Towards 5G

Applications, Requirements & Candidate Technologies

Edited by
Rath Vannithamby • Shilpa Talwar

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TOWARDS 5G

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APPLICATIONS, REQUIREMENTS AND CANDIDATE TECHNOLOGIES

Edited by

Rath Vannithamby and Shilpa Talwar
Intel Corporation, USA

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List of Acronyms

Chapter 1

1G	First Generation
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
CDMA	Code Division Multiple Access
TDMA	Time Division Multiple Access
OFDMA	Orthogonal Frequency Division Multiple Access
GSM	Global System for Mobile communications
IMT	International Mobile Telecommunications
ITU-R	International Telecommunication Union-Radio
WCDMA	Wideband CDMA
3GPP	Third Generation Partnership Project
HSPA	High Speed Packet Access
LTE	Long-Term Evolution
FDMA	Frequency Division Multiple Access
SC-FDMA	Single Career Frequency Division Multiple Access
M2M	Machine to Machine communications
IoT	Internet of Things
QoE	Quality of Experience
RAT	Radio Access Technology
MIMO	Multiple Input Multiple Output
SDN	Software Defined Network
NFV	Network Function Virtualization

Chapter 2

5GMF	5G Mobile Communications Promotion Forum
NGMN	Next Generation Mobile Networks
D2D	Device to Device
FHD	Full High Definition
UHD	Ultra High Definition
V2V	Vehicle-to-Vehicle
C2C	Car-to-Car
V2I	Vehicle-to-Road Infrastructure
C2P	Car-to-Pedestrian
V2D	Vehicle-to-Device
BYOD	Bring Your Own Device
SoLoMo	Social Local Mobile
HMI	Human-Machine Interface
CAGR	Compound Annual Growth Rate
WRC	World Radio Conference
AR	Augmented Reality
RTT	Round Trip Time
TTI	Transmission Time Interval
HARQ	Hybrid Automatic Repeat reQuest

Chapter 3

3GPP	3rd Generation Partnership Project
BS	Base Station
D2D	Device to Device
DL	Downlink
EE	Energy Efficiency
EEC	European Economic Union
EFTA	European Free Trade Association
EP	European Parliament
ETP	European Technology Platform
ETSI	European Telecommunications Standards Institute
EU	European Union
HetNet	Heterogeneous network
ICT	Information and Communication Technology
IST	Information Society Technology
LTE	Long-Term Evolution
LTE-A	Long-Term Evolution-Advanced
LSA	Licensed Shared Access
MIMO	Multiple Input Multiple Output
MTC	Machine Type Communication
PPP	Public Private Partnership
QoS	Quality of Service

RAT	Radio Access Technology
TDMA	Time-Division Multiple Access
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System

Chapter 4

ISRA	Intel Strategic Research Alliance
NTIA	National Telecommunications and Information Association
GHz	Gigahertz
THz	Terahertz
Gbps	Gigabits per second
MIMO	Multi Input Multi Output
MU-MIMO	Multi-User MIMO
VLM	Very Large MIMO
CP	Cyclic Prefix
OFDM	Orthogonal Frequency Division Multiplexing
RAN	Radio Access Network
RAT	Radio Access Technology
WAN	Wide Area Network
LAN	Local Area Network
PAN	Personal Area Network
IoT	Internet of Things
QoE	Quality of Experience
QoS	Quality of Service
RFP	Request For Proposals
OTT	Over-The-Top
ARQ	Automatic Repeat reQuest
PHY	Physical Layer
FFR	Fractional Frequency Reuse
LSA	Licensed Shared Access
REM	Radio Environment Map
PC	Personal Computer
GNU	GNUs Not Unix

Chapter 5

SE	Spectral Efficiency
EE	Energy Efficiency
LSAS	Large Scale Antenna System
NOMA	Non Orthogonal Multiple Access
C-RAN	Cloud Radio Access Network
ICT	Information and Communications Technologies

MTC	Machine Type Communications
QoS	Quality of Service
MAC	Medium Access Control
PA	Power Amplifier
CSI	Channel State Information
TDD	Time Division Duplex
FDD	Frequency Division Duplex
UDN	Ultra Dense Network
DAS	Distributed Antenna System
CoMP	Coordinated Multi-Point
IM	Instant Messaging
LAPI	Low Access Priority Indication
RRC	Radio Resource Control

Chapter 6

SCN	Small Cell Network
UT	User Terminal
ICIC	Inter-Cell Interference Coordination
TTT	Time to Trigger
SINR	Signal-to-Interference-plus-Noise Ratio
OPEX	Operational Expenditures
CF	Collaborative Filtering
SVD	Singular Value Decomposition
CDN	Content Delivery Network
ICN	Information Centric Networks
MAB	Multi-Armed Bandit
ADMM	Alternating Direction Method of Multipliers
DMT	Diversity-Multiplexing Tradeoff
SNR	Signal-to-Noise Ratio
PPP	Poisson Point Process

Chapter 7

D2D	Device-to-Device
QoS	Quality of Service
RAT	Radio Access Technology
UE	User Equipment
HetNets	Heterogeneous Networks
WLAN	Wireless Local Area Network
3GPP	Third Generation Partnership Project
UMTS	Universal Mobile Telecommunications System
LTE	Long-Term Evolution
RAN	Radio Access Network
ANDSF	Access Network Discovery and Selection Function

SINR	Signal-to-Interference-plus-Noise Ratio
DL	Downlink
UL	Uplink
MIMO	Multiple Input Multiple Output
PPP	Poisson Point Process
AP	Access Point
BS	Base Station
MP	Maximum Power
FU	Full Utilization
SNR	Signal-to-Noise Ratio
SLS	System Level Simulator

Chapter 8

LTE-A	Long-Term Evolution-Advanced
ABS	Almost Blank Subframe
RB	Resource Block
CSI	Channel State Information

Chapter 9

D2D	Device-Device
FCC	Federal Communications Commission
V2V	Vehicle to Vehicle
D2I	Device-to-Infrastructure
RMS	Root Mean Square
GSCM	Geometry-based Stochastic Channel Model
BS	Base Station
MAC	Medium Access Control
DVCS	Directional Virtual Carrier Sensing
DCF	Distributed Coordinated Function
CS	Compressed Sensing
ZC	Zhadoff–Chu
CSI	Channel State Information
TDMA	Time Division Multiple Access
CSMA/CS	Carrier Sense Multiple Access with Collision Sensing
LATS	Location Aware Training Scheme
NMSE	Normalized Mean Square Error
QoS	Quality of Service
SINR	Signal-to-Interference-plus-Noise Ratio
SNR	Signal-to-Noise Ratio
SIR	Signal-to-Interference ratio
INR	Interference-to-Noise Ratio
PPP	Poisson Point Processes
MINLP	Mixed-Integer Nonlinear Programming

NE	Nash Equilibrium
PSO	Particle Swarm Optimization
OFDMA	Orthogonal Frequency Division Multiple Access
FDMA	Frequency Division Multiple Access
ITIS	Information-Theoretic Independent Sets
CU	Cellular User
ZF	Zero-Forcing
MC	Mobile Cloud
PCH	Primary Cluster Head
SCH	Secondary Cluster Head
MR-D	Maximum Rate towards Destination
RTS	Request To Send
CTS	Clear To Send
SIB	System Information Block
QoE	Quality of Experience

Chapter 10

OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
EE	Energy Efficiency
QoS	Quality of Service
AWGN	Additive White Gaussian Noise
DOF	Degree(s) of Freedom
SE	Spectral Efficiency
CSI	Channel State Information
CNR	Channel gain to Noise Ratio
LDD	Lagrange Dual Decomposition
MDSA	Maximum Downlink Subcarrier Assignment
MUSA	Maximizing Uplink Subcarrier Assignment
BPA	Bisection Power search Algorithm
LT	Luby Transform
MIMO	Multiple Input Multiple Output
PA	Power Amplifier

Chapter 11

MIMO	Multiple Input Multiple Output
SV-MIMO	Smart Vertical MIMO
SIMO	Single Input Multiple Output
NOMA	Non-Orthogonal Multiple Access
FDMA	Frequency Division Multiple Access
TDMA	Time Division Multiple Access
CDMA	Code Division Multiple Access
OFDMA	Orthogonal Frequency Division Multiple Access

SDMA	Spatial Division Multiple Access
OMA	Orthogonal Multiple Access
LTE	Long-Term Evolution
SU-MIMO	Single User MIMO
MU-MIMO	Multi-User MIMO
RAT	Radio Access Technology
ICIC	Inter-Cell Interference Coordination
CoMP	Coordinated Multi-Point
IRC	Interference Rejection Combining
MMSE	Minimum Mean Squared Error
NAICS	Network-Assisted Interference Cancellation and Suppression
MLD	Maximum Likelihood Detection
SIC	Successive Interference Cancellation
AAS	Active Antenna System
FD-MIMO	Full Dimensional MIMO
LOS	Line-Of-Sight
NLOS	Non Line-Of-Sight
SINR	Signal to Interference plus Noise Ratio
BS	Base Station
UE	User Equipment
AWGN	Additive White Gaussian Noise
CSI	Channel State Information
CQI	Channel Quality Indicator
SLIC	Symbol-Level Interference Cancellation
CWIC	Codeword Level Interference Cancellation
LLR	Log-Likelihood Ratio
MRC	Maximal Ratio Combining
BLER	Block Error Rate
RS	Reference Signal
C-RS	Common Reference Signal
UE-RS	UE-specific Reference Signal
SCM	Spatial Channel Model
HARQ	Hybrid Automatic Repeat reQuest
MCS	Modulation and Coding Scheme
MCPS	Modulation, Coding, and Power Set
TPA	Transmit Power Allocation
FSPA	Full Search Power Allocation
SFBC	Space Frequency Block Coding
CDD	Cyclic Delay Diversity
CRS	Cell Specific Reference Signal
BF	Beamforming
BB	Base-Band
PSS	Primary Synchronization Signal
SSS	Secondary Synchronization Signal
PDCCH	Physical Downlink Control Channel
EPDCCH	Enhanced PDCCH

PBCH	Physical Broadcast Channel
PDSCH	Physical Downlink Shared Channel
DM-RS	Demodulation Reference Signal
MS	Mobile Station

Chapter 12

RFID	Radio Frequency Identification
EDGE	Enhanced Data rates for GSM Evolution
RAN	Radio Access Network
UE	User Equipment
BS	Base Station
MME	Mobility Management Entity
PLMN	Public Land Mobile Network
EAB	Extended Access Barring
ACB	Access Class Barring
eNB	Evolved Node B (base station)
RF	Radio Frequency
PMU	Power Management Unit
BOM	Bill of Material
FFT	Fast Fourier Transform
TBS	Transport Block Size
PRACH	Physical Random Access Channel
PUSCH	Physical Uplink Shared Channel
PUCCH	Physical Uplink Control Channel
PDSCH	Physical Downlink Shared Channel
PBCH	Physical Broadcast Channel
EPDCCH	Enhanced Physical Downlink Control Channel
PSS	Primary Synchronization Signal
SSS	Secondary Synchronization Signal
MIB	Master Information Block
SIB	System Information Blocks
MCL	Maximum Coupling Loss
PRB	Physical Resource Block
NB	Narrow-Band
NB-IoT	Narrow-Band Internet of Things
TDM	Time Division Multiplexing

Chapter 13

PHY	Physical layer
HARQ	Hybrid Automatic Repeat reQuest
AIC	Advanced Interference Cancellation
LOS	Line Of Sight
NLOS	Non Line Of Sight

CP	Cyclic Prefix
GP	Guard Period
TA	Timing Alignment
Tx	Transmission
Rx	Reception
WLAN	Wireless Local Area Network
FCC	Federal Communications Commission
BF	Beam-Forming
CRS	Common Reference Symbol
DLCRS	Downlink Common Reference Symbol
DLCCH	Downlink Control Channels
ACK	Acknowledgement
DLSCH	Downlink Shared Channel
DMRS	Demodulation Reference Symbols
ULCRS	Uplink Common Reference Symbols
ULSCH	Uplink Shared Channel
ULDCH	Uplink Data Channel
RACH	Random Access Channel
ULCCH	Uplink Control Channel
MCS	Modulation and Coding Scheme

Chapter 14

PHY	Physical layer
DFT	Discrete Fourier Transform
MTC	Machine-Type Communication
IoT	Internet of Things
RACH	Random Access Channel
CoMP	Coordinated Multi-Point
CP	Cyclic Prefix
CS	Cyclic Suffix
FBMC	Filter Bank Multi-Carrier
TTI	Transmission Time Interval
ICI	Inter-Carrier Interference
GI	Guard Interval
ISI	Inter-Symbol Interference
IDMA	Interleave-Division Multiple Access
PRACH	Physical Layer Random Access Channel
D-PRACH	Data PRACH
ATA	Autonomous Timing Advance
OFDM	Orthogonal Frequency Division Multiplexing
UFMC	Universal Filtered Multi-Carrier (also UF-OFDM)
FFT	Fast Fourier Transform
IFFT	Inverse Fast Fourier Transform
QAM	Quadrature Amplitude Modulation

CFO	Carrier Frequency Offset
MUD	Multi-User Detection
MPR	Multi Packet Reception
MMC	Massive Machine Communication
GFDM	Generalized Frequency Division Multiplexing
AWGN	Additive White Gaussian Noise
MF	Matched Filter
ZF	Zero-Forcing
MMSE	Minimum Mean Square Error
DZT	Discrete Zak Transform
STC	Space Time Coding
TR-STC	Time-Reversal Space Time Coding
GFDM	Generalized Frequency Division Multiple Access
BER	Bit Error Rate
OQAM	Offset Quadrature Amplitude Modulation
FS-FBMC	Frequency Spreading FBMC
PPN-FBMC	Poly-Phase Network FBMC
SINR	Signal to Interference plus Noise Ratio
MQAM	M-ary Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
BFDM	Bi-orthogonal Frequency Division Multiplexing
PUSCH	Physical Uplink Shared Channel
ACK/NACK	Acknowledgment/Negative Acknowledgment

Chapter 15

MIMO	Multiple Input Multiple Output
CoMP	Coordinated Multi-Point
FD-MIMO	Full Dimension MIMO
SU-MIMO	Single-User MIMO
MU-MIMO	Multi-User MIMO
CRS	Common Reference Signals
CSI-RS	Channel State Information Reference Signals
DMRS	Dedicated Modulation Reference Signals
UE	User Equipment
CS	Coordinated Scheduling
CB	Coordinated Beamforming
DPS	Dynamic Point Selection
JP	Joint Processing
JT	Joint Transmission
NIB	Non-Ideal Backhaul
FDD	Frequency Division Duplexing
TDD	Time Division Duplexing
LOS	Line-of-Sight
NLOS	Non-Line-of-Sight

SNR	Signal-to-Noise Ratio
PMI	Precoder Matrix Indicator
AP	Access Point
RFIC	RF Integrated Circuit
MMIC	Monolithic Microwave Integrated Circuit
LTCC	Low Temperature Co-fired Ceramic
LCP	Liquid Crystal Polymer
QAM	Quadrature Amplitude Modulation

Chapter 16

LTE	Long-Term Evolution
SNR	Signal-to-Noise Ratio
MIMO	Multiple Input Multiple Output
PHY	Physical Layer
OFDM	Orthogonal Frequency Division Multiplexing
PCB	Printed Circuit Board
WARP	Wireless Open Access Research Platform
LO	Local Oscillator
ADC	Analog to Digital Converter
PAPR	Peak to Average Power Ratio
QAM	Quadrature Amplitude Modulation
AGC	Automatic Gain Control
LNA	Low Noise Amplifier
IQ	Inphase/Quadrature
USRP	Universal Software Radio Peripheral
RS	Rohde–Schwarz
QPSK	Quadrature Phase Shift Keying
FD	Full Duplex
HD	Half Duplex

Chapter 17

BS	Base Station
MS	Mobile Station
CoMP	Coordinated Multi-Point
PMP	Point-to-Multipoint
AGW	Access Gateway
BL	Backhaul Link
AL	Access Link
UL	Uplink
DL	Downlink
ISD	Inter-Site Distance
LOS	Line-of-Sight
NLOS	Non-Line-of-Sight

SDM	Spatial Division Multiplexing
TDM	Time Division Multiplexing
SDMA	Space Division Multiple Access
SIR	Signal to Interference Ratio
W-BS	Wired BS
U-BS	Unwired BS
TDD	Time Division Duplex

Chapter 18

SDN	Software Defined Networking
NFV	Network Function Virtualization
EPC	Evolved Packet Core
CSP	Communication Service Provider
KPI	Key Performance Indicator
BGR	Border Gateway Router
TOC	Total Cost of Ownership
SEGW	Service Edge Gateway
PCRF	Policy Rules Charging Function
PGW	Packet Gateway
UP	User Plane
NAS	Non-Access Stratum
HSS	Home Subscription Server
TEID	Tunnel End Point Identifier
VoIP	Voice over IP

About the Companion Website

This book is accompanied by a companion website:

www.wiley.com/go/vannithamby/towards5g

There you will find valuable material designed to enhance your learning, including:

- Abstract and Keywords
- List of Contributors

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Part I

Overview of 5G

1

Introduction

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1.1 Evolution of Cellular Systems through the Generations

The first large-scale commercial cellular communications systems were deployed in the 1980s and these became known as first-generation (1G) systems. 1G systems were built on narrowband analog technology, and provided a basic voice service. These were replaced by second-generation (2G) cellular telecom networks by the early 1990s. 2G networks marked the start of the digital voice communication era, and provided a secure and reliable communication channel. 2G systems use either time division multiple access (TDMA) or code division multiple access (CDMA) technologies, and provided higher rates. The European Global System for Mobile Communications system is based on TDMA technology while IS-95 (also known as CDMA One) is based on CDMA technology. These 2G digital technologies provide expanded capacity, improved sound quality, better security and unique services such as caller ID, call forwarding, and short messaging. A critical feature was seamless roaming, which let subscribers move across provider boundaries.

The third-generation (3G) – International Mobile Telecommunications-2000 (IMT-2000) – is a set of standards for mobile phones and mobile telecommunications services fulfilling the recommendations of the International Telecommunication Union-Radio (ITU-R). 3G mobile networks became popular due to ability of users to access the Internet over mobile devices and laptops. The speed of data transmission on a 3G network is up to 2 Mbps, and therefore the network enables voice and video calling, file transmission, internet surfing, online TV, playing of games and much more. 3G uses CDMA technology in various forms. Wideband CDMA and High Speed Packet Access technologies were developed as part of the Third Generation Partnership Project (3GPP) organization, and CDMA2000 was developed as part of the 3GPP2 organization.

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Fourth-generation (4G) requirements – the International Mobile Telecommunications Advanced (IMT-Advanced) specification – were specified by ITU-R in March 2008. The key requirements specified 4G peak service speeds of 100 Mbps for high-mobility communication (such as from trains and cars) and 1 Gbps for low-mobility communication (such as pedestrians and stationary users). A 4G system not only provides voice and other 3G services but also provides ultra-broadband network access to mobile devices. Applications vary from IP telephony, HD mobile television, video conferencing to gaming services and cloud computing. There are two 4G technologies: Long-Term Evolution (LTE) and Worldwide Interoperability for Microwave Access (WiMAX). LTE was developed as part of 3GPP and WiMAX was developed as part of IEEE. LTE uses orthogonal frequency division multiple access (OFDMA) in the downlink and single carrier frequency division multiple access in the uplink whereas WiMAX uses OFDMA in both uplink and downlink.

1.2 Moving Towards 5G

4G standards were completed in 2011 and networks are currently being deployed. The attention of the mobile research community is now shifting towards what will be the next set of innovations in wireless communication technologies, which we will refer to collectively as 5G (fifth-generation technologies). Given a historical 10-year cycle for every generation of cellular advancement, it is expected that networks with 5G technologies will be deployed around 2020. Similar to 3G/4G, where ITU-R issued a recommendation for IMT-2000/IMT-Advanced [1], ITU-R has recently released a recommendation for the framework and overall objectives of the future development of systems for 2020 and beyond [2]. This highlights the emerging consensus on the use cases and requirements that systems deployed in 2020 must address. These include requirements for new services such as smart grids, e-health, autonomous transport, augmented reality, wireless industry automation, remote tactile control and so on, which cannot be met by IMT-2000 systems.

The usage scenarios envisioned for IMT for 2020 and beyond can be broadly classified as follows:

Enhanced Mobile Broadband The dramatic growth in the number of smartphones, tablets, wearables, and other data-consuming devices, coupled with the advent of enhanced multimedia applications, has resulted in a tremendous increase in the volume of mobile data traffic. According to industry estimates, this increase in data traffic is expected to continue in the coming years and around 2020 cellular networks might need to deliver as much as 100–1000 times the capacity of current commercial cellular systems [3, 4]. While the roll-out of 4G technologies with their expected enhancements will address some of capacity demands of future mobile broadband users, a mobile broadband user in 2020 will expect to be seamlessly connected all the time, at any location, to any device. This poses stringent requirements on the 5G network, which must provide users with a uniform and seamless connectivity experience regardless of where they are and what device/network they connect to.

Massive Machine-type Communications This use case refers to the growing interest in the area of machine-to-machine (M2M) communications and the Internet-of-Things (IoT). Together, these represent a future in which billions of everyday objects are connected and managed through wireless networks and management servers [5]. One can envisage creating an immensely rich set of applications by connecting the thousands of objects surrounding us. Examples include:

- smart homes, in which intelligent appliances autonomously minimize energy use and cost
- remote monitoring of expensive industrial or medical equipment
- remote sensing of environmental metrics such as water pressure, air pollution and so on.

These applications and services demand communication architectures and protocols that are different from traditional human-based networks. The integration of human and machine-type traffic in a single 5G network is therefore a challenge. In addition, IoT traffic can be quite diverse, from low to high bandwidth, from delay-sensitive to delay-tolerant, from error-tolerant to high reliability, which poses additional complexity. This use case focuses on applications where a very large number of connected devices transmit relatively low volumes of non-delay-sensitive data. The devices are typically low-cost and low-complexity, and require a very long battery life.

Ultra-reliable and Low-latency Communications. This use case addresses IoT applications that have stringent requirements for reliability, latency, and network availability. Examples include:

- connected cars, which react in real time to prevent accidents
- body area networks, which track vital signs and trigger an emergency response when life is at risk
- wireless control of industrial manufacturing or production processes.

As evidenced by diverse set of usages anticipated by 2020, the 5G system will require enhancements to performance metrics beyond the “hard” metrics of 3G/4G, which included peak rate, coverage, spectral efficiency, and latency. The 5G system will see expanded performance metrics centered on the user’s quality of experience (QoE), including factors such as ease of connectivity with nearby devices, connection density, area traffic capacity, and improved energy efficiency. The eight parameters in Table 1.1 are considered to be key capabilities of IMT-2020 systems. Their target values are also summarized. These are currently recommendations, and subject to further research and technological development [2].

1.3 5G Networks and Devices

As it can be seen from the description above, 5G networks will have to accommodate diverse types of traffic, spectrum, and devices. The network itself is anticipated to consist of hierarchical nodes of various characteristics and capacities. The 5G network will support multiple radio access technologies (RATs), such as 3G/4G/5G, WiFi, and WiGig, and also multiple modes ranging from ultradense small cells, device-to-device (D2D) communications, and new sub-networks oriented toward wearable devices. Inevitably, the user experience and quality will need to be maintained as users move along various networks and get connected to the various types of node. 5G networks will likely use a multi-layer network

Table 1.1 Key parameters of IMT-2020 systems.

Parameter	Details	Target
Peak data rate	Maximum achievable data rate under ideal conditions per user/ device	10–20 Gbps
User-experienced data rate	Achievable data rate that is available ubiquitously across the coverage area to a mobile user/device	100 Mbps–1 Gbps, depending on wide-area or hotspot coverage
Latency	Time contribution by the radio network from the time from when the source sends a packet to when the destination receives it	1 ms over-the-air latency
Mobility	Maximum speed at which a defined QoS and seamless transfer between radio nodes which may belong to different layers and/or radio access technologies (multi-layer/-RAT) can be achieved	To provide high mobility up to 500 km/h with acceptable QoS
Connection density	Total number of connected and/or accessible devices per unit area	To support a connection density of up to 10^6/km^2, for example in massive machine-type communication scenarios
Energy efficiency		
(a) Network side	Quantity of information bits transmitted to/received from users, per unit of energy consumption of the radio access network (RAN) (in bit/Joule)	Target is at least 10x on network energy efficiency The 5G network must not consume more energy, while providing enhanced features
(b) Device side	Quantity of information bits per unit of energy consumption of the communication module (in bit/ Joule)	
Spectrum efficiency	Average data throughput per unit of spectrum resource and per cell (bit/s/Hz)	3–5× increase in spectrum efficiency
Area traffic capacity	Total traffic throughput served per geographic area	10 Mbit/s/m^2 in hotspot scenarios

architecture, where the macro layer provides coverage to users moving at high speeds or for secure control channels, while a lower layer comprising network nodes with smaller capabilities provides high data rates and connectivity to other RATS (say, WiFi or new mmWave RATs). Moreover, a 5G device may have simultaneous active connections to more than one network node, with the same or different RATs, each connection serving a specific purpose, for example one connection to a given node for data and a second connection to another node for control. In addition, the use of remote radio heads connected to central processing nodes with the aid of ultra-high-speed backhaul is expected to be extended to more areas. Fast and high-capacity backhaul will enable tighter coordination between network nodes in a larger area. All of these changes will require a high level of integration of different nodes in the network and of technologies located even within the same node. In short, the 5G system will need to provide a flexible technological framework in which networks, devices, and applications can be co-optimized to meet the great diversity of requirements anticipated by 2020.

As the 5G usage models and networks evolve, 5G device architectures will also be more complex than in 4G. Devices will be capable of operating in multiple spectrum bands, ranging from RF to mmWave, while being compatible with existing technologies such as 3G and 4G. The need to support several RATs with multiple RF-chains will impose tremendous challenges for 5G device chipset and front-end module suppliers, as well as system and platform integrators. Another key feature of 5G devices will be their advanced interference suppression capabilities. The dense deployment of network nodes and increasing sources of interference will require that the devices deployed autonomously detect, characterize, and suppress interference from any source: intra-cell, inter-cell, or D2D. The task of interference cancellation will be exacerbated by the existence of strong self-interference in the case of simultaneous transmission and reception. In addition, devices will be required to actively manage all the available network connections, including D2D links, as well as to share contextual information with network layers so that network resources can be efficiently utilized. All of these enhanced features will need to be implemented in such a way that energy consumption is optimized for a small wireless device platform.

1.4 Outline of the Book

In this book we bring together a group of visionaries and technical experts from academia and industry to discuss the applications and technologies that will comprise the 5G system. It is expected that some of the new technologies comprising 5G will be evolutionary, covering gaps and enhancements from 4G systems, while some of the technologies will be disruptive, covering fundamentally new waveforms, duplexing methods, and new spectrum. These technologies will encompass the end-to-end wireless system: from wireless network infrastructure to spectrum availability to device innovations.

The book is organized into three parts. Part I has four chapters. In Part I, we provide an overview of 5G, address trends in applications and services, and summarize 5G requirements that will be need to be addressed in next-generation technologies and system architectures. We also provide an overview of some 5G research programs around the world: Horizon 2020 in Europe and Intel's 5G University Research Program in USA.

Part II has nine chapters. In Part II, we address evolutionary technologies that will be needed to meet 5G requirements, including:

- co-operative radio access architectures to enable greater energy efficiency and network performance
- small-cell networks with in-built caching
- multiple RAT integration, which is inevitable to provide a seamless user experience
- distributed resource allocation
- advances in device-to-device communications
- energy-efficient network design
- multi-antenna processing and interference co-ordination techniques
- design for M2M communications
- design for ultra-low latency.

These technologies are already being developed in 3GPP Release 11 and beyond as part of the evolution of 4G systems.

Part III has five chapters. In Part III, we discuss "revolutionary" candidate technologies: those that are essentially disruptive and different from 4G. These include:

- new physical layer waveforms that offer enhanced flexibility and performance
- massive MIMO technologies that enable large numbers of simultaneous users
- mmWave technologies to harness new spectrum for access and backhaul
- simultaneous transmit and receive on the same time/frequency resource
- software defined networking and network function virtualization to enable software-based flexible infrastructures.

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2

5G Requirements

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2.1 Introduction

Over the last few decades, mobile communications have significantly contributed to the economic and social development of both developed and developing countries. Today, mobile communications form an indispensable part of the daily lives of billions of people in the world, a situation that is expected to continue and become even more widespread in the future. Currently, the 4G radio access system using Long-Term Evolution (LTE) is being deployed by many operators worldwide in order to offer faster access with lower latency and more efficiency than 3G/3.5G. In the future, however, it is foreseen that demand for higher volumes of traffic, many more connected devices with diverse service requirements, and better and uniform quality of user experience will bring a need for evolved systems with extended capabilities.

In order to meet these evolving needs for mobile communications, discussions on visions, requirements, and technologies for the 5G mobile communications system have been initiated by many organizations. 5G-related discussions are ongoing in the ITU-R Study Group 5 Working Party 5D (WP5D), which issued a new recommendation, "IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond". Also, technical studies on 5G have gained attention worldwide as evidenced by the acceleration of efforts by governmental entities and research bodies from both academia and industry. Many special sessions are also being held on the topic of 5G in international conferences. Several governments and groups of commercial companies and academic institutions have established projects and fora to study and promote 5G mobile technology. Examples of projects and initiatives with focus on 5G include the METIS project in Europe, the ARIB 2020 and Beyond Ad-hoc (20B AH) group, and the 5G Mobile Communications Promotion Forum (5GMF) in Japan, the operators' alliance Next Generation Mobile Networks (NGMN), IMT-2020 in China, and the 5G Forum in Korea.

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Companion website: www.wiley.com/go/vannithamby/towards5g

2.2 Emerging Trends in Mobile Applications and Services

More and more customers are expecting to have the same quality of experience from Internet applications anytime, anywhere, and through any means of connectivity. This expectation is now being better fulfilled as the gap of user experience between mobile and fixed environments becomes narrower and higher data rates are offered by mobile networks. In the future we can therefore expect a further shift of services from the fixed to the mobile network, with users making use of the added value of mobility and location/context awareness. Furthermore, the emergence of new applications and needs are constantly changing user behavior. The younger generation now uses the Internet for gaming, social networking, and online education, among other things. At the same time, the introduction of IMT-Advanced networks, which substantially reduce network latency, will in the future provide better user experiences and make possible more advanced real-time services. Technological developments, such as faster radio interfaces, advanced graphical processing, and multiprocessing units at the device, will also contribute to the increase in user demand for mobile data. Growth will also be accelerated by new types of communications and devices, such as device-to-device communications between mobile users in proximity (user-to-user), and machine-type communications such as user-controlled mobile devices (user-to-machine) and inter-machine communications (machine-to-machine). The future trends in services and applications will generally be shaped by the evolution of the needs of the new generation of users and progress in technology and services.

In the following sections, we explain the main market trends and new services that have been observed in recent years and have the potential to drive and change the landscape of the future mobile market. Note that future services include, but are not limited to, the mere interpolation of current trends.

2.2.1 New Types of Mobile Device

The transition to the Internet era has significantly contributed to the rapid rise of data services as a significant revenue source for businesses. This trend has been accelerated by the introduction of always-on smartphones and new types of conversation via social networks. In recent years, a wide range of new smart devices – smartphones, dongles, and tablets – have emerged and have been key drivers of increased mobile broadband traffic. With rapid advances in display technologies, these devices offer larger screen sizes and high resolution, and hence increase data consumption and encourage the use of traffic-intensive applications such as video streaming. This type of Internet access via mobile terminals is spreading very rapidly. As a result, the volume of smartphone data carried by cellular networks is growing rapidly, driven predominantly by increases in device penetration, but also by increases in average usage. In developed markets, a typical smartphone generates about 50 times more data per month than a typical feature phone [1]. In the future, one notable development will be full high definition (FHD) and ultra-high definition (UHD) displays, which are anticipated to become well established on smartphones; it is estimated that these future smartphones could generate many times more traffic than established user applications. In addition, open operating systems (OSs), such as Android, iOS, and HTML5, have been another key force in the mobile internet ecosystem. With open OSs, the development and commercialization of new applications has become much easier than before. Users are able to access a wide variety of new applications on diverse smart devices, resulting in increased opportunities, as well as challenges, for all players in the mobile Internet ecosystem. Operators are making great efforts to embrace these changes and challenges, although they represent a double-edged sword. On the one hand, the majority of mobile applications on smart devices are planned with the assumption that users are online and connected, consequently increasing both control signaling and user mobile broadband traffic: video, music, games, and so on. On the other hand, memory as well as processor technologies are expected to improve according to Moore's law, and with reduced energy consumption. This will bring huge potential for information storage and processing on mobile devices and increased user-generated content. Furthermore, new types of user-to-device interaction can be expected to be triggered by novel user interfaces such as 3D cameras, and movement and gesture recognition. These will increase the generation and flow of information and beyond that of traditional human audio and visual capabilities.

2.2.2 Video Streaming and Download Services

Video streaming and download are among the most dominant traffic generators in mobile networks. Currently, the majority of streaming services are based on progressive downloading technologies utilizing the HTTP protocol. Video streaming services can be classified into server-client unidirectional applications and bidirectional streaming services.

Bidirectional streaming services with high quality of service demands are expected to become a dominant source of traffic in the near future. One example is the virtual classroom, with video streamed between a remote teacher and students in a classroom. Moreover, video consumption for many users is no longer limited to streaming but also involves sharing it with the community. Uploading of videos on social networking sites is becoming a way to share them. This contributes to increasing video consumption, as community networks are also becoming video viewing sites. In the future, video streaming or downloading will be responsible for most mobile data traffic growth, with a cumulative average growth rate (CAGR) of 69% expected between 2013 and 2018. Furthermore, it is predicted that video will account for more than 69% of mobile data traffic by 2018 [1]. In the future, the introduction of advanced graphical processing units will enhance the performance of video applications and thus promote mobile video consumption. In addition, mobile services that require 3D video and higher-definition video will proliferate and thus create significantly increased traffic over mobile networks.

2.2.3 Machine-to-machine Services

One big wave that will to contribute to the increase in mobile data demand is machine-to-machine (M2M) applications and devices. M2M is rapidly growing and is expected to continue to be one of the fastest growing segments in the future [1]. The growth of the M2M market has been driven by sectors such as fleet management, industrial asset management, point of sales, security, and healthcare. The number of M2M connections could be several orders of magnitude larger than the world population. The market for M2M systems is expected to grow by 30–40% per year. Cisco IBSG predicts there will be 25 billion devices connected to the Internet by 2015 and 50 billion by 2020 [2]. In terms of traffic, M2M's share will depend on the related applications. For instance, smart utility meters in homes consume some hundreds of kilobytes per second while surveillance video monitoring consume tens of megabytes per second. In the future, agricultural science will also benefit from the ability to communicate information remotely. Another potential service is smart energy-distribution grid systems. For example, the European commission mandated that 80% of consumers in its member countries should be equipped with smart meters by the year 2020 [3].

Another set of applications for M2M is for communications in the transport sector:

- car-to-car (C2C)/vehicle-to-vehicle (V2V)
- car-to-road/vehicle-to-road infrastructure (V2I)
- car-to-pedestrian (C2P)/vehicle-to-device (V2D).

These are collectively referred to as C2X or V2X communications. They will improve traffic safety, both for drivers and pedestrians, provide in-car infotainment services, and bring new business opportunities, such as highly automated driving and augmented-reality head-up displays.

M2M services will be a big trend in 2020 and beyond. One issue, however, is the very wide range of requirements this trend will bring with it. For example, sensor-type applications will require the support of massive machine communications, while other safety and remote-control-related M2M applications will require ultra-low latency and/or ultra-reliable machine communication. In order to facilitate the study of such a wide variety of requirements, the principal market segments and categories of M2M services will need to be identified and defined.

2.2.4 Cloud Services

The demand for mobile cloud services is also expected to grow exponentially as users adopt services that must be ubiquitous. In particular, the rapid development of ICT technologies and mobile network capabilities will enable a wide range of cloud services to be available on mobile devices, for example cloud speech services, such as speech recognition and synthesis. Mobile cloud traffic will grow 12-fold from 2013 to 2018, a compound annual growth rate of 64%. Cloud applications will account for 90% of total mobile data traffic by 2018, compared to 82% at the end of 2013 [1]. It is expected that in the future health, education, and other government services will be accessible by mobile devices, which will contribute to improvements in social welfare. These services will require guaranteed reliability and security of data communications between the clients and the cloud data centers.

However, harnessing and extracting value from the “big data” stored in the cloud is seen by many operators as a route to enhance the customer experience and to generate new revenues from them. Via user data collection and mining, operators can enhance the user experience. They can also compile this data, selling it on in anonymized or aggregated form as business and marketing reports. For instance, data on customer footfall patterns could be sold to retailers, helping them target promotions according to store location and the buying patterns of consumers in that area. It will also help them decide where to open new shops, and in what format. Another recent trend for cloud services is termed “bring your own device”, which enables employees to bring personally owned mobile devices (laptops, tablets, and smart phones) to their workplace, and use them to access company information and applications stored in the cloud.

2.2.5 *Context-based and Location-based Services*

Context/location awareness will be an important enabler for providing user-centered services in the future. With such capabilities, mobile devices will not only act as personal communication devices but also as gateways to services in diverse environments that support personalized interactions and proactive assistance tailored to the user preferences and behaviors. Context/location-aware applications and devices capture context information from multiple sources and learn the associations between context cues and personal preferences and behaviors in order to adapt the configuration of devices and the behavior of interfaces, or to offer personalized access to services. Learning the user's important locations, known as their semantic locations, will be one of the most important tasks involved. Examples of semantic locations are "Main campus, Kyoto University" or "City center of Tokyo".

Several location-aware applications for mobile devices have been developed recently. These applications make use of colloquial places and paths rather than just geographical coordinates, for example by accessing personal applications such as geo-reminders and location diaries. The combination of the cloud and location information will also create what is called the personal cloud, which will gradually replace the PC as the location where individuals keep their personal content and personal preferences, access services, and center their digital lives [4]. The personal cloud will shift the focus from the services delivered on client devices to cloud-based services delivered *across* devices. Examples of context-based and location-based services (LBS) include:

Augmented Reality. Augmented reality is a live – direct or indirect – view of a physical, real-world environment whose elements are augmented by computer-generated sensory input such as sound, video, graphics, or GPS data [5]. With the help of technologies such as computer vision and object recognition, information about the real world surrounding the user becomes interactive and digitally manipulable. Artificial information about the environment and its objects can be overlaid on the real world. Services based on these technologies are expected to expand in the future.

Proximity-based Services. As the number of mobile devices continues to increase, it becomes important to take advantage of the physical proximity of communicating devices and provide proximity services, such as social networking and proximity-based multiplayer games. To this end, peer-to-peer discovery and communication becomes an important enabler of such services. Such features will also enable new services, for example allowing direct communication between devices when the network is damaged in the aftermath of a natural disaster.

SoLoMo. Social local mobile (SoLoMo) is a new marketing concept that refers to the convergence of social, local, and mobile technologies. SoLoMo aims to "hyper-target", that is, to reach the right consumer, at the right time, in the right place. For example, retailers can utilize the mobile experience to their advantage, using location targeting, in-store mobile marketing, gamification, and so on. With SoLoMo, a specific retailer can broadcast offers – retail deals, coupons, consumer events, and shopping and dining opportunities – to a mobile user based on their geographic proximity, brand/retailer allegiance, and shopping/check-in history. In addition, the integration of location-based functions with social networks can lead to new applications on mobile networks that are expected to generate more mobile data traffic.