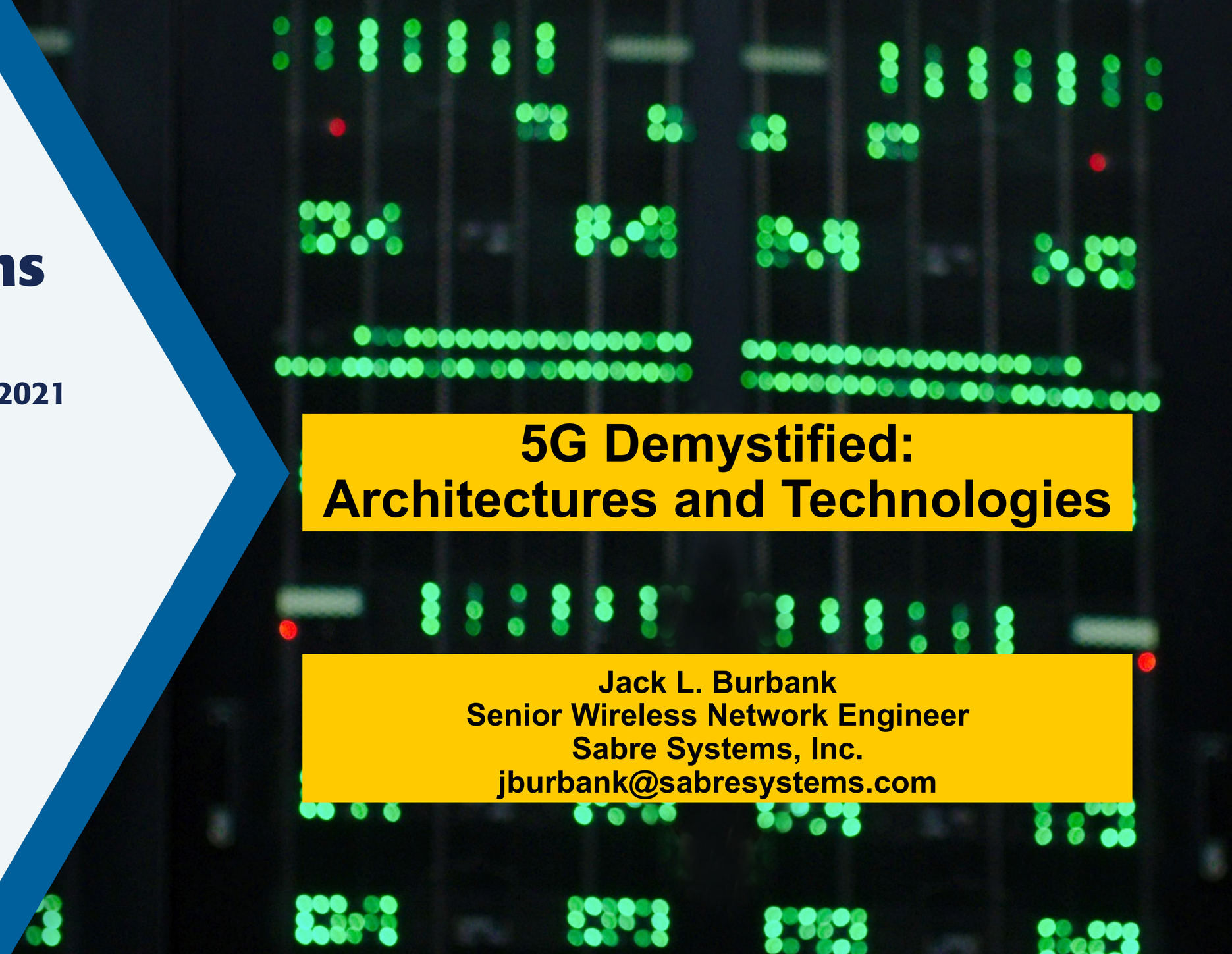
MILCOM

Military Communications Conference

29 November–2 December 2021
San Diego, CA, USA

IEEE ComSoc
IEEE Communications Society

AFCEA

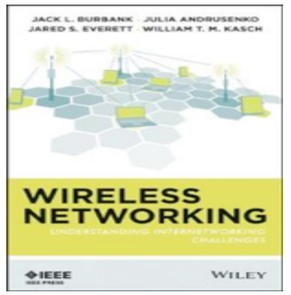


5G Demystified: Architectures and Technologies

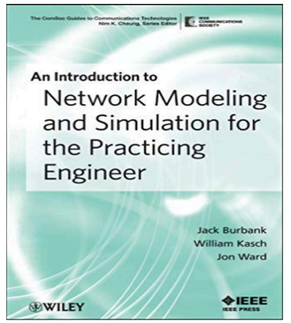
Jack L. Burbank
Senior Wireless Network Engineer
Sabre Systems, Inc.
jburbank@sabresystems.com

Who I am – Jack Burbank

- MS-EE from North Carolina State University
- Senior Wireless Network Engineer at Sabre Systems
  - Supports US Army CCDC C5ISR Center, Engineering & Systems Integration Directorate, Tactical Communications Division
- Taught courses on Wireless Networking and Principles of Network Engineering in the Johns Hopkins Engineering for Professionals Program for 13 years
- 25 years of experience in wireless systems research and development
- Published over 50 articles in technical journals and two books related to wireless technology



- Editor of Wiley / IEEE Press Standards Series on IEEE Standards
  - Interested in writing a book? Come see me!



- Senior Member IEEE

Tutorial Logistics

- Schedule
  - Tutorial time is 1 hour and 40 minutes
    - 10:20 – 12:00

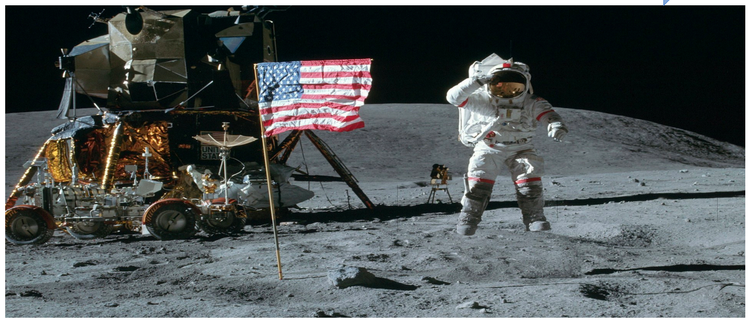
- Continuing Education Credit

Goals of this Tutorial

- To provide an overview of the 5G landscape
- To describe the major technologies that comprise the 5G architecture
- To provide familiarity with the 5G network architecture
- To understand some of the key technologies powering 5G networks
- What this tutorial is not going to do
  - Attempt to cover every single bit and byte of protocols and formats
  - Focus more on concepts
  - Bits and bytes can be found in specifications
  - Fundamental concepts and ideas are more important
  - Besides, it would not be practical to attempt in a 1.5-hour session

Before we Continue…

60 Years



3G

4G LTE

5G

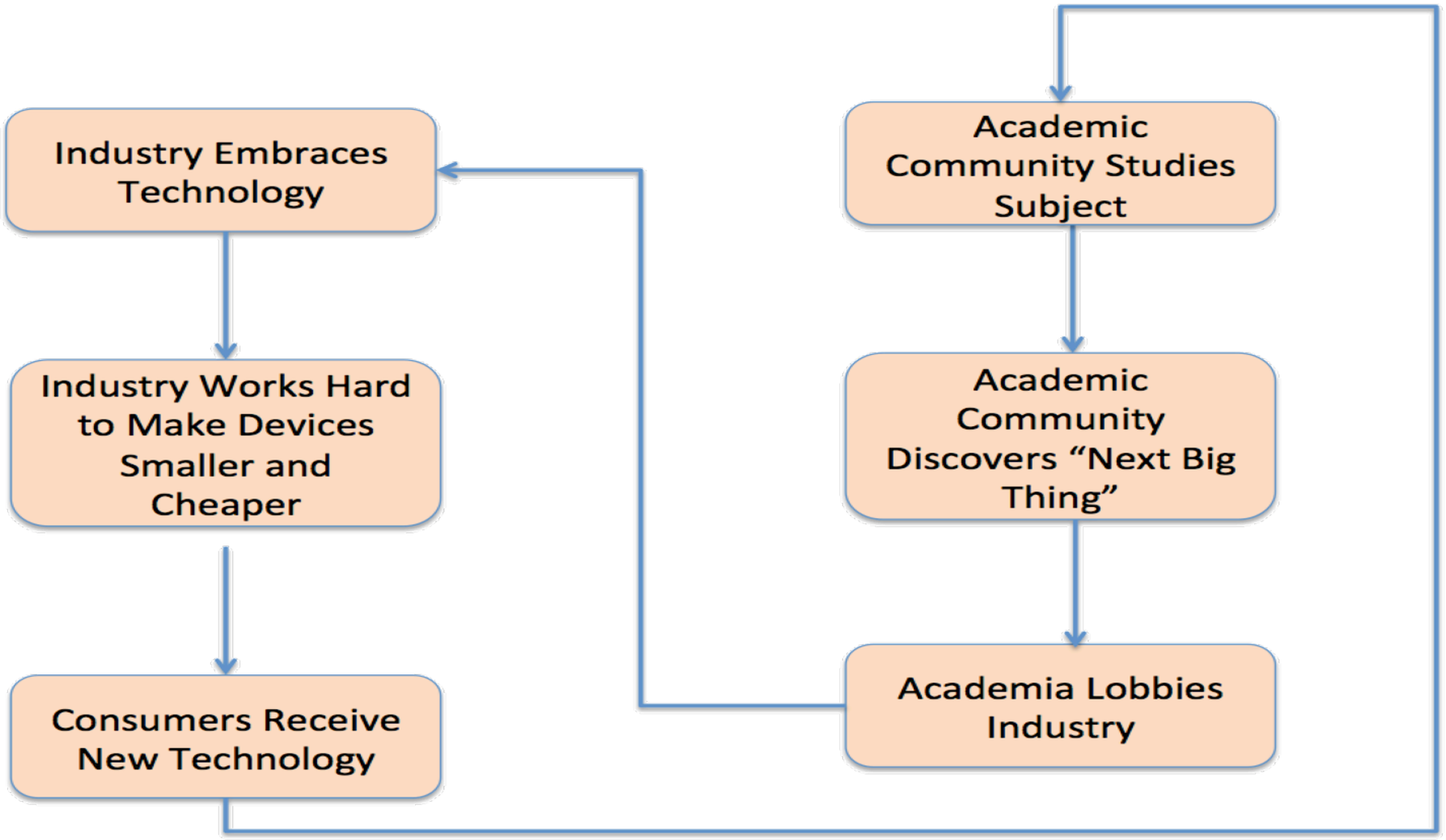
20 Years

Tutorial Overview

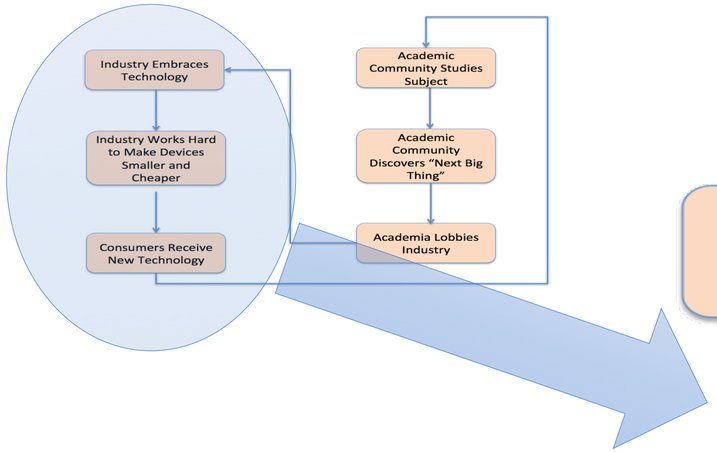
- The Current 5G Landscape
- Spectrum
- 5G Network Architecture
- 5G Cellular Technology Overview
- Next-Generation WLANS
- Tools and Resources
- Conclusions

The Overwhelming 5G Landscape

The Technology Path: Idea to Reality



The Technology Path: Idea to Reality



Establishment of Technical Vision

Industry Players Develops IP Positions

Industry Players Develop Spectrum Positions

Technology Standards Development

Proprietary Solutions

Vendors Implement / Improve Hardware and Software

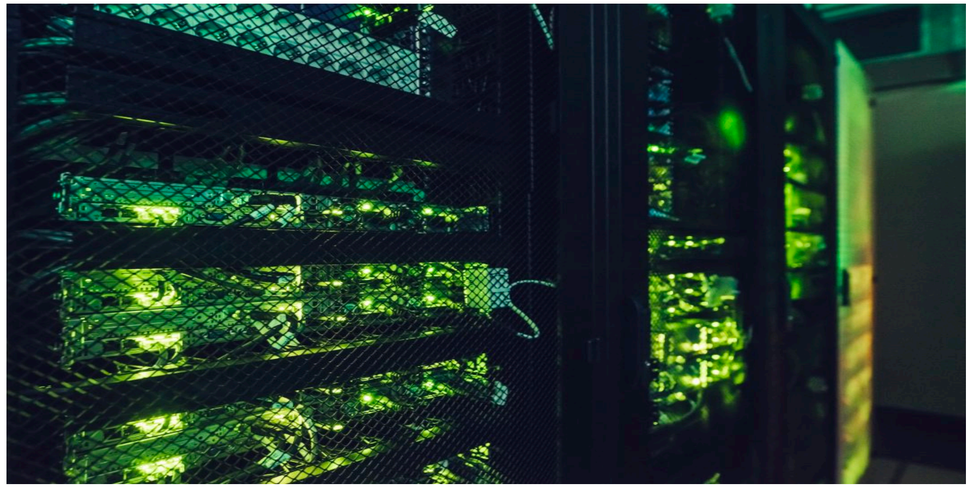
Service Providers Deploy Technology

Consumer Approval or Disapproval

5G Infrastructure

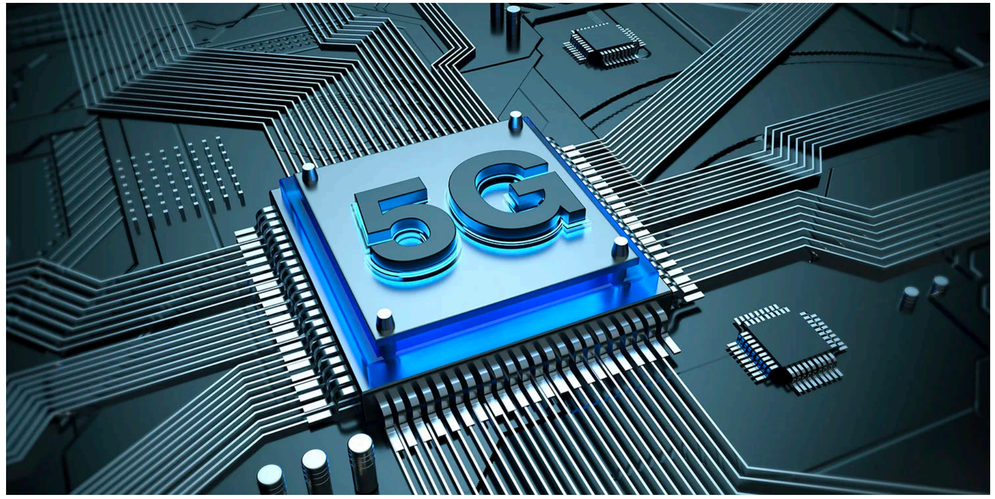
- Infrastructure eco-system robust and mature

- Several product offerings current and emerging across RAN and Core by all major infrastructure vendors
- Many, many companies, but some of biggest players are:
  - Ericsson
  - Nokia
  - Huawei
  - ZTE
  - Samsung
  - NEC
  - Cisco



