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Green and Software-Defined Wireless Networks

From Theory to Practice

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Contents

Preface

The past several decades have witnessed revolutionary progress in wireless networks, from the early first-generation systems to the current fourth-generation systems. Since the 1980s, the coverage, capacity, and capability of wireless networks have been marvelously improved, in correspondence with the dramatically increasing number of mobile subscribers. The market is now demanding fifth-generation (5G) systems, to be deployed in the coming years, that can support higher capacity, higher mobility, lower latency, lower cost, and better service. In addition to these requirements, 5G cellular networks are also anticipated to be more environmentally friendly to tackle the global warming crisis. As a by-product, the rapid growth of the worldwide information and communication industry also contributes a large amount of carbon emissions, which is comparable to the aviation industry and marks an undesirable increasing trend. Therefore, reducing carbon emissions and operating expenditure costs becomes more and more important goals for network infrastructure design. Meanwhile, from the perspective of user devices, how to reduce their battery consumption is also a major concern for network evolution. Faced with these challenges, energy efficiency has become an important metric for 5G cellular networks, and so-called green communications have been a growing trend.

On the other hand, by leveraging programmable control, management, and data planes, software-defined networking (SDN) makes it possible to enable flexible, scalable, configurable, and reliable mobile networks. Therefore, the industry and academia have launched several research initiatives on SDN-enabled 5G cellular networks worldwide. The soft design of cellular networks can be implemented in many aspects, such as cloud radio access network (C-RAN), baseband processing virtualization, and the software-defined air interface (SDAI).

Aiming at providing green and soft network architecture, infrastructure, and protocol, the traditional design philosophy of cellular networks should be revisited. For instance, the classical Shannon theory suggested a monotonic relationship between the energy efficiency (EE) and spectral efficiency (SE). However, with circuit power being considered, the SE–EE relation is no longer monotonic, therefore optimal SE and EE may be achieved simultaneously. Moreover, the idea of cell-centric design has been adopted for every generation of cellular networks. However, the soft concept enables a user-centric network architecture that no longer relies on the traditional cellular topology. Other design philosophies that can also be revisited include the decoupling of data and control

planes, the reconfiguring of spectrum and air interference, and the application of big data analytics for wireless communications, just to name a few.

This book aims to provide a comprehensive overview of green and software-defined wireless networks, covering both theory and practice aspects. We start from the theoretical framework of green communications, including the information theoretical analysis of energy-efficient design and some fundamental trade-offs in green radio networks. Then, we introduce several design principles and practical architectures to facilitate green networks, with emphases on C-RAN and big-data-enabled networks. After that, several strategies on energy-efficient signaling design and resource management for next-generation networks are presented. The framework of SDAI for SDN-enabled 5G networks and some key design issues, are also provided. The book ends with some practices for energy saving solutions for different cellular networks, most of which are from China Mobile, the largest cellular operator in the world.

This book serves as an important reference for both academic students and engineers in this area. It includes both theoretical and practical results on future green and soft wireless networks, aiming at providing a compressive overview from both academic and industrial viewpoints. The theoretical part of this book is mainly contributed by Professor G. Yu and Professor G. Y. Li, while the practical part is mainly contributed by Dr. C.-L. I and Dr. S. Han. Although we try to include recent progresses on green and soft wireless networks as much as possible, we cannot cover all important results in this field due to the rapid development of 5G wireless techniques. The authors would like to thank the experts in the Green Communication Research Center of the China Mobile Research Institute for their contribution to the book, particularly Qi Sun, Jinri Huang, Sen Wang, Jiqing Ni, Gang Li, Siming Zhang, Guozhen Xu, Wei Zhou, Jun Zuo, Zhiming Liu, Yami Chen, Ailing Wang, Kai Yan, Zhiming Fan, Guizhen Wang, Junshuai Sun, Xueyan Huang, Xingyu Han, Sen Bian, Ke Li, Xidong Wang, Yaxing Qiu, Zecai Shao, Tian Xie, Ran Duan, and Chunfeng Cui.

