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WiMAX Evolution

Emerging Technologies and Applications

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Foreword

Mobile WiMAX: the Enabler for the Mobile Internet Revolution

The Internet has become one the most important assets for the growth of economies across the globe. More than a billion people use the Internet at their workplace and in their daily lives for business interactions, social interactions and entertainment. The Internet has had a profound effect on the economy of developed and developing nations having made economic activity more efficient, accessible and affordable. Most of the productivity gains in today's economies are thanks to the Internet and ecommerce. There have been profound social impacts from increased the access to valuable information and social interaction between the masses. The impact is at many socioeconomic levels: business productivity, energy savings, healthcare delivery, improved government functions, education, improved citizen interactions (locally and globally), etc. Despite the benefits of the Internet, today only about 20% of the World's population have access to the Internet. In particular, the emerging countries that could benefit greatly are seriously deprived of this valuable asset. There are a number of reasons for the small number of users in the emerging countries: lack of infrastructure, affordability of personal computers, unaffordable access fees, etc.

The next big step in the evolution of the Internet is ubiquitous availability enabled through mobile Internet. This revolutionary step is poised to increase the value of the Internet enormously as it will create a fundamental shift in the use of the Internet by bringing the Internet to the users as opposed to users having to go to the Internet. For this vision to become a reality, a number of requirements need to be met. First and foremost, affordable and ubiquitous mobile Internet access needs to be provided using the mobile cellular concept. This is poised to be fulfilled thanks to mobile WiMAX. Secondly, affordable and low-power mobile Internet devices and mobile PCs are needed. This is also happening with the computer industry making huge strides in making these devices more affordable. The low-cost netbook category with examples such as the ASUS Eee PC and variety of small mobile PCs or Mobile Internet Devices (MIDs) are now available and will undoubtedly become even more affordable in the near future.

Mobile WiMAX has been designed with the purpose of enabling mobile Internet from the physical layer to the network layer. The physical layer design relies on Orthogonal Frequency Division Multiple Access (OFDMA) and Multiple Input Multiple Output (MIMO) as the two key technologies to optimize coverage and spectral efficiency. In addition, sophisticated techniques for link adaptation and error control provide improved performance and robustness. Mobile WiMAX technology includes many other important aspects such as security

and power-saving methods, provisions for location-based services, support for hierarchical deployments, quality-of-service, and open Internet user and network management schemes, which are essential in enabling deployment and consumer adoption of the technology.

The Internet is dynamic by nature and is evolving rapidly on the application level and creating ever-increasing demands on connectivity. Studies indicate that Internet traffic has been doubling roughly every two years. Mobile Internet will undoubtedly change the Internet as we know it today and may create even more traffic than ever anticipated. Mobile WiMAX needs to evolve constantly to keep up with the growth of mobile Internet. The WiMAX industry has already been working on the next technology in IEEE 802.16m to build the basis for the next generation of mobile Internet.

This book provides the material that is essential to understand the underlying concepts for mobile WiMAX and it also provides an overview of technologies that will enable the evolution of the technology in the future. I sincerely hope that the book will further motivate researchers and developers to create innovative ideas and techniques that will help fulfill the promise of the new era of mobile Internet.

Siavash M. Alamouti, Intel Fellow
Chief Technology Officer, Mobile Wireless Group