5G Chipsets and Handsets

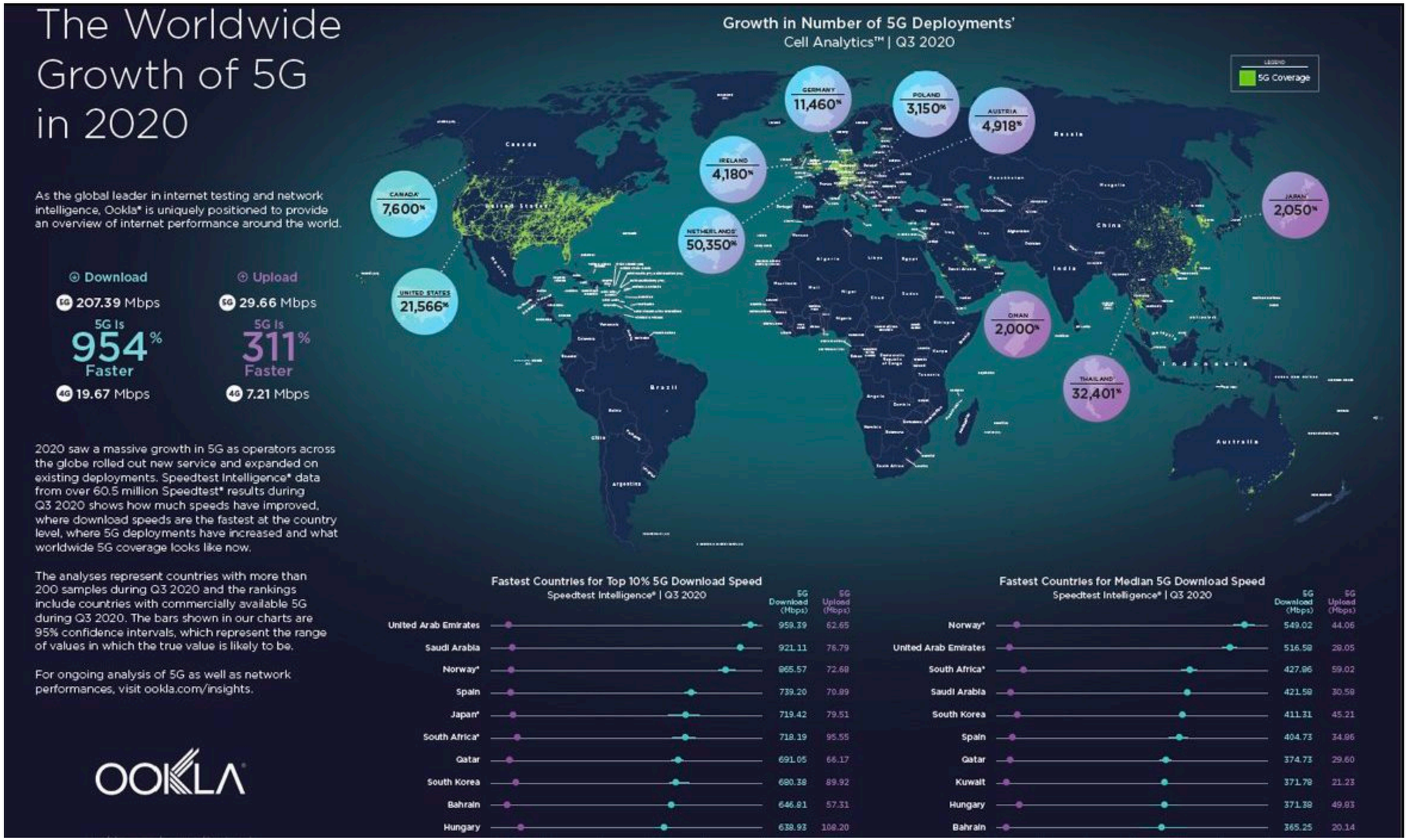
- Consumer device eco-system has matured substantially over past 2-3 years
- A number of existing and emerging 5G chipset vendors
  - Qualcomm
  - Samsung
  - Huawei
  - MediaTek
  - Many others…
- Increasing number of 5G handsets (over 50% of handsets sold in 2023 estimated to be 5G)
  - Samsung
  - Apple
  - LG
  - Motorola
  - Huawei
  - ZTE
  - Many others…



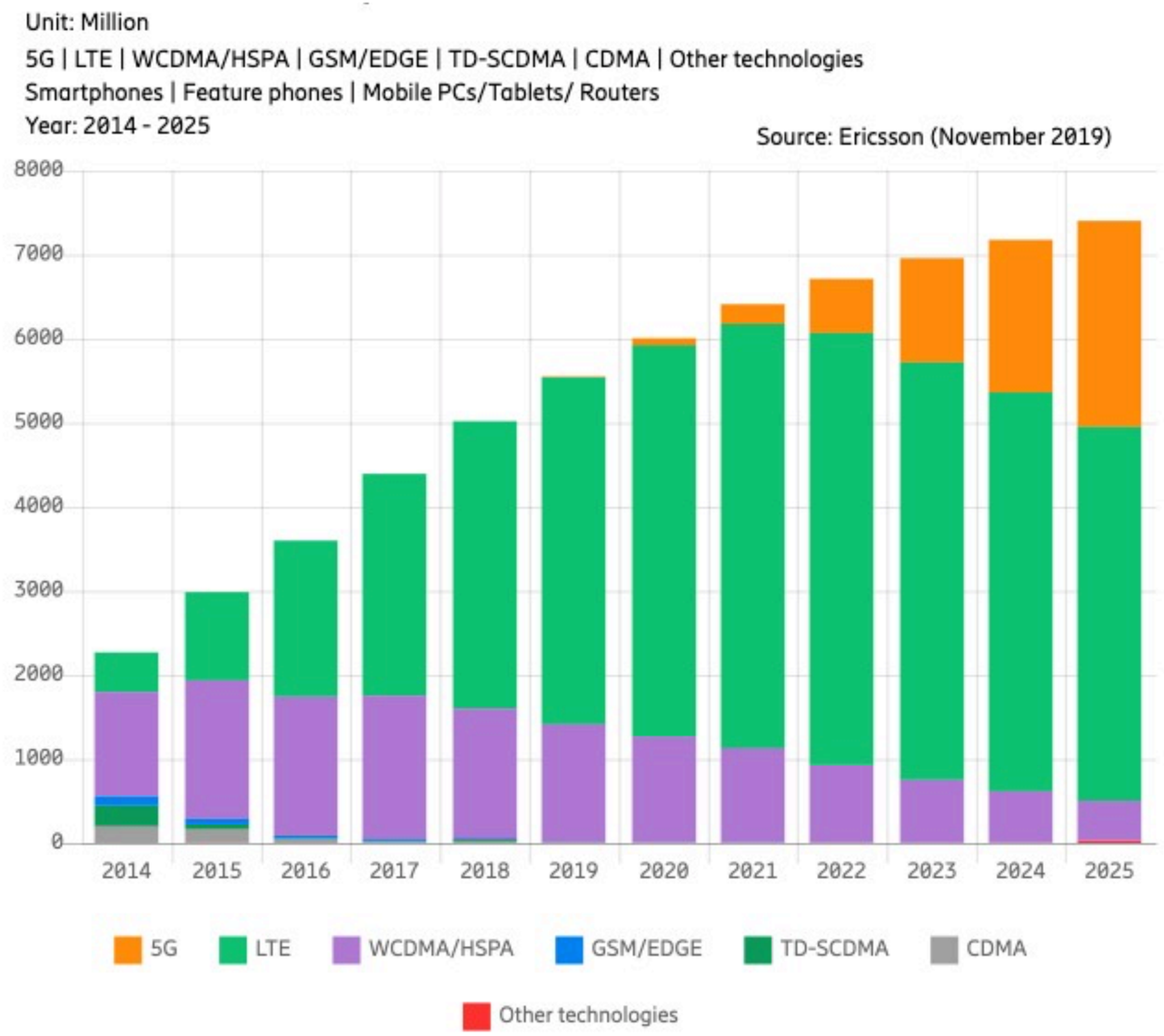
Current and Near-Term 5G Deployments

- Interactive 5G deployment map maintained by Ookla
  - https://www.speedtest.net/ookla-5g-map

