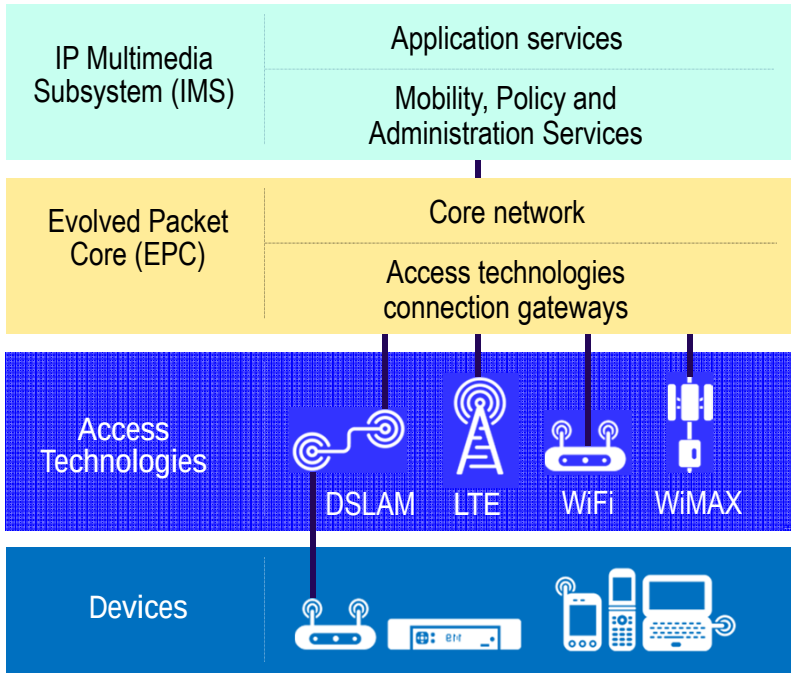
Wireless Broadband Access Communications: An Overview

Tho Le-Ngoc,

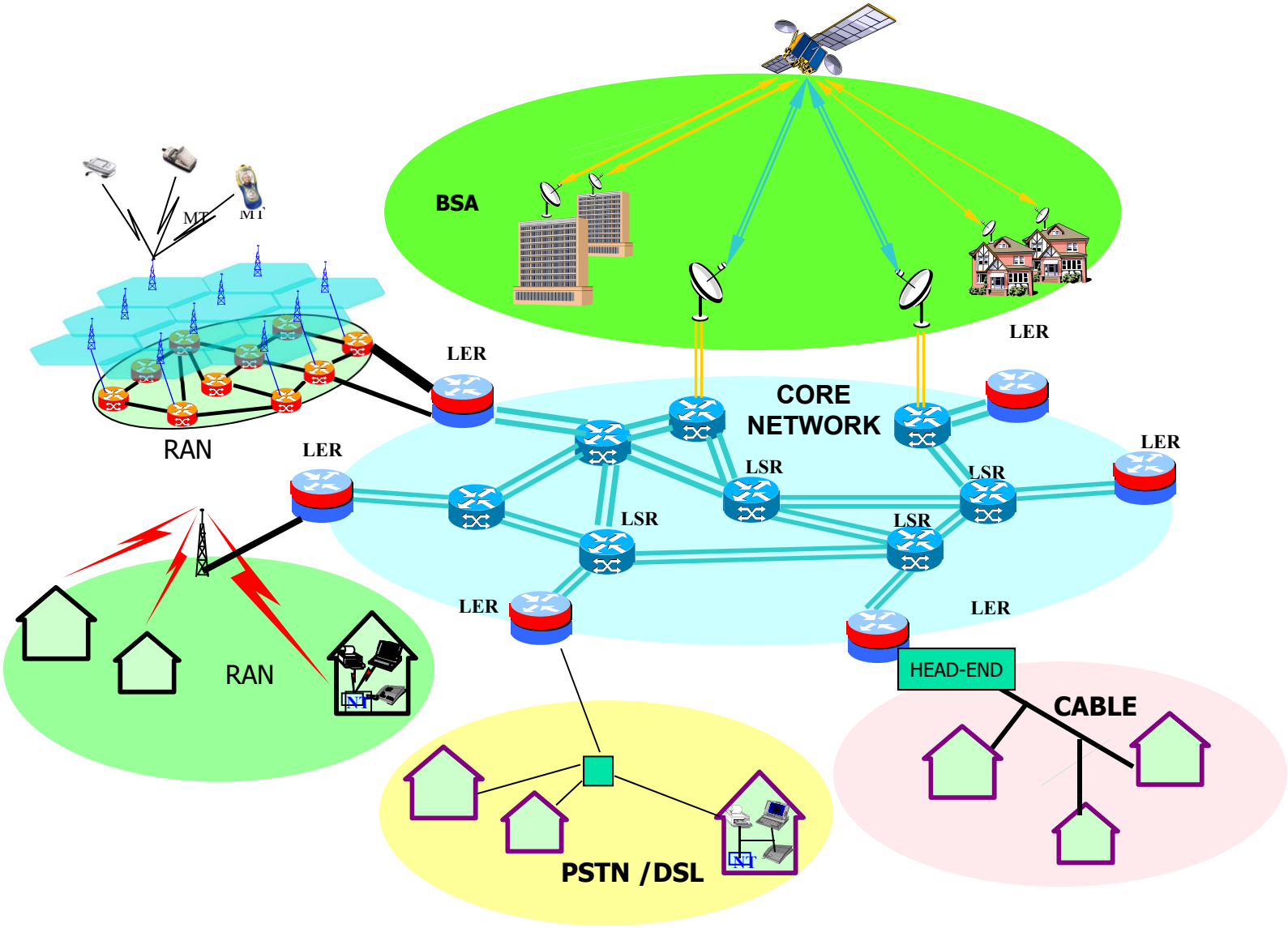
Professor, Department of Electrical and Computer Engineering,
McGill University



Contents:

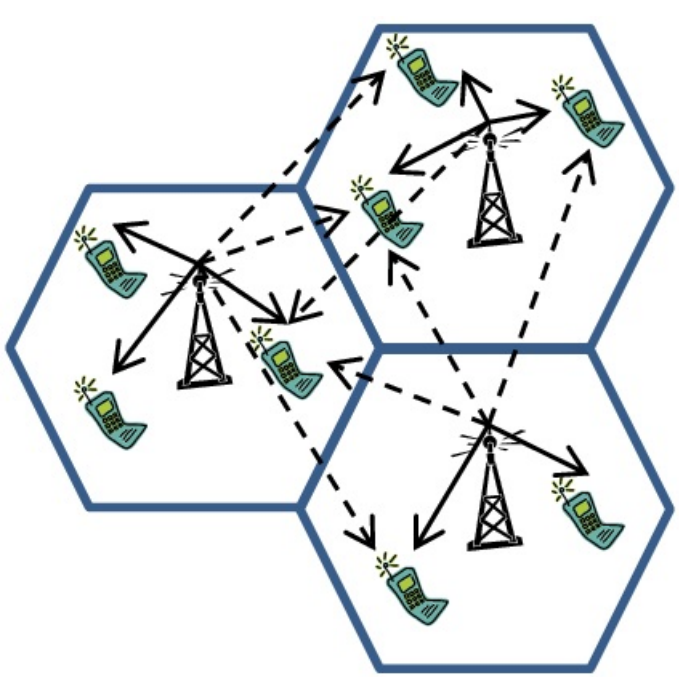
- An Overview
- Cellular Wireless Evolution
- LTE/SAE
- LTE-Advanced

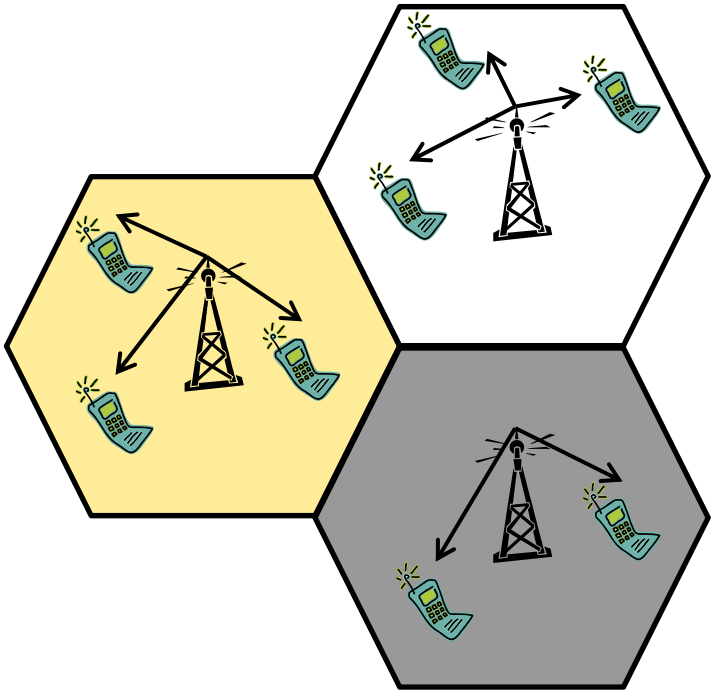
CORE & ACCESS TECHNOLOGIES: EXAMPLES



Cellular Systems

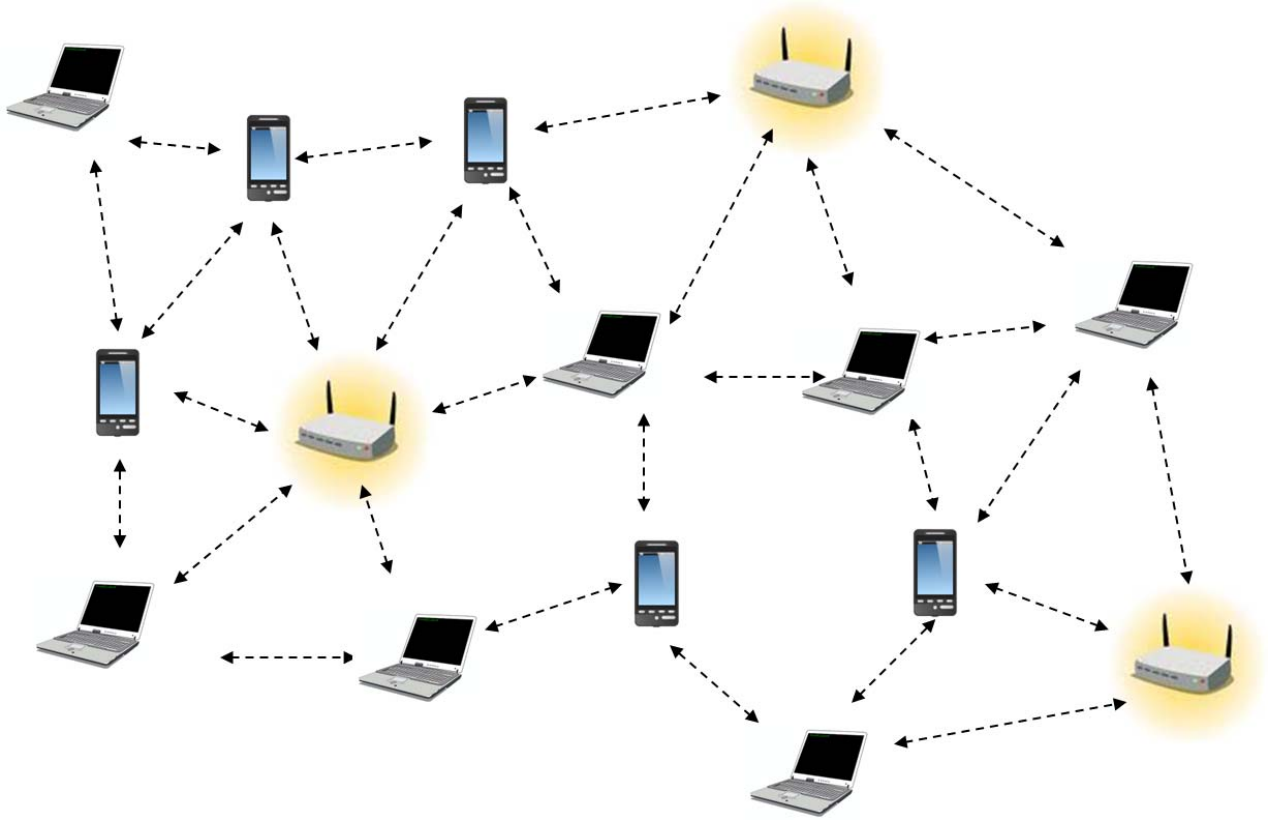
- Downlink (broadcast) vs. Uplink (multiple access)
- Frequency re-use
- Dynamic resource allocation (frequency, time, power)
- Interference management





Ad Hoc Networks

- Distributed wireless network (no centralized operator)
  - No centralized structure (e.g., cell tower)
  - Routing



COMMUNICATIONS NEEDS & TRENDS

- **multimedia** services: Voice, Video distribution, Real-time videoconferencing, Data,… for both business and residential customers:
  - Explosive traffic growth
  - Internet growth, VoIP, VideoIP, IPTV
  - Internet of Things (IoT)
- Cell phone popularity worldwide
- **Ubiquitous** communication for people and devices
- Emerging systems opening new applications
- **Unified** network: Single distributed network, multiple services, packet architecture

explosive acceptance of the Internet

- The explosive acceptance of the Internet as indicated by the time taken to reach the 10 million customer mark after being introduced to the mass market:
  - 38 years for telephone
  - 25 years for cable TV
  - 9 years for cell phone
  - 6 years for wireless data
  - <2 years for Internet
- Internet users want & demand speed

Multimedia Services: Requirements

- attributes: high-speed, bursty traffic, various QoS requirements, mobility
- technical requirements: efficient use of broadband transmission resources

	Voice	Video	Data
Rate	8-32 Kbps	1-20 Mbps	1-100 Mbps
BER	10^{-3}	10^{-6}	10^{-6}
Delay	<100ms	<100ms	-
Packet Loss	<1%	<1%	0
Traffic	Continuous	Continuous	Bursty

CONSIDERATIONS:

DEMANDS:

- Users want more capacity at good quality for various applications that need fast response, large volume of information.
- Operator wants more subscribers sharing the network for higher revenue, i.e., more efficient use of resources while offering QoS requirements

ENVIRONMENT & SERVICES:

- Limited resources (bandwidth, power).
- channels: time-varying, (multipath) frequency-selective fading, interference-limited
  - wireless Near-LOS, Non-LOS: indoor, outdoor
- Multimedia services with different QoS requirements.
- Large number of nodes in a dynamic network

TECHNICAL CHALLENGES

- *Higher rates* requires consideration of advanced transmission and signal processing techniques with better performance:
  - new dimensions, e.g., multiple-input multiple-output
  - adaptive to dynamic environmental changes
  - better interference-awareness
- Dynamic performance and resource management
- *supports* of different *QoS requirements* need more efficient *dynamic* resource allocation
- *Better connectivity* needs *reconfigurable* topology that can adapt to the changes.
- Efficient utilities of resources,
- Relatively low cost and complexity.

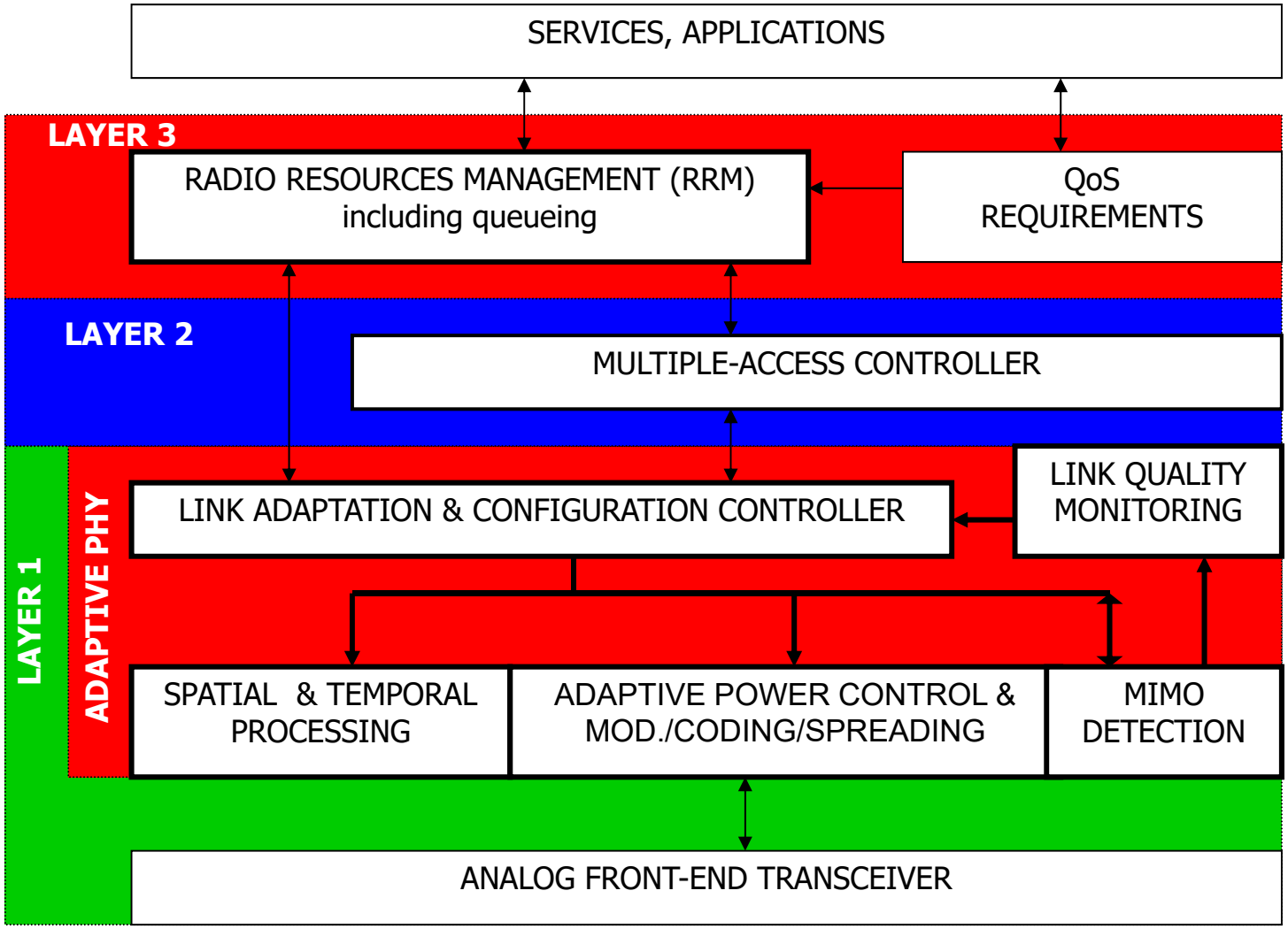
APPROACHES:

- adaptive multiple-dimensional transmission techniques in time-varying, frequency-selective fading channels:
  - space-time-frequency coding, precoding, modulation, decoding schemes that improves both coding and diversity gains
  - Reconfigurable, collaborative processing

in conjunction with

- dynamic resource allocation strategies across the "layers"
  - to improve resource utility in interference-limited environment
  - to promote collaboration between entities in efficiently sharing common communication resources

EXAMPLE: "CROSS-LAYER" STRUCTURE



Cellular Wireless Access Communications: Evolution

Cellular Wireless System Evolution: 1G-3G

- **1G** (Early 1980s): Analog FDMA for voice communications, e.g., AMPS
- **2G** (Early 1990s): Digital TDMA and narrowband CDMA for voice communications, e.g., started with GSM (mainly voice), IS-95 (cdmaOne), PDC,
  - **2.5G**: Adding Packet Services: GPRS, EDGE, new services: SMS and low-rate data
- **3G** (Late 1990s): ITU global standard International Mobile Telecommunications (IMT)-2000 required 144kbps mobile, 384kbps pedestrian, 2Mbps indoors
  - Wideband CDMA & Global harmonization and roaming
  - Rel-99 (Mar.00): UMTS 3.84Mcps (WCDMA FDD&TDD,
  - Rel-4 (Mar.01): 1.28Mcps TDD (TD-SCDMA).
  - WiMAX: an official 3G technology
- **3G Extensions** (3GPP): IP Multi Media Subsystem (IMS), Inter-working with WLAN (I-WLAN)
  - Rel-5 (Jun.02): High-Speed Packet Access (HSPA): HSDPA (D:down)
  - Rel-6 (Mar.05): and HSUPA (E-DCH) (U:up)
  - Rel-7 (Dec.07): HSPA+(64QAM DL, MIMO; 16QAM UL), IMS (IP Multimedia Subsystem), VoIP, gaming, push-to-talk; EDGE Evolution;

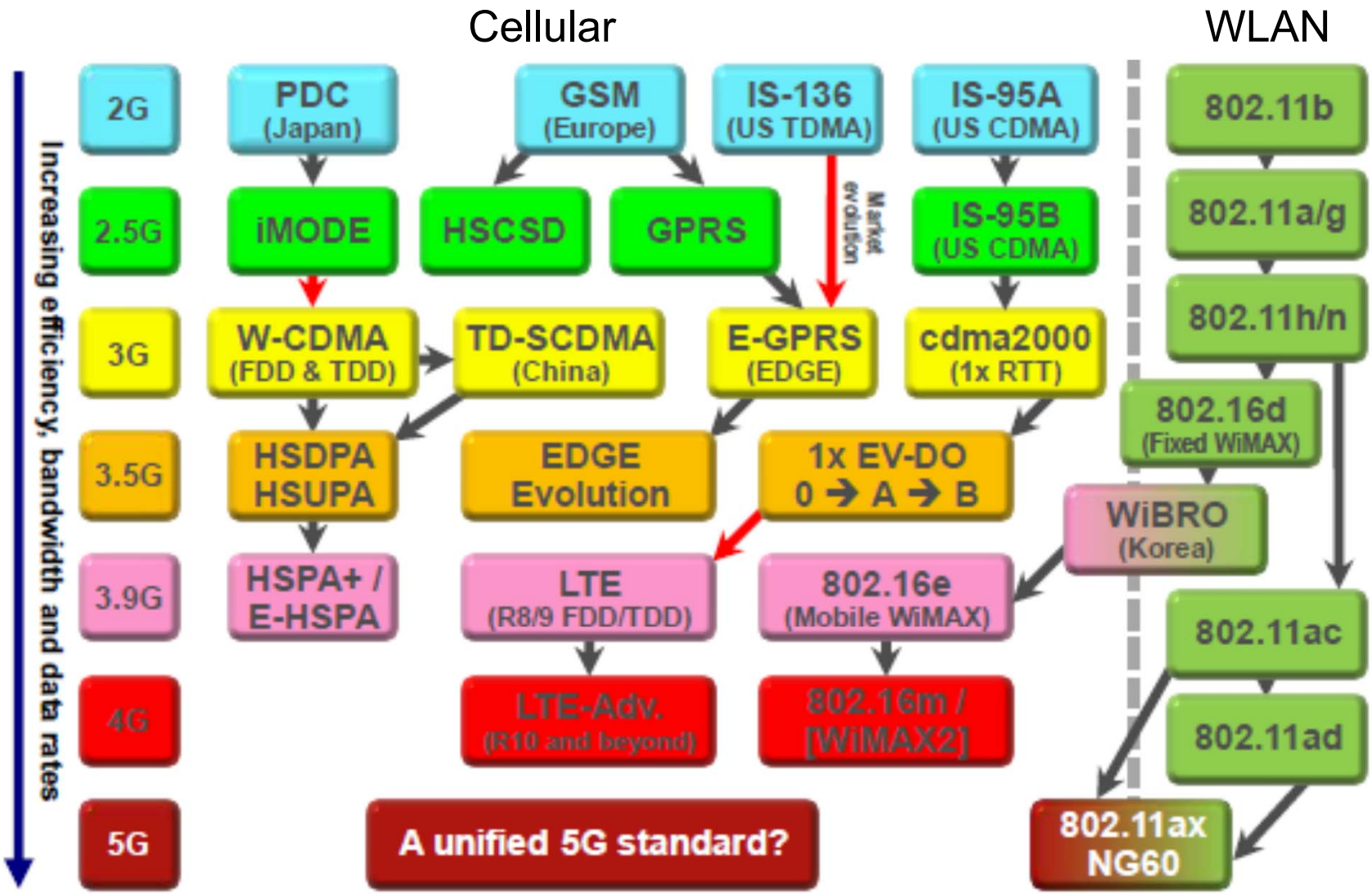
    LTE&SAE Feasibility Study

Cellular Wireless System Evolution: beyond 3G

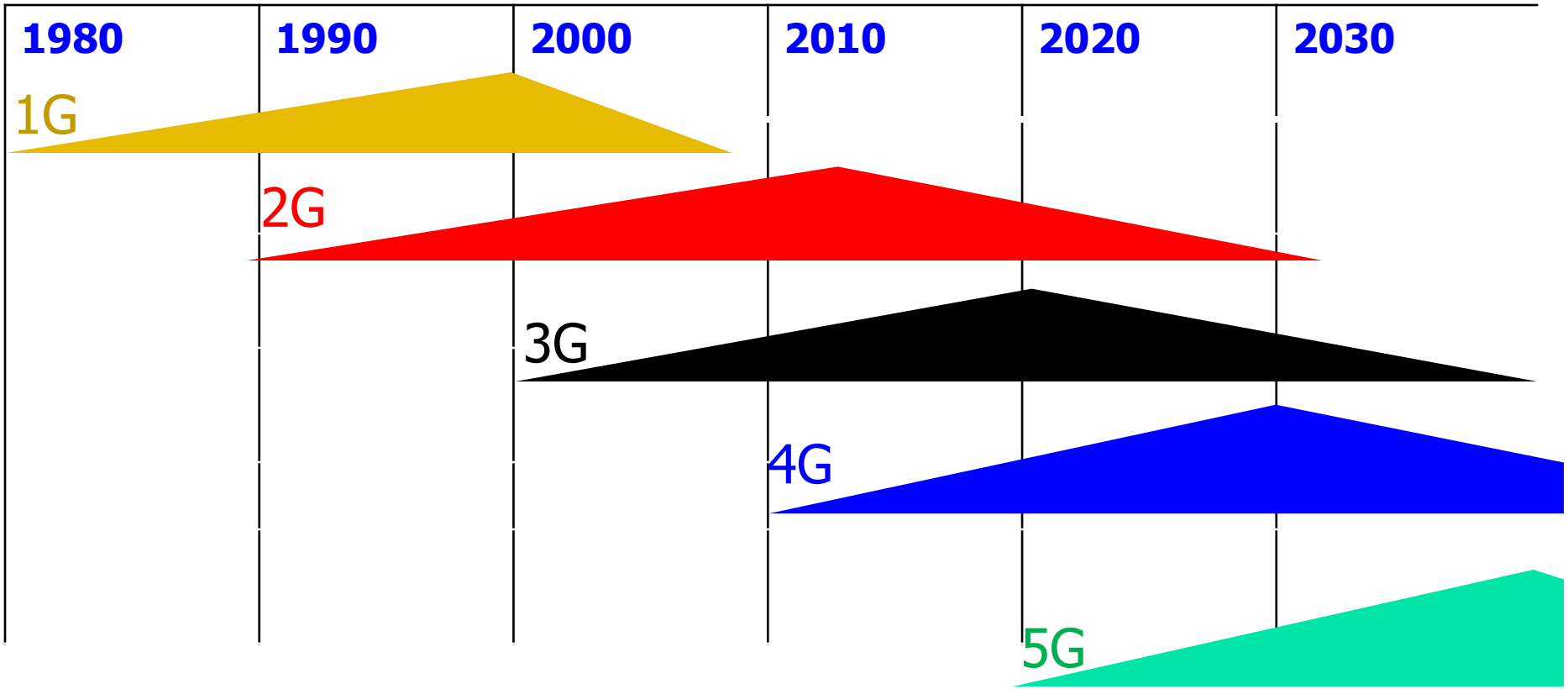
- **3.9G:**
  - IEEE 802.16e (mobile WiMAX)
  - Rel-8 (Mar.09): 3GPP Long Term Evolution (LTE) WI: OFDMA & System Architecture Evolution (SAE) WI: new IP core network; UMTS Femtocells, Dual Carrier HSDPA; Adding Mobility towards I-WLAN and non-3GPP air interfaces
  - Rel-9 (Mar.10): multi-standard radio (MSR), dual-carrier HSUPA, dual-band HSPDA, SON, LTE Femtocells (HeNB), LTE-Advanced feasibility study

- **4G**: ITU's IMT-Advanced (evolutionary path beyond IMT-2000): requires ability of up to 40MHz radio channels with very high spectral efficiency; targets 100Mbps (high mobility) and 1Gbps (low mobility, e.g., nomadic, local area):
  - Rel-10 (Sep.11): LTE-Advanced (4G) WI, CoMP study, 4-carrier HSDPA.
  - IEEE 802.16m (WiMAX) is also evolving towards 4G.
  - Rel-11 (Mar.13): CoMP, eDL MIMO, eCA, MIMO OTA, HSUPA TxD & 64QAM MIMO, HSDPA 8C & 4x4 MIMO, MB MSR
  - Rel-12 (Mar.15): 3DL CA, D2D, MTC, NAICS, dual-connectivity, small-cells,…
  - Rel-13 (Mar.16): LAA (LTE-U), 4CA, >5CA study, MIMO OTA, FD MIMO

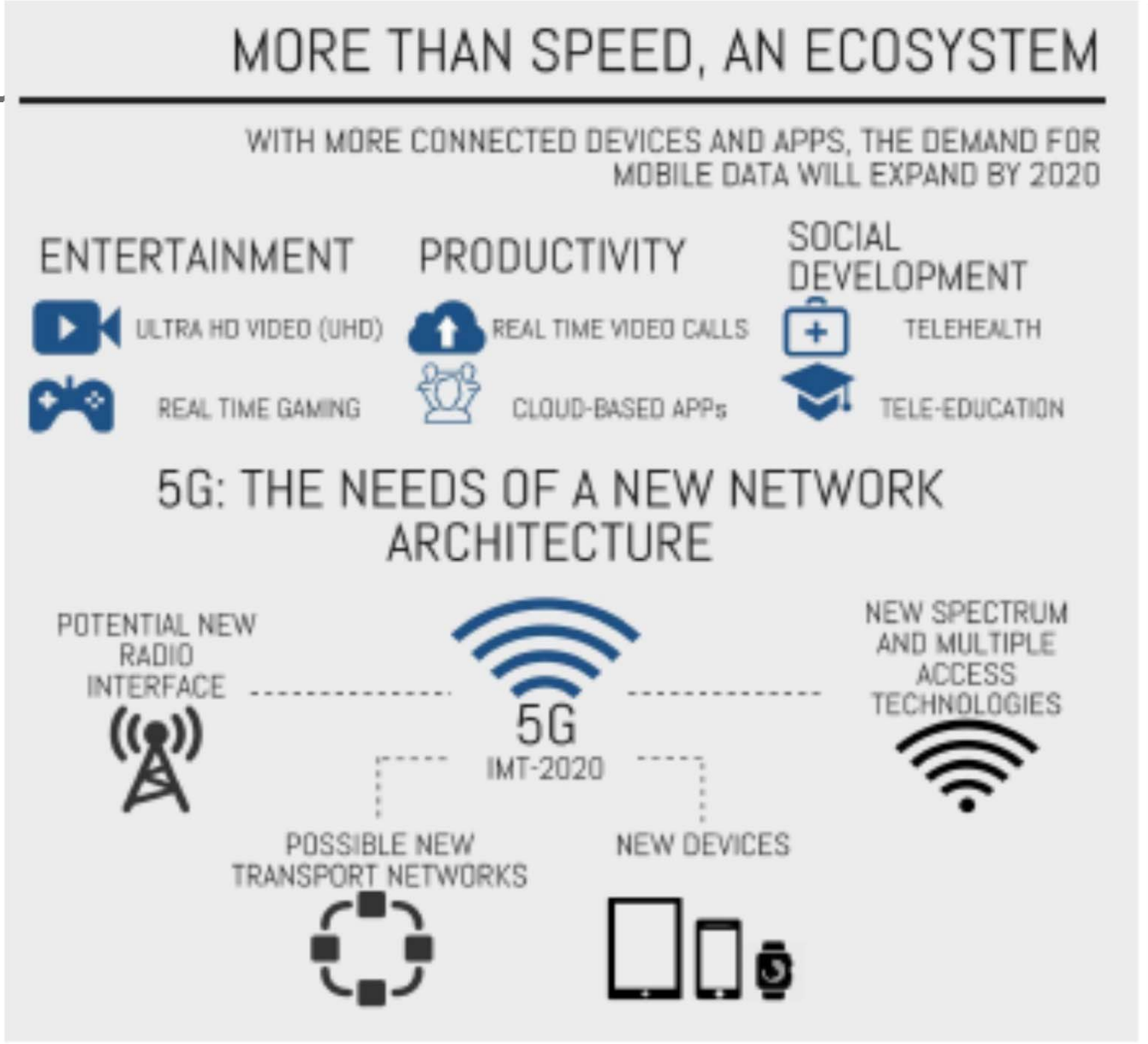
Wireless System Evolution 1990–2015



Wireless Communications: Technology Co-existence



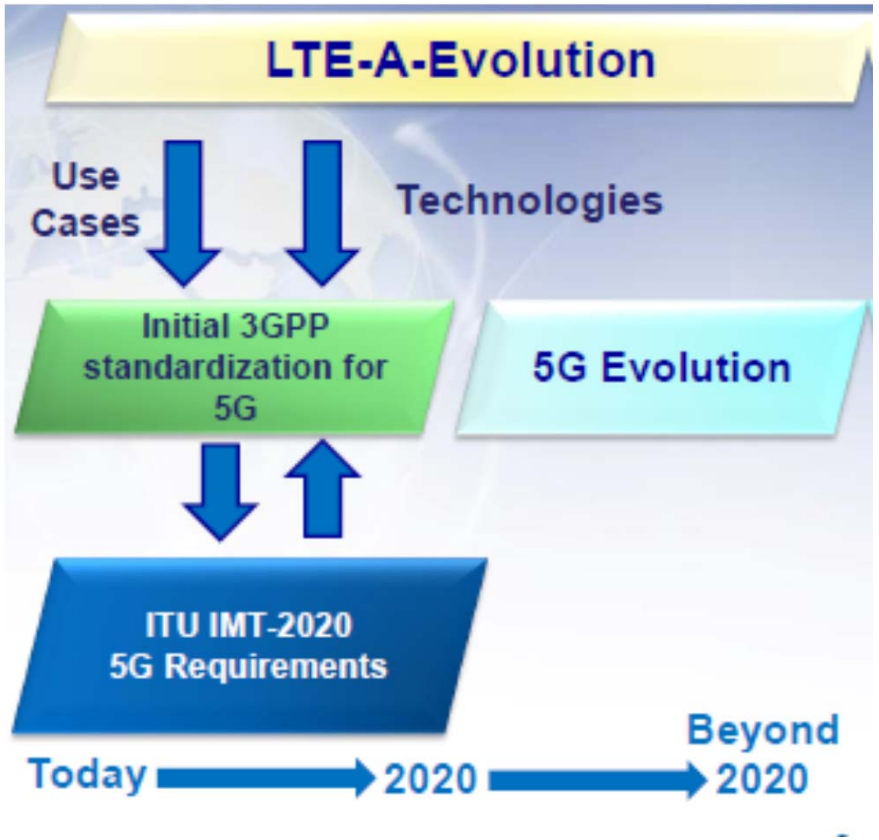
ITU IMT-2020 5G



Source ITU

ABOUT 5G

- The standard that will be known as 5G has yet to be defined
- 2G, 3G, 4G, 5G are commercial names, not technological definitions
- The telecoms industry has been discussing the official requirements and specifications for IMT-2020 to be completed before 2020.
- LTE Evolution forms a base to introduction of 5G
- 5G Standardization and requirement specification starting 3GPP standardized 5G commercial launches expected around 2020
- LTE Evolution and 5G will co-exist well beyond 2020

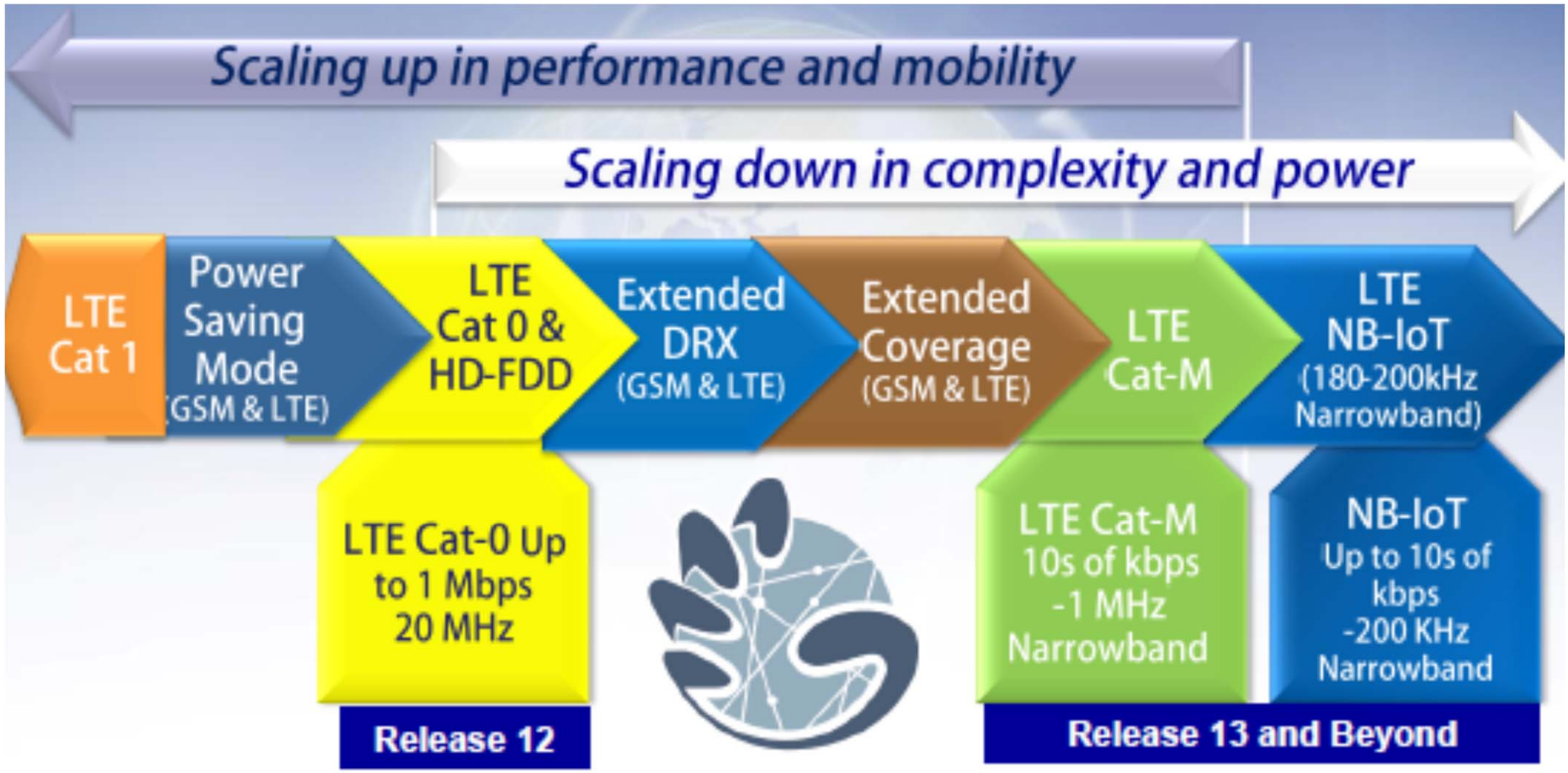


Paradigm Shift in Spectrum

- Additional spectrum needed in existing (<6GHz) and new bands: cmWaves (6-30GHz) , mmWaves (>30GHz)
- High frequencies for ultra-dense 5G small cell deployments
- Both licensed and unlicensed, exclusive and shared spectrum

Licensed	Exclusive rights granted to an operator by regulator	Provides reliable, secured spectrum for predictable quality/capacity	Critical part of LTE Evolution and 5G deployments
Shared	Shared with incumbents	Coordinated access when/where not used by incumbents.	Facilitates timely access to spectrum in shared bands
Unlicensed	No registration or individual permission	Rules established to avoid interference	Complement for LTE & 5G, e.g. in small cell deployment

IoT Standardization Progress



LTE-Advanced Maturation

Performance

Device Interference Cancellation

SON

Coordinated Multipoint

Flexibility

Evolving Carrier Aggregation

Further Enhanced HetNets

More advanced antenna features and 256 QAM

Creativity

LTE Broadcast

LTE Direct D2D

Higher bands and new licensing models (Authorized Shared Access)

Higher capacity for M2M and Smartphone signaling

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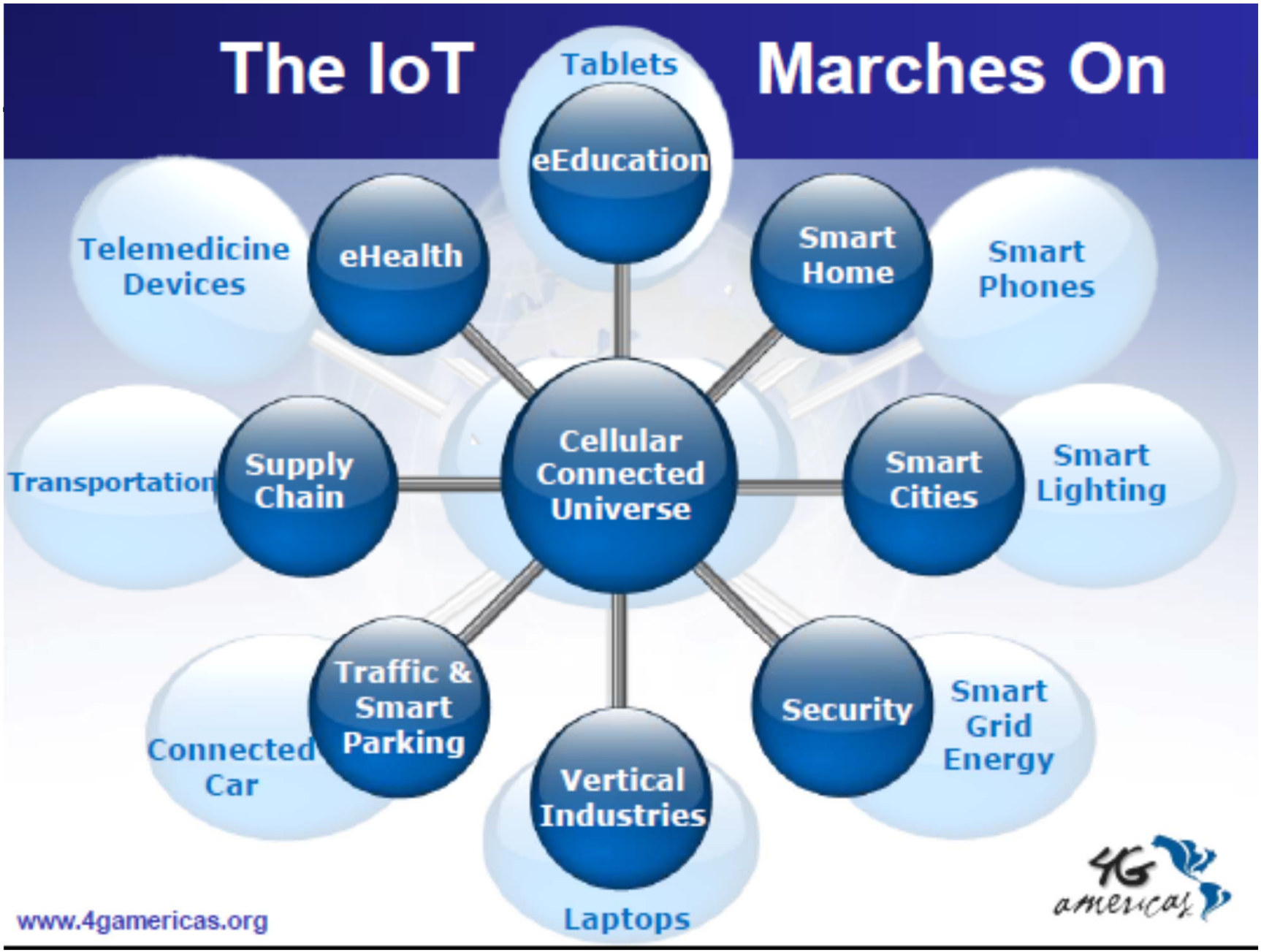
The IoT Marches On
Tablets
eEducation
Telemedicine Devices
eHealth
Smart Home
Smart Phones
Transportation
Supply Chain
Cellular Connected Universe
Smart Cities
Smart Lighting
Traffic & Smart Parking
Connected Car
Vertical Industries
Security
Smart Grid Energy
Laptops
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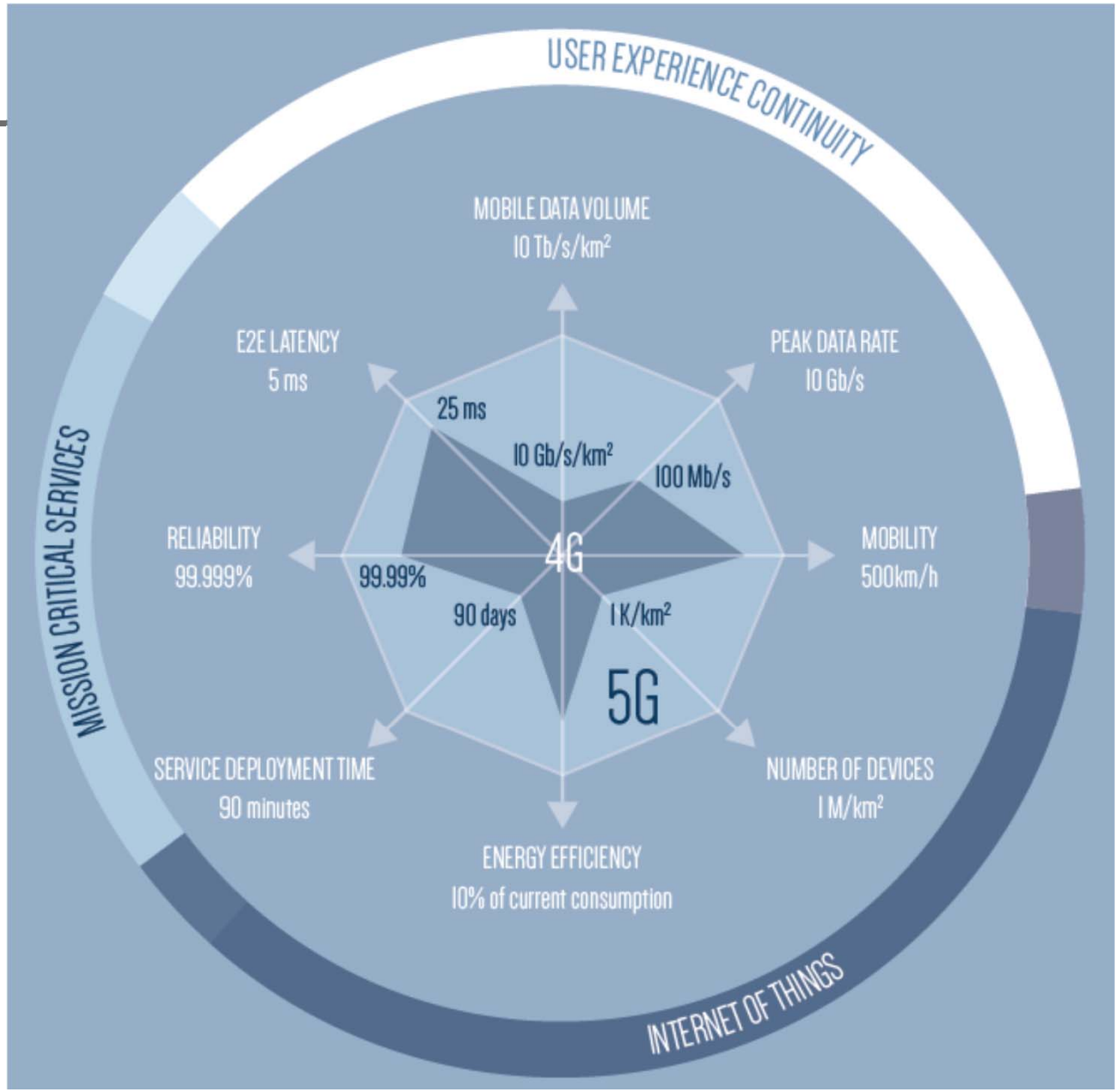
5G:

- 5G services will complement and largely outperform the current operational capabilities for wide-area systems, reaching the following high-performance indicators:
  - Guaranteed user data rate ≥ 50Mb/s
  - Capable of human-oriented terminals ≥ 20 billion
  - Capable of IoT terminals ≥ 1 trillion
  - Aggregate service reliability ≥ 99.999%
  - Mobility support at speed ≥ 500km/h for ground transportation
  - Accuracy of outdoor terminal location ≤ 1 meter
- Efficiency and security will be of paramount importance

- 5G will leverage on the strengths of both optical and wireless technologies
- 5G will be driven by software: Network functions virtualization (NFV) and software-defined networking (SDN) provide examples

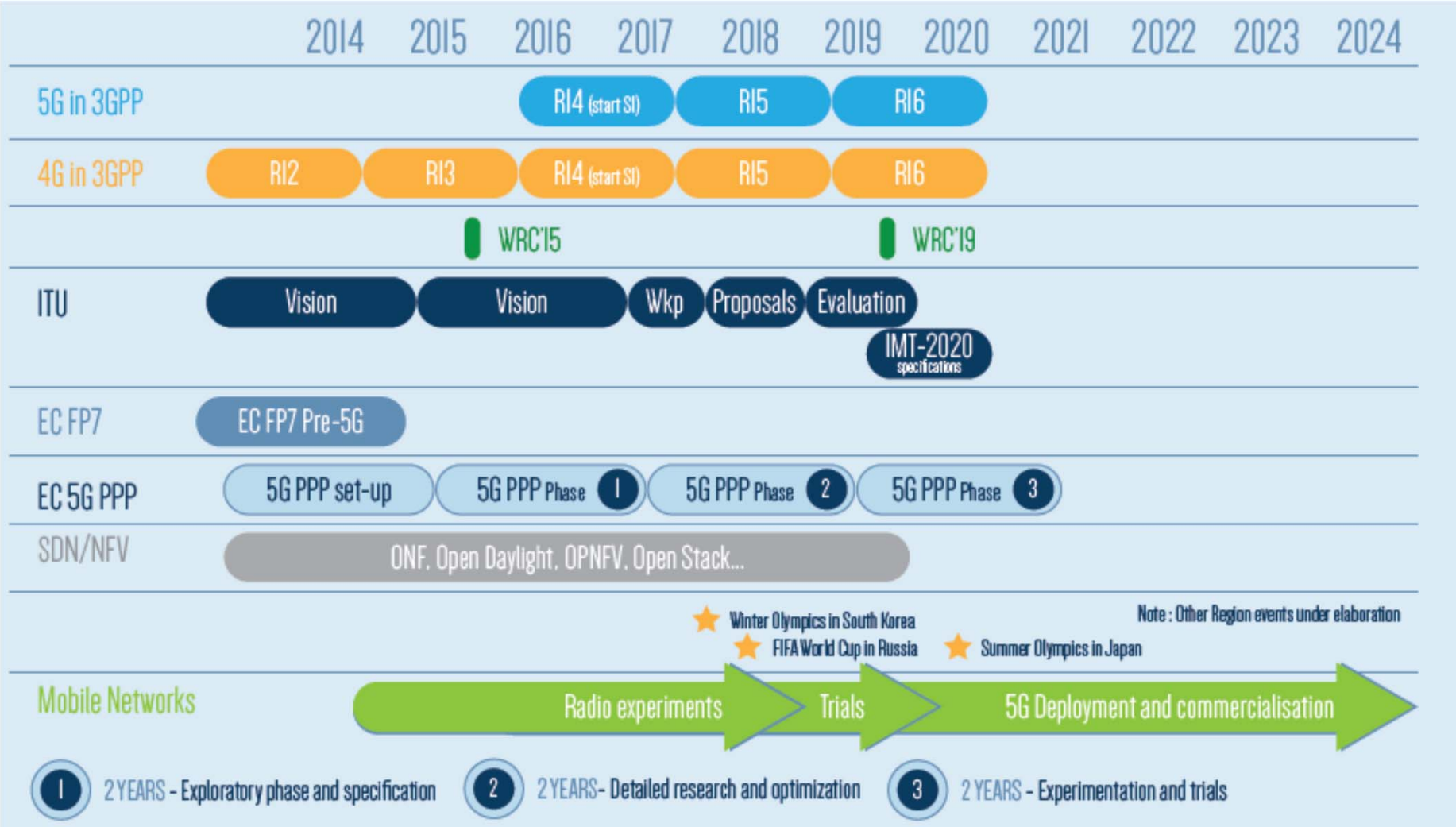
5G disruptive capabilities



5G: from exploration to deployment

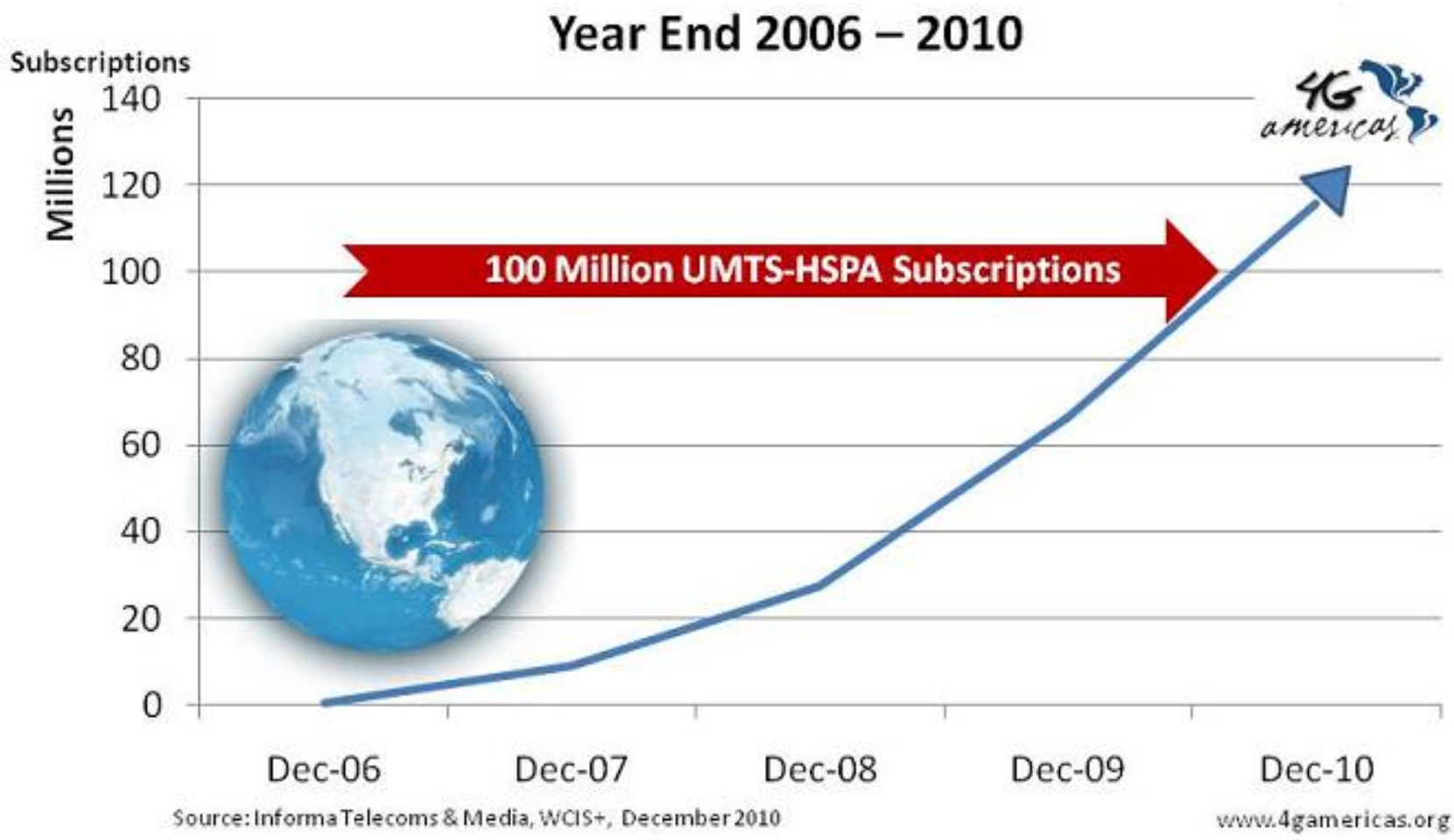
- 2014-2015
  - understanding detailed requirements,
  - identifying most promising functional architectures and technology options for 5G future systems.
- 2015-2017 Detailed system R&D
  - for all access means, backbone and core networks (e.g., SDN, NFV, cloud systems, …)
  - by taking into account economic conditions for future deployment.
- 2016-2018
  - Detailed system optimisation to meet all identified requirements and constraints.
  - Contributions to initial global standardisation activities e.g. in 3GPP.
  - Preparation of WRC19.
  - Support of regulatory bodies for new frequency-band allocation to be available around 2020 & system deployment.
- 2017-2018
  - Investigation, prototypes, technology demos and pilots of network management/operation, cloud-based distributed computing, big data for network operation
  - Detailed standardisation process based on validated system concepts by simulations and trials.
- 2018-2020 Demonstrations, trials and scalability testing of different complexity depending on standard readiness and component availability.

European Commission 5G Public-Private-Partnership (5G PPP) ROADMAP www.5g-ppp.eu

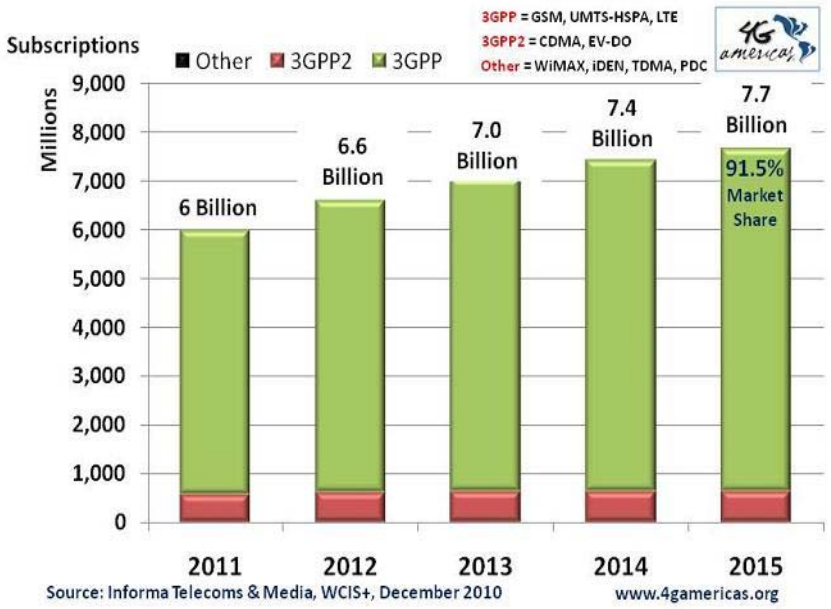


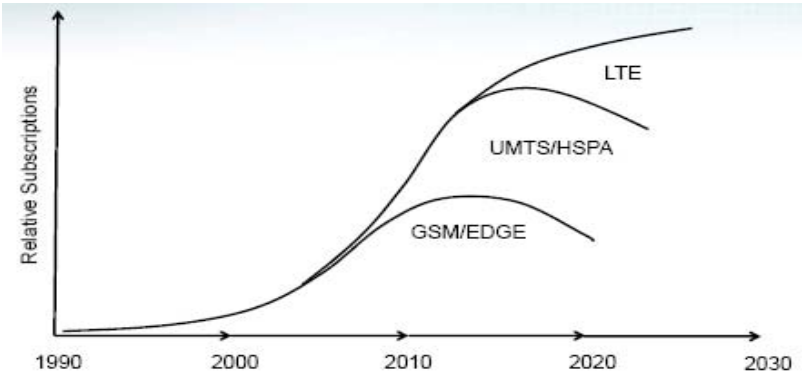
3GPP Mobile Broadband Growth

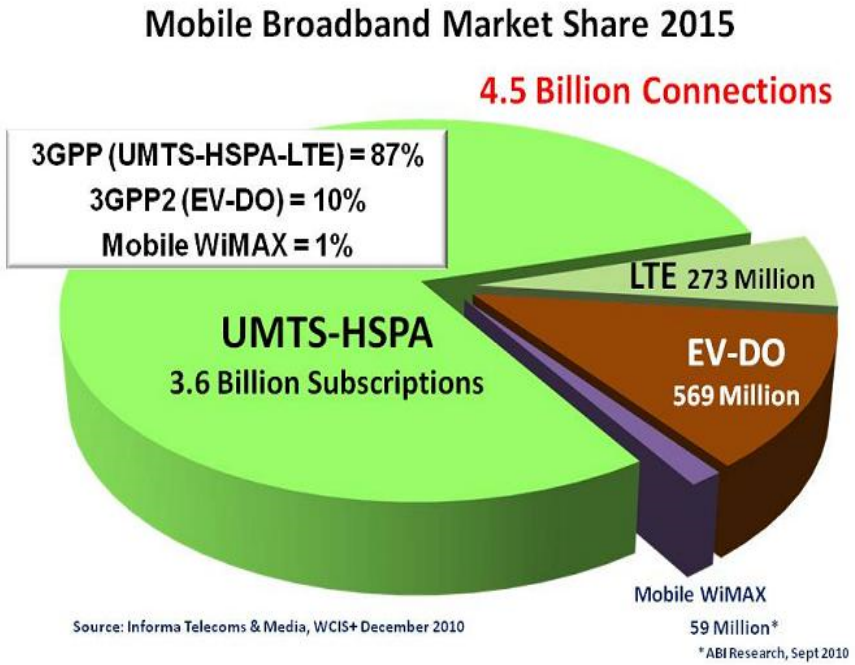
3GPP Mobile Broadband Growth in the Americas: 2006-2010



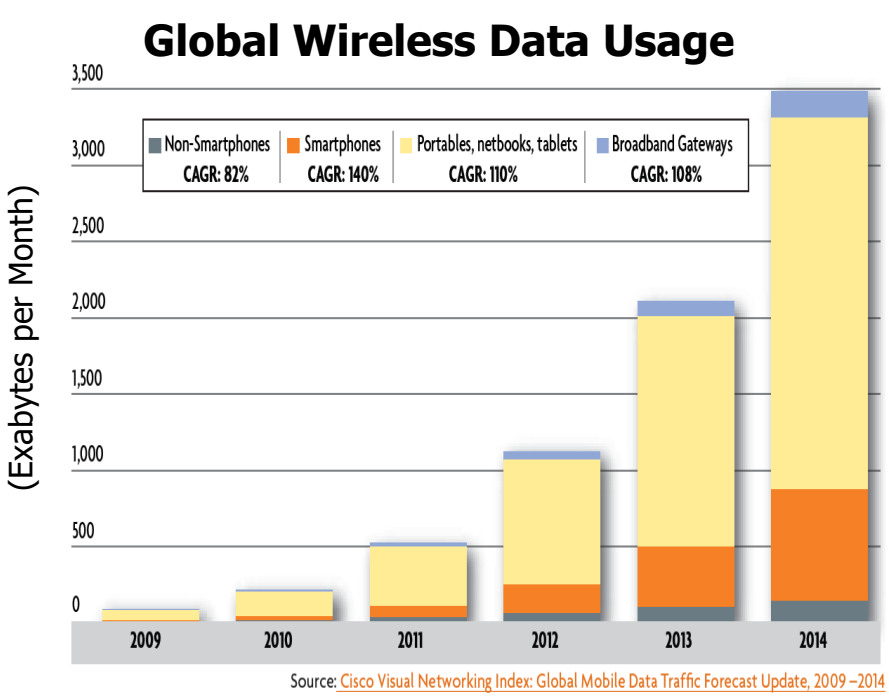
Global Mobile Broadband Forecast in 2010

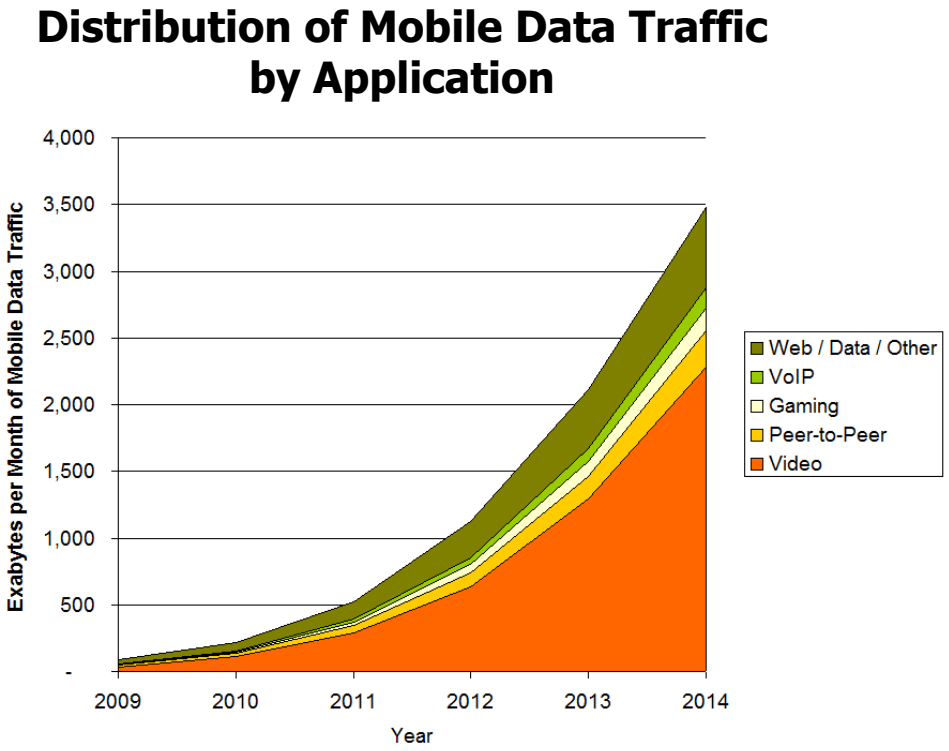






Fast growing wireless data capacity demands

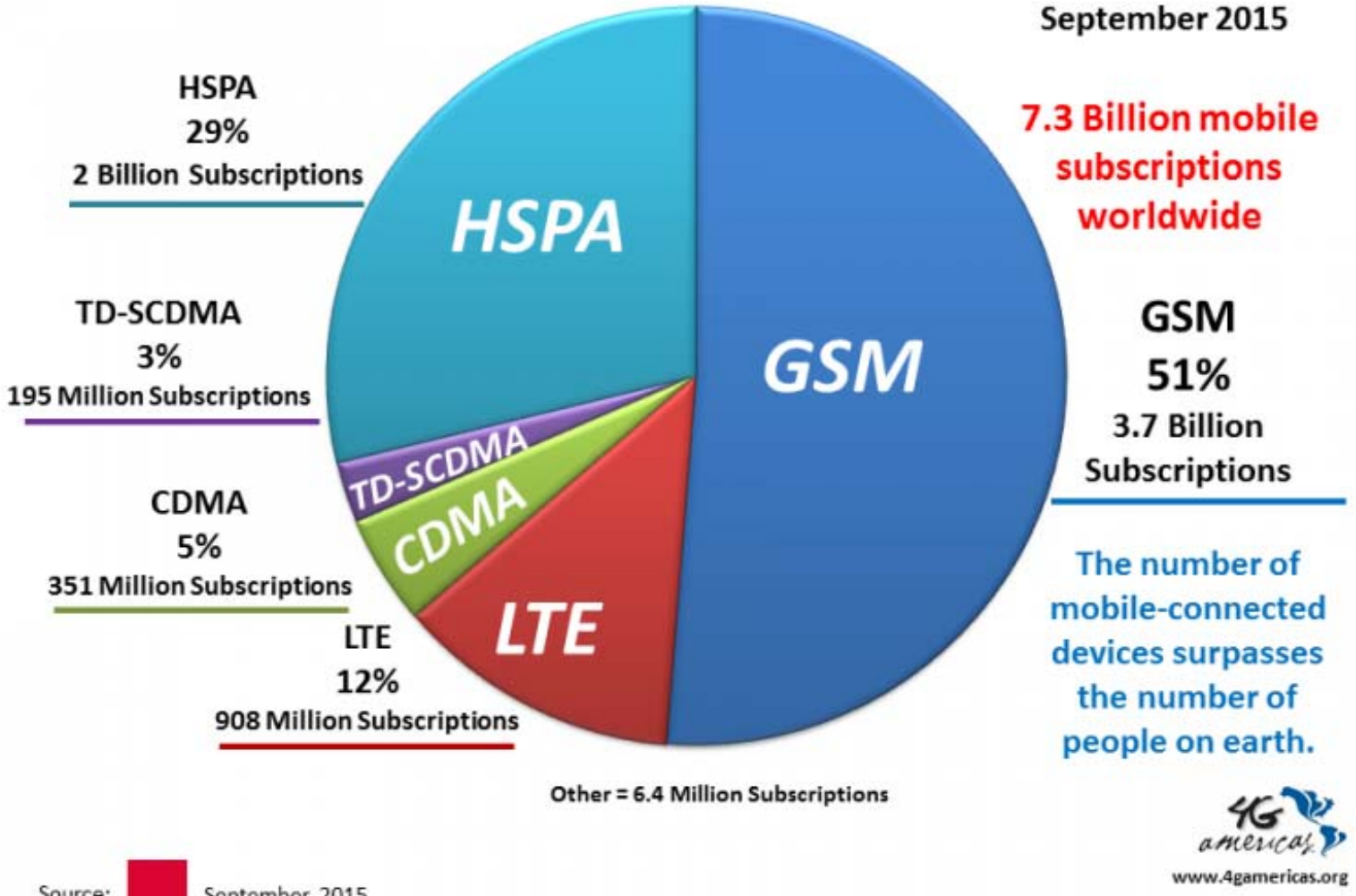




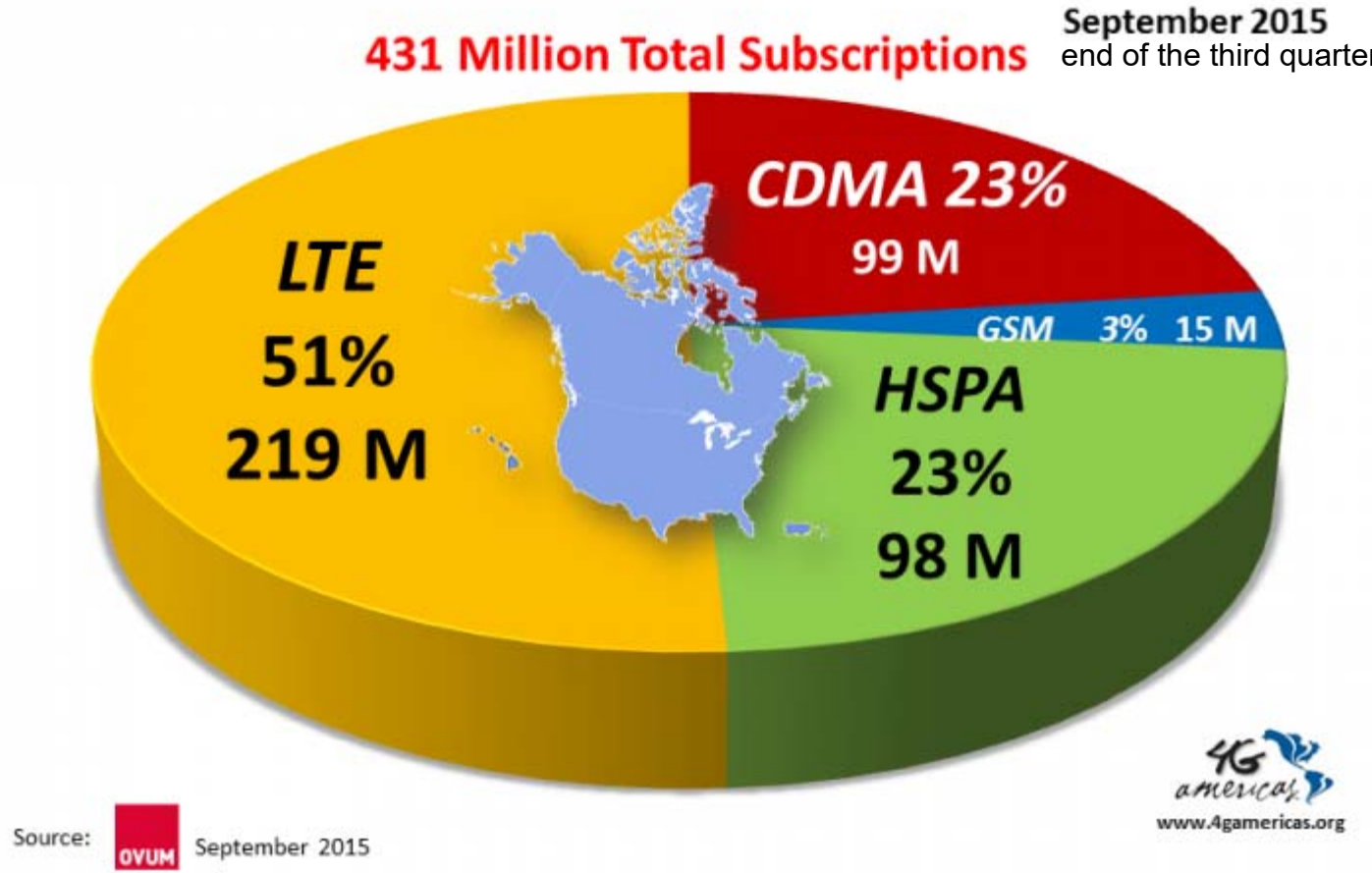
1 Exabyte=10^{18} bytes = 1 billion gigabytes

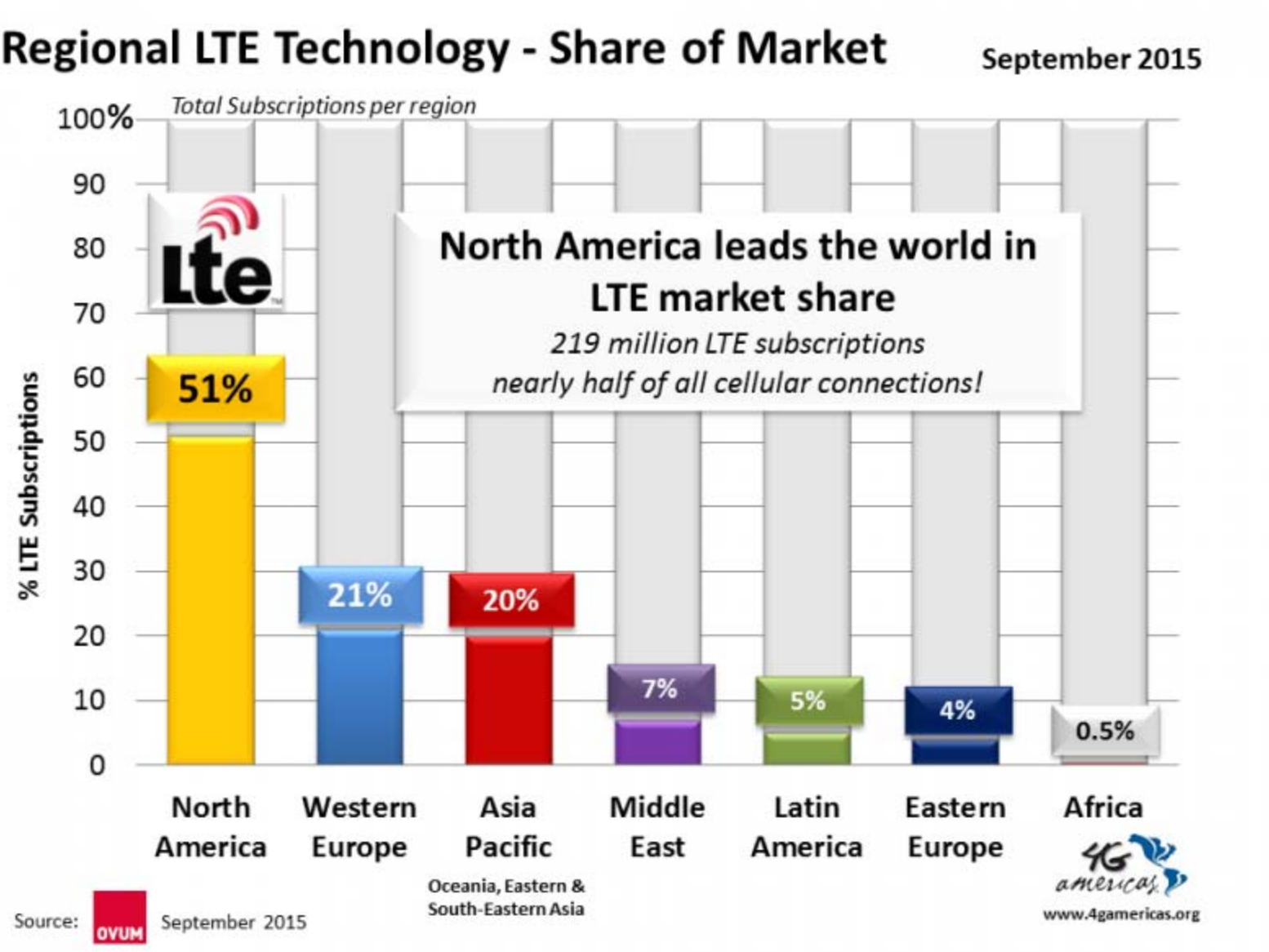
- due to smartphones and high growth in web, streaming and interactive video apps
- LTE & LTE-Advanced coupled with small cells & relays will address these fast growing wireless data capacity demands

Global Mobile Subscribers and Market Share by Technology



Mobile Subscribers and Market Share by Technology – US and Canada




Regional LTE Technology - Share of Market
September 2015
Total Subscriptions per region
100%
90
80
70
60
50
40
30
20
10
0
% LTE Subscriptions
Lte
North America leads the world in LTE market share
219 million LTE subscriptions
nearly half of all cellular connections!
51%
21%
20%
7%
5%
4%
0.5%
North America
Western Europe
Asia Pacific
Oceania, Eastern & South-Eastern Asia
Middle East
Latin America
Eastern Europe
Africa
Source: OVUM September 2015
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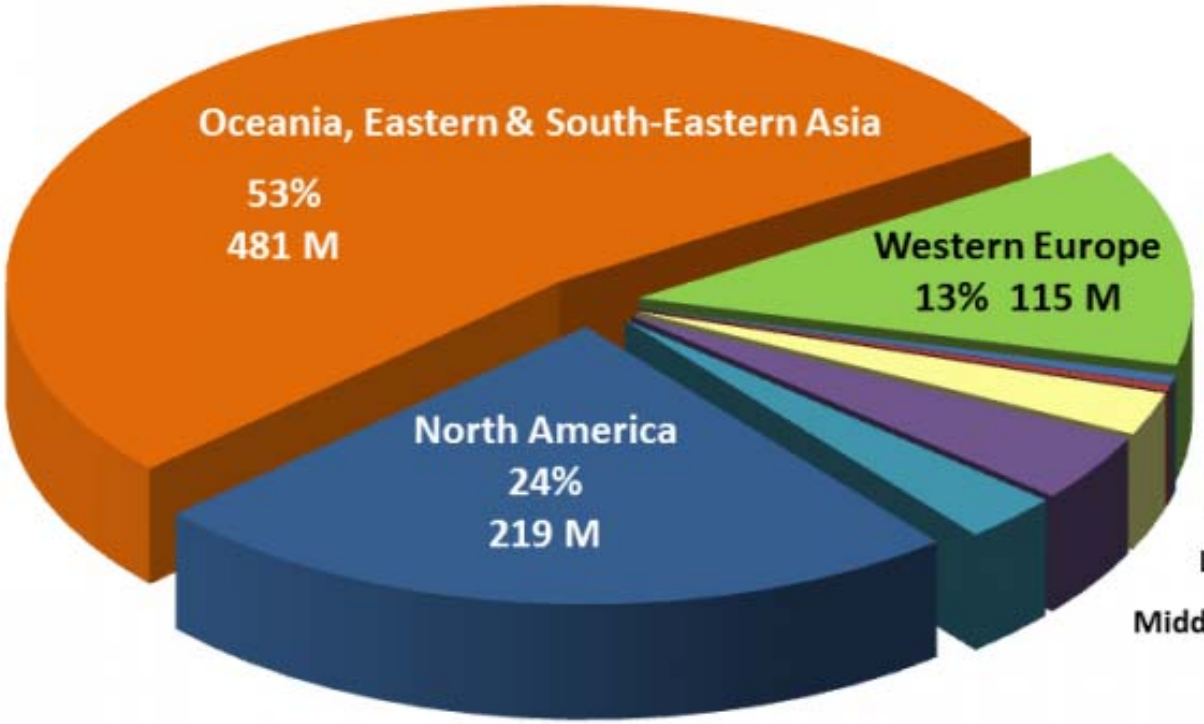
3Q 2015 LTE Subscribers and Market Shares by World Region

908 million global LTE subscriptions



Africa	1%
Central & Southern Asia	0.25%
Eastern Europe	3%
Latin America	4%
Middle East	3%

Source: OVUM September 2015

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LTE & LTE-Advanced Deployments as of Jan.1, 2016:

- 104 Global LTE-Advanced Commercial Networks in 51 Countries
- 445 Global LTE Commercial Networks in 148 Countries

- USA & Canada: 69 Networks in 2 Countries
- Caribbean: 19 Networks in 12 Countries
- Latin America: 55 Networks in 18 Countries

http://www.4gamericas.org/en/resources/lte-and-lte-advanced-deployments/

LTE/SAE: Overview

LTE history

- **November 2004**: Kick-off in RAN LTE Toronto workshop
- November 2005: Decision on basic LTE radio access, DL: OFDM, UL: SC-FDMA
- June 2006: Close of LTE Study Item, Start of LTE Work Item
- Study Item: TR feasibility on system level (Dec 2004 – June 2006)
  - TR 25.912: Feasibility Study for Evolved UTRA and UTRAN
  - TR 25.913: Requirements for E-UTRAN
  - TR 25.813: EUTRA and EUTRAN radio interface protocol aspects
  - TR 25.814: Physical layer aspects for E-UTRA
- March 2007: Approval of LTE, Stage 2 specification
- June 2007: Detailed standard work: Standardized in the form of Rel-8.

UMTS Universal mobile telecommunications system
UTRA Universal terrestrial radio access
UTRAN Universal terrestrial radio access network

LTE: Faster & More Responsive

- **30-10msec latency for**
  - Improved user experience
  - Fast VoIP call set-up
  - Instantaneous web pages
  - Streaming fast buffering
  - Online mobile gaming
- **40-100Mbps for**
  - True high-speed mobile data
  - Full-motion HD video anywhere
  - Stream any content
  - Mobile peer-2-peer & Web 2.0
  - Quadruple play
  - Faster email access
  - Instantaneous web pages

LTE Motivation

- Spectrum:
  - Highly efficient radio technology
    - Increased spectrum efficiency for larger carriers and therefore increased capacity
    - Lower cost per bit and lower prices for the end user
  - Flexibility and scalability in deployment
    - Operating in various frequencies and bandwidths
    - Operators can start with smaller deployment and increase bandwidth as demand increase
    - Supports resource aggregation of radio band resources
- Architecture:
  - Architecture simplicity and reduced protocol complexity
  - reduced number of network elements
  - Simplified protocol stack & all IP network
    - Reduced latency
    - Easier network management
- Mobility: Seamless handover ensuring service continuity with legacy systems

LTE features

- Very high data rates
  - Peak data rates: >100 Mbps (downlink)/50Mbps (uplink) in 20MHz
  - Improved cell-edge user throughput

FDD downlink peak data rates (64QAM)			
Antenna configuration	SISO	2x2 MIMO	4x4 MIMO
Peak data rate Mbps	100	172.8	326.4

FDD uplink peak data rates (single antenna)			
Modulation depth	QPSK	16QAM	64QAM
Peak data rate Mbps	50	57.6	86.4

- Very low latency: Sub-5 ms latency for small internet protocol (IP) packets; U-Plane transit time (<10ms); C-Plane dormant-to-active transition(<50ms)
- Spectrum flexibility
  - Deployable in a wide-range of spectrum allocations of different sizes
  - Both paired and unpaired spectrum
  - Scalable bandwidths: 1.4, 3, 5, 10, 15, and 20 MHz
- Spectral efficiency improvements over Release 6 high speed packet access (HSPA) of three to four times in the downlink and two to three times in the uplink

LTE features

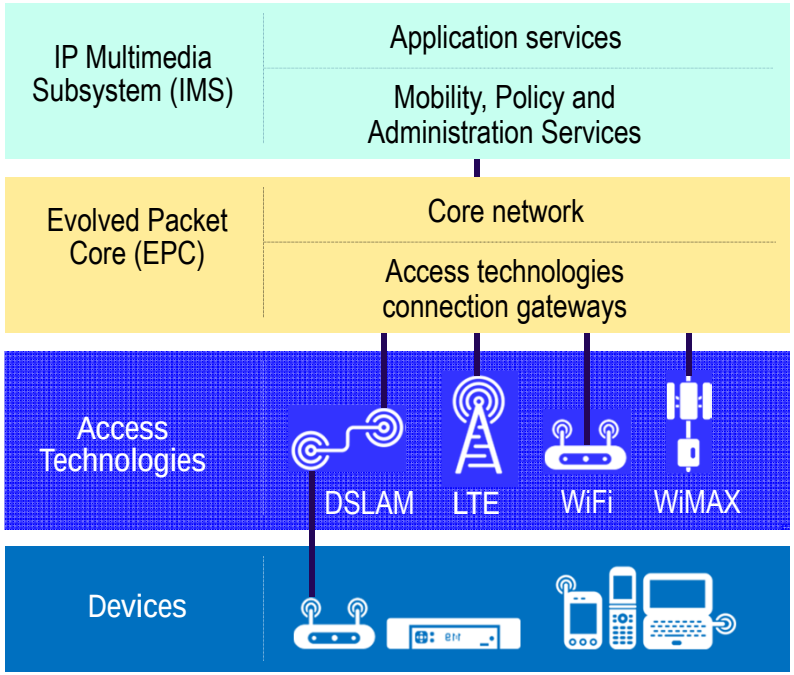
- Coverage: 5km (full performance), 5-30km (slight degradation), up to 100km, Up to 200 active users in a cell (5 MHz)
  - improved inner cell average data throughputs (MIMO needed)
  - improved "cell edge rates" and spectral efficiency (e.g. 2-4 x Rel6)
- Mobility: Performance
  - optimized for low mobile speeds from 0 to 15 km/h,
  - supported with high performance from 15 to 120 km/h
  - functional support from 120 to 350 km/h, under consideration for 350 to 500 km/h.
- Co-existence with legacy standards while evolving toward an all-IP network
  - less complexity in RAN (architecture, signaling procedures/protocols)
  - economic usage of backhaul capacity; simplified and unified transport (IP)
  - interworking with legacy 3G and cost effective migration
  - support of available and future advanced services VoIP
  - Enhanced multimedia broadcast multicast service (E-MBMS)
  - Enhanced support for end-to-end QoS

3GPP LTE/SAE

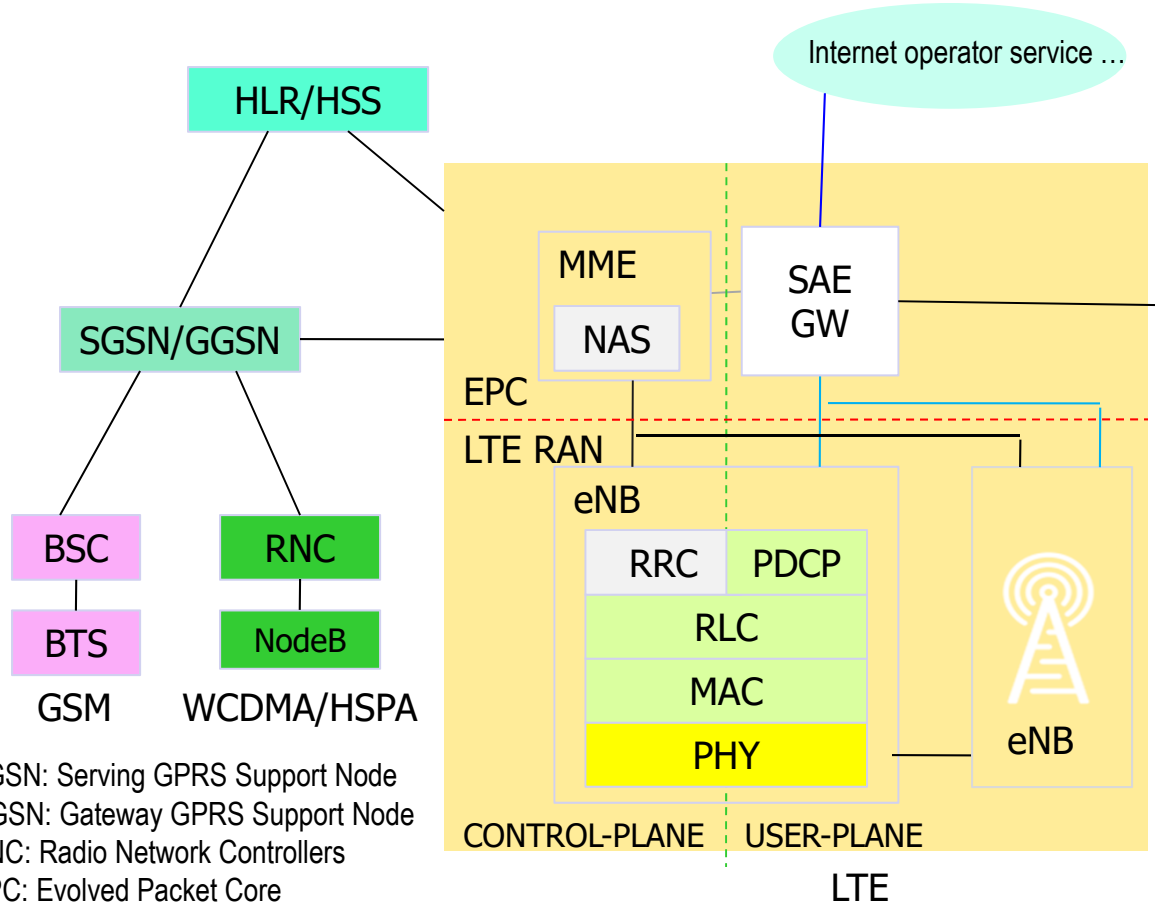
- **Long Term Evolution (LTE)**: work of RAN WG started in 2004 to create a new evolved RAN (E-UTRAN), and technology as an emerging broadband wireless access solution
- **System Architecture Evolution (SAE)**: work of SA2 WG in parallel to LTE
  - to develop a framework for an evolution or migration of the 3GPP system to higher data rate, lower latency, packet-optimized system, support multiple RATs
  - Focus on creating an evolved packet core (EPC) including interfaces to selected external network entities

LTE/SAE Architecture Features

- New core network architecture to support the high-throughput/low latency LTE access system
- Simplified network architecture
- All IP (packet-switched) network
- Support mobility between multiple heterogeneous access system
  - 2G/3G, LTE, non 3GPP access systems, e.g., WLAN, WiMAX
  - Inter-3GPP handover (e.g., between GPRS and E-UTRAN):
  - Inter 3GPP/non-3GPP mobility



LTE/SAE – Architecture Overview



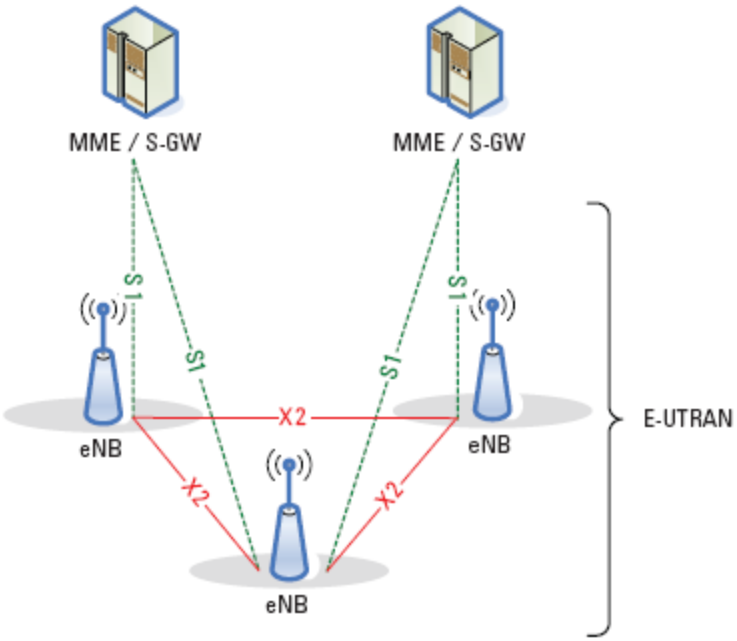
Access Gateway (aGW) has combined most of the SGSN and GGSN functionality

SGSN: Serving GPRS Support Node
GGSN: Gateway GPRS Support Node
RNC: Radio Network Controllers
EPC: Evolved Packet Core
MME: Mobility Management Entity
RRC: Radio Resource Control
PDCP: Packet Data Convergence Protocol
NAS: Non-Access Stratum

SAE: System Architecture Evolution
RRC: radio resource control
RLC: radio link control

Enhanced Node B (eNB) contains most of Node B and RNC functionality: All Radio-related issues & Decentralized mobility management, i.e., also includes, distributed RRM functions e.g., Radio Bearer Control (RBC), Radio Admission Control (RAC), Connection Mobility Control (CMC), Dynamic Resource Allocation or scheduling (DRA), Radio Configuration (RC)

LTE architecture with E-UTRAN

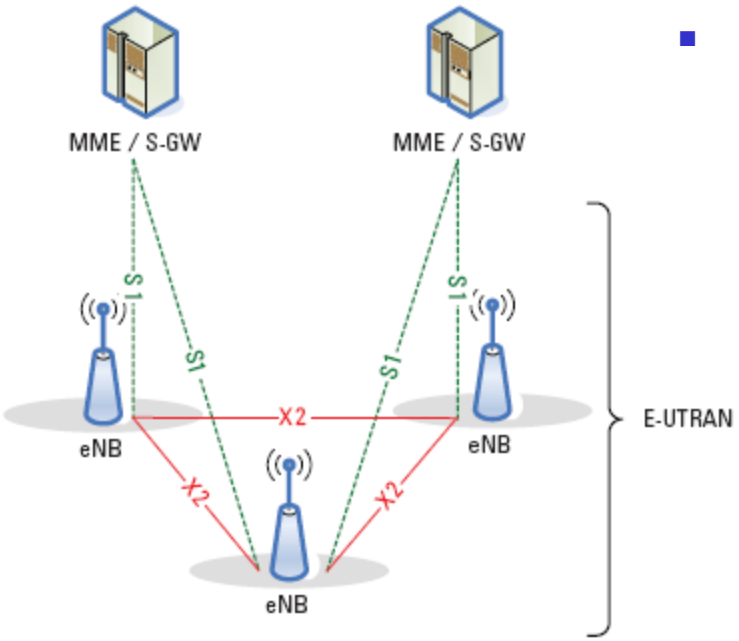


- X2 enables direct communication between the elements and eliminates the need to funnel data back and forth through a radio network controller (RNC).

(36.300 Figure 4)

- The **evolved Node B (eNB)** hosts these functions:
  - Radio resource management
  - IP header compression and encryption
  - Selection of MME at UE attachment
  - Routing of user plane data towards S-GW
  - Scheduling and transmission of paging messages and broadcast information
  - Measurement and measurement reporting configuration for mobility and scheduling
  - Scheduling and transmission of ETWS messages

Functions of MME and S-GW

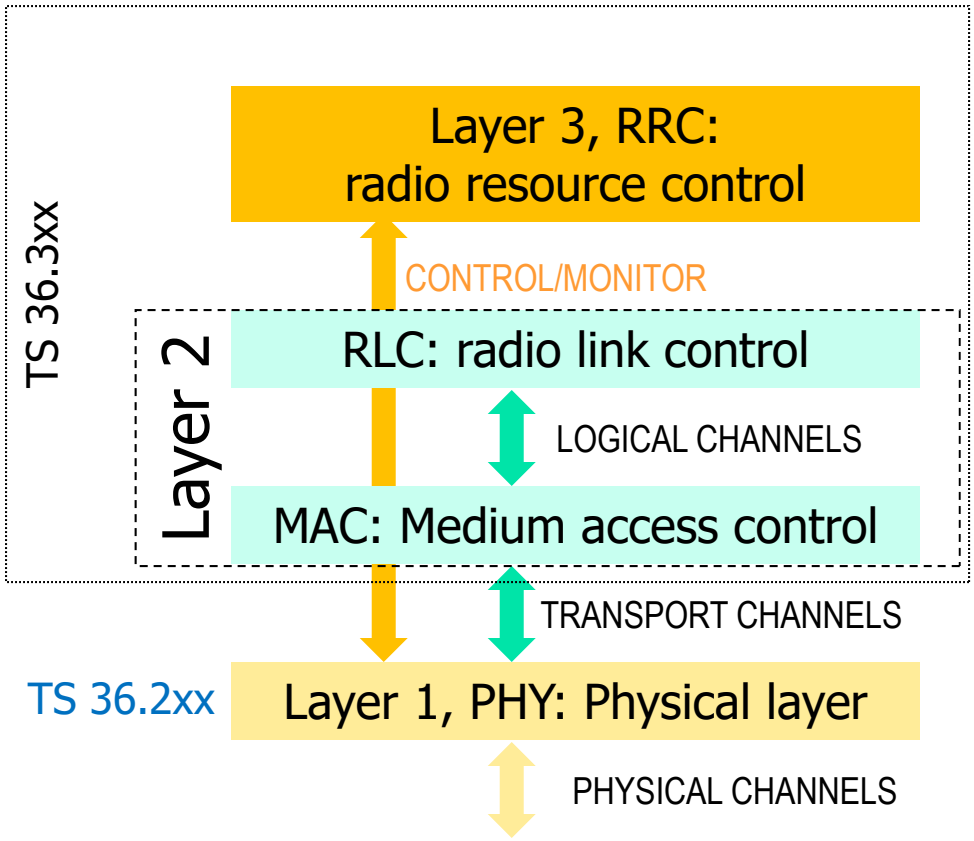


- The **Serving Gateway (S-GW)** provides these functions:
  - Mobility anchor point for inter eNB handovers
  - Termination of user-plane packets for paging reasons
  - Switching of user plane for UE mobility

  The packet data network (PDN) gateway (P-GW) functions include:
  - UE IP address allocation
  - Per-user-based packet filtering
  - Lawful interception

- The **Mobility Management Entity** (**MME**) hosts many functions including:
  - Non-access stratum (NAS) signaling and NAS signaling security
  - Access stratum (AS) security control
  - Idle state mobility handling
  - EPS bearer control

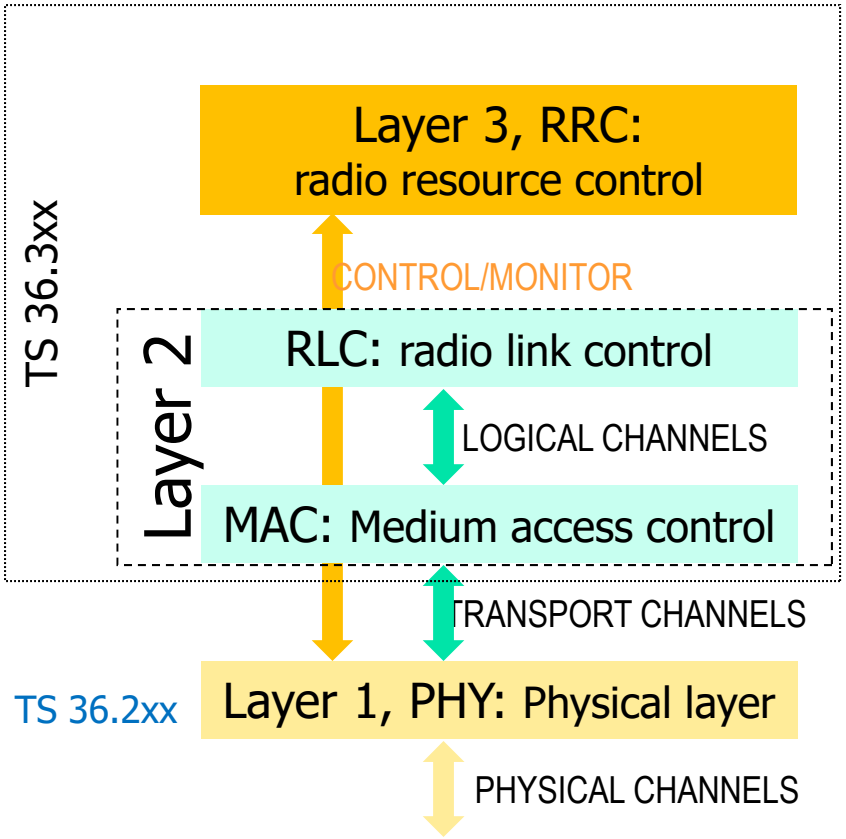
LTE Standard Specifications



- TS 36.5xx Conformance testing.
- TS 36.4xx: Infrastructure communications (UTRAN = UTRA Network) including base stations and mobile management entities.
- TS36.201 (general), 211 (channels & modulation), 212 (mux & channel coding), 213 (procedures), 214 (measurements)
- TS 36.1xx Equipment requirements: Terminals, base stations, and repeaters.

http://www.3gpp.org/ftp/Specs/html-info/36-series.htm

LTE protocol structure



LTE Standard Specifications:
http://www.3gpp.org/ftp/Specs/html-info/36-series.htm

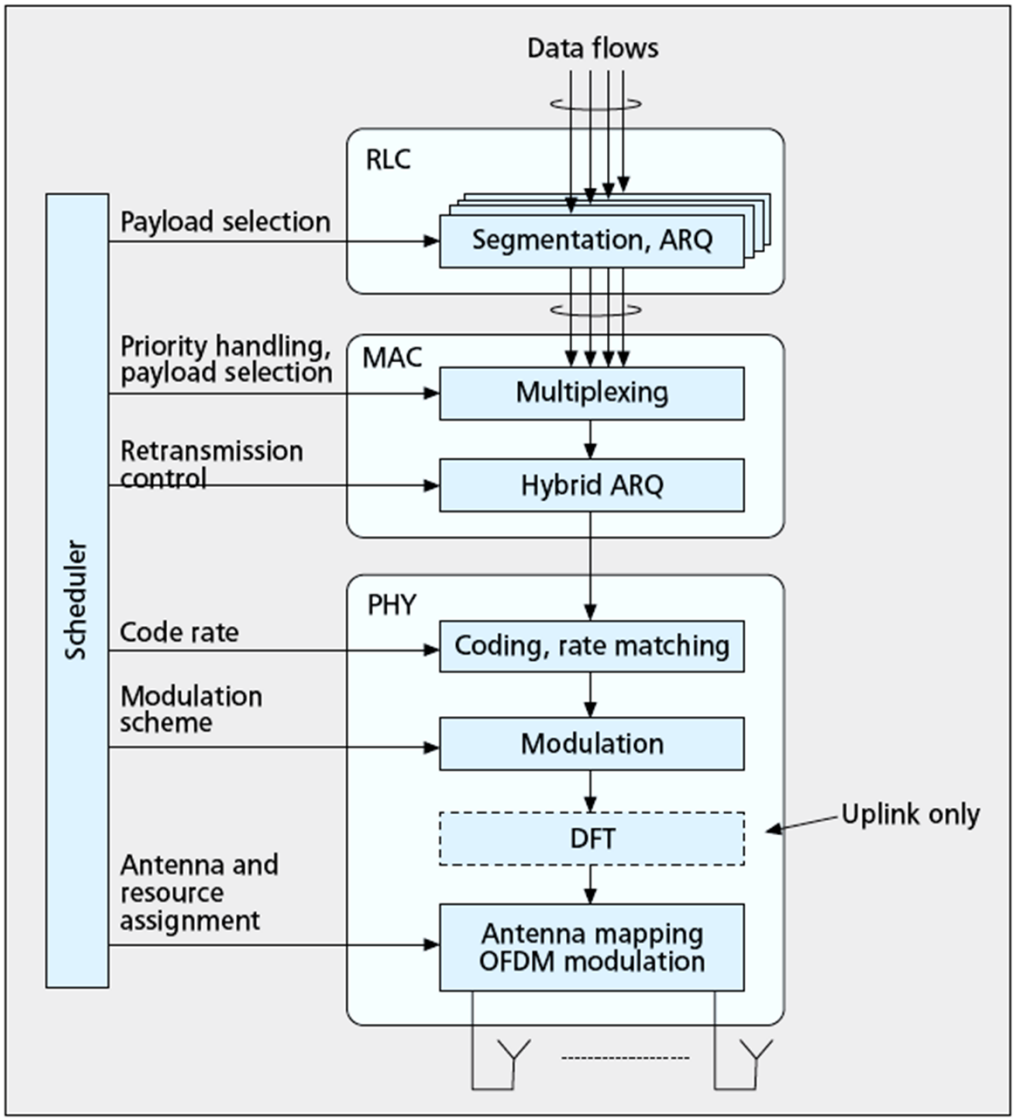


Figure 1. *LTE protocol structure (simplified).*
Astely, D.; Dahlman, E.; Furuskar, A.; Jading, Y.; Lindstrom, M.; Parkvall, S., "LTE: the evolution of mobile broadband", *IEEE Communications Magazine*, vol. 47, no. 4, April 2009, pp. 44–51.

LTE PHY: Key Features

- Spectrum flexibility:
  - consideration of a wide range of different frequency bands: Current and future 3G bands (e.g., 2 GHz, 2.6 GHz), Migration of 2G bands (e.g., 900 MHz), Re-farming of other bands (e.g., UHF bands)
  - Flexible bandwidth: 1.25 MHz to >20 MHz in steps of 200 kHz
  - Duplex flexibility: FDD and TDD
- Multiple access scheme:
  - Downlink: OFDM & OFDMA
  - Uplink: SC-FDMA for low PAPR
  - Multi-dimensional channel-dependent resource scheduling
- Adaptive modulation and coding
  - DL/UL modulations: QPSK, 16QAM, and 64QAM
  - Convolutional code and Rel-6 turbo code
- MIMO (Multi-Input Multi-Output) techniques
  - Downlink:4x2, 2x2, 1x2, 1x1 and uplink: 1x1, 1x2
  - Diversity for robust, high-performance links
  - Beam-forming for better coverage
  - Multi-layer (spatial multiplexing) transmission for high rate
  - Multi-user MIMO also supported.

WCDMA, HSPA, LTE

	WCDMA	HSPA	eHSPA	LTE
DL(Mb/s) DL with MIMO	2	14	42 (84 provisional)	100+ 172.8 (2x2) 326.4 (4x4)
UL(Mb/s)	0.384	5.7	11.52 (22 provisional)	50+ 57.6 (1x2)
BW(MHz)	5	5	5	1.25-20
DL Modulation MIMO option	QPSK	4/16QAM	4/16/64QAM up to 2x2	4/16/64QAM up to 4x4
UL modulation	π /2 BPSK	π /2 BPSK, QPSK	π/2BPSK,4/16QAM	4/16/64QAM MIMO
Access	CDMA	CDMA	CDMA	OFDMA DL SC-FDMA UL
3GPP release	99/4	5/6(HSUPA)	7(first work on LTE/SAE)/8	8 (LTE/SAE specs)

high speed downlink packet access (HDSPA), HSPA evolution: HSPA+ or eHSPA,

HSxPA & LTE

Parameter:	HSxPA:	LTE:
TTI Size	2 msec	1.0 msec
Modulation	QPSK, 16-QAM DL, QPSK, 2-QPSK UL	QPSK, 16-QAM, 64-QAM DL, QPSK, 16-QAM UL
HARQ + N-channel Stop-and-Wait	N=6 DL, N=8 UL Async DL, Sync UL IR is default	Synchronous UL / Asynchronous DL IR is default
Coding	Conv & Turbo Code	Advanced coding with lower base rate

Parameter:	HSxPA:	LTE:
Peak data rate	14 Mbps DL / 5.76 Mbps UL	100 Mbps DL / 50 Mbps UL
Spectral Efficiency	0.6 – 0.8 DL / 0.35 UL (bps/Hz/sector)	3-4x DL / 2-3x UL improvement
5% packet call throughput	64 Kbps DL / 5 Kbps UL	3-4x DL / 2-3x UL improvement
Averaged user throughput	900 Kbps DL / 150 Kbps UL	3-4x DL / 2-3x UL improvement
U-Plane Latency	50 ms	5 ms
Call setup time	2 sec	50 ms
Broadcast data rate	384 Kbps	6-8x improvement
Mobility	Up to 250 km/h	Up to 350 km/h
Multi-antenna support	No	Yes
Bandwidth	5 MHz	Scalable (up to 20 MHz)

EUTRA operating bands

E-UTRA operating band	Uplink (UL) operating band BS receive UE transmit	Downlink (DL) operating band BS transmit UE receive	Duplex mode
	$F_{UL\_low} - F_{UL\_high}$	$F_{DL\_low} - F_{DL\_high}$	
1	1920 – 1980 MHz	2110 – 2170 MHz	FDD
2	1850 – 1910 MHz	1930 – 1990 MHz	FDD
3	1710 – 1785 MHz	1805 – 1880 MHz	FDD
4	1710 – 1755 MHz	2110 – 2155 MHz	FDD
5	824 – 849 MHz	869 – 894 MHz	FDD
6	830 – 840 MHz	875 – 885 MHz	FDD
7	2500 – 2570 MHz	2620 – 2690 MHz	FDD
8	880 – 915 MHz	925 – 960 MHz	FDD
9	1749.9 – 1784.9 MHz	1844.9 – 1879.9 MHz	FDD
10	1710 – 1770 MHz	2110 – 2170 MHz	FDD
11	1427.9 – 1452.9 MHz	1475.9 – 1500.9 MHz	FDD
12	698 – 716 MHz	728 – 746 MHz	FDD
13	777 – 787 MHz	746 – 756 MHz	FDD
14	788 – 798 MHz	758 – 768 MHz	FDD
...			
17	704 – 716 MHz	734 – 746 MHz	FDD
...			
33	1900 – 1920 MHz	1900 – 1920 MHz	TDD
34	2010 – 2025 MHz	2010 – 2025 MHz	TDD
35	1850 – 1910 MHz	1850 – 1910 MHz	TDD
36	1930 – 1990 MHz	1930 – 1990 MHz	TDD
37	1910 – 1930 MHz	1910 – 1930 MHz	TDD
38	2570 – 2620 MHz	2570 – 2620 MHz	TDD
39	1880 – 1920 MHz	1880 – 1920 MHz	TDD
40	2300 – 2400 MHz	2300 – 2400 MHz	TDD

LTE – FDD and TDD

- FDD: Simultaneous downlink/uplink transmission in separate frequency bands
  - requiring paired spectrum with large Tx/Rx frequency separation
  - used in all commercial cellular systems
- TDD: Non-overlapping downlink/uplink transmission times in the same frequency band
- Suitable for deployment in unpaired spectrum
- Requires tight inter-cell synchronization/coordination
- Requires higher Tx power or implies reduced coverage

LTE UE Categories (LTE-Release 8):

Category		1	2	3	4	5
Peak rate Mbps	DL	10	50	100	150	300
	UL	5	25	50	50	75
Capability for physical functionalities						
RF bandwidth		20MHz				
Modulation	DL	QPSK, 16QAM, 64QAM				
	UL	QPSK, 16QAM				QPSK, 16QAM, 64QAM
Multi-antenna						
2 Rx diversity		Assumed in performance requirements.				
2x2 MIMO		Not supported	Mandatory			
4x4 MIMO		Not supported				Mandatory

DL spatial mux:	1	2	4

LTE-Advanced

Performance targets for LTE, LTE-Advanced, and IMT-Advanced

Parameters:		LTE (3.9G)	LTE-Advanced (4G)	IMT-Advanced (4G)
Peak spectral efficiency (b/s/Hz)	Downlink	16.3 (4x4 MIMO)	30 (up to 8x8 MIMO)	15 (4x4 MIMO)
	Uplink	4.32 (64 QAM SISO)	15 (up to 4x4 MIMO)	6.75 (2x4 MIMO)
Downlink cell spectral efficiency (b/s/Hz), 3 km/h, 500 m ISD	2x2 MIMO	1.69	2.4	
	4.2 MIMO	1.87	2.6	2.6
	4x4 MIMO	2.67	3.7	
Downlink cell-edge user spectral efficiency (b/s/Hz) 5 percentile, 10 users, 500 m ISD	2x2 MIMO	0.05	0.07	
	4x2 MIMO	0.06	0.09	0.075
	4x4 MIMO	0.08	0.12	

Requirements and LTE fulfillment

TYPE	IMT-ADVANCED REQUIREMENT	LTE REL-8	LTE REL-10
Transmission bandwidth	At least 40 MHz	up to 20 MHz	Up to 100 MHz
Peak spectral efficiency			
▸ Downlink	▸ 15 bps/Hz	▸ 16 bps/Hz	▸ 16.0 [30.0]* bps/Hz
▸ Uplink	▸ 6.75 bps/Hz	▸ 4 bps/Hz	▸ 8.1 [16.1]** bps/Hz
Latency			
▸ Control plane	▸ Less than 100 ms	▸ 50 ms	▸ 50 ms
▸ User plane	▸ Less than 10 ms	▸ 4.9 ms	▸ 4.9 ms

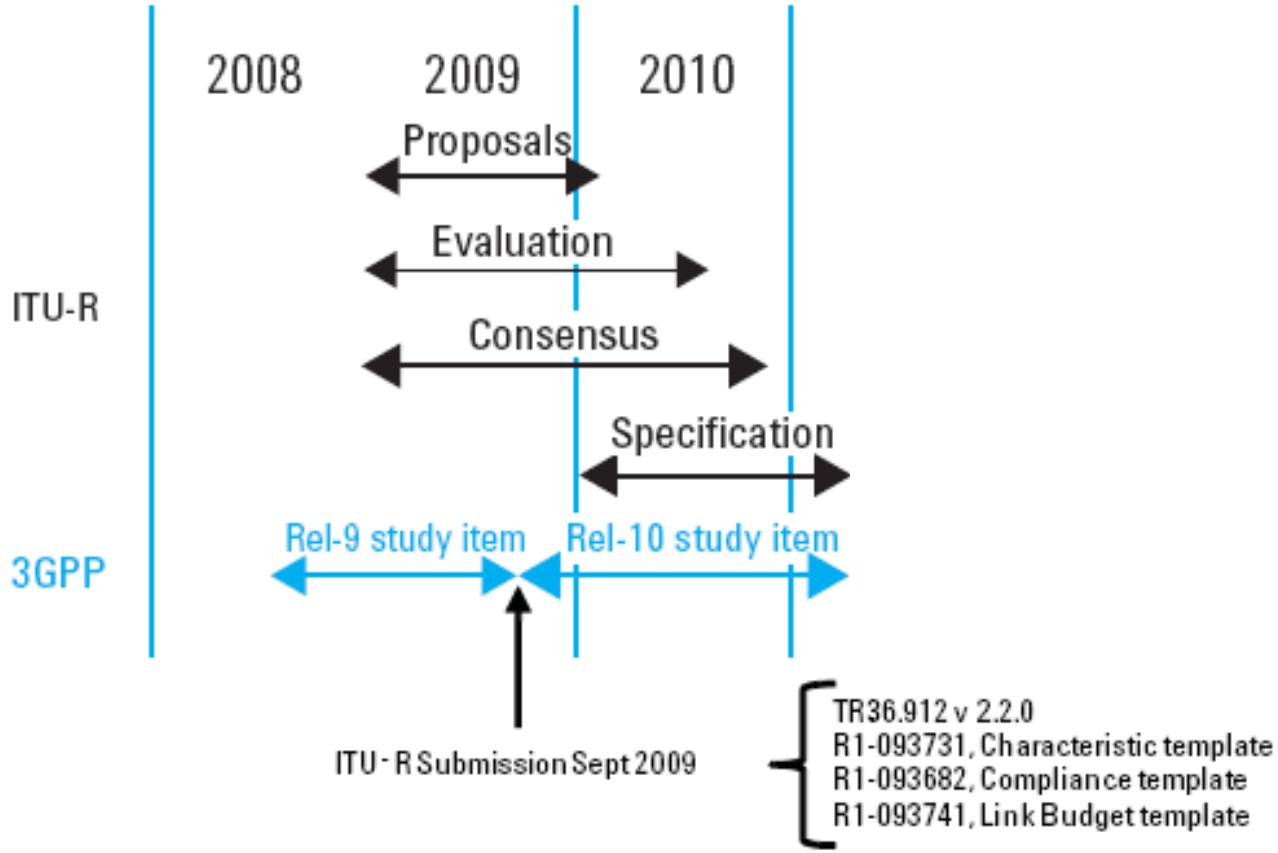
* Value is for a 4x4 antenna configuration. Value in parentheses for 8x8
** Value is for a 2x2 antenna configuration. Value in parentheses for 4x4

Item	IMT-Advanced Requirement	LTE-Advanced Projected Capability
Peak Data Rate Downlink		1 Gbps
Peak Data Rate Uplink		500 Mbps
Spectrum Allocation	Up to 40 MHz	Up to 100 MHz
Latency User Plane	10 msec	10 msec
Latency Control Plane	100 msec	50 msec
Peak Spectral Efficiency DL	15 bps/Hz	30 bps/Hz
Peak Spectral Efficiency UL	6.75 bps/Hz	15 bps/Hz
Average Spectral Efficiency DL	2.2 bps/Hz	2.6 bps/Hz
Average Spectral Efficiency UL	1.4 bps/Hz	2.0 bps/Hz
Cell-Edge Spectral Efficiency DL	0.06 bps/Hz	0.09 bps/Hz
Cell-Edge Spectral Efficiency UL	0.03 bps/Hz	0.07 bps/Hz

LTE-Advanced

- High peak data rates:
  - 1 Gbps downlink (DL),
  - 500 Mbps in the uplink (UL)
- Higher spectrum efficiency enabled by enhanced uplink multiple access and enhanced MIMO techniques:
  - Peak: 30 bps/Hz DL (8x8), 15 bps/Hz UL (4x4)
  - cell-edge (2 times that of LTE): 0.12 bps/Hz DL (4x4) and 0.07 bps/Hz UL (2x4)
  - Average (3 times that of LTE): 3.7 bps/Hz/cell DL (4x4) and 2.0 bps/Hz/cell UL (2x4)
- Wider bandwidth up to 100 MHz, enabled by carrier aggregation, high spectrum flexibility, additional bands: • 450–470 MHz band • 698–862 MHz band • 790–862 MHz band • 2.3–2.4 GHz band • 3.4–4.2 GHz band • 4.4–4.99 GHz band
- Backward compatibility to LTE

Timelines for IMT-Advanced (4G) and LTE-Advanced development



IMT: International Mobile Telecommunications

Key Rel-10/Rel-11 LTE-Advanced Technologies and HSPA+ Enhancements:

LTE-Advanced

- Carrier aggregation (CA)
- Enhanced uplink multiple access
- Enhanced multiple antenna transmission (MIMO Enhancements)
- Coordinated multipoint transmission and reception (CoMP)
- LTE self-optimizing networks (SON), WiFi Interworking
- HNB, Home enhanced-node-B (HeNB) mobility enhancements
- HetNet Enhancements (eICIC, feICIC)
- Relays

HSPA+ Enhancements

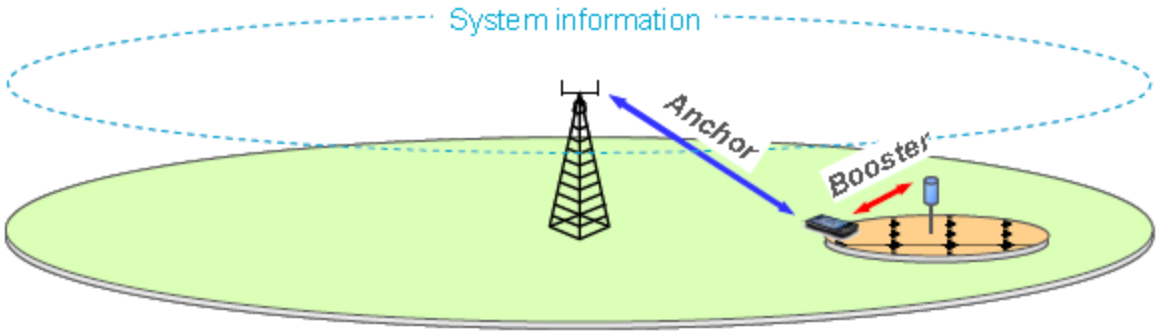
- Four and eight carrier HSPA
- Downlink Multi-flow Transmission
- Downlink 4-branch MIMO
- UL MIMO and 64QAM

Release 12 highlights

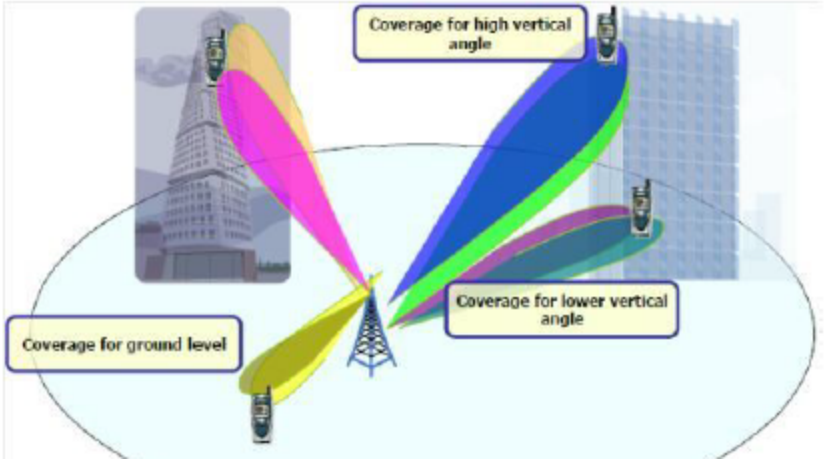
- Spectrum: addition of three new FDD bands, 30, 31 and 32.
  - 30 Uplink: 2305-2315 MHz Downlink: 2350-2360 MHz
  - 31 Uplink: 452.5-457.5 MHz Downlink: 462.5-467.5 MHz
  - 32 Downlink: 1452-1496MHz 2nd supplemental downlink (SDL) used for downlink-only carrier aggregation to improve data rates
- LTE TDD-FDD joint operation
- Study on Coordinated Multipoint Transmission and Reception (CoMP) for LTE with Non-Ideal Backhaul
- Core part: Inter-eNB CoMP for LTE
- Study and Core part: Network-Assisted Interference Cancellation and Suppression (NAICS) for LTE
- Studies on 3D-channel model for Elevation BF and FD-MIMO, Active Antenna Array Systems (AAS), MIMO OTA
- E-UTRA Small cell enhancements - Physical layer aspects
- WLAN/3GPP interworking
- Dual connectivity
- Group communications
- LTE Device to Device Proximity Services
- Machine Type Communications

Rel-12: some areas of focus

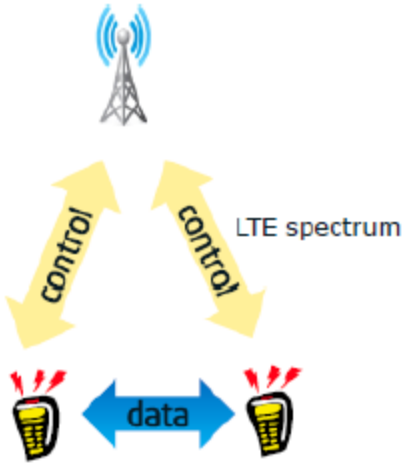
LTE Small Cell/HetNet Enhancements



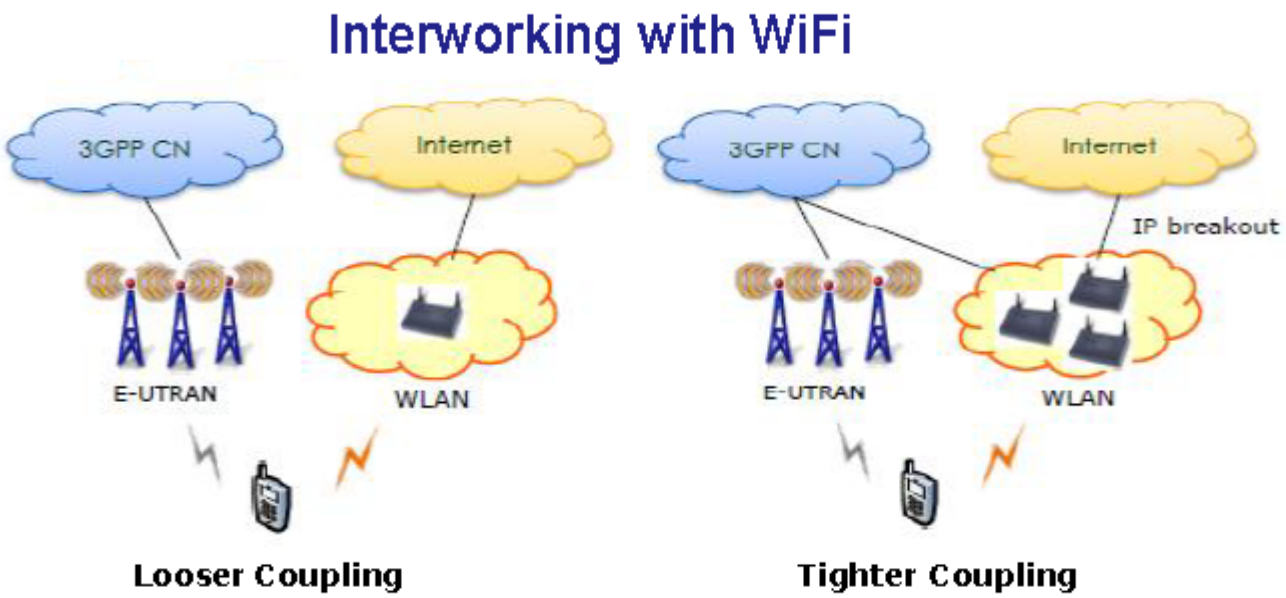
LTE Multi-Antenna Enhancements



Device-to-Device

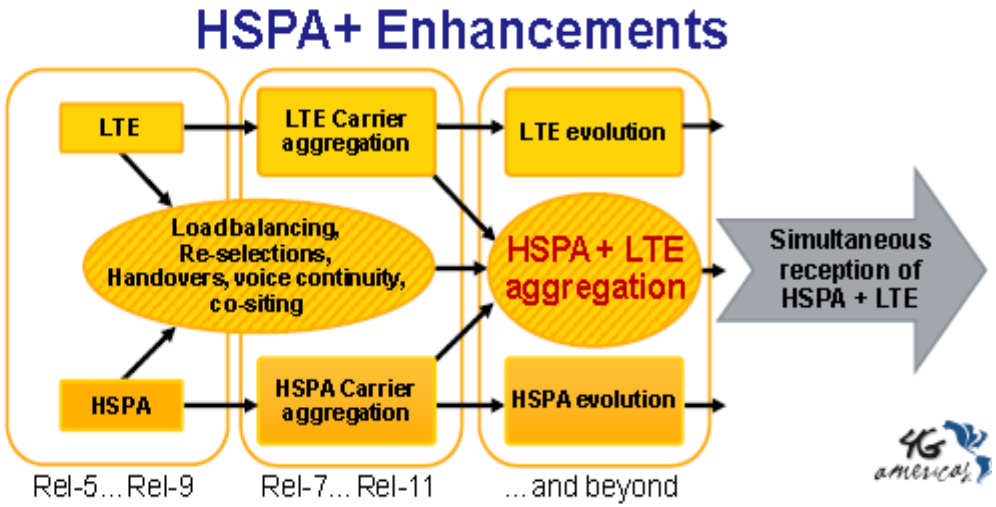


Rel-12: interworking with WiFi



Further enhancements to

- MTC
- LTE procedures to support diverse traffic types
- SON
- Advanced Receivers



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Rel-13 for LTE-A and HSPA+ enhancements

- To be completed in Mar16
- arrives just as the mobile industry begins discussion and development of 5G (IMT-2020) to face unprecedented challenges: accommodating skyrocketing traffic growth amid a spectrum shortage, escalation of the Internet of Things (IoT) and a vision for network transformation that will create an all-IP environment with more than 7.2 billion mobile connections worldwide.
- provides greater efficiency for networks and devices, newer services.
- Indoor Positioning System (IPS) enhancements
- For HSPA+, enhancements for reducing control channel overhead and support for dual band Uplink (UL) Carrier Aggregation.
- For LTE-Advanced,
  - Dual Connectivity (DC) enhancements to better support multi-vendor deployments with improved traffic steering.
  - Improvements in Radio Access Network (RAN) sharing
  - enhancements to support Mission Critical Push-to-Talk (MCPTT) over LTE for public safety.

Rel-13 for LTE-Advanced enhancements

- optimizing performance for Machine Type Communication (MTC) services by defining a Dedicated Core (DECOR) and Monitoring Enhancement (MONTE), enhancements to Proximity Services (ProSe) and group communications
- Wi-Fi integration enhancements to support Network-Based IP Flow Mobility (NBIFOM) to harmonize the support of voice and video services over Wi-Fi
- Licensed Assisted Access for LTE (LAA-LTE) initiated in June 2014: LTE can be deployed in unlicensed spectrum, LTE Wireless Local Area Network (WLAN) Aggregation (LWA) where Wi-Fi can now be supported by a radio bearer and aggregated with an LTE radio bearer,
- Downlink (DL) Multi-User Superposition Transmission (MUST): transmitting more than one data layer to multiple users without time, frequency or spatial separation.
- Active Antenna Systems (AAS): BF, MIMO, and SON aspects,
- enhanced signaling to support inter-site CoMP,
- CA enhancements to support up to 32 component carriers

5G Key Enabling Technologies