Preface

The remarkable development of wireless and mobile communications in the last two decades is a unique phenomenon in the history of technology. Even the most optimistic predictions on penetration of mobile subscribers and capabilities of wireless devices have been surpassed by reality. In a quarter of century the number of mobile subscribers soared from a few to half the world population (in 2008), and according to some forecasts by 2010 the number of mobile users will exceed the number of toothbrush users (four billion). The Wireless World Research Forum (WWRF) envisions that by year 2017 there will be seven trillion wireless devices serving seven billion people. Two main development directions in untethered communications can be identified, wide-area communications, with the omnipresent cellular systems as the most representative example, and short-range communications, involving an array of networking technologies for providing wireless connectivity over short distances, for instance Wireless Local Area Networks (WLANs), Wireless Personal Area Networks (WPANs), Wireless Body Area Networks (WBANs), Wireless Sensor Networks (WSNs), Bluetooth, etc. Recent years have witnessed an enormous growth in interest in the metropolitan wireless networks. This should not be a surprise, as in 2008, for the first time in history more than half of the world population lives in urban areas, according to the United Nations Population Fund. WiMAX (Worldwide Interoperability for Microwave Access) is the most representative worldwide initiative focusing on metropolitan communications. WiMAX, based on the IEEE 802.16 standard, defines wireless networks combining key characteristics of wide-area cellular networks as well as short-range networks, namely mobility and high data throughput. IEEE 802.16 is a very active and rapidly evolving standard that serves as the fundamental basis for WiMAX systems. Several amendments are currently being developed addressing particular technical aspects or capabilities, including 802.16g, 802.16h, 802.16i, 802.16j, 802.16k and 802.16m. There are already several books dealing with WiMAX technology, describing mostly the basic operating principles, current standards and associated technical solutions. The current vertiginous developments in the WiMAX arena have lead the Editors to conceive of this book, taking over where most of the published WiMAX volumes left off, that is, looking in future directions. Leading research scientists and engineers from key WiMAX industry, academia and research centers worldwide have contributed to this book with their ideas, concepts, concrete technical suggestions and visions.

As WiMAX as a whole encompasses a very broad area, it is impossible to find a single author able to write in detail about a large array of advanced concepts and solutions applicable at different system levels of WiMAX: the Editors have thus invited specialists in the field to contribute with their ideas in different chapters. The goal of this book is

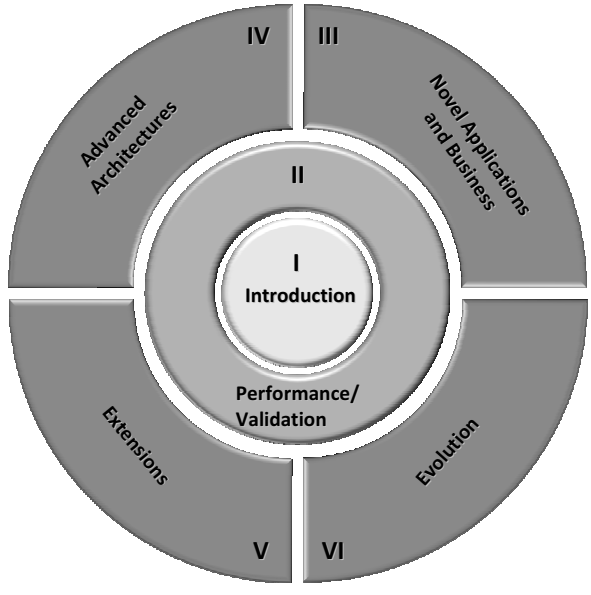

Figure 1 WiMAX evolution: organization of the book.

to create concrete supportive links between the presented concepts and future metropolitan communication systems, discussing technical solutions as well as novel identified scenarios, business applications and visions that are likely to become integral parts of the future WiMAX. Thus, this book tries to answer questions including the following. Which are the emerging WiMAX technologies that are being developed? What are the new scenarios for deploying WiMAX? What are the most promising WiMAX applications and business? How are standards evolving? What are the visions of industry? What are the capabilities and measured performance of real (commercial) WiMAX systems?

As shown in Figure 1, this book has been organized into six independent parts, covering different aspects of WiMAX technology and its evolution. Part One overview of the current state of WiMAX technology, serving as an introduction to WiMAX. Part Two presents measurements and validation results carried out on real state-of-the-art WiMAX testbeds (fixed and mobile), providing unique results on the achievable capabilities of commercial equipment operating in real scenarios. Novel scenarios and business cases for WiMAX are considered in Part Three. In Part Four new promising architectures for WiMAX are discussed, including wireless sensor networks, mesh and cooperative networking as well as femtocells. Part Five discusses several extensions to the current WiMAX, that is, new solutions that can be used in conjunction with the current WiMAX standard. Finally, Part Six looks into technical developments beyond the immediate WiMAX future, including PHY and MAC evolution, prospects and visions, emerging technologies, evolution of standards, etc.

