Quality Indicator
D2D	Device-to-Device
DAG	Directed Acyclic Graphs
DASH	Dynamic Adaptive Streaming over HTTP
DC	Data Center
DDoS	Distributed Denial-of-Service
DL	Deep Learning
DLT	Distributed Ledger Technology
DNN	Deep Neural Network

E2E	End-to-End
EM	Enforcement Module
FC	Fog Computing
GBM	Gradient Boosting Machine
GCN	Graph Convolutional Network
GNN	Graph Neural Network
GP	Gaussian Process
GUI	Graphical User Interface
HDFS	Hadoop Distributed File System
HetNets	Heterogeneous Networks
IAM	Identity and Access Management
ILP	Integer Linear Programming
IoT	Internet of Things
kNN	*K*-Nearest Neighbors
KPI	Key Performance Indicator
LoRaWAN	Long-Range Wide-Area Network
LP-WAN	Low-Power Wide Area Network
LSTM	Long-Short Term Memory
MAC	Media Access Control
MANO	Management and Orchestration
MDP	Markov Decision Process
MEC	Multi-access Edge Computing
MIB	Management Information Base
MILP	Mixed-Integer Linear Programming
MINLP	Mixed Integer Nonlinear Programming Problems
ML	Machine Learning
MLP	Multilayer Perceptron
MM	Monitor Module
mMTC	Massive Machine Type Communications
mmWave	Millimeter Wave
MNO	Mobile Network Operator
MOS	Mean Opinion Score
MPLS	Multiprotocol Label Switching
MSE	Mean Squared Error
MTU	Maximum Transmission Unit
NFV	Network Function Virtualization
NFVI	Network Function Virtualization Infrastructure
NFVO	Network Function Virtualization Orchestrator
NIC	Network Interface Controller
NN	Neural Network
NOC	Network Operation Center

ONF	Open Networking Foundation
OTN	Optical Transport Network
OTS	Optical Transport Section
P2P	Peer-to-Peer
PK	Public Key
PoP	Point of Presence
QC	Quantum Computing
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RAP	Radio Access Point
RDD	Resilient Distributed Dataset
RIP	Routing Information Protocol
RL	Reinforcement Learning
RNN	Recurrent Neural Network
RRM	Radio Resource Management
RTT	Round Trip Time
SC	Smart Contract
SDN	Software Defined Networking
SFC	Service Function Chaining (updated in regards to Service Function Chain)
SINR	Signal-to-Interference-Plus-Noise Ratio
SJF	Shortest Job First
SLA	Service Level Agreement
SNMP	Simple Network Management Protocol
SNR	Signal-to-Noise Ratio
SVM	Support Vector Machine
SVR	Support Vector Regression
TO	Traffic Optimization
TPS	Transaction Per Second
TSP	Traveling Salesman Problem
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
vBS	Virtual Base Station
VM	Virtual Machine
VMO	Virtual Mobile Operator
VNE	Virtual Network Embedding
VNF	Virtual Network Function
WAN	Wide Area Network
WLAN	Wireless Local Area Network
WN	Wireless Nodes