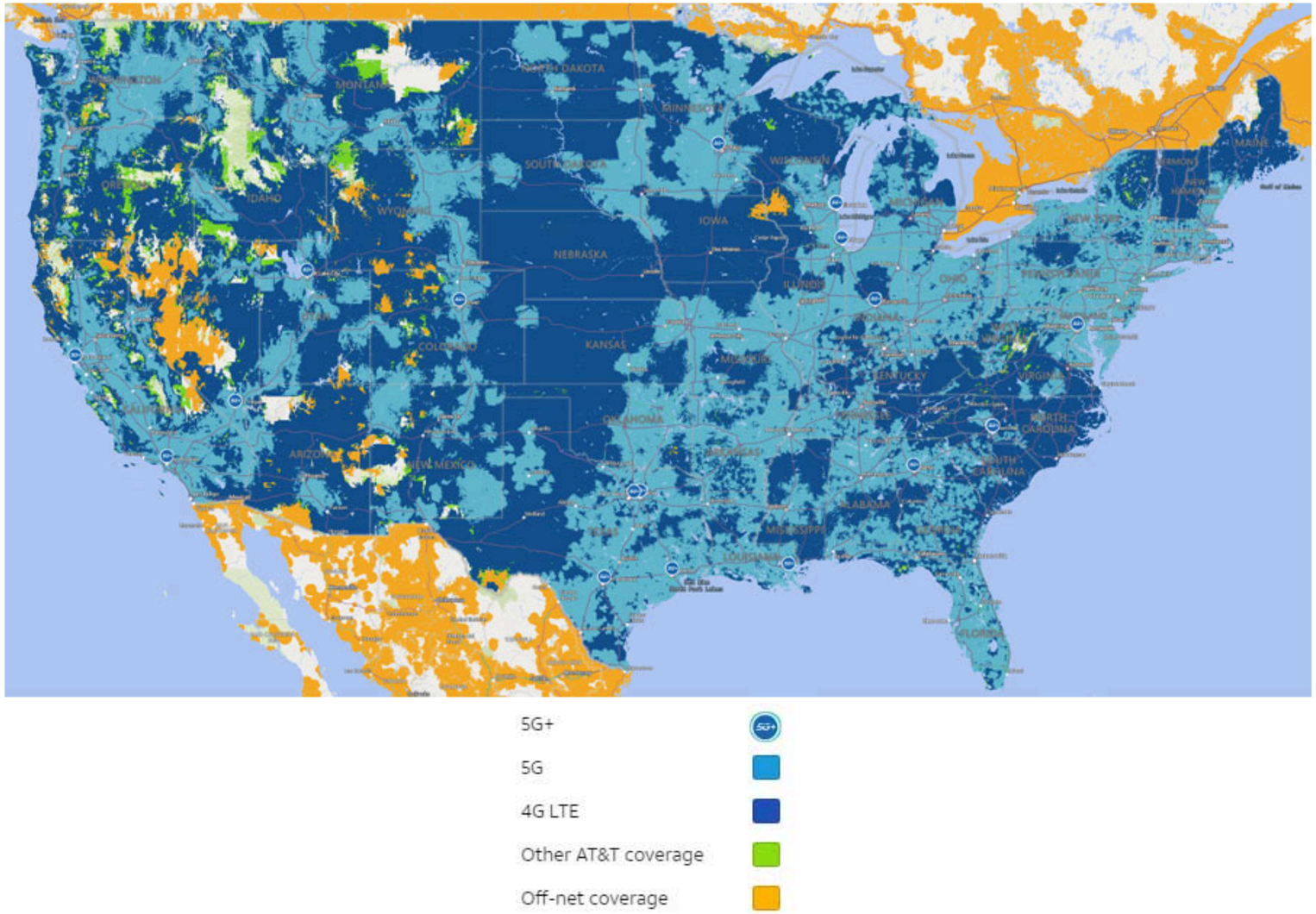
The Recent Explosion of 5G Deployments



The Expected Explosion of 5G Subscribers

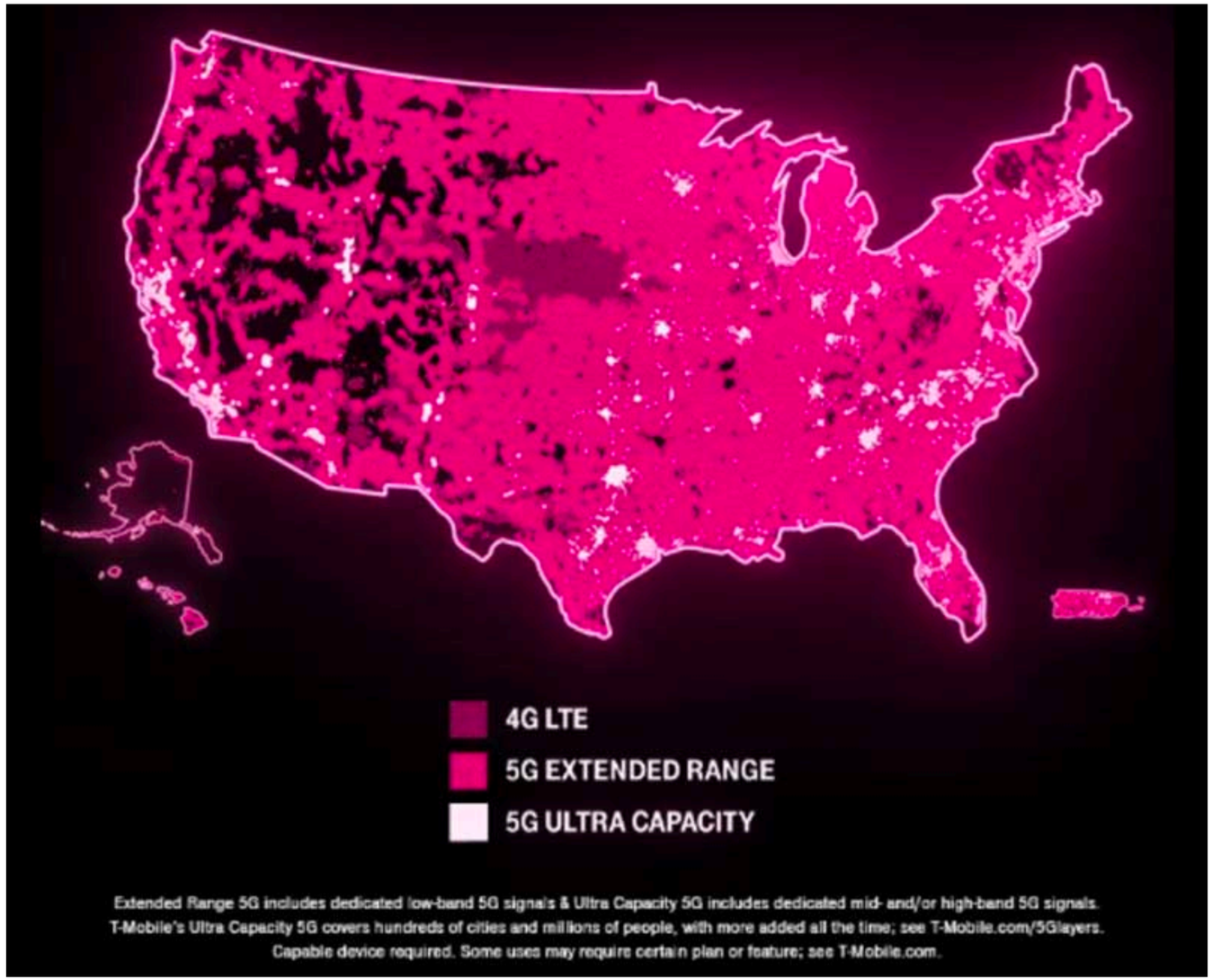


5G in the US – AT&T



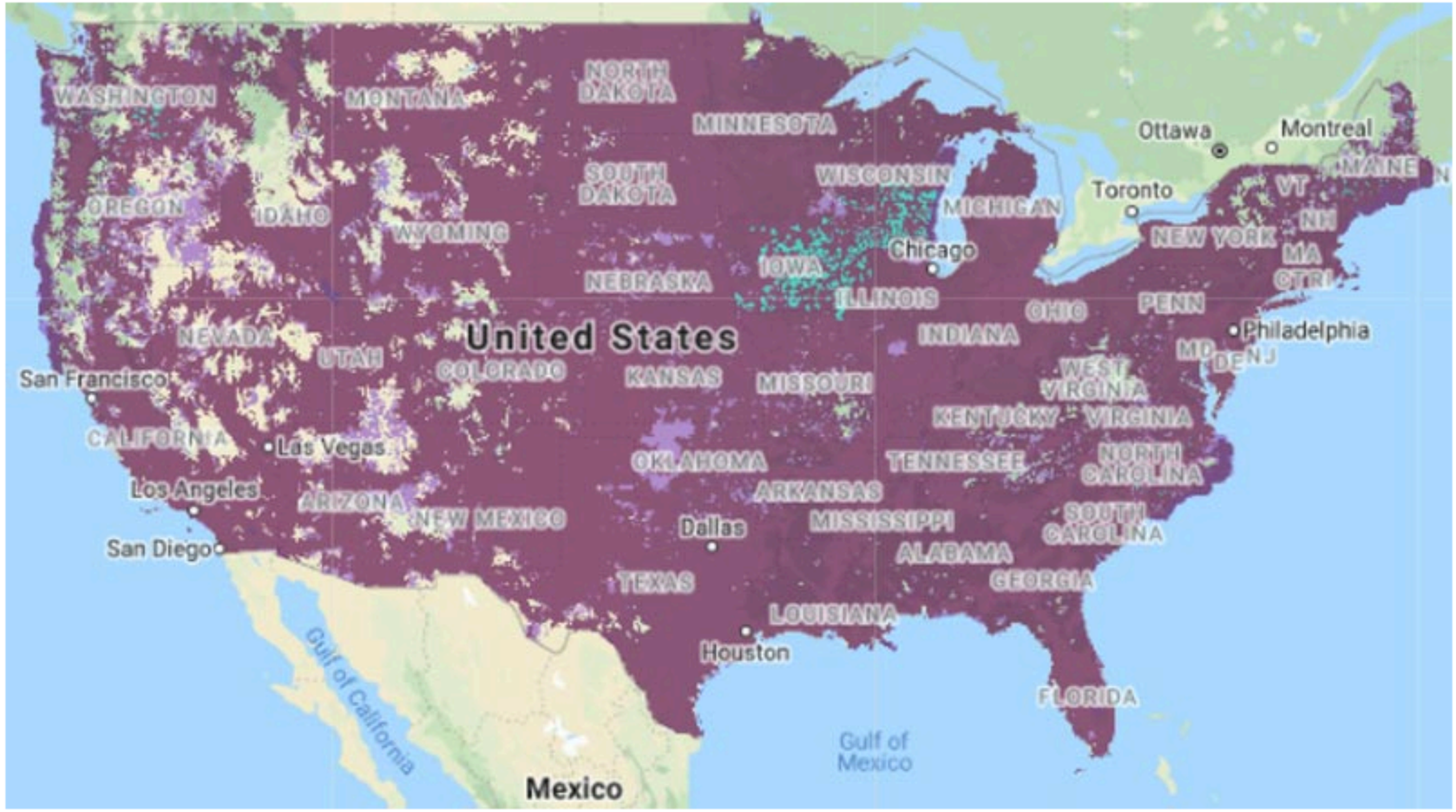
https://www.cellularmaps.com/

5G in the US – T-Mobile



https://www.cellularmaps.com/

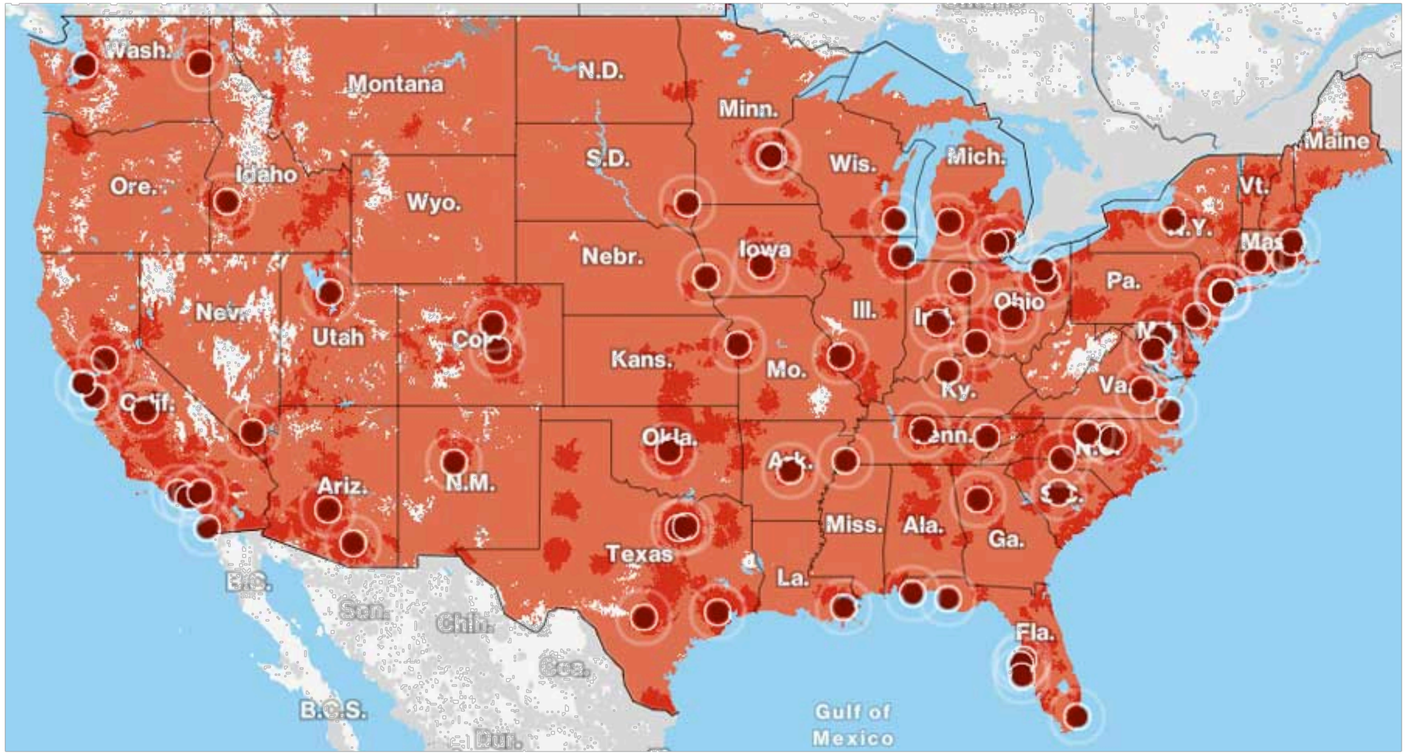
5G in the US – US Cellular



5G Coverage 4G LTE Data Coverage

https://www.cellularmaps.com/

5G in the US – Verizon

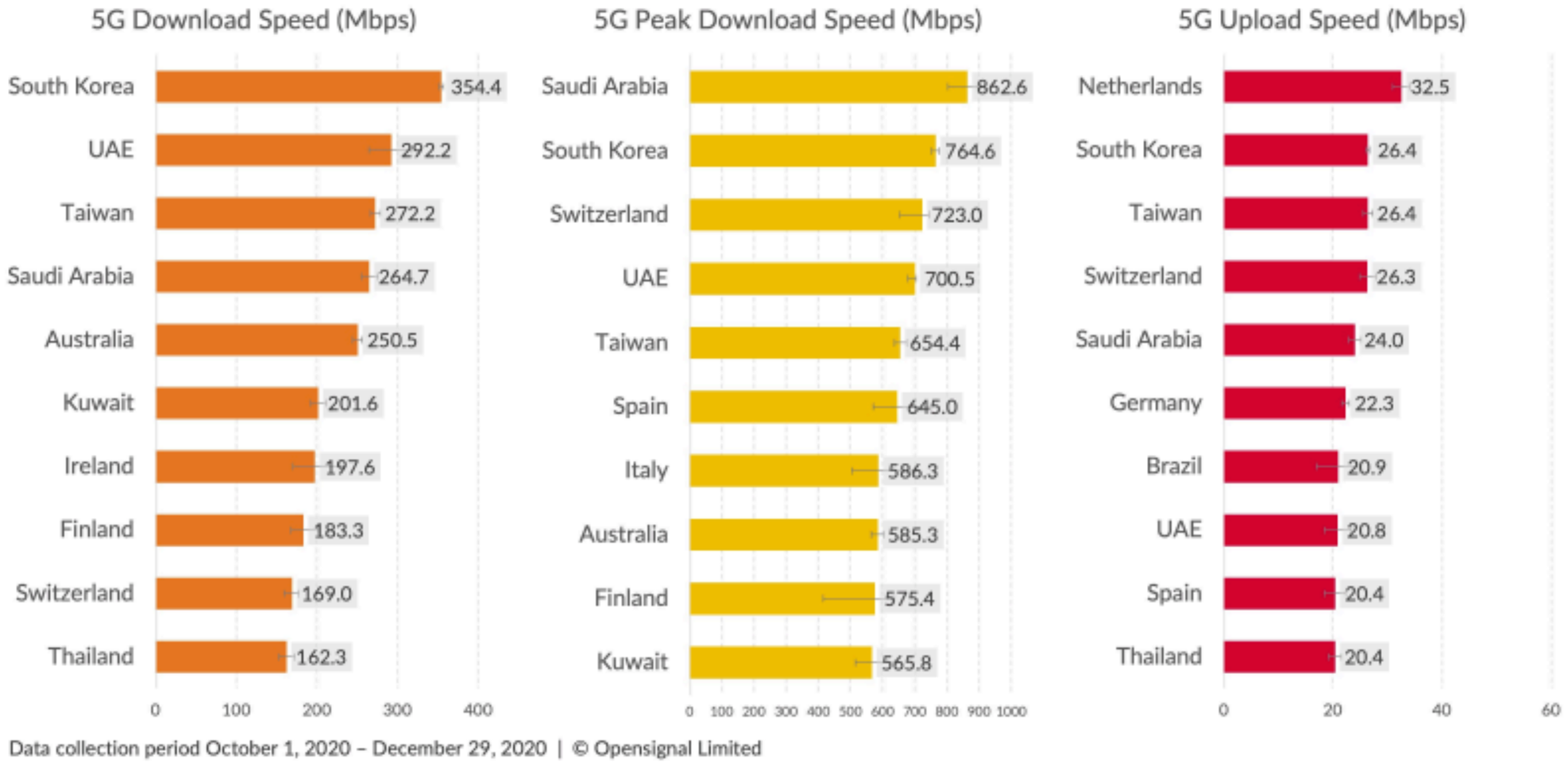


Legend

- **5G Ultra Wideband** — Available in parts of these cities
- **5G Nationwide** — Includes 4G LTE coverage
- **4G LTE**
- **3G**
- **International**
- **No Coverage**

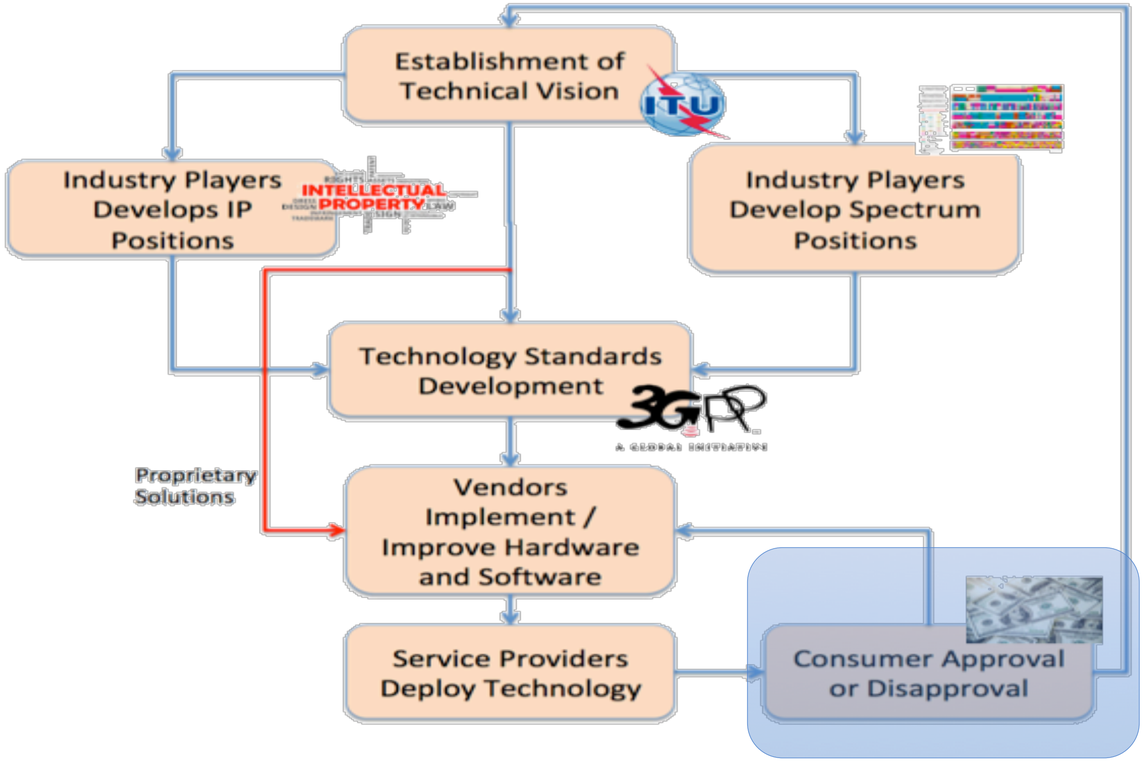
https://www.cellularmaps.com/

5G Leaders in Terms of Data Rates



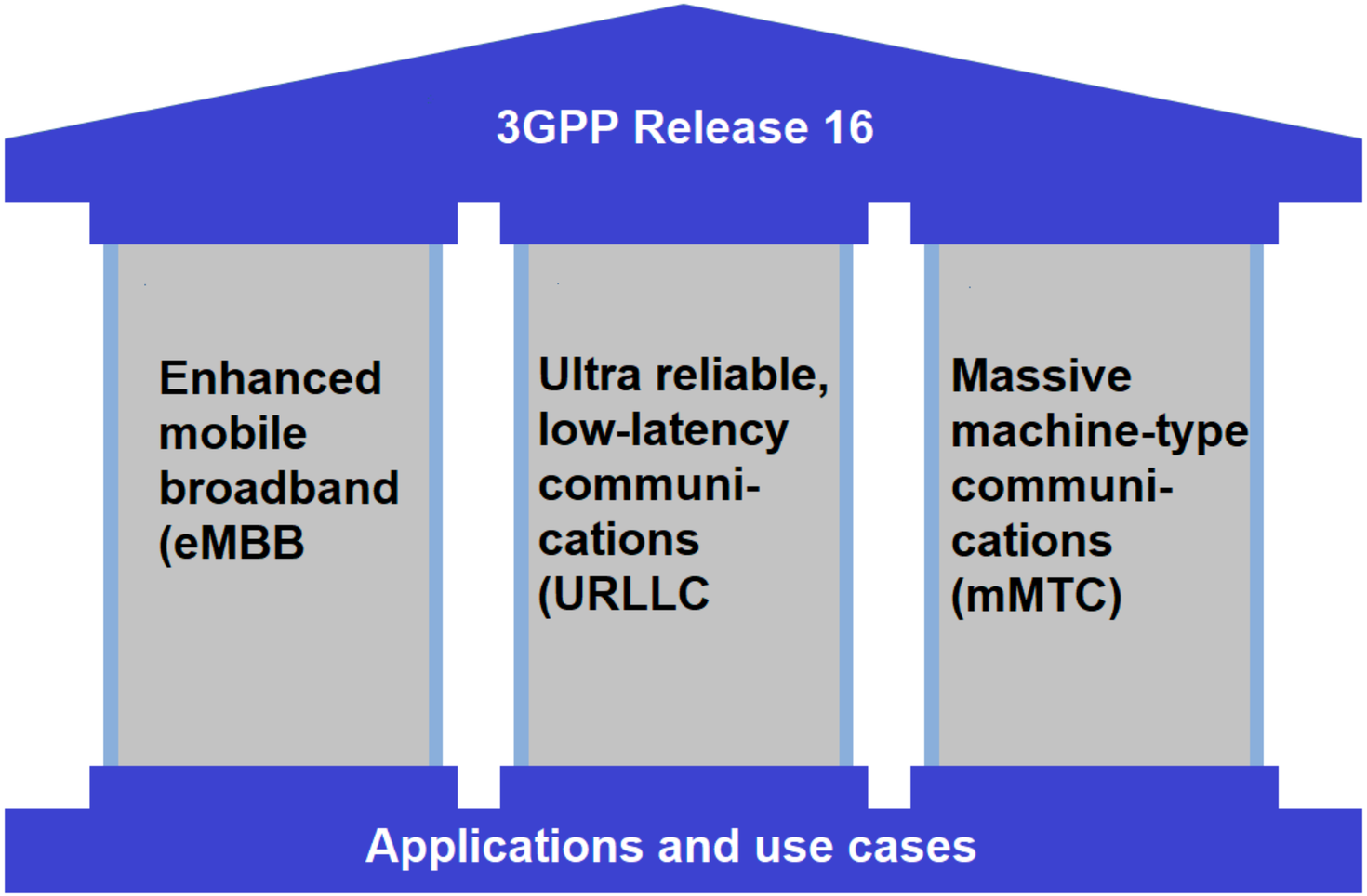
5G Status – You are Here

- The 5G Vision was well established with IMT-2020
- The 5G standards are well underway in development
- Infrastructure, handset, and chipset eco-system is mature
- Service providers have been aggressively rolling out deployments and trials in high-density population areas
- What hasn't happened yet is perhaps the most important step – consumer approval
  - But wait, isn't 5G already here and successful?



