THE TECHNOLOGY AND BUSINESS OF MOBILE COMMUNICATIONS

AN INTRODUCTION

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IEEE PRESS

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WILEY

IEEE PRESS

This edition first published 2022

Registered Offices
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial Office
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

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Library of Congress Cataloging-in-Publication Data
Names: Hunukumbure, Mythri, 1972- author.
Title: The technology and business of mobile telecommunications : an introduction / Mythri Hunukumbure, Justin P. Coon, Ben Allen, Tony Vernon.
Description: Hoboken, NJ : John Wiley & Sons, 2022. | Includes bibliographical references and index.
Identifiers: LCCN 2021020796 (print) | LCCN 2021020797 (ebook) | ISBN 9781119130291 (hardback) | ISBN 9781119130307 (pdf) | ISBN 9781119130314 (epub) | ISBN 9781119130345 (ebook)
Subjects: LCSH: Mobile communication systems. | Cell phone services industry.
Classification: LCC TK5103.2 .H85 2022 (print) | LCC TK5103.2 (ebook) | DDC 621.384--dc23
LC record available at https://lccn.loc.gov/2021020796
LC ebook record available at https://lccn.loc.gov/2021020797

Cover image: © Tony Vernon
Cover design by Wiley

Set in 9.5/12.5pt STIXTwoText by Integra Software Services Pvt. Ltd, Pondicherry, India

10 9 8 7 6 5 4 3 2 1

To Dilshani, Kaveesha and Nethaya and to my parents Leela and Jayatissa

–Mythri Hunukumbure

To my mother, Jennifer Hill, and my father, Bob Coon

–Justin P. Coon

To Louisa, Nicholas and Bethany and my whole family, friends and colleagues past and present

–Ben Allen

For Christopher, Marcus and Caitlin

–Tony Vernon

Contents

Foreword

I am thrilled to have been invited to write the foreword to this text as the authors are former doctoral students of mine. This book expertly draws together the technology and business of mobile communications. Whilst both the technical and business elements are thought by many to be highly complex in their own right, and may only be grasped by 'experts', this text renders both as readily accessible to those with an understanding of the basic concepts and an interest in the subject matter. This text is further commendable since it is rare that a single volume seamlessly tackles both technical and business elements in such a way that the reader with a background in either is readily drawn to appreciate the other.

Cellular or mobile communication technologies and their capabilities have evolved rapidly over the last 40 years, with 5 generations (the'G') of research, standardisation, product development, and roll-out now serving more than 14 billion devices. With each transition between the generations, users have benefited from an evolution in connectivity performance and new service offerings. This rapid growth is not solely driven by innovation, but, as a sound economic case is a key requirement given the level of investment required.

The authors of this book, with their doctoral research contributing to wireless communications and enriched by their industrial and academic contributions, have brought together this textbook as a one-stop reference of the journey through the 5 generations of cellular, as well as what is to follow. The breadth of knowledge and experience from the team provides a rich narrative on the mobile telecommunications ecosystem, including spectrum, standards, costing and disruptors, alongside network architecture design. An accessible explanation of the Radio Access Network (RAN) and the mechanisms of call setup, control and mobility complements the former. This is followed by highlights of numerous technology evolutions, including antenna arrays, interference management, network planning, electromagnetic field safety and development of greener technology. The final chapter takes a look forwards in terms of applications in the vertical industrials as well as the application of machine learning (ML) and artificial intelligence (AI), and higher frequency bands (Tera-Hertz) as we enter the era of 6G R&D.

At the time of writing, 5G mobile technologies are being rolled out and becoming embedded in mobile communications networks in many countries. This text provides a gateway into 5G technologies and networks such as the 'core' and RAN and also details forthcoming network technologies such a Cloud-RAN, Network Function Virtualisation (NFV) and Software Defined Networks (SDN). An in-depth look into techno-economic aspects of the emerging 5G verticals is also covered, where the related-use cases underpin the economic outlook for 5G networks and associated businesses.

It is also an exciting and pivotal time for mobile communications research. As 5G networks are being established, research into 6G is underway with increasing intensity. This includes identifying key challenges and technologies for addressing them, hence providing momentum for further research and development. This book also provides further details of some of the key potential technological enablers for 6G.

For those entering the field of mobile communications, this book provides a valuable resource to capture four decades of cellular development. For those already working in this domain, a handy reference.

I commend this book and sincerely hope you enjoy the read, as I have done.

Mark
Professor Mark Beach
Professor of Radio Systems Engineering
Department of Electrical and Electronic Engineering
University of Bristol

Preface

Mobile communications is one of the most rapidly evolving technical fields, with a new generation of mobile communications appearing every 10 years or so. For a new entrant to this field, be it as a post-graduate student or an industry employee, keeping pace with the current developments in their specialisation becomes the priority. While this is critically important, it can obscure or delay development of an overall understanding of the different components of this wide ecosystem and their interactions. Having this overall view of how the different pieces of this complex 'jigsaw puzzle' fit together can be really useful when they want to navigate beyond their specialised area.

The intention of this book is to provide such an overall view of the Mobile ecosystem and show the interactions of individual components, their evolutions and future directions in an introductory manner. The authors and the specialised chapter contributors use their knowledge and wide experience in industry, academia and regulatory domains to provide a broad encapsulation of all the critical components in this field. Special care has been taken to acknowledge that all readers of this book will not have a deep technical background or the requirement to master all the technical details of this field. A separate chapter sequence for following this book while omitting the deep technical details and focussing more on the business aspects has been suggested in the introduction (Chapter 1).

In a book covering a broad array of topics and a target audience with a wide span of interests in mobile communications, it is not possible to delve deeper into a single topic. Ample references, which provide in-depth coverage of particular topics, have been provided particularly in deeply technical chapters. All efforts have been taken to capture the latest developments in each of the topics at the time of writing. However, in such a dynamic field as mobile communications, the lead time in bringing written content to print can mean that the 'latest' has moved a few notches forward. We have also captured many web resources as citations, especially in chapters looking at the latest and future technology trends, where printed and published citation options are somewhat in short supply. We have reviewed the chapter contents several times to remove any errors or inconsistencies but if a reader finds any such inconsistencies we would be very happy to be notified of such. This will help us to improve any subsequent editions or prints of this book.

We hope that this book will become a useful resource to aspiring practitioners in this highly dynamic and exciting field of mobile communications.

Mythri, Justin, Ben and Tony.

About the Authors

Mythri Hunukumbure
Dr. Mythri Hunukumbure obtained his BSc (Eng) degree with first-class honours from the University of Moratuwa, Sri Lanka in 1998 and MSc and PhD degrees in Telecommunication Engineering from the University of Bristol in 2000 and 2004 respectively. He is currently a Principal Research Engineer and a Project Lead at the Samsung Electronics R&D Institute, UK. In an industry career spanning over 15 years, he has contributed to, and later led, mobile communication research, standardisation and product development activities. Whilst at Samsung, he has participated in flagship EU projects mmMAGIC, ONE5G and 5G LOCUS as a work package leader. He is also actively contributing to 3GPP RAN1 and SA2 standardisation topics, securing vital IPR. He has filed around 50 patents to date and has also published extensively in leading conferences and journals, receiving the best paper award at the World Telecommunications Congress (WTC) in 2012.

Justin P. Coon
Professor Justin P. Coon received a BSc degree (with distinction) in electrical engineering from the Calhoun Honours College, Clemson University, USA and a PhD in communications from the University of Bristol, UK in 2000 and 2005, respectively. From 2004 until 2013, he held various technical and management positions at Toshiba Research Europe Ltd. (TREL). Prof. Coon also held a Reader position in the Department of Electrical and Electronic Engineering at the University of Bristol from 2012 until 2013. In 2013, he took a faculty position at Oxford University with a Tutorial Fellowship at Oriel College. Prof. Coon is a Fellow of the Institute of Mathematics and Its Applications (FIMA) and a Senior Member of the Institute of Electrical and Electronics Engineers (IEEE). He is also a regular consultant to industry.

Ben Allen
Dr. Ben Allen completed his MSc and PhD degrees at the University of Bristol in 1997 and 2001 respectively. His career has spanned academia and industry, most recently as a Royal Society Industry Fellow with the University of Oxford and Network Rail. He has been the lead for several R&D activities involving telecoms for railways, several of which exhibited state-of-the-art advances. He has published numerous papers and

several books on radio and telecommunications research developments. Dr. Allen is a Chartered Engineer, Fellow of the Institution of Engineering & Technology, Institute of Telecommunications Professionals and the Higher Education Academy.

Tony Vernon

Dr. Vernon graduated from the University of Glasgow in 1987 with a Joint Honours in Electronic Engineering with Physics. After a few years in the cellular industry, he obtained chartered status and, in 2002, received a PhD in Mobile Telecoms from the University of Bristol. His main interests and career contributions lie in the planning and optimisation of digital mobile networks ranging from the dawn of 2G in 1991 to 5G in 2021. With 6G on the horizon, Dr. Vernon's focus has moved to the vehicular channel (V2X) and the future use of soon-to-be-ubiquitous mobile broadband networks for national and public-access broadcasting. He is based on the Scottish Outer Hebridean island of South Uist and is thus passionate about expanding 4G and 5G mobile broadband connectivity to rural and remote areas.

Acknowledgements

This book has truly been a collective effort, with the authors and contributors providing expertise and resources from a wide array of specialisations within mobile communications. The authors would like to jointly thank Wiley publishers, especially Sandra Grayson, Juliet Booker and Britta Ramaraj, for their continued support throughout this project. The authors also acknowledge the three specialised chapters provided by the contributors, which really widen the scope of this book:

Daniel Warren (Samsung Research UK): Chapter 4: Why Standards Matter?

Abhaya Sumanasena (Real Wireless): Chapter 7: Spectrum – the life blood of radio communications

Jie Zhang (University of Sheffield and Ranplan) and **Haonan Hu** (Chongqing University of Posts and Telecommunications): Chapter 10: Small Cells – an evolution or a revolution?

The authors fondly reminisce of the opportunity they had to pursue further studies at the Electrical and Electronics Department, the University of Bristol, all these years ago. They gratefully recall the guidance they received from their common PhD supervisor Dr. Mark Beach and also thank him for providing an insightful foreword to this book.

Mythri Hunukumbure wishes to acknowledge Samsung Electronics R&D Institute UK and thanks his colleagues for their fellowship and support. He also acknowledges the European Commission funded 5G research projects mmMAGIC, ONE5G and 5G LOCUS where the cutting-edge research conducted has helped him to grow his expertise and knowledge in this field. He wishes to thank Fujitsu Labs of Europe and the University of Bristol where he previously worked. Last, but not least, he is so grateful for the support he has received from his family members and friends here in the UK and in Sri Lanka without which this book would not have been possible.

J. P. Coon would like to acknowledge Oxford University and, in particular, the Department of Engineering Science, for providing an atmosphere of academic freedom that has allowed him to follow his curiosities over the past decade. He also wishes to thank Oriel College, in its 695th year of existence, for continuing to be such a welcoming and collegiate seat of learning and fellowship. Additionally, he gratefully acknowledges the support of EPSRC, the US ARO, the John Fell Fund, Toshiba Europe Ltd, and Moogsoft, which has enabled him to explore many exciting areas of research during the writing of this book.

Ben Allen particularly wishes to thank Dr. Mythri Hunukumbure for organising this book, as well as Drs. Justin Coon and Tony Vernon for their substantial contributions and fellowship over the years. He also gratefully acknowledges those who have contributed both directly and indirectly to this text, without which this book would not have come to fruition, especially Dr Kafil Ahmed of Network Rail for his contribution of section 2.10 and companionship during overlapping time with Network Rail. Finally, he wishes to thank his family for their enduring love and support. Thank you!

Tony Vernon would like to thank, first and foremost, Dr. Mythri Hunukumbure for his unstinting patience, understanding and encouragement over the five-year gestation of this book, and Drs. Justin Coon and Ben Allen for their expert contributions and fellowship during some personally difficult years spent together at Bristol University. Grateful thanks are also due to Professors Mark Beach and Joe McGeehan, who took a gamble on a chap who had failed first-time round, but came good on his second chance. Finally, he pays tribute to all of the great engineering managers he has had over the course of a three-decade career; most notable in this number is Phil Cornforth, currently VP Emerging Technologies with Deutsche Telecom, whose 'servant-not-master' example he has always tried to follow.

List of Abbreviations

6G	6th Generation
5G	5th Generation
4G	4th Generation
3G	3rd Generation
2G	2nd Generation
1G	1st Generation
3GPP	3rd Generation Partnership Project
8-PSK	8-Phase Shift Keying
AAA	Authentication, Authorisation and Accounting
ABS	Almost Blank Sub-frames
AI	Artificial Intelligence
AMF	Access and Mobility Function
AMPS	Advanced Mobile Phone System
ANDSF	Access Network Discovery and Selection Function
ANR	Automatic Neighbour Relation
API	Application Programming Interfaces
AR	Augmented Reality
ARPU	Average Revenue Per User
AUSF	Authentication Server Function
AWGN	Additive White Gaussian Noise
B2B	Business to business
BBU	Baseband Processing Unit
BER	Bit Error Rate
BiTA	Blockchain in Transport Alliance
BJCR	Bahl-Cocke-Jelinek-Raviv
bps	bits per second
BSC	Base Station Controller
BSS	Base Station Subsystem
BTS	Base Transceiver Station
BWP	Bandwidth Parts
CA	Carrier Aggregation
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure

CBRS	Citizen's Broadband Radio Service
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
C-ITS	Co-operative Intelligent Transport Systems
CLSP	Close-loop Spatial Multiplexing
CN	Core Network
CO	Central Office
CoMP	Coordinated Multipoint
COTS	commercial off-the-shelf
CP	Control Plane
CPE	Common Phase Error
CPRI	Common Public Radio Interface
CQI	Channel Quality Indicator
C-RAN	Cloud Radio Access Network
CRC	Cyclic Redundancy Check
CRE	Cell Range Expansion
CRS	Common Reference Signal
CU	Centralised Unit
D2D	Device to Device
DAB	Digital Audio Broadcasting
DAS	Distributed Antenna Systems
DC	Dual Connectivity
DEM	Digital Evaluation Model
DFD	Division Free Duplex
DFE	Decision Feedback Equalizer
DFP	Dynamic Frequency Planning
DRX	Discontinuous Reception Cycle
DSCs	Drone Small Cells
DSP	Digital Signal Processing
DSRC	Dedicated Short Range Communications
DSSS	Direct-sequence spread spectrum
DTM	Digital Terrain Model
DU	Dense Urban
DVB	Digital Video Broadcasting
DWDM	Dense Wavelength Division Multiplexing
EB	Exabyte
ECC	Electronic Communications Committee
EDGE	Enhanced Data rates for GSM Evolution
EEA	European Economic Area
Eicic	Enhanced Inter-cell Interference Coordination
EMF	Electromagnetic Field
EPC	Evolved Packet Core
ESN	Emergency Services Network
ETSI	European Telecommunications Standards Institute
E-UTRAN	Evolved UTRAN

EV-DO	Evolution Data Only
EV-DO	Evolution Data Optimised
FAT	Frequency Allocation Table
FCC	Federal Communications Commission
FD	Full Duplex
FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access
FFM	Fast Fade Margin
FFR	Fractional Frequency Reuse
FOMA	Freedom of Mobile Multimedia Access
FPS	Full Power Sub-frames
FRAND	Fair, Reasonable and Non-Discriminatory
FSPL	Free-space Path Loss
FTP	File Transfer Protocol
FTTH	fibre-to-th-home
FWA	Fixed Wireless Access
GAN	Generic Access Network
Gbps	gigabits per second
GBT	Guaranteed Bit Rate
GCF	Global Certification Forum
GDP	Gross Domestic Product
GGSN	Gateway GPRS Support Node
GMSK	Gaussian Minimum Shift Keying
GPRS	General Packet Radio System
GSM	Groupe Spécial Mobile
HARQ	Hybrid Automatic Repeat Request
HEO	High Elliptical Satellite
GSMA	Global System for Mobile Communications
GSS	GPRS sub-system
HAP	High Altitude Platforms
H-CRAN	Heterogeneous Cloud Radio Access Network
HDD	Hard Disk Drive
HetNet	Heterogeneous Network
HH	Horizontal to Horizontal
HLR	Home Location Register
HeNB	Home eNodeB
HM	Hysteresis Margin
HNB	Home NodeB
HOFs	Hand Over Failures
HSS	Home Subscription Server
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSUPA	High Speed Uplink Packet Access
IAB	Integrated Access and Backhaul
ICIC	Inter-cell Interference Coordination

ICNIRP	International Commission on Non-Ionising Radiation Protection
ICO	Intelligent Cell Optimisation
IETF	Internet Engineering Task Force
IFFT	Inverse Fast Fourier Transform
IMS	IP Multimedia Sub-system
IP	Internet Protocol
IPR	Intellectual Property Rights
IoT	Internet of Things
ISD	Inter-site Distance
ISG	Industry Specification Group
ISI	Inter-Symbol Interference
ITU	International Telecommunication Union
kbps	kilobits per second
KPI	Key Performance Indicator
LA	Location Area
LAA	Licensed Assisted Access
LAMM	Linear Angular Momentum Multiplexing
LAPD-m	Link Adaptation Channel D – mobile
LDC	Local Data Centre
LDPC	Low-density parity check
LEO	Low Earth Orbits
LLC	Logical Link Layer
LMR	Land Mobile Radio
LNA	Low-noise amplifier
LNFM	log normal fade margin
LOS	Line of Sight
LSAS	Large-scale Antenna Systems
LTE	Long Term Evolution
MAC	Medium Access Control
MANO	Management and Network Orchestration
MC-PTT	Mission Critical Push To Talk
MCS	Modulation and Coding Scheme
MEC	Multi-access Edge Computing
MIB	Master Information Block
MIMO	Multiple Input Multiple Output
ML	Machine Learning
MLB	Mobility Load Balancing
MM	Mobility Management
MMDS	Multi-point Microwave Distribution Systems
MME	Mobility Management Entities
M2M	Machine to Machine
MMSE	Minimum mean-square error
mMTC	massive Machine Type Communication
MORAN	Multi Operator Radio Access Networks
MRC	Maximum Ratio Combining

MRO	Mobility Robustness Optimisation
MRP	Market Representation Partner
MRRC	Maximum Ratio Receiver Combining
MSC	Mobile Switching Centre
MUD	Multi User Detection
MVNO	Mobile virtual network operator
N3IWF	Non-3GPP Interworking Function
NaaS	Network as a Service
NAS	Non-Access Stratum
NCS	Network Slice Controller
NB-IoT	Narrow Band Internet of Things
NEF	Network Exposure Function
NFV	Network Function Virtualisation
NFVI	Network Function Virtualisation Infra-structure
NLOS	Non-line of Sight
NMT	Nordic Mobile Telephones
NOMA	Non-orthogonal multiple access
NRZ	Non-return-to-zero
NSA	Non-StandAlone
NSS	Network and Switching Sub-System
NTN	Non-Terrestrial Networks
OAI	Open Air Interface
OAM	Orbital Angular Momentum
OBSAI	Open Base Station Architecture Initiative
OFDMA	Orthogonal Frequency Division Multiple Access
O&M	Operations and Maintenance
ONF	Open Networking Foundation
OOK	on off keying
OPEX	Operational Expenditure
OSI	Open Systems Interconnection
OSS	Operations Support Systems
OTT	over-the-top
OVSF	Orthogonal Variable Spreading Factor
OWB	Optical Wireless Broadband
P2P	Point-to-point
P2MP	Point-to-multipoint
PaaS	Platform as a Servide
PAPR	Peak-to-average Power Ratio
PBCH	Physical Broadcast Channel
PCEF	Policy and Charging Enforcement Function
PCF	Policy Control Function
PCI	Physical Cell Identity
PCRF	Policy Control and Charging Rules Function
PDF	Probability Density Function
PDSCH	Physical Downlink Shared Channel

PDU	Protocol Data Unit
PF	Proportional Fair
PL	Path Loss
PLE	Path Loss Exponent
PLL	Phase Locked Loop
PLMN	Public Land Mobile Networks
PN	Pseudo Noise
PNDS	Packet Data Networks
PoP	Point of Presence
PPC	Policy and Charging Control
PRB	Physical Resource Block
PRS	Positioning Reference Signal
P-SCH	Primary Synchronisation Channel
PSK	Phase Shift Keying
PSS	Primary Synchronisation Signal
PSTN	Public Switched Telephone Networks
PUSH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QFI	Quality of Service Flow Identifier
QPSK	Quadrature Phase-shift Keying
QoE	Quality of Experience
QoS	Quality of Service
RA	Routing Area
RACH	Random Access Channel
RAN	radio access network
RDC	Regional Data Centre
RE	resource element
RED	Radio Equipment Directive
RGC	Rural Gigabit Connectivity
RIP	Received Interference Power
RLAH	Roam Like At Home
RLF	Radio Link Failure
RNC	Radio Network Controller
ROI	Return on Investment
RPE	Radiation Pattern Envelope
RPS	Reduced Power Sub-frames
RRH	Remote Radio Head
RRM	Radio Resource Management
RRPS	Ranplan Radio Propagation Simulator
RSPG	Radio Spectrum Policy Group
RSQ	Received Signal Quality
RSS	Received Signal Strengths
RU	Rural
RWP	Random Waypoint
SA	StandAlone

SAE	System Architecture Evolution
SAW	Stop and Wait
SBA	Service-Based Architecture
SC	Small Cell
SC-FDE	Single Carrier with Frequency Domain Equalisation
SC-FDMA	Single Carrier Frequency Division Multiple Access
SCH	Synchronisation Channel
SDN	Software Defined Network
SER	Symbol Error Rate
SGW	Serving Gateways
SGSN	Serving and Gateway Support Nodes
SIB	System Information Block
SIC	Successive Interference Cancellation
SIM	Subscriber Identity Module
SINR	Signal to Noise Ratio
SMF	Session Management Function
SON	Self Organised Networks
SSB	Synchronisation Signal Blocks
SSD	Solid-State Drive
S-SCH	Secondary Synchronisation Channel
SSS	Secondary Synchronisation Signal
SU	Suburban
SVD	Singular Value Decomposition
TACS	Total Access Communication System
TCH	Traffic Channels
TCO	Total Cost of Ownership
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TDE	Time-Domain Equalisation
TDMA	time Division Multiple Access
TD-SCDMA	Time Division – Synchronous CDMA
TEID	Tunnel End-point ID
TETRA	Terrestrial Trunked Radio
TMA	Tower Mount Amplifier
TNGF	Trusted Non-3GPP Gateway Function
TPS	Transmit Power Control
TRAU	Transcoder/Rate Adaptor Unit
TSG	Technical Specification Groups
TTT	Time to Trigger
U	Urban
UAVs	Unmanned Ariel Vehicles
UDP	User Datagram Protocol
UE	User Equipment
UMB	Ultra-Mobile Broadband
UMTS	Universal Mobile Telecommunication System