List of Abbreviations

(I)FFT	(Inverse) Fast Fourier Transformation
2G/3G/4G	Second/Third/Fourth Generation
3GPP	3rd Generation Partnership Project
5G	Fifth Generation
AAS	Active Antenna System
ACK	Acknowledgment
ACLR	Adjacent Channel Leakage Ratio
ADC	Analog-to-Digital Converter
AI	Artificial Intelligence
AM	Acknowledged Mode
ANDSF	Access Network Discovery Support Functions
AOA	Angle of Arrival
AP	Access Point
AP	Application Protocol
API	Application Programmable Interface
AR	Augmented Reality
ARQ	Automatic Repeat Request
ATCA	Advanced Telecom Computing Architecture
BBU	Baseband Unit
BC	Broadcast Channel
BD	Big Data
BOM	Bill of Material
BP	Back-Propagation
BS	Base Station
CA	Carrier Aggregation
Caffe	Convolutional Architecture for Feature Extraction
CAPEX	Capital Expenditure
CDMA	Code Division Multiple Access
CM	Channel Measurement
CMCC	China Mobile Communications Corporation
CN	Core Network
CN-GW	Core Network Gateway
CNN	Convolution Neural Network
CoMP	Coordinated Multipoint

CP	Control Plane
CP-OFDM	Cyclic Prefix Orthogonal Frequency-Division Multiplexing
CPRI	Common Public Radio Interface
CQI	Channel Quality Indicator
CRS	Cell-Specific Reference Signal
CSI	Channel State Information
CSIR	CSI at the Receiver
CSIT	CSI at the Transmitter
CU/DU	Central Unit/Distributed Unit
CU-C	Central Unit – Control
CU-U	Central Unit – User Plane
D2D	Device-to-Device
D2I	Device-to-Infrastructure
DAC	Digital-to-Analog Converter
DAQ	Data Acquisition
DAS	Distributed Antenna System
DC	Dual Connectivity
DFT-S-OFDM	Discrete Fourier Transform-Spread-OFDM
DL	Downlink
DMRS	Demodulation Reference Signal
DNN	Depth Neural Network
DOA	Direction of Arrival
DRB	Data Radio Bearer
DS-CDMA	Direct-Sequence Code Division Multiple Access
DSP	Digital Signal Processing (*or* Processor)
DT	Data Technology
DTX	Discontinuous Transmission
DwPTS	Downlink Pilot Time Slot
E2E	End-to-End
EE	Energy Efficiency
eMBB	Enhanced Mobile Broadband
eNodeB/eNB	Enhanced Node B
EPC	Evolved Packet Core
E-RAB	Evolved Radio Access Bearer
ERP	Effective Radiated Power
e-UTRAN	Evolved UMTS Terrestrial Radio Access Network
EVM	Error Vector Magnitude
FBMC	Filter Bank Multi-Carrier
FDD	Frequency Division Duplex
FH	Fronthaul
f-OFDM	Filtered-OFDM
FPGA	Field-Programmable Gate Array
GBSCM	Geometry-Based Stochastic Channel Model
GFDM	Generalized Frequency Division Multiplexing

GFS	Google File System
GMSK	Gaussian Filtered Minimum Shift-Keying
gNB	gNodeB
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GTX	Gigabit Transceiver
HARQ	Hybrid ARQ
HPBW	Half-Power Beam Width
HSR	High-Speed Railway
HSS	Home Subscriber Server
Hys	Handover Hysterias Value
I2I	Indoor-to-Indoor
IF	Intermediate Frequency
IoT	Internet of Things
IP	Internet Protocol
IS-95	Interim Standard 95
IT	Information Technology
JT	Joint Transmission
KPI	Key Performance Indicator
L1/L2	Layer1/Layer2
LNA	Low-Noise Amplifier
LO	Local Oscillator
LSAS	Large-Scale Antenna System
LTE	Long-Term Evolution
LVDS	Low-Voltage Differential Signaling
MA	Multiple Access
MAC	Media Access Control
MANO	Management and Orchestration
MAP	Maximum A Posteriori Probability
MBSFN	Multicast Broadcast Single Frequency Network
MCD	Multilevel Centralized and Distributed
MCES	Multi-RAT Cooperation Energy-Saving System
MCPA	Multi-Carrier Power Amplification
MCS	Modulation and Coding Schemes
MCU	Microcontroller Unit
MEC	Mobile Edge Computing
MeNB	Master eNB
MIB	Main Information Block
MIMO	Multi-Input Multi-Output
MLP	Multiple Layer Perception
MME	Mobility Management Entity
MMSE	Minimum Mean Square Error
mMTC	Massive Machine-Type Communication
mmWave	Millimeter Wave

MPA	Message-Passing Algorithm
MPC	Multipath Components
MPM	Mobile Platform Monitor
MR	Measure Report
MRS	Mobile Relay Station
MSK	Minimum Shift-Keying
MU-MIMO	Multi-User MIMO
MUSA	Multi-User Shared Access
NACK	Negative Acknowledgement
NEF	Network Exposure Function
NF	Network Functions
NFV	Network Function Virtualization
NG Core	Next-Generation Core
NGFI	Next-Generation Front-Haul Interface
NIST	National Institute of Standards and Technology
NLOS	Non-Line-of-Sight
NLP	Natural Language Processing
NoMA	Non-Orthogonal Multiple Access
NR	New Radio
NSSF	Network Slice Selection Function
NWD	Network Data Analytic
O2I	Outdoor-to-Indoor
O2O	Outdoor-to-Outdoor
OAM	Operation Administration and Maintenance
OBSAI	Open Base Station Architecture Initiative
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
OMA	Orthogonal Multiple Access
OMC	Operating and Maintenance Center
OMC-R	Operation and Maintenance Center-Radio
ONU	Optical Network Unit
OOB	Out-of-Band
OPEX	Operational Expenditure
OQAM	Offset Quadrature Amplitude Modulation
OTA	Over the Air
OTFS	Orthogonal Time Frequency Space
OTN	Optical Transport Networks
OTT	Over the Top
PA	Power Amplifier
PAN	Personal Area Network
PAPR	Peak-to-Average Power Ratio
PAS	Power Angular Spectrum
PBCH	Physical Broadcast Channel
PCF	Policy Control Function

PCFICH	Physical Control Format Indicator Channel
PCRF	Policy and Charging Rules Function
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
PDMA	Pattern Based Division Multiple Access
PDSCH	Physical Downlink Shared Channel
PDU	Protocol Data Unit
PER	Packet Error Rate
PGW	Packet Gateway
PHICH	Physical Hybrid-ARQ Indicator Channel
PHY	Physical Layer
PoE	Power Over Optical Network Unit Ethernet
PRACH	Physical Random Access Channel
PS	Phase Shifter
PSD	Power Spectrum Density
PSS	Primary Synchronization Signals
PUSCH	Physical Uplink Shared Channel
QoE	Quality of Experience
QoS	Quality of Service
QPSK	Quadrature Phase Shift-Keying
QSFP	Quad Small Form-Factor Pluggable
RAN	Radio Access Networks
RAN1	Radio Access Network Layer 1
RAT	Radio Access Technology
RB	Resource Blocks
RE	Resource Element
RF	Radio Frequency
RFIC	Radio Frequency Integrated Circuits
RLC	Radio Link Control
RNC	Radio Network Controller
RNN	Recurrent Neural Network
ROHC	Robust Header Compression Mechanism
RRC	Radio Resource Control
RRM	Radio Resource Management
RRU	Remote Radio Unit
RS	Reference Signal
RSMA	Resource Spread Multiple Access
RSRP	Reference Signal Receiving Power
RSRQ	Reference Signal Receiving Quality
RT	Real Time
SA	Standalone
SC-FDMA	Single-Carrier FDMA
SCMA	Sparse Code Multiple Access
SCPA	Single-Carrier Power Amplification

SDAI	Software-Defined Air Interface
SDN	Software-Defined Network
SDU	Service Data Unit
SE	Spectral Efficiency
SeNB	Secondary eNB
SERDES	Serializer-Deserializer
SFP	Small Form-Factor Pluggable
SGW	Serving Gateway
SIB	System Information Block
SIC	Successive Interference Cancellation
SINR	Signal-to-Interference Plus Noise Ratio
SISO	Single Input Single Output
SLA	Service Level Agreement
SN	Sequence Number
SNR	Signal-to-Noise Ratio
SOA	Service Oriented Architecture
SON	Self-Organized Network
SRB	Signaling Radio Bearer
SRS	Sounding Reference Signal
SVD	Singular-Value Decomposition
TB	Transport Block
TCO	Total Cost of Owner
TCP	Transmission Control Protocol
TCSL	Time Cluster-Spatial Lobe
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TD-SCDMA	Time Division-Synchronous Code Division Multiple Access
TTI	Transmission Time Interval
TTT	Time to Trigger
TXRU	Transmit and Receive Unit
UCN	User-Centric Network
UDN	Ultradense Network
UE	User Equipment
UFMC	Universal Filtered Multi-Carrier
UL	Uplink
UM	Unacknowledged Mode
UpPTS	Uplink Pilot Time Slot
UP	user plane
URLLC	Ultra-Reliable Low Latency Communications
UW	Unique Word
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VCR	Virtual Channel Representation
WBD	Wireless Big Data

WDM	Wavelength Division Multiplexing
WLAN	Wireless Local Area Networks
w-OFDM	Windowed OFDM
WOLA	Weighted Overlap and Add
WPAN	Wireless Personal Area Network
WSSUS	Wide-Sense Stationary Uncorrelated Scatter
ZFBF	Zeroforcing Beamforming
ZIF	Zero Intermediate Frequency