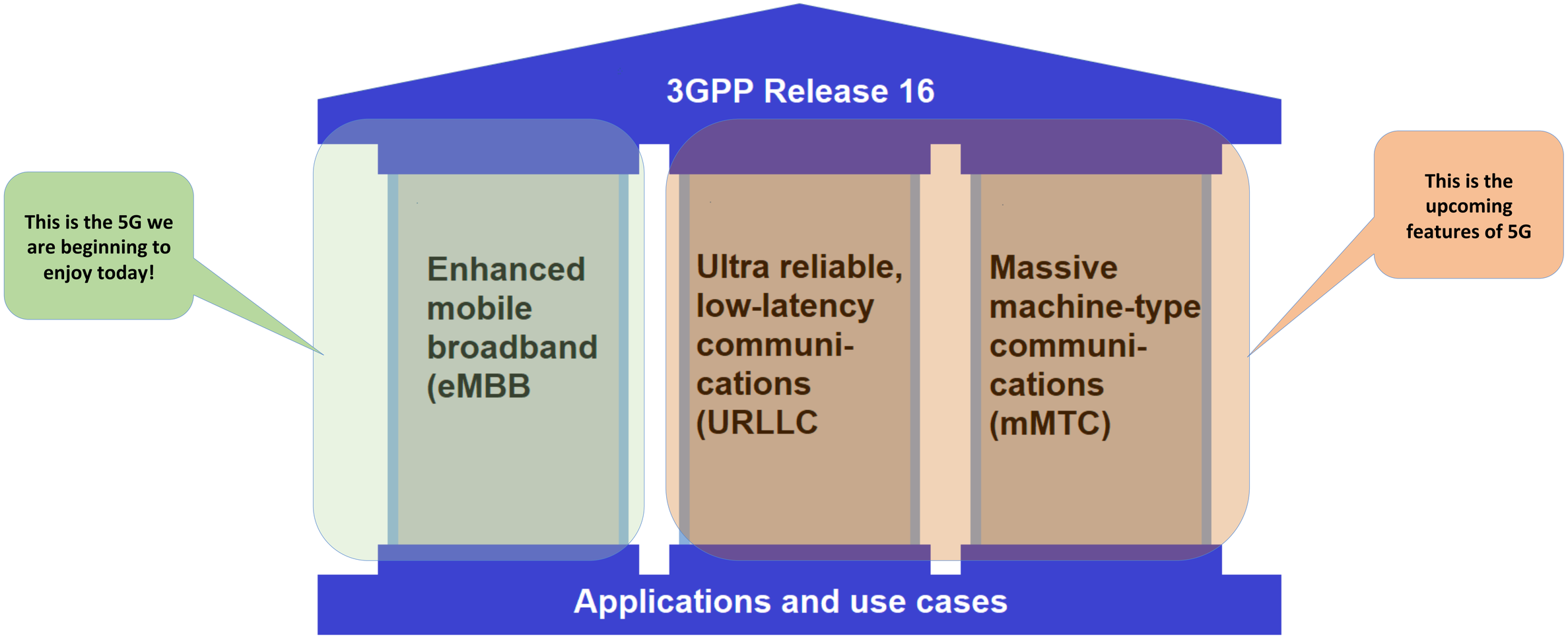
What is 5G?
Ask me in a few years!

The Three Pillars of 5G



https://www.edn.com/what-to-expect-in-5g-2-0/

The Three Pillars of 5G



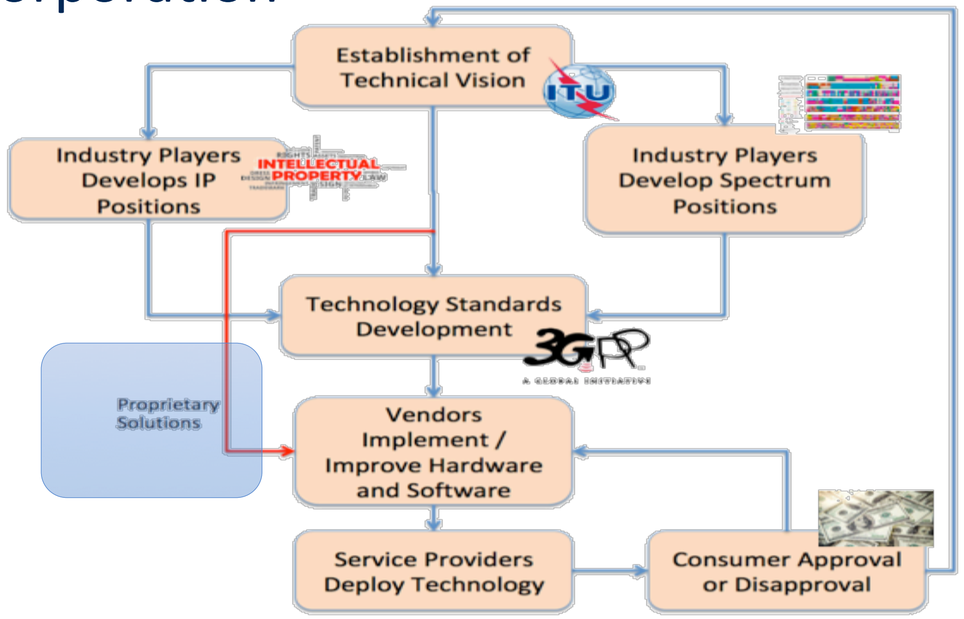
https://www.edn.com/what-to-expect-in-5g-2-0/

Pre-Standard Versions of “5G”

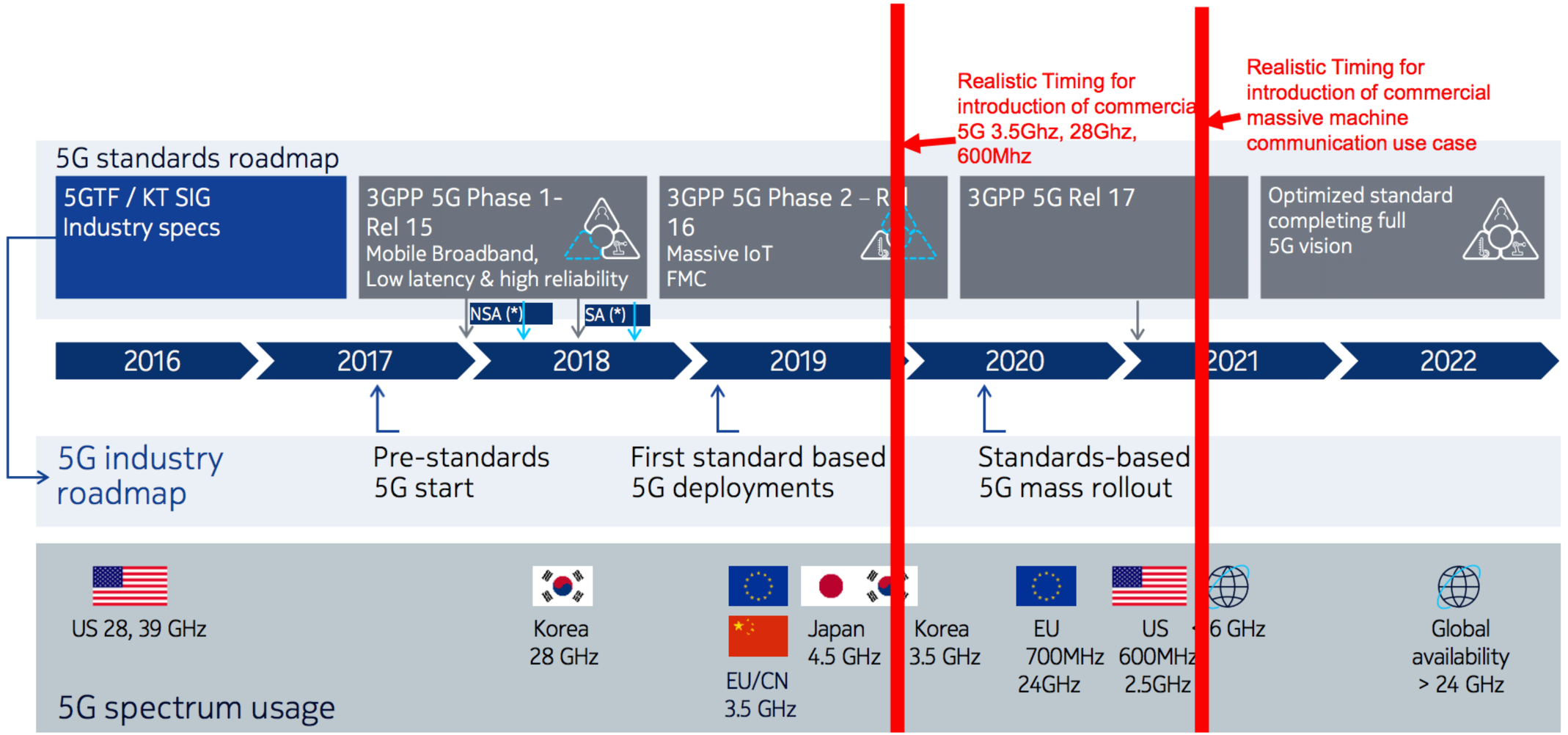
- 5G-TF: Verizon established 5G Task Force (TF) and developed proprietary version of 5G incompatible with 3GPP 5G “New Radio” or NR standard
  - Actually caused acceleration within 3GPP due to concerns that Verizon would move out with large-scale 5G-TF deployments

- 5G-SIG: Pre-standard specification developed by KT Corporation

https://m.corp.kt.com/eng/html/biz/services/sig.html

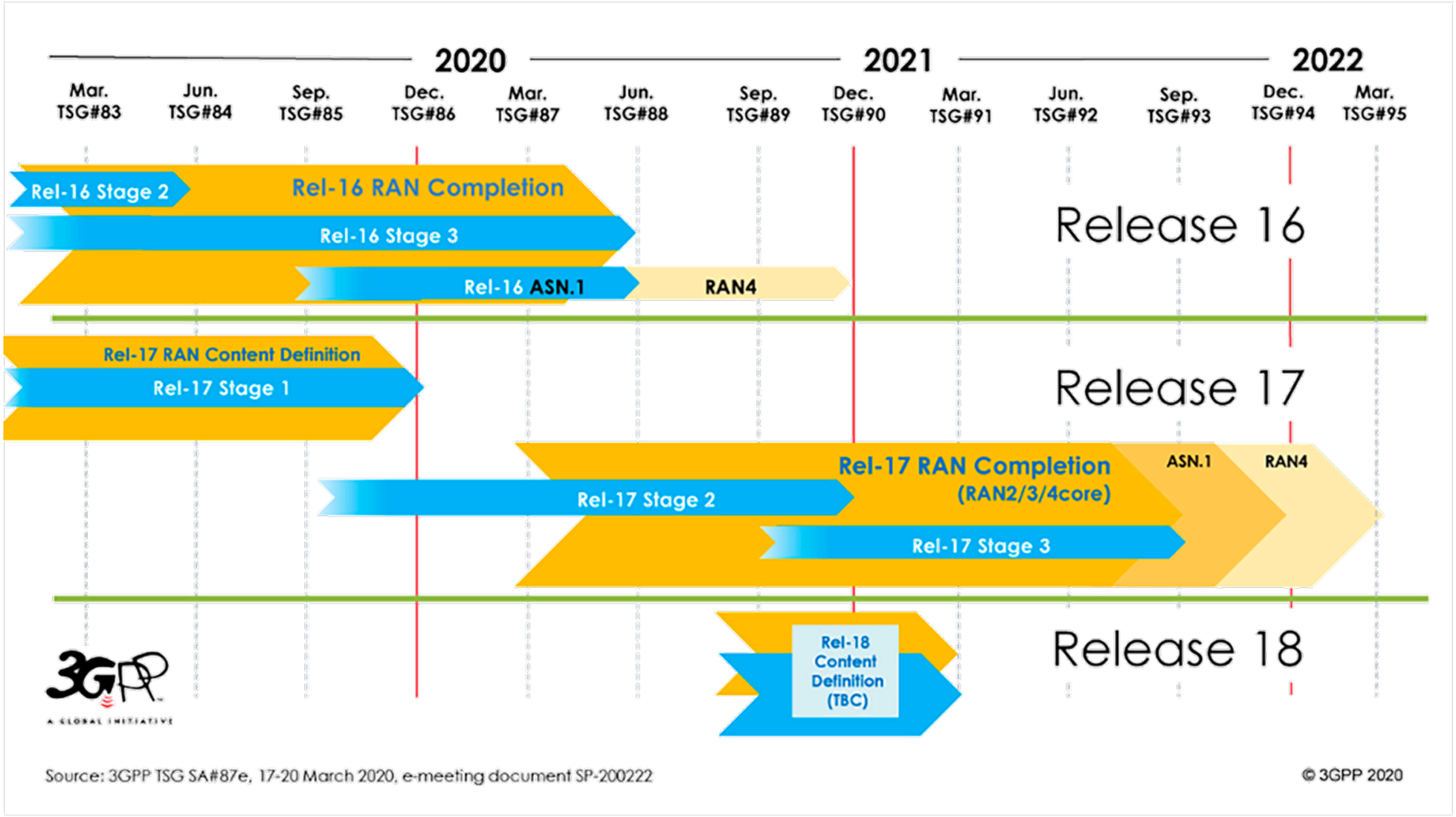


5G Standardization and Deployment



A. Ghosh, Nokia Networks, "5G NR: Physical Layer Overview and Performance," IEEE Communications Theory Workshop, May 2018.

5G Standardization and Deployment



Section1: Spectrum

New Spectrum Opportunities

New Spectrum Access Models

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5G Spectrum

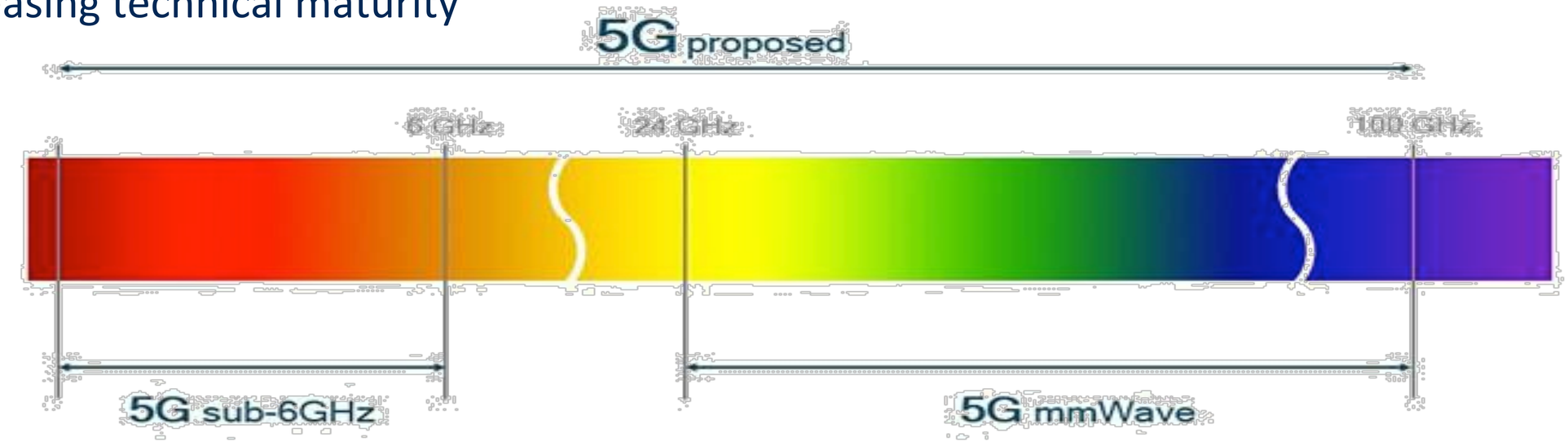
- New 5G Spectrum Opportunities
  - Low band: less than 1 GHz
    - 600 MHz band
  - Mid-Band: 1-6 GHz
  - High-Band: Above 6-GHz
    - mmWave

- Citizens Band Radio System (CBRS)

- Multefire

5G Spectrum

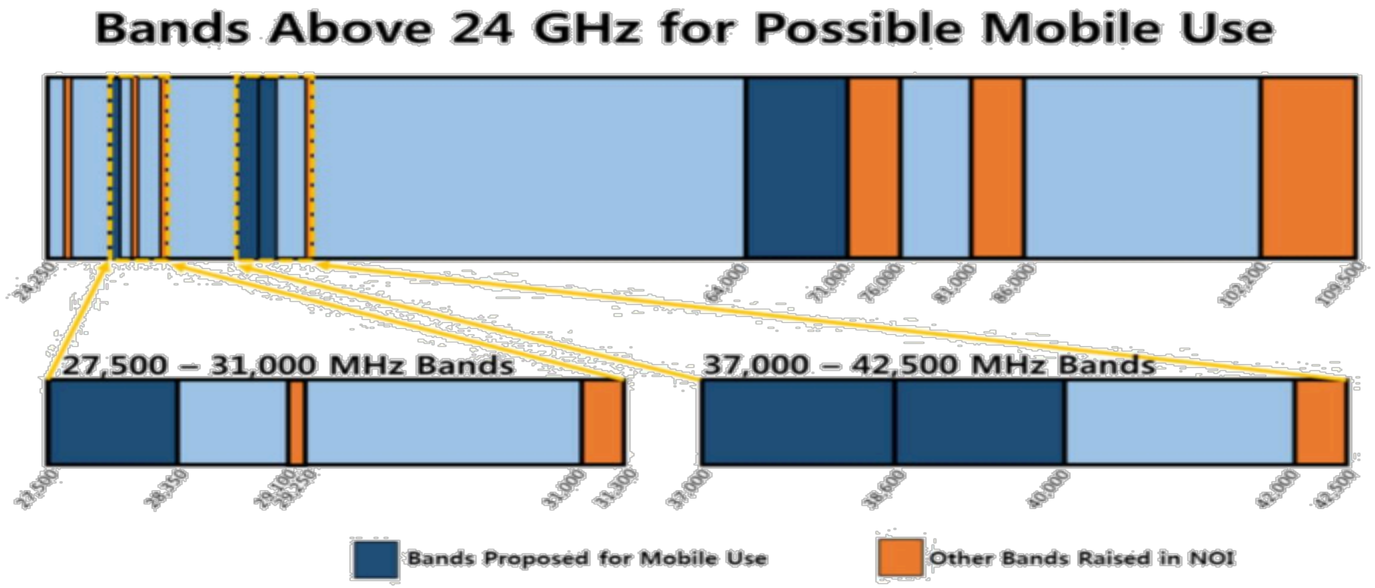
- mmWave extremely attractive to 5G community for several reasons
  - Enormous amount of available spectrum has and is being made available
  - Service providers aggressively retiring 3G/4G spectrum for 5G launches
  - Short-range nature of technology synergistic with emerging small-cell networking concepts
    - Enables extremely dense networks due to spatial reuse
  - Lowering price points
  - Increasing technical maturity



https://www.qualcomm.com/news/onq/2016/07/12/upcoming-fcc-vote-will-pave-path-5g-advancements-mobilize-mmwave

5G Spectrum - mmW

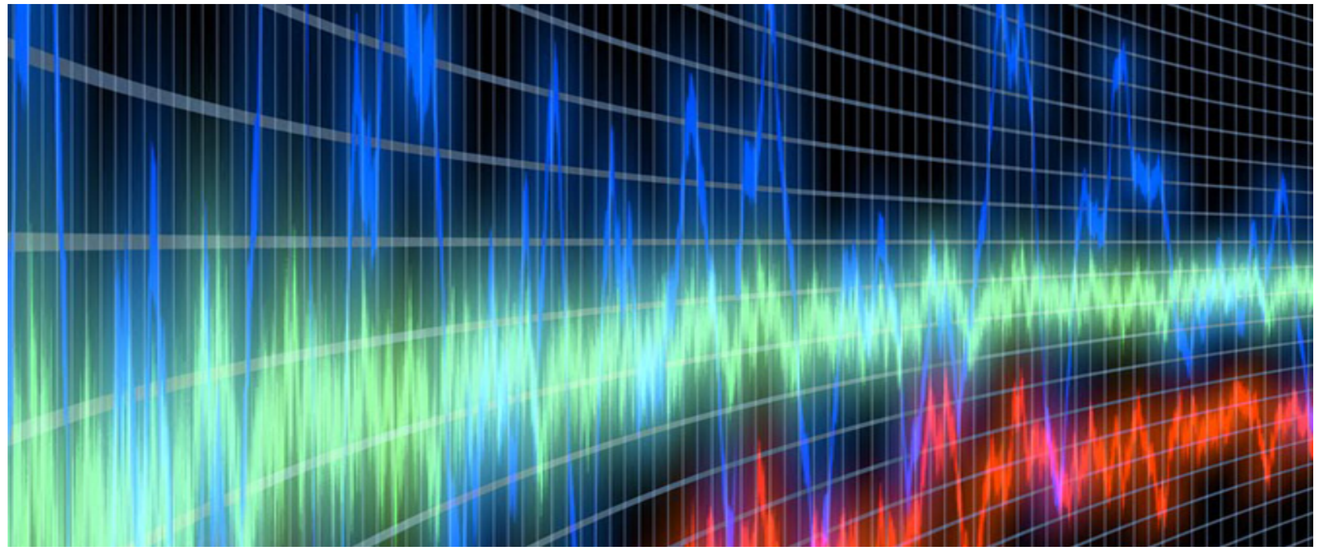
- Several bands have been considered by 3GPP for 5G
  - 57-64 GHz
  - **28/38 GHz band (7 GHz total)**
  - 71/81/92 GHz (12.9 GHz total)



Source: National Instruments

5G Spectrum - mmW

- ITU has proposed several viable frequencies between 24 and 86 GHz
  - **24.25 - 27.5 GHz**
  - 31.8 – 33.4 GHz
  - 37 – 40.5 GHz
  - 40.5 – 42.5 GHz
  - 45.5 – 50.2 GHz
  - 50.4 – 52.6 GHz
  - 66 – 76 GHz
  - 81 – 86 GHz



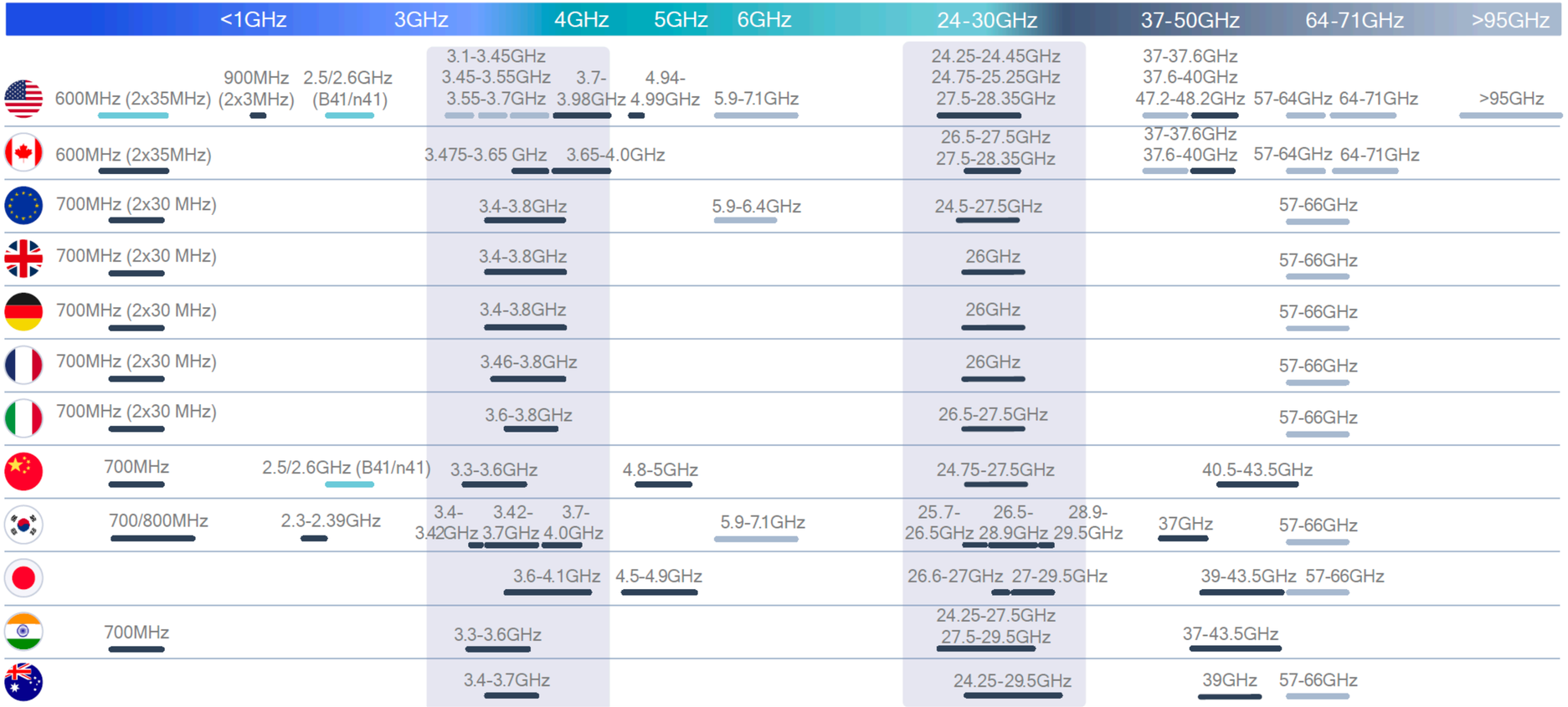
5G Spectrum: Auctions, Reallocations, and Repurposing

- Previous mmWave auctions have made massive amounts of spectrum available to carriers
  - 24 GHz
  - 28 GHz
  - 37 GHz
  - 39 GHz
  - 47 GHz

- Reallocation and auctioning of sub-6 GHz spectrum
  - 600 MHz

- Repurposing of existing cellular spectrum

Worldwide 5G Spectrum View

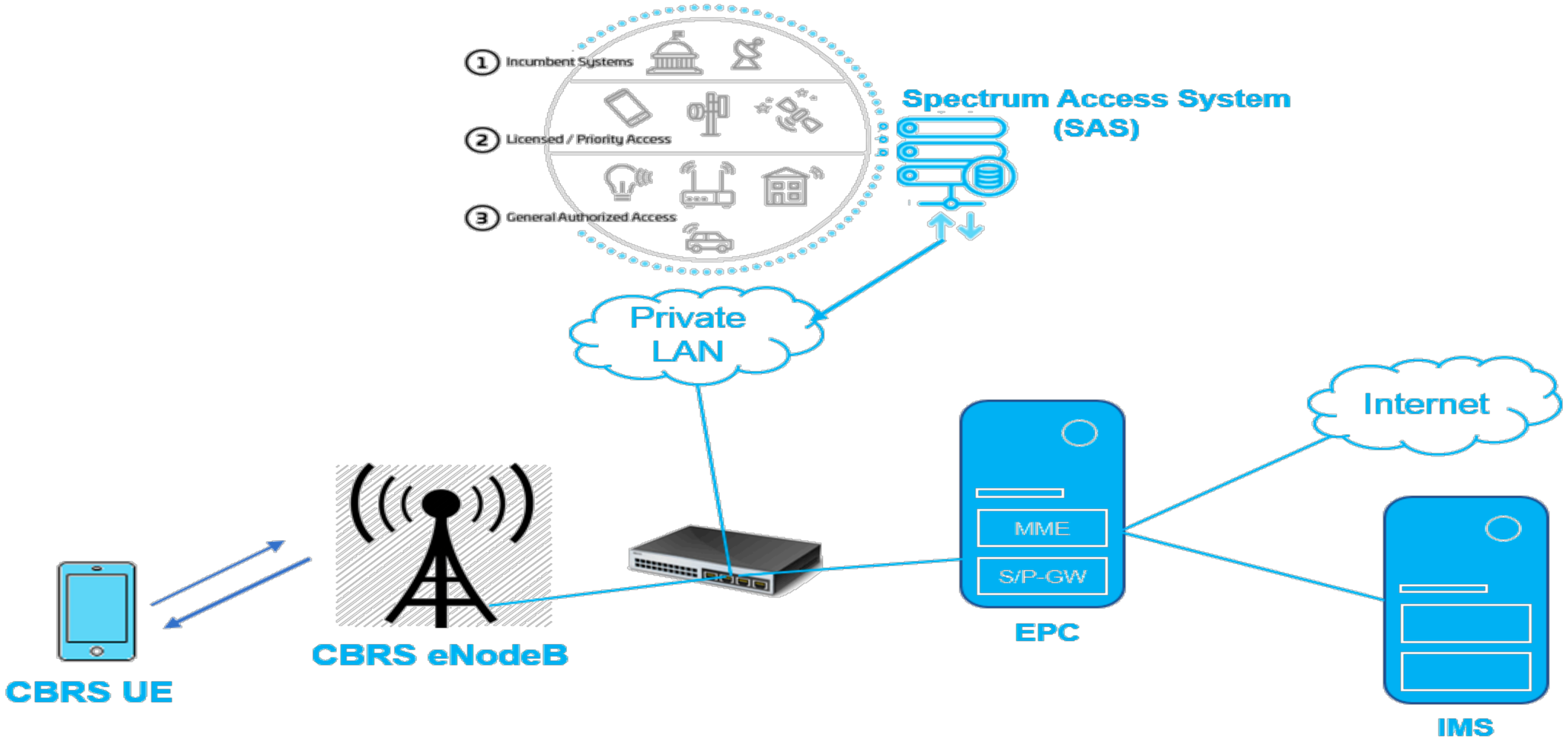


Qualcomm, 2020

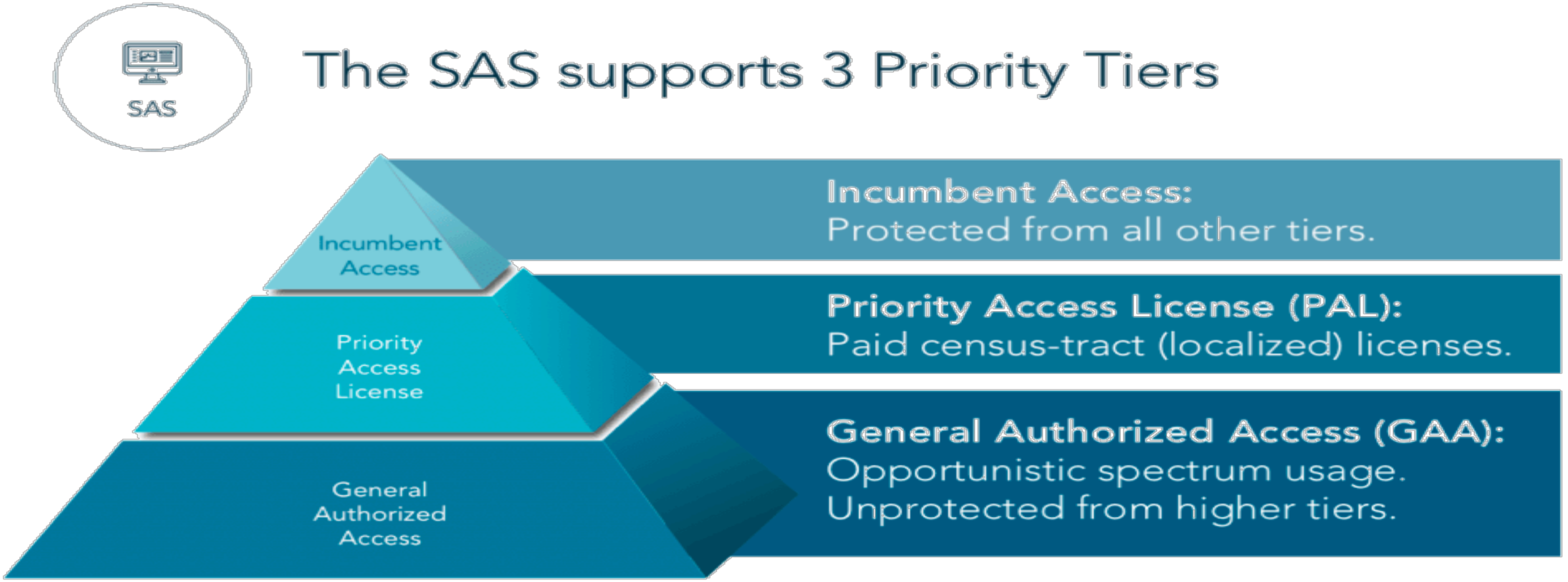
CBRS

- The Citizens Broadband Radio Service (CBRS) is an initiative to develop a viable shared spectrum model in the 3.5 GHz band in the United States
- Championed by the CBRS Alliance
- Goal: Allow LTE networks to co-exist in 3.5 GHz band with incumbent licensed users
  - US Navy, satellite service providers, utilities
- Development of specifications for operations in this shared band
- Spectrum Access System (SAS) and Environmental Sensing Capability to avoid potential interference between users
- More information can be found at: https://www.cbrsalliance.org

CBRS Network



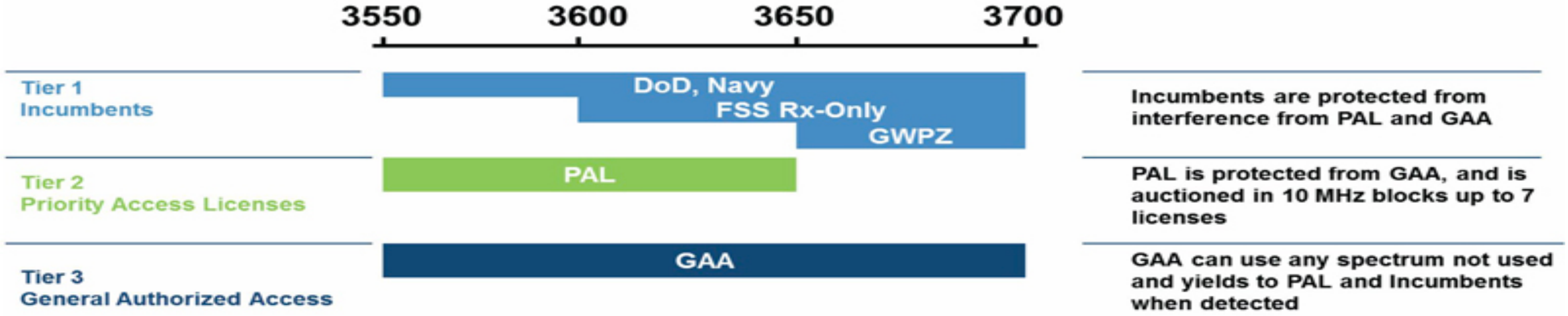
CBRS: Tiered Access Approach



https://www.airspan.com/cbrs/

CBRS: Tiered Access Approach

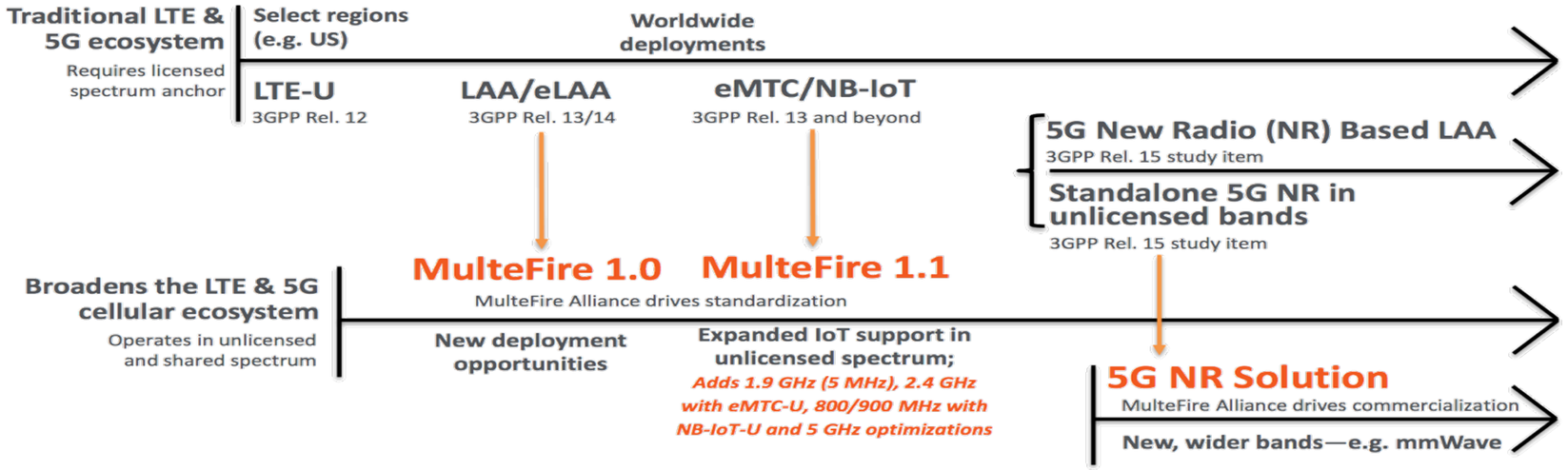
Opens up 150 MHz spectrum in a tiered model



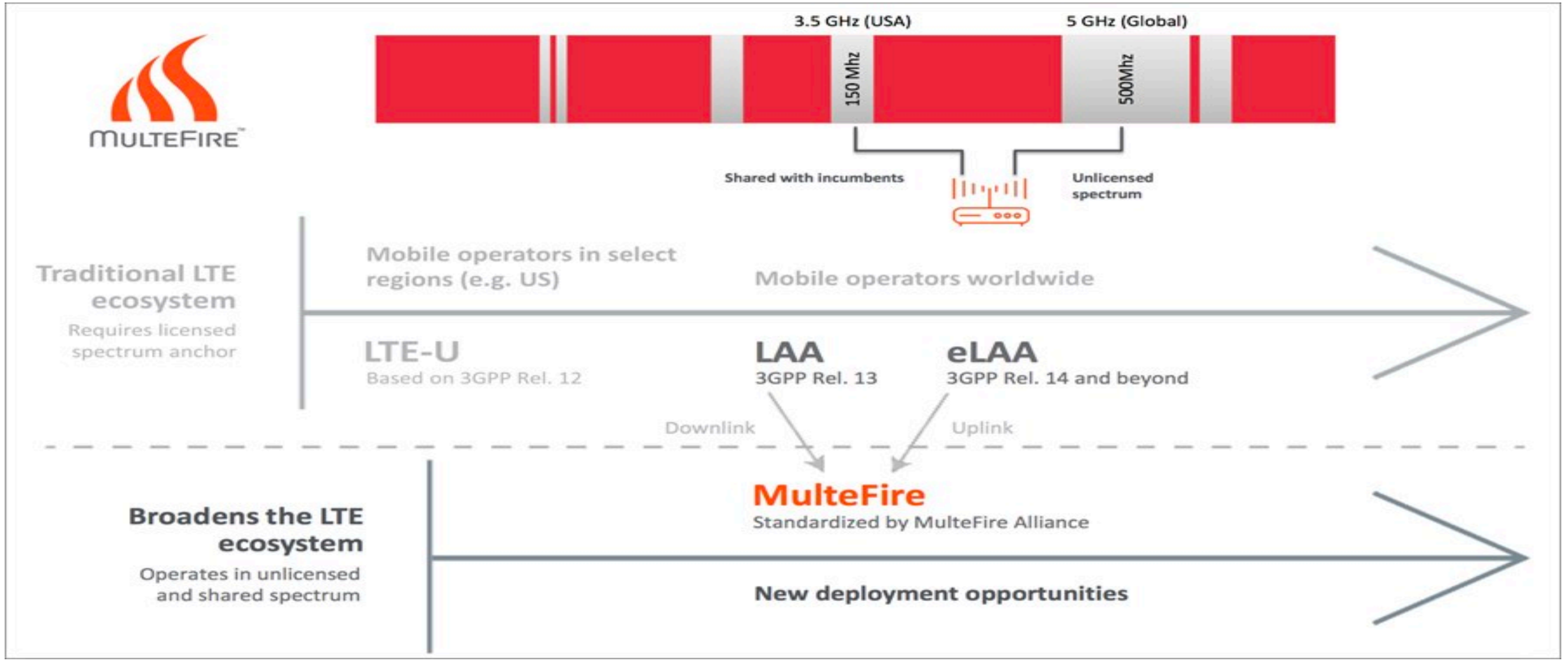
https://broadbandlibrary.com/cbrs-a-spectrum-policy-experiment-cable-is-best-positioned-to-benefit/ghai-chart-800/

MulteFire

- Multefire aims to enable cellular operation in unlicensed or shared spectrum
- Championed by the MulteFire Alliance
- Goal: Allow LTE and 5G networks to co-exist across multiple bands worldwide
  - Shared with incumbent users
  - Unlicensed spectrum
- Development of specifications for operations in shared and unlicensed bands
- More information can be found at: https://www.multefire.org



MulteFire (continued)



Section 2:
The 5G Architecture

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International Mobile Telecommunications

- The International Mobile Telecommunications (IMT) series of documents published by the International Telecommunications Union (ITU)
- Establishes market and traffic forecasts for future timeframes
- Key step in the development of new technologies
  - Establishes / influences performance goals for future standardization efforts
- Roadmap established by the ITU Radiocommunication Sector (ITU-R) for future networks, devices, and services
  - Defines overall performance goals
    - Mobility support, data rates, latencies, user densities

IMT Vision – Where the G's Come From

3G
IMT-2000

ITU-R M-1457.14

UMTS

CDMA2000 EV-DO

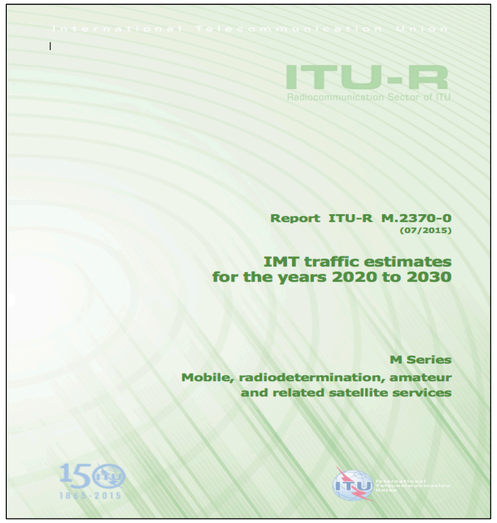
4G
IMT-Advanced

ITU-R M.2012-3

LTE

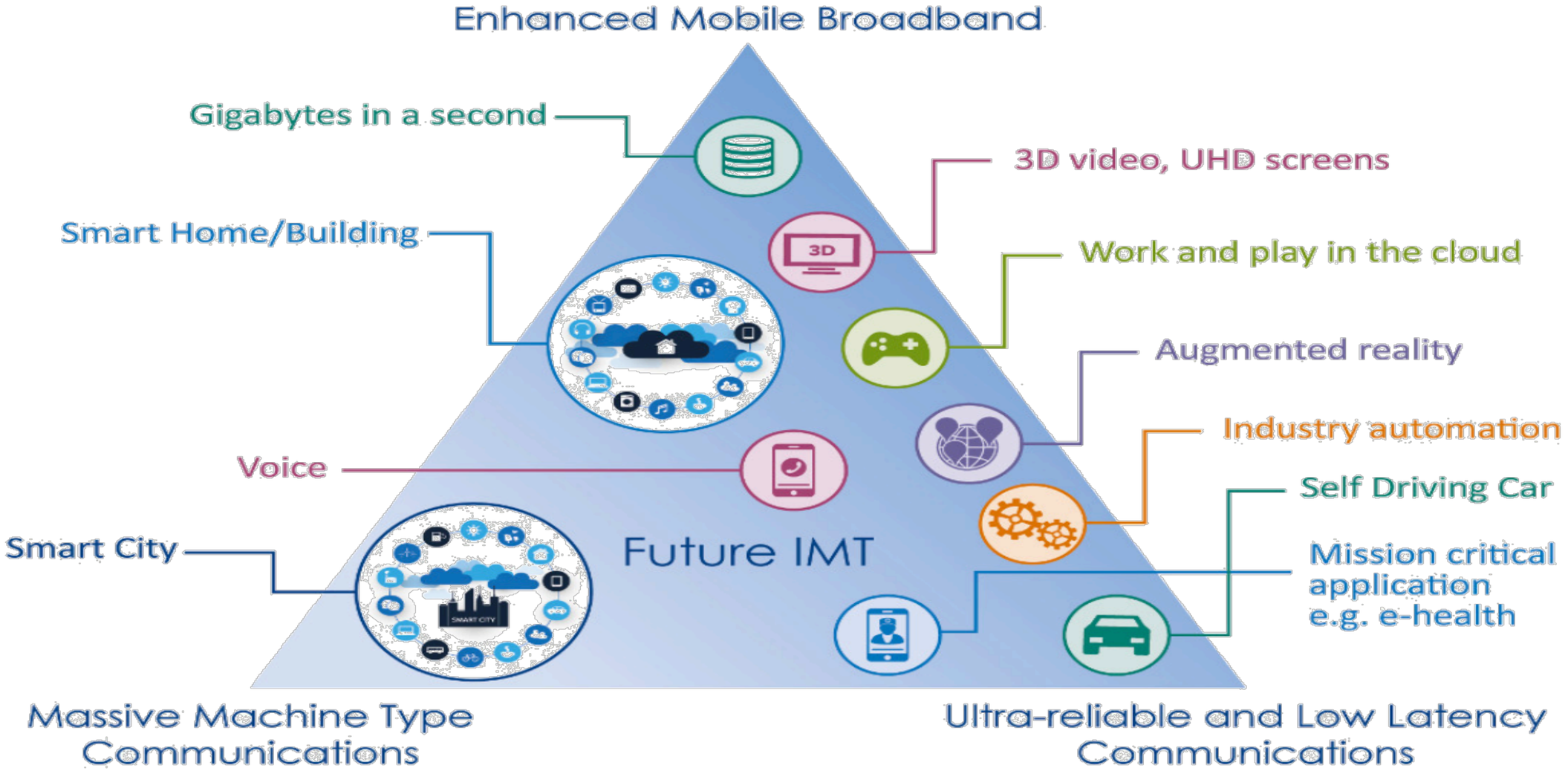
IMT 2020

- Defines the framework and overall objectives for 2020 and beyond



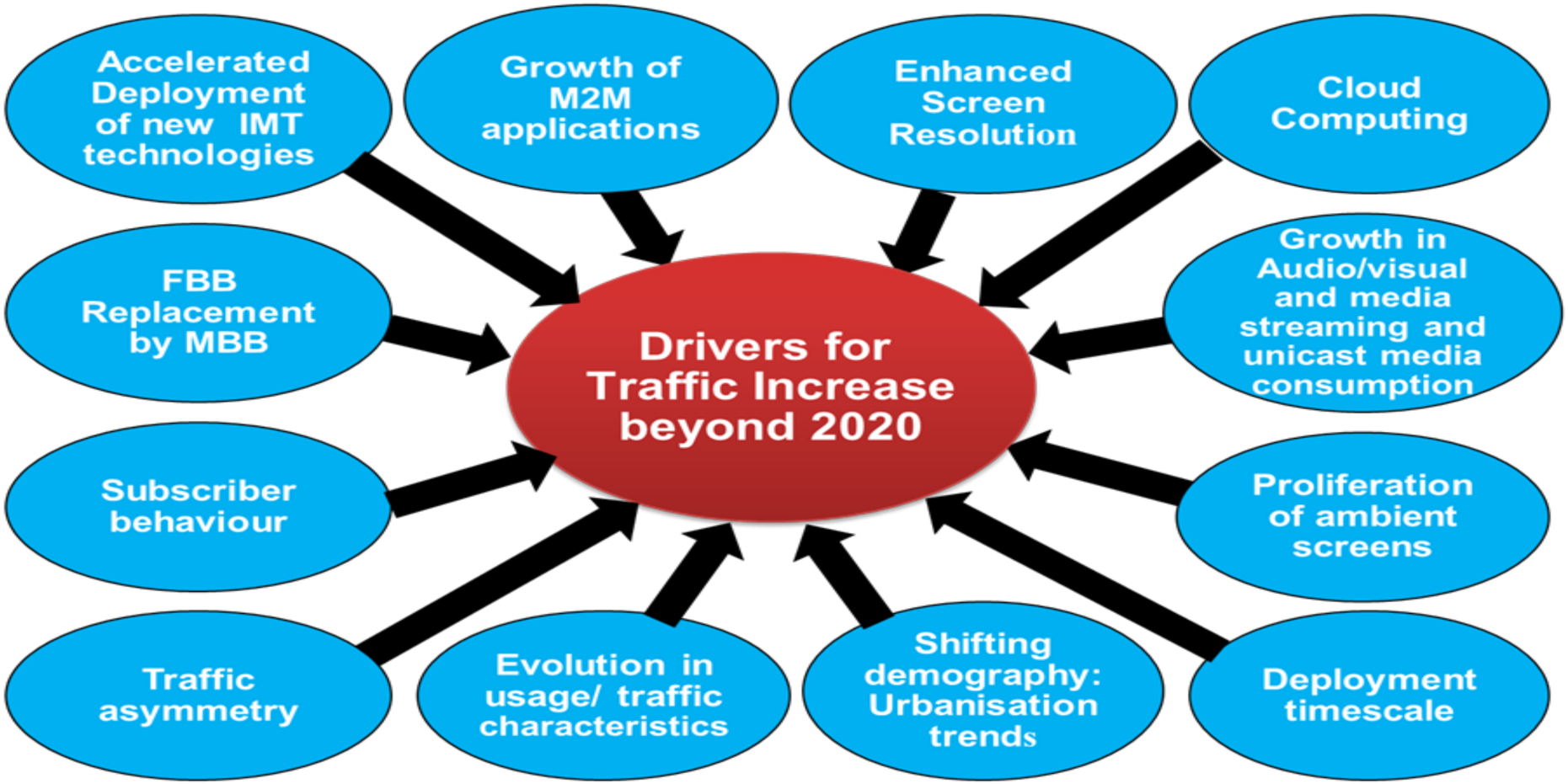
Document Number	Year Published	Document Title
ITU-R M-2083-0	2015	IMT-Vision − Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond
ITU-R M.2376-0	2016	Technical Feasability of IMT in Bands above 6 GHz
ITU-R M-2370-0	2015	IMT Traffic Estimates for the Years 2020 to 2030

IMT-2020 Usage Scenarios



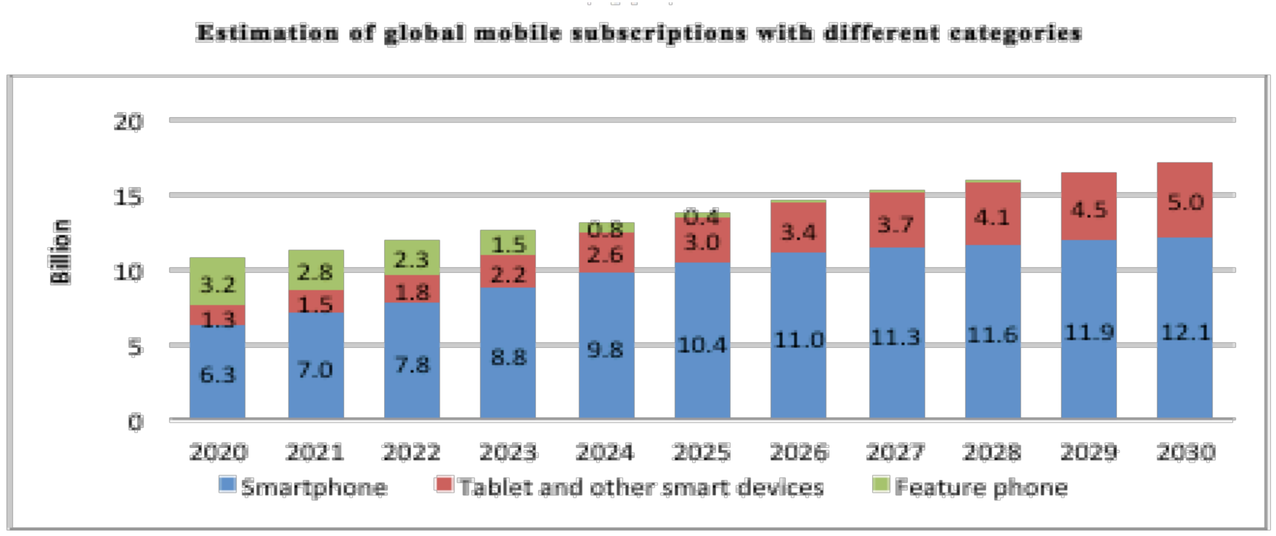
ITU-R M-2083-0, “IMT-Vision − Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond“

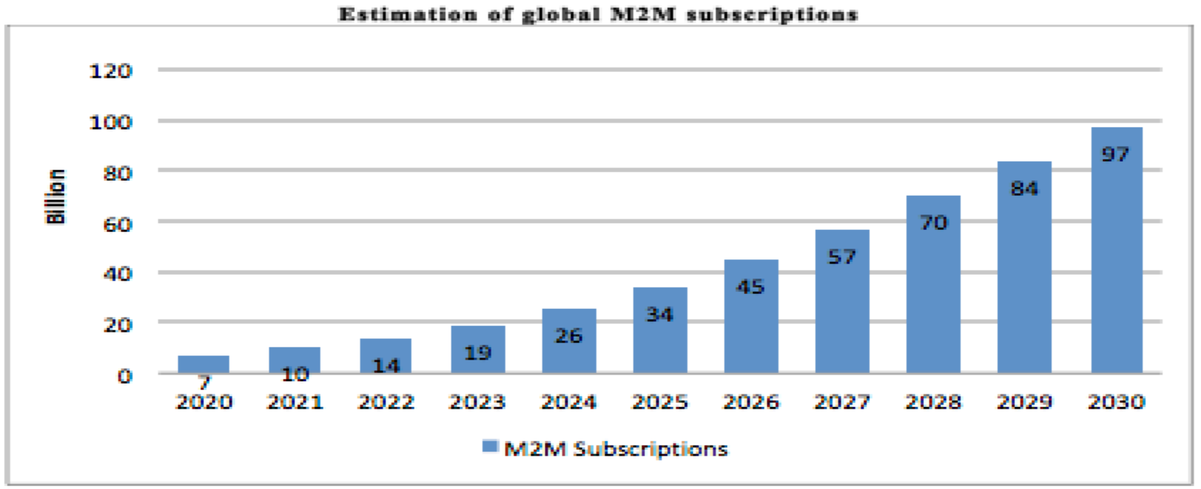
IMT 2020-2030

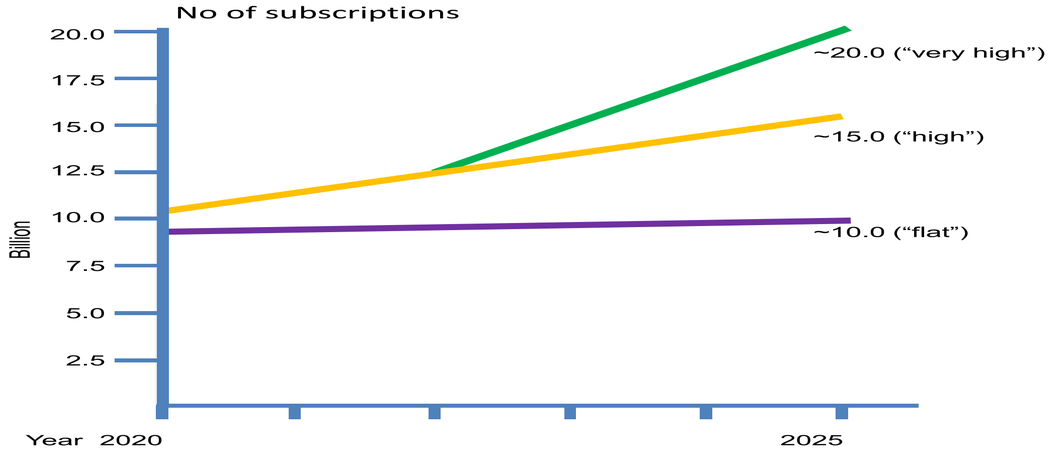


ITU-R M-2370-0, “IMT Traffic Estimates for the Years 2020 to 2030 “

IMT 2020-2030



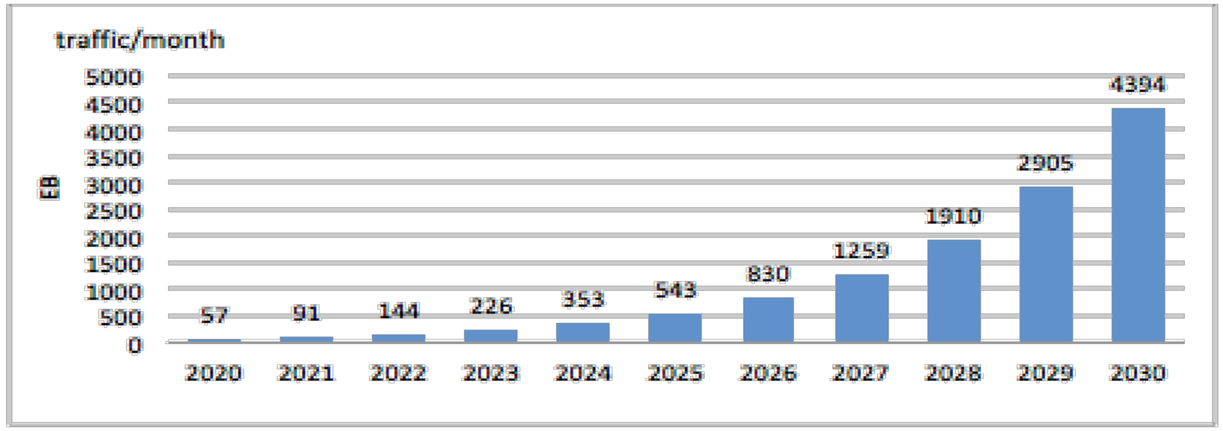




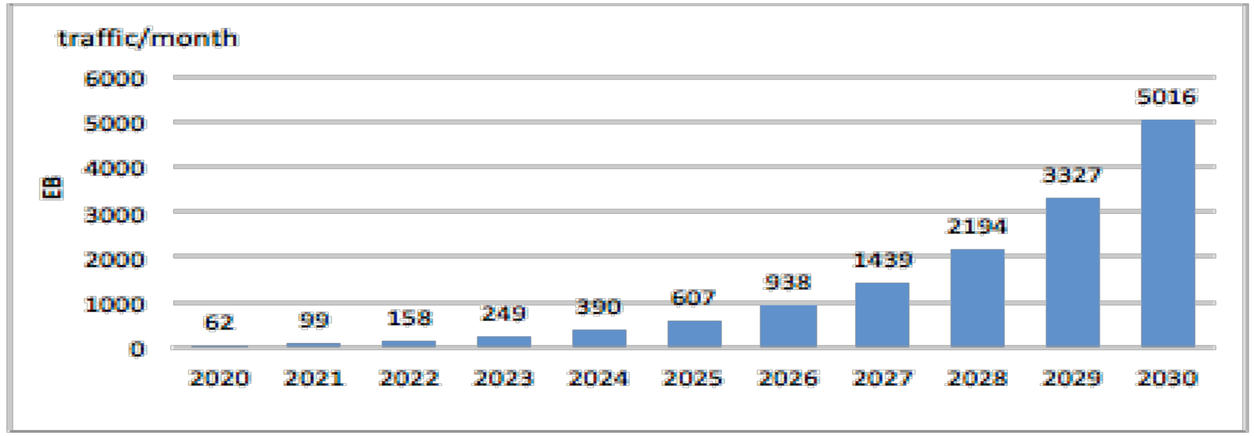
ITU-R M-2370-0, “IMT Traffic Estimates for the Years 2020 to 2030 “

IMT 2020-2030

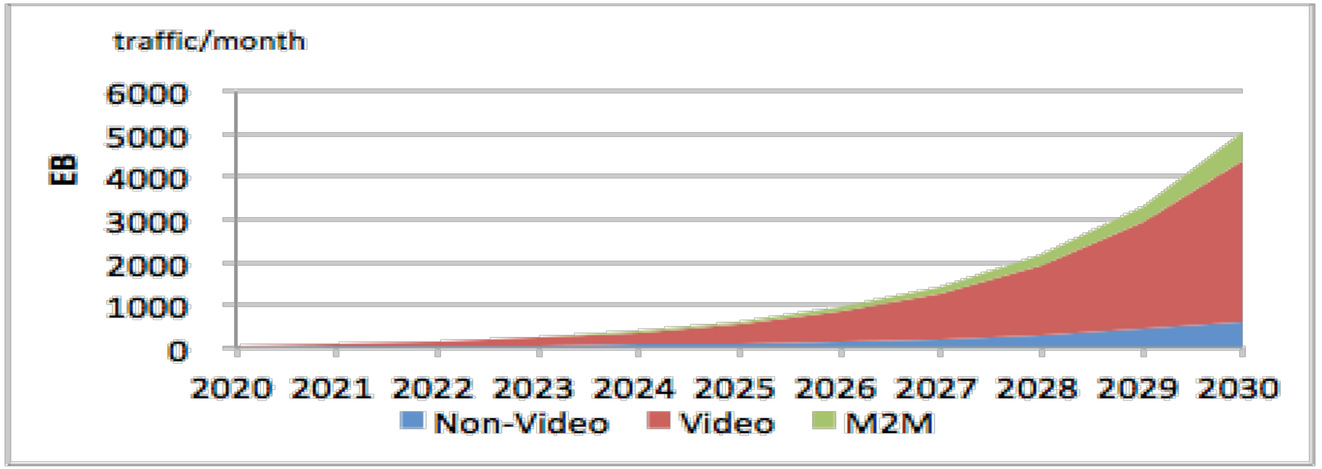
Estimations of global mobile traffic from 2020 to 2030 (M2M traffic not included)



Estimations of global mobile traffic in 2020-2030 (M2M traffic included)



Estimation of mobile traffic by different service types globally

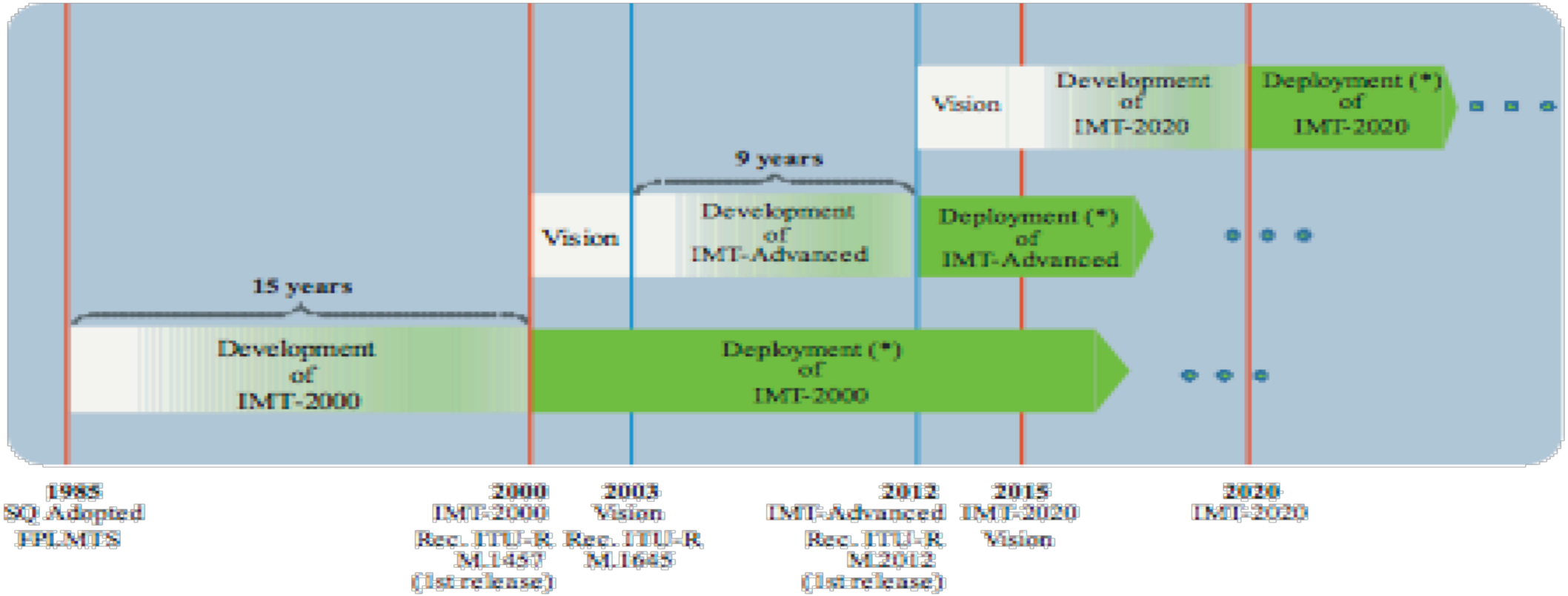


ITU-R M-2370-0, “IMT Traffic Estimates for the Years 2020 to 2030 “

IMT 2020 Timeline

FIGURE 1

Overview of timeline for IMT development and deployment

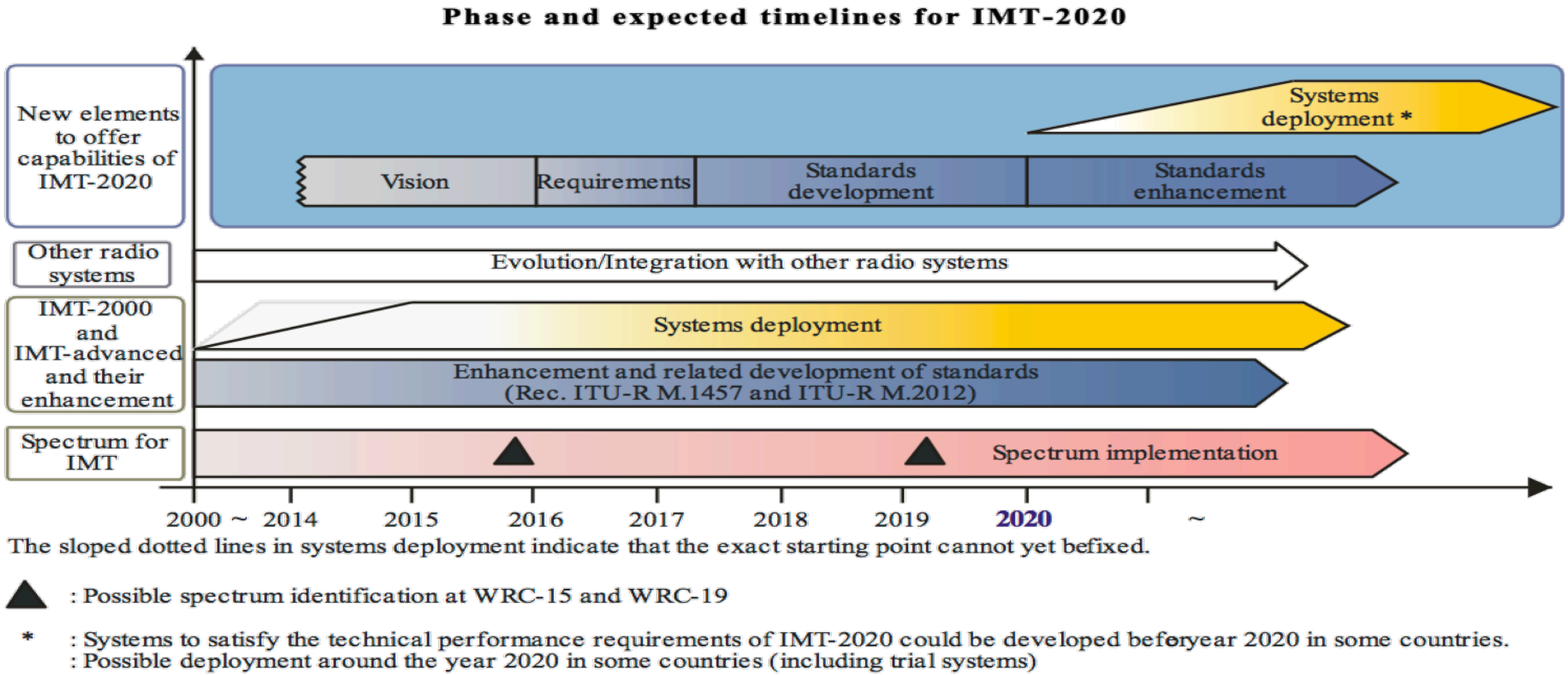


(*) Deployment timing may vary across countries.

M.2083-01

ITU-R M-2083-0, “IMT-Vision − Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond“

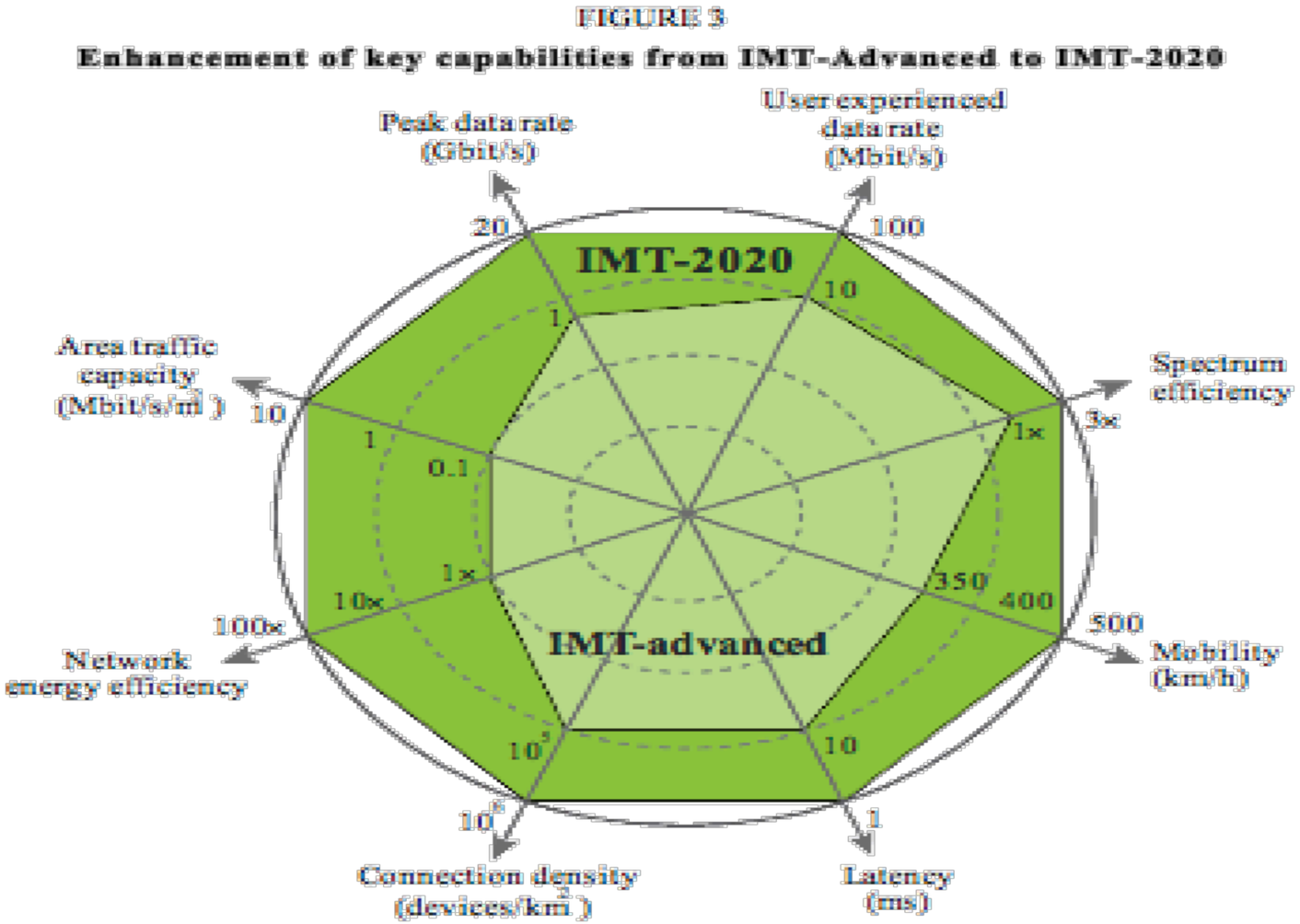
IMT 2020 Timeline



ITU-R M-2083-0, “IMT-Vision − Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond“

IMT 2020 Performance

- **Much higher Network Capacity**
  - 10 Mbps per meter
  - 20 Gbps peak data rate (D/L)
  - 100 Mbps per user data rate (D/L)
- **Improved Latency**
  - Less than 1 ms
- **Much Higher User Density**
  - 1 millions devices per square km
- **Improved Network Efficiency**
  - 100x network efficiency
  - 3x spectrum efficiency



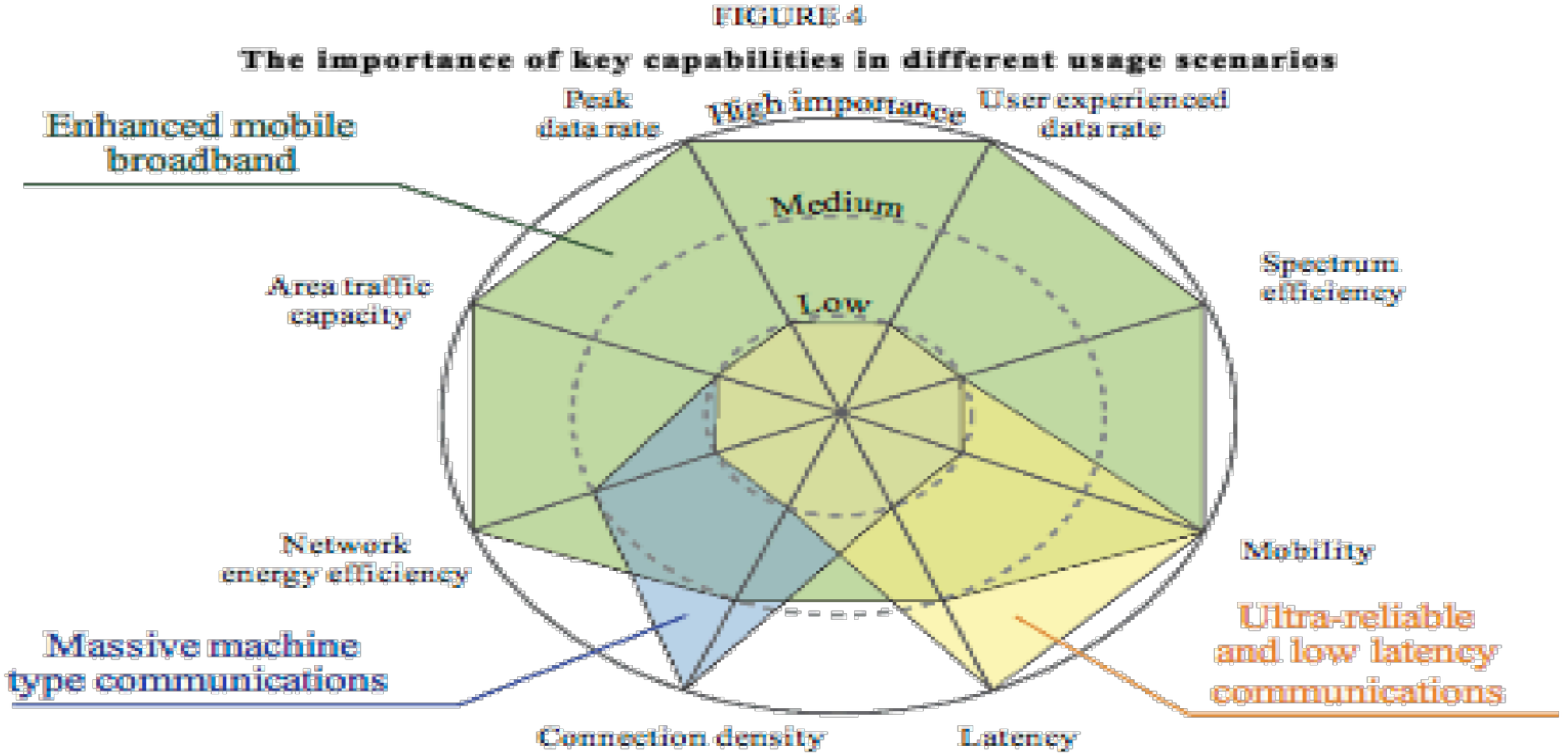
ITU-R M-2083-0, “IMT-Vision − Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond“

IMT 2020 Performance

Metric	Requirement	Comments
Peak Data Rate	DL: **20 Gb/s** UL: 10 Gb/s	Single eMBB mobile in ideal scenarios assