5G Mobile and Wireless Communications Technology

Written by leading experts in 5G research, this book is a comprehensive overview of the current state of the 5G landscape. Covering everything from the most likely use cases, to a wide range of technology options and potential 5G system architectures, to spectrum issues, it is an essential reference for academics and professionals involved in wireless and mobile communications.

- Describes and explains key technology options, including 5G air interfaces, device-to-device communication, mm-wave communications, massive MIMO, coordinated multi-point, wireless network coding, interference and mobility management, and spectrum issues.
- Summarizes the findings of key global 5G research collaborations such as METIS and outlines key scenarios, network requirements, and system architectures.
- Demystifies the relation between IoT, machine-type communications, and cyber physical systems, and describes the impact of 5G on sectors such as automotive, building, and energy.
- Equips readers with a solid insight into the impact and opportunities of 5G.

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CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781107130098

First published 2016

Printed in the United Kingdom by TJ International Ltd. Padstow Cornwall

A catalogue record for this publication is available from the British Library

Library of Congress Cataloguing in Publication data
Osseiran, Afif, editor.
5G mobile and wireless communications technology / [edited by] Afif Osseiran, Ericsson, Jose F. Monserrat, Polytechnic University of Valencia, Patrick Marsch, Nokia Networks.
New York : Cambridge University Press, 2016.
LCCN 2015045732 | ISBN 9781107130098 (hardback)
LCSH: Global system for mobile communications. | Mobile communication systems – Standards.
LCC TK5103.483 .A15 2016 | DDC 621.3845/6–dc23
LC record available at http://lccn.loc.gov/2015045732

ISBN 978-1-107-13009-8 Hardback

To my new born son S., my twin sons H. & N., my wife L. S-Y for her unwavering encouragement, and in the memory of a great lady, my aunt K. E.

A. Osseiran

To my son, the proud fifth generation of the name Jose Monserrat. And with the warmest love to my daughter and wife, for being always there.

J. F. Monserrat

To my two small sons for their continuous energetic entertainment, and my dear wife for her amazing patience and support.

P. Marsch

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Foreword

The ICT industry has settled into the fourth round of the game, where everyone is guaranteed to win; the successes of 2G and 3G in the past and the promise of 4G in the current decade are leading to consensus on the new fifth generation (5G) of mobile systems. These successes started off as a movement of telephony to the mobile environment, and have, by 2015, already brought the Internet into the end user's hand. This new generation of mobile systems feels different. The global scale of enthusiasm and motivation is unprecedented. Even marketing has not been shy in proclaiming the advent of 5G on the roadmap, quite in contrast to the resistance in applying the name "4G" to LTE until Release 10 of the 3GPP standards.

We are still painting the empty canvas of that system which will appear as a small icon one day on our smartphones (or equivalent) as "5G". Can history help us predict what this system will all be about? Indeed, 2G was about global voice; 3G was about voice and data; 4G was about voice, data and applications. What about 5G?

We have witnessed mobile systems becoming an essential social infrastructure, mobilizing our daily life and facilitating digital economy. This trend will expand for 5G, boosting user experience and empowering industries with ICT, and the Internet of Things (IoT) will emerge as a new paradigm.

Credible details on the technology roadmap have started to emerge, which are largely articulated in this excellent book. 5G – so it seems – will require scale mainly in three dimensions.

First, rather traditionally, we need a massive scale in rate beyond the 4G capabilities of LTE Release 10. Spectrum is scarce in traditional cellular bands below 6 GHz, and improvement of spectrum efficiency is increasingly challenging. The only ways out seem to be through fresh approaches in system design, such as massive MIMO, mm-wave communications, relaying, network coding, advanced techniques in interference and mobility management, among others. Early prototypes and studies indicate that much of that is indeed feasible!

The world is starting to consume media such as video programming in more interactive ways, and the prospect for more immersive experiences in the form of Virtual Reality (VR) and Augmented Reality (AR) shows great challenge and promise. This places incredible requirements on mobile systems; large amounts of data have to be delivered to the user on demand, and end users can become the producers of copious amounts of information. These requirements do not merely affect the capacity of air interfaces and will cause re-architecture of transport networks and cloud systems to form

a more distributed topology that extends to the converged mobile core, with storage and computing being spread all the way to the wireless edge.

Second, quite unsurprisingly, we need massive scale in the number of devices within the IoT that we want to connect. 5G will play an instrumental role in ensuring universal connectivity for myriad devices of very different characteristics. Indeed, prior system designs have not delivered the required IoT capabilities – an opportunity which 5G may want to capitalize on.

Third, rather excitingly, mobile technologies must attend to criticality, articulated in terms of much quicker round-trip times and higher system reliability. This will underpin the emerging Tactile Internet, manufacturing and industrial process control, utilities, intelligent transportation systems and all the fascinating derivative applications that these areas will engender. Some dramatic changes to system design, however, are needed to make this reality. Notably, ultra-low end-to-end delays are not possible unless we witness a major overhaul of the wireless air interface and system architecture. As with media delivery, designers will have to bring computation and storage closer to the end user.

All these approaches will undergo rigorous standardization activities that will commence leading up to and beyond an agreed agenda item for IMT-2020 during the WRC-19 meetings. This will ensure global harmonization in the form of common frequency bands, common global standards and a common framework for requirements, capability and performance. Various 5G initiatives have absorbed diverse ideas on what 5G may be and have shaped a common conceptual understanding of 5G. Although 3GPP has been and will continue capturing the requirements of the machine-type communications, differences in requirements for various market segments of the IoT remain and will have to be dealt with in future standards.

We don't completely know every use that 5G will be put to, but we are not worried about this. As one CEO observed recently: "We started developing 3G before the Internet was really operational and we started with 4G before the iPhone came around"[1]. It is hence a perfect time to commence with 5G.

Now, will that 5G be something we have not witnessed to date? You will find out in this fascinating book written by some of the most prominent experts in mobile system design, people who always live 10 years into the future.

We hope you enjoy the read, as much as we did!

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[1] Statement by Hans Vestberg, CEO of Ericsson, 2015.

Acknowledgments

This book would never exist without the EU project Mobile and wireless communication Enablers for the Twenty-twenty Information Society (METIS), which was funded under the Seventh Framework Program between 2012 and 2015.

The journey began in April 2011 when a small group of engineers from Ericsson, Alcatel-Lucent[1], Huawei Europe, Nokia Corporation[1] and Nokia Siemens Networks[1] started to reflect on what may lay the foundation for a 5G project with a global impact. Their collaboration materialized into an EU project proposal that was later accepted by the EU commission (under the Seventh Framework Program). METIS included the following 25 companies and institutions that deserve our gratitude for their support in developing the basis for this book and helping to finalize it: Ericsson, Aalborg University, Aalto University, Alcatel-Lucent, Anite, BMW Group Research and Technology, Chalmers University of Technology, Deutsche Telekom, NTT DOCOMO, France Telecom-Orange, Fraunhofer-HHI, Huawei Technologies European Research Center, KTH – Royal Institute of Technology, National and Kapodistrian University of Athens, Nokia Corporation, Nokia Siemens Networks, University of Oulu, Poznan University of Technology, RWTH Aachen, Institut Mines-Télécom, Telecom Italia, Telefónica, University of Bremen, University of Kaiserslautern and Universitat Politècnica de València. It should be mentioned that the views expressed are those of the authors and do not necessarily represent METIS.

The EU commission has been unwavering in their support all through the project. Luis Rodriguez-Rosello, now retired, had been an encouraging influence from the beginning. The support and encouragement from the Commission continued over the lifetime of METIS from many other persons as well, a few key names being Bernard Barani, Mario Campolargo, Pertti Jauhiainen and Philippe Lefebvre. Barani and Lefebvre had been supportive when it came to strengthening METIS external exposure on 5G. Pertti Jauhiainen, the METIS project officer, must be acknowledged for his very pertinent advice throughout the project. At the highest level of the EU commission, especially the digital Single Market, EU commissioners have provided strong support in raising awareness about future wireless communication technologies across the world.

The bulk of the material in this book has been extracted from or based on several of the public deliverables of METIS. However, to provide the comprehensive picture on

[1] Now Nokia.

current 5G considerations, this was complemented by substantial additional material from authors and entities from outside of the METIS project (e.g. iJoin and 5GNow projects). We would therefore like to thank all our colleagues involved in the book for the support and cooperation that made the book possible.

The authors of this manuscript have shown great commitment and dedication during the writing process. Many worked during their free time, in the evenings and over weekends. They have demonstrated an exemplary spirit of collaboration, always being available when interrupted in the midst of their professional and private lives.

We wish to also thank those who reviewed the various chapters in this book, many drawn from the pool of authors for other chapters of this book. We are particularly indebted to Dr. Kumar Balachandran for his scrutiny and review of several parts of the book, including his significant edits to the introductory chapter. We are likewise thankful to our external reviewers: Dr. Jesus Alonso-Zarate, Prof. Mischa Dohler, Dr. Klaus Doppler, Salah-Eddine Elayoubi, Dr. Eleftherios Karipidis, Per Skillermark, Stefano Sorrentino, Dr. Rapeepat Ratasuk, Dr. Stefan Valentin, Dr. Fred Vook, Dr. Gerhard Wunder and Prof. Jens Zander.

Dr. Osseiran would also like to acknowledge the generosity of Dr. Magnus Frodigh and Mikael Höök of Ericsson. They were helpful in making the resources available that made this book possible.

We would like to thank Cambridge University Press for their help in finalizing this book.

Finally, some specific thanks in

- Chapter 1: to Hugo Tullberg for his careful review of the text and input on security. Mikael Fallgren and Katsutoshi Kusume are also thanked for their input on economic sectors.
- Chapter 2: to the colleagues in METIS who contributed to the 5G scenarios, use cases and system concept.
- Chapter 3: to the colleagues in work package 6 in METIS and work package 5 in iJOIN. Special thanks go to Joachim Sachs for his careful review and helpful comments.
- Chapter 4: to Erik Ström for his input regarding the representation of the reliability/latency targets.
- Chapter 5: to Byungjin Cho, Riku Jäntti and Mikko A. Uusitalo for their contributions related to multi-operator D2D operation.
- Chapter 6: to Johan Axnäs for his contributions related to mobility and beam finding.
- Chapter 7: to Frank Schaich, Hao Lin, Zhao Zhao, Anass Benjebbour, Kelvin Au, Yejian Chen, Ning He, Jaakko Vihriälä, Nuno Pratas, Cedomir Stefanovic, Petar Popovski, Yalei Ji, Armin Dekorsy, Mikhail Ivanov, Fredrik Brännström and Alexandre Graell i Amat.
- Chapter 8: to Paolo Baracca and Lars S. Sundström for their thorough review of the chapter.

- Chapter 9: to Antti Tölli, Tero Ihalainen, Martin Kurras and Mikael Sternad for their contributions. The authors would also like to thank Dennis Hui for his careful review and precious comments.
- Chapter 10: to Henning Thomsen for his contribution related to multi-flow wireless backhauling, and Sumin Kim and Themistoklis Charalambous for their contributions related to buffer-aided relaying.
- Chapter 11: to Patrick Agyapong, Daniel Calabuig, Armin Dekorsky, Josef Eichinger, Peter Fertl, Ismail Guvenc, Petteri Lundén, Zhe Ren, Paweł Sroka, Sławomir Stańczak, Yutao Sui, Venkatkumar Venkatasubramanian, Osman N. C. Yilmaz and Chan Zhou.
- Chapter 12: to their colleagues in work package 5 in METIS.
- Chapter 13: to David Martín-Sacristán for his thorough review of the chapter. The authors would also like to thank all the people who contributed to the METIS channel modeling.
- Chapter 14: to the colleagues in METIS who worked so intensively in the simulation activities.

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Acronyms

Acronym	Definition
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
5G-PPP	5G Public Private Partnership
ABS	Almost Blank Subframe
ACK	Acknowledged Message
A/D	Analogue-to-Digital
ADC	Analogue-to-Digital Converter
ADWICS	Advanced Wireless Communications Study Committee
AEI	Availability Estimation and Indication
AF	Amplify-and-Forward
AI	Availability Indicator
AMC	Adaptive Modulation and Coding
AMPS	Advanced Mobile Phone System
AN	Access Node
AoA	Angle of Arrival
AoD	Angle of Departure
AP	Access Point
API	Application Programming Interface
AR	Availability request
ARQ	Automatic Repeat Request
ASA	Azimuth Spread of Arrival
A-SAN	Assistant Serving Access Node
ASD	Azimuth Spread of Departure
AWGN	Additive White Gaussian Noise
BB	Baseband
BER	Bit Error Rate
BF	Beamforming
BH	Backhaul
BLER	Block Error Rate
BP	Break Point
BS	Base Station

BW	Bandwidth
CA	Carrier Aggregation
CapEx	Capital Expenditure
CB	Coordinated Beamforming
CC	Channel Component
CDD	Cyclic Delay Diversity
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CDPD	Cellular Digital Packet Data
CDR	Coordinated Direct and Relay Transmission
CEPT	European Conference of Postal and Telecommunications Administrations
CH	Cluster Head
Cloud-RAN	Cloud Radio Access Network
CMOS	Complementary Metal Oxide Semiconductor
cmW	centimeter Wave
CN	Core Network
CNE	Core Network Element
CoMP	Coordinated Multi-Point
CP	Cyclic Prefix
CPE	Common Phase Error
C-Plane	Control Plane
CPRI	Common Public Radio Interface
CPS	Cyber-Physical Systems
C-RAN	Centralized Radio Access Network
CRS	Common Reference Signal
CS	Coordinated Scheduler
CSI	Channel State Information
CSIT	Channel State Information at Transmitter
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CS-MUD	Compressed Sensing Based Multi-User Detection
CTS	Clear to Send
CU	Central Unit
CWIC	CodeWord level Interference Cancellation
D2D	Device-to-Device
DAC	Digital to Analog Conversion
dB	Decibel
DBSCAN	Density-Based Spatial Clustering of Applications with Noise
DCS	Dynamic Channel Selection
DEC	Decoder
Demod.	Demodulation
DER	Distributed Energy Resources
DET	Detection
DF	Decode-and-Forward

DFS	Dynamic Frequency Selection
DFT	Discrete Fourier Transform
DFTS-OFDM	Discrete Fourier Transform Spread OFDM
DID	Device-Infrastructure-Device
Div	Diversity
DL	Downlink
DMRS	Demodulation Reference Signal
DoA	Direction of Arrival
DoD	Direction of Departure
DoF	Degrees of Freedom
DPB	Dynamic Point Blanking
DPS	Dynamic Point Selection
DR	Decode-and-Reencode
D-RAN	Distributed Radio Access Network
DRX	Discontinuous reception
DyRAN	Dynamic Radio Access Network
E2E	End-to-End
EC	European Commission
EDGE	Enhanced Data rates for GSM Evolution
EGF	Enhanced Gaussian Function
eICIC	enhanced Inter Cell Interference Cancellation
EM	Eigenmode
EMF	Electromagnetic Field
eNB	enhanced NodeB
ENOB	Effective Number of Bits
EPA	Extended Pedestrian A
EPC	Evolved Packet Core
E-PDCCH	Enhanced PDCCH
ESA	Elevation Spread of Arrival
ESD	Elevation Spread of Departure
ESE	Elementary Signal Estimator
ETSI	European Telecommunications Standards Institute
ETU	Extended Typical Urban
EVA	Extended Vehicular A
EVM	Error Vector Magnitude
FBC	First bounce cluster
FBCP	Fixed BF and CSI-Based Precoding
FBMC	Filter-Bank Multi-Carrier
FCC	Federal Communications Commission
FD	Full duplex
FDD	Frequency Division Duplexing
FDM	Frequency Division Multiplex
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction

FFT	Fast Fourier Transform
FinFET	Fin-Shaped Field Effect Transistor
FoM	Figure-of-Merit
FP7	Seventh Framework Programme
FRN	Fixed Relay Node
FWR	Four-Way Relaying
GaAs	Gallium Arsenide
GaN	Gallium Nitride
GHz	Giga Hertz
GLDB	Geolocation Database
GoB	Grid of Beams
GP	Guard Period
GPRS	General Packet Radio Service
GSCM	Geometry-Based Stochastic Channel Model
GSM	Global System for Mobile communications
HARQ	Hybrid Automatic Repeat Request
HBF	Hybrid Beamforming
HD	Half Duplex
HetNet	Heterogeneous networks
HO	Handover
HPBW	Half Power Beam Width
HSCSD	High Speed Circuit Switched Data
HSDPA	High Speed Downlink Packet Access
HSM	Horizontal Spectrum Manager
HSPA	High Speed Packet Access
HSUPA	High Speed Uplink Packet Access
HTC	Human-Type Communication
i.i.d. or iid	independently and identically distributed
I2I	Indoor to Indoor
IA	Interference Alignment
IBC	Interfering Broadcast Channel
IC	Interference Cancellation
ICI	Inter-Cell Interference
ICIC	Inter-Cell Interference Coordination
ICNIRP	International Commission on Non-Ionizing Radiation Protection
ICT	Information and Communications Technologies
IDFT	Inverse Discrete Fourier Transform
IDMA	Interleave Division Multiple Access
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
IMF-A	Interference Management Framework from Artist4G
IMT	International Mobile Telecommunications
IMT-2000	International Mobile Telecommunications 2000
IMT-A	International Mobile Telecommunications-Advanced

InH	Indoor Hotspot
InP	Indium Phosphide
IoT	Internet of Things
IR	Impulse Response
IRC	Interference Rejection Combining
IS	Interference Suppression
ISA	International Society for Automation
ISD	Inter-Site Distance
IT	Information Technology
ITS	Intelligent Transport Systems
ITU	International Telecommunication Union
ITU-R	International Telecommunications Union – Radiocommunication Sector
ITU-T	International Telecommunications Union – Telecommunication Standardization Sector
JSDM	Joint Spatial Division Multiplexing
JT	Joint Transmission
KPI	Key Performance Indicator
LA	Link Adaptation
LAA	Licensed-Assisted Access
LBC	Last-Bounce Cluster
LBS	Last-Bounce Scatterer
LDPC	Low Density Parity Check
LO	Local Oscillator
LOS	Line of Sight
LR-WPAN	Low-Rate Wireless Personal Area Networks
LaS	Large Scale
LS	Least Square
LSA	Licenced Shared Access
LSCP	Lean System Control Plane
LSP	Large Scale Parameters
LTE	Long Term Evolution
LTE-A	Long Term Evolution-Advanced
LTE-U	Long Term Evolution-Unlicensed
M2M	Machine to Machine
MAC	Medium Access Control
MAP	Maximum A Posteriori
MBB	Mobile Broadband
MCS	Modulation and Coding Scheme
MET	Multiuser Eigenmode Transmission
METIS	Mobile and wireless communications Enablers for Twenty-twenty (2020) Information Society
MF	Matched Filter
MH	Multi-Hop

MHz	Mega Hertz
MIIT	Ministry of Industry and Information Technology
MIMO	Multiple Input Multiple Output
ML	Maximum Likelihood
MME	Mobility Management Entity
MMSE	Minimum Mean Square Error
mMTC	massive Machine-Type Communication
mmW	millimeter Wave
MN	Moving Networks
MNO	Mobile Network Operator
MODS	Multi-Operator D2D Server
MOST	Ministry of Science and Technology
MPA	Massage Passing Algorithm
MPC	Multipath Components
MPLS	Multiprotocol Label Switching
MRC	Maximal Ratio Combining
MRN	Moving Relay Node
MRT	Maximum Ratio Transmission
MoS	Mode Selection
MS	Mobile Station
MTC	Machine-Type Communication
MU	Multi User
MU MIMO	Multi User MIMO
MUI	Multi User Interference
MUICIA	Multi User Inter Cell Interference Alignment
MU-MIMO	Multi User MIMO
MU-SCMA	Multi User SCMA
MUX	MUltipleXing
n.a.	not applicable
NA	Network Assistance
NAIC	Network Assisted Interference Cancellation
NA-TDMA	North American TDMA
NDRC	National Development and Reform Commission
NE	Network Element
NF	Network Function
NFV	Network Function Virtualization
NFVI	Network Function Virtualization Infrastructure
NGMN	Next Generation Mobile Networks
NLOS	Non-Line of Sight
NMSE	Normalized Mean Square Error
NMT	Nordic Mobile Telephone
NN	Nomadic Nodes
NOMA	Non-Orthogonal Multiple Access
NRA	National Regulatory Authorities

NSPS	National Security and Public Safety
O2I	Outdoor-to-Indoor
O2O	Outdoor-to-Outdoor
Ofcom	Office of communications
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OL	Open Loop
OLOS	Obstructed Line of Sight
OLPC	Open Loop Path Loss Compensating
OMD	OFDM Modulation/Demodulation
OP CoMP	OPportunistic CoMP
OPEX	Operational Expenditures
OPI	Overall Performance Indicator
OQAM	Offset QAM
ORI	Open Radio Equipment Interface
P2P	Peer to Peer
PAPC	Per Antenna Power Constraint
PAPR	Peak to Average Power Ratio
PAS	Power Angular Spectrum
PC	Power Control
PCC	Phantom Cell Concept
PDC	Personal Digital Cellular
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
PDSCH	Physical Downlink Shared Channel
PER	Packet Error Rate
P-GW	Packet data network Gateway
PHY	PHYsical layer
PiC	Pilot Contamination
PLC	Programmable Logic Controller
PLL	Phase Locked Loop
PMU	Phasor Measurement Unit
PN	Phase Noise
PNL	Power Normalization Loss
PPC	Pilot Power Control
PPDR	Public Protection and Disaster Relief
PRACH	Physical Random Access Channel
PRB	Physical Resource Block
ProSe	Proximity Service
P/S	Parallel to Serial
P-SAN	Principal Serving Access Node
PSD	Power Spectral Density
PSM	Power Saving Mode
PUSCH	Physical Uplink Shared Channel

QAM	Quadrature Amplitude Modulation
QoE	Quality of Experience
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RA	Random Access
RACH	Random Access Channel
RAN	Radio Access Network
RAT	Radio Access Technology
RB	Resource Block
Rel	Release
ReA	Resource Allocation
RF	Radio Frequency
RLC	Radio Link Control
RLS	Recursive Least Squares
RMT	Random Matrix Theory
RN	Relay Node
RNE	Radio Network Element
RRC	Radio Resource Control
RRM	Radio Resource Management
RS	Relay Station
RSRP	Reference Signal Received Power
RTL	Reliable Transmission Link
RTS	Request to Send
RTT	Round Trip Time
Rx	Receiver
SA	Service and System Aspects
SBC	Single Bounce Cluster
SC	Single Carrier
SCM	Spatial Channel Model
SCMA	Sparse Code Multiple Access
SCME	Spatial Channel Model Extended
SDF	Spatial Degrees of Freedom
SDN	Software Defined Networking
SE	Switching Element
SFBC	Space Frequency Block Coding
S-GW	Serving Gateway
SIC	Successive Interference Cancellation
SiGe	Silicon Germanium
SIMO	Single Input Multiple Output
SINR	Signal to Interference plus Noise Ratio
SIR	Signal to Interference Ratio
SLIC	Symbol Level Interference Cancellation
SLNR	Signal to Leakage Interference plus Noise Ratio
SM	Spatial Multiplexing

SMEs	Small and Medium-sized Enterprises
SMS	Short Message Service
SNR	Signal-to-Noise Ratio
SoA	State of the Art
SOCP	Second Order Cone Programming
S/P	Serial to Parallel
SS	Small Scale
SU-MIMO	Single User MIMO
SUS	Semi-orthogonal User Selection
SvC	Serving Cluster
SVD	Singular Value Decomposition
TACS	Total Access Communications System
TAU	Tracking Area Update
TCP	Transmission Control Protocol
TD-CDMA	Time Division CDMA
TDD	Time Division Duplexing
TDM	Time Division Multiplex
TDMA	Time Division Multiple Access
TeC	Technology Component
TTI	Transmission Time Interval
TV	Television
TVWS	TV White Space
TWR	Two-Way Relaying
Tx	Transmitter
UDN	Ultra-Dense Network
UE	User Equipment
UFMC	Universal Filtered Multi-Carrier
UF-OFDM	Universal Filtered OFDM
UL	Uplink
ULA	Uniform Linear Array
UM	Utility Maximizing
UMa	Urban Macro
UMi	Urban Micro
uMTC	ultra-reliable Machine-Type Communication
UMTS	Universal Mobile Telecommunication System
UPA	Uniform Planar Array
U-Plane	User Plane
UTD	Uniform Theory of Diffraction
V2D	Vehicle-to-Device
V2I	Vehicle-to-Infrastructure
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Anything
VCO	Voltage Controlled Oscillator