WiMAX Evolution: Emerging Technologies and Applications is a book intended for research, development and standardization engineers working in industry, as well as for scientists in academic and research institutes. Graduate students conducting research in

WiMAX and next generation mobile communications will also find in this book relevant material for further research. The Editors think that this book provides novel views and detailed technical solutions, foreseeing future WiMAX while being a stimulating source of inspiration for further advanced research in the field.

The Editors welcome any suggestions, comments or constructive criticism on this book. Such feedback will be used to improve forthcoming editions. The Editors can be contacted at wimaxeditor@es.aau.dk.

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List of Acronyms

μC MicroController
16-QAM 16 Quadrature Amplitude Modulation
2G 2nd Generation
3G 3rd Generation
3GPP 3rd Generation Partnership Project
3GPP2 3rd Generation Partnership Project 2
4G Fourth Generation
A/V Audio/Visual
AAA Authentication, Authorization and Accounting
AAS Adaptive Antenna System
AC Admission Control; Antenna Circulation
ACIR Adjacent Channel Interference Ratio
ACK Acknowledgement
ACR Absolute Category Rating
ADSL Asymmetric Digital Subscriber Line
AG Antenna Grouping
AMC adaptive modulation and coding
AMR Adaptive Multi-Rate
AMS Adaptive MIMO Switching
AP Access Point
APD Adaptive Power Distribution
APFR Adaptive Power Fixed Rate
API Application Programming Interface
APMC Adaptive Power, Modulation and Coding
AQ Assessed QoS
ARP Address Resolution Protocol
ARQ Automatic Repeat Request
AS Antenna Selection
ASN Access Service Network
ASN-GW Access Service Network Gateway
ATM Asynchronous Transfer Mode
AVC Advanced Video Coding
AWGN Additive White Gaussian Noise
BD Block Diagonalization
BE Best Effort
BER Bit Error Rate
BF Beamforming
BGP Border Gateway Protocol (routing)
BLER Block Error Rate
BOM Bill Off Materials
bps Bits Per Second
BPSK Binary Phase Shift Keying
BS Base Station
BSID Base Station Identifier
BWA Broadband Wireless Access
C/I Carrier to Interference Ratio
CAPEX Capital Expenditures
CATV Cable Television
CBC Cipher Block Chaining
CBF Coordinated Beamforming
CBR Constant Bit Rate
CC Chase Combining; Convolutional Code; Coordination Center
CCF Call Control Function
CCP2P Cellular Controlled Peer to Peer
CDF Cumulative Distribution Function
CDL Clustered Delay Line

CDMA Code Division Multiplex Access

CELP Code Excited Linear Prediction

CH Compressed Header

C/I Carrier-to-Interference Ratio

CID Connection Identifier

CI-STBC Coordinate Interleaved Space–Time Block Code

CMIP Client Mobile IP

CN Correspondent Node

CN Core Network

CNL VTT Converging Networks Laboratory

CNR Channel-to-Noise Ratio

CoA Care-of-Address

CODEC Compression/Decompression

COST European Cooperation in the Field of Scientific and Technical Research

COTS Commercial Off The Shelf

CP Cyclic Prefix

CPE Customer Premises Equipment

CPS Common Part Sublayer

CPU Central Processing Unit

CQI Channel Quality Indicator

CQICH Channel Quality Indicator Channel

CRC Cyclic Redundancy Check

CS Convergence Sublayer

C-SAP Control Service Access Point

CSG Closed Subscriber Group

CSI Channel State Information

CSN Connectivity Services Network

CTS Clear to Send

DAS Distributed Antenna System

DCA Dynamic Channel Allocation

DCD Downlink Channel Descriptor

DCF Discounted Cash Flow

DES Data Encryption Standard

DFB Distributed Feedback

DHCP Dynamic Host Configuration Protocol

DL Downlink

DMTBR Dynamic Multiple-Threshold Bandwidth Reservation

DNS Domain Name System

DNS-SD Dynamic Name System Service Discovery

DPT Dirty Paper Theory

DRR Deficit Round Robin

DRX Discontinuous Reception

DS-CDMA Direct Sequence Code Division Multiple Access

DSL Digital Subscriber Line

DSLAM Digital Subscriber Line Access Multiplexer

DWRR Deficit Weighed Round Robin

EAP Extensible Authentication Protocol

ECMP Equal Cost Multi-Path

EDF Earliest Deadline First

EpBR Energy per Bit Ratio

ertPS Extended Real-Time Polling Service

ERT-VR Extended Real-Time Variable Rate

ESP Encapsulating Security Payload

ETX Expected Transmission Count

EVD Eigenvalue Decomposition

EVRC Enhanced Variable Rate Codec

FA Foreign Agent

FBSS Fast Base Station Switching

FCH Frame Control Header

FDD Frequency-Division Duplex

FDM Frequency Division Multiplexing

FEC Forward Error Correction

FER Frame Error Rate

FFMS Forest Fire Monitoring Station

FFT Fast Fourier Transform

FIFO First In First Out

FP Framework Programme

FPAR Fixed Power Adaptive Rate

FPGA Field-programmable Gate Array

FTP File Transfer Protocol

FUSC Fully Used Subcarriers

GA Generic Adapter

GIS Geographic Information Systems

GIST General Internet Signaling Transport

GMH Generic MAC Header

GoS Grade of Service

GPRS General Packet Radio Service

GPS Global Positioning System

GRE Generic Routing Encapsulation

GSM Global System for Mobile Communications

GTP GPRS Tunneling Protocol

GUI Graphical User Interface

GW Gateway

HA High Availability; Home Agent

HARQ Hybrid Automatic Repeat Request

HD High Definition

HFC Hybrid Fiber Coaxial

HFDD Half-duplex Frequency Division Duplex

HFR Hybrid Fiber Radio

HHO Hard Handover

HO Handover

HSDPA High Speed Data Packet Access

HSPA High Speed Packet Access

HSRP Hot Standby Router Protocol

HTTP Hyper Text Transfer Protocol

HW Hardware

ICMP Internet Control Message Protocol

ICT Information and Communication Technologies

ID Identification

IETF Internet Engineering Task Force

IFFT Inverse Fast Fourier Transform

IMDD Intensity Modulation, Direct Detection

IMS IP Multimedia Subsystem

IMT International Mobile Telecommnications

IP Internet Protocol

Ipsec Internet Protocol Security

IPTV Internet Protocol Television

IPv4 Internet Protocol version 4

IPv6 Internet Protocol version 6

IQ Intrinsic QoS

IQA Instrumental Quality Assessment

IRR Internal Rate of Return

ISD Inter-site Distance

IST Information Society Technologies

ITU International Telecommunications Union

kbps kilobits per second (1000 bits s^{-1})

KPI Key Performance Indicator

L1 Layer 1 (Physical Layer)

L2 Layer 2 (Data Link Layer)

L2TP Layer 2 Tunneling Protocol

LA Link Adaptation

LACP Link Aggregation Control Protocol

LAG Ling Aggregation

LAN Local Area Network

LBC Load Balancing Cycle

LBS Location Based Services

LDAP Lightweight Directory Access Protocol

LLA Low Level Agent

LLL Lenstra–Lenstra–Lovász

LOS Line-of-Sight

LPC Linear Predictive Coding

LPM Loss Packet Matrix

LSB Least Significant Bit

LTE Long Term Evolution

LU Lenstra–Lenstra–Lovász

MAC Medium Access Control

MAN Metropolitan Area Network

MAP Medium Access Protocol; Mobile Application Part

MBAC Measurement Based Admission Control

MBB Make Before Break

MBMS Multimedia Broadcast Multicast Service

Mbps Megabits per second (1 000 000 bits s^{-1})

MBS Mesh Base Station; Multicast and Broadcast Service

MCBCS Multicast and Broadcast Service

MCS Modulation and Coding Scheme

MCW Multi Codeword

MDHO Macro Diversity Handover

MeSH IEEE 802.16-2004 Mesh Mode

MIB Management Information Base

MICS Media Independent Command Service

MIES Media Independent Event Service

MIH Media Independent Handover

MIHF Media Independent Handover Function

MIHO Mobile Initiated Handover

MIHU Media Independent Handover User

MIIS Media Independent Information Service

MIMO Multiple Input Multiple Output

MIP Mobile Internet Protocol

ML Maximum Latency

MLD Maximum Likelihood Decoder

MLI Modulation Level Information

MM Mobility Management

MMF Multimode Fiber

MMR Mobile Multihop Relay

MMSE Minimum Mean Square Error

MN Mobile Node

MOS Mean Opinion Score

MPEG Moving Picture Experts Group

MRC Maximum Ratio Combining

MRT Maximum Ratio Transmission

MRTR Minimum Reserved Traffic Rate

MS Mobile Station

M-SAP Management Service Access Point

MSB Most Significant Bit

MSDU MAC Service Data Unit

MSE Mean Square Error

MSID Mobile Subscriber ID

MSTR Maximum Sustained Traffic Rate

MTBF Mean Time Between Failures

MTU Maximum Transmission Unit

NACK Negative Acknowledgement

NAI Network Access Identifier

NC Network Coding

NCMS Network Control and Management System

NDCQ Nondegenerate Constraint Qualification

NE Network Element

NET Network Layer

NGMN Next-Generation Mobile Network

NGN Next Generation Network

NIHO Network Initiated Handover

NLOS Non-Line-of-Sight

NMS Network Management System

NPV Net Present Value

NRM Network Reference Model

nrt Non-real-time

nrtPS Non-real-time Polling Service

NSIS Next Steps in Signaling

NSLP NSIS Signaling Layer Protocol

NTLP NSIS Transport Layer Protocol

NTP Network Time Protocol

NWG Network Working Group

O&M Operations and Management

OFDM Orthogonal Frequency Division Multiplexing

OFDMA Orthogonal Frequency Division Multiple Access

OGBF Orthogonal Beamforming

OMC Operation and Maintenance Center

OMF Operation and Maintenance Function

OPEX Operational Expenditures

OSPF Open Shortest Path First

P2P Peer to Peer

PA ITU Pedestrian A

PB ITU Pedestrian B

PAN Personal Area Network

PAPR Peak to Average Power Ratio

PBE Perfect Bayesian Equilibrium

PC Paging Controller; Power Control

PCM Pulse Code Modulation

PDA Personal Digital Assistant

PDU Protocol Data Unit

PEP Performance Enhancing Proxy

PER Packet Error Rate

PHB Per Hop Behavior

PHY Physical Layer

PLC Packet Loss Concealment

PLR Packet Loss Rate

PMIP Proxy Mobile IP

PMP Point to Multipoint

PN Psedorondam Noise

POF Plastic Optical Fiber

PQ Perceived QoS

PSTN Public Switched Telphone Network

PTMP Point-to-Multipoint

PTP Precision Time Protocol

PTP Point-to-point

PU2RC Per-User Unitary and Rate Control

PUSC Partially Used Subcarrier; Partially Used Subchannelization

QAM Quadrature Amplitude Modulation

QoE Quality of Experience

QoS Quality of Service

QPSK Quadrature Phase-Shift Keying

RADIUS Remote Authentication Dial-In User Service

RAN Radio Access Network

RAU Remote Antenna Unit

RB Resource Block

RF Radiofrequency

RFC Request for Comments (IETF standard document)

RMF Resource Management Function

RMS Root Mean Square

RoF Radio-over-Fiber

ROHC Robust Header Compression

RRM Radio Resource Management

RS Relay Station

RSS Received Signal Strength

RSSI Received Signal Strength Indicator

rt real-time

RTP Real-time Transport Protocol

rtPS Real-Time Polling Service

RTS Request to Send

RTT Round Trip Time

RT-VR Real-Time Variable Rate

Rx Receive

SA Specific Adapter

SAF Service Availability Forum

SAMPDA Simple Adaptive Modulation and Power Adaptation Algorithm

SAP Service Access Point

SBS Serving Base Station

SC Serra do Carvalho

SCM Spatial Channel Model

SCR Spare Capacity Report

SCTP Stream Control Transmission Protocol

SCW Single Codeword

SDMA Spatial Division Multiple Access

SDU Service Data Unit

SE Spectral Efficiency

SF Service Flow

SFDR Spurious Free Dynamic Range

SFM Service Flow Management

SID Silent Insertion Descriptor

SINR Signal-to-Interference + Noise Ratio

SIP Session Initiation Protocol

SISO Single Input Single Output

SL Serra da Lousã

SLA Service Level Agreement

SM Spatial Multiplexing

SMF Singlemode Fiber

SMS Short Message Service

SNMP Simple Network Management Protocol

SNR Signal-to-Noise Ratio

S-OFDMA Scalable Orthogonal Frequency Division Multiple Access

SOHO Small Office/Home Office

SON Self-Organized Network

SP Synchronization Pattern

SRA Simple Rate Adaptation

SRD System Requirement Document

SS Subscriber Station

SSL Secure Socket Layer

STBC Space Time Block Coding

STC Space-Time Coding

SUI Standford University Interim

SW Software

TBS Target Base Station

TCP Transmission Control Protocol

TDD Time Division Duplex

TDM Time Division Multiplexing

TDMA Time Division Multiple Access

TEM Telecommunications Equipment Manufacturer

TETRA Terrestrial Trunked Radio

TTI Transmission Time Interval

TTP Trusted Third Party

TWG Technical Working Group

Tx Transmit

UC University of Coimbra

UCD Uplink Channel Descriptor

UDP User Datagram Protocol

UGS Unsolicited Grant Service

UL Uplink

UMB Ultra Mobile Broadband

UMTS Universal Mobile Telecommunications System

UMTS-LTE Universal Mobile Telecommunications Systems – Long Term Evolution

VAD Voice Activity Detection

VBR Variable Bit Rate

VCEG Video Coding Experts Group

VCSEL Vertical Cavity Surface Emitting Laser

VDT Virtual Drive Test

VLSI Very-Large-Scale Integration

VoD Video on Demand

VoIP Voice over Internet Protocol

VP Vector Perturbation

VR Virtual Router

VRRP Virtual Router Redundancy Protocol

W3GPP third generation partnership project

WAC Wireless Access Controller

WDM Wavelength Division Multiplexing

WEIRD WiMAX Extension to Isolated Research Data Networks

WEP Wired Equivalent Privacy

WiFi Wireless Fidelity

WiMAX Worldwide Interoperability for Microwave Acccess

WINNER Wireless World Initiative New Radio

WLAN Wireless Local Area Network

W-LSB Windowed Least Significant Bits

WMAN Wireless Metropolitan Area Network

WMN Wireless Mesh Network

WNC Wireless Network Coding

WNEA WiMAX Network Element Advertisement

WPAN Wireless Personal Area Network

WRR Weighted Round Robin

WSN Wireless Sensor Network

WT WiMAX Terminal

WWRF Wireless World Research Forum

ZFBF Zero-Forcing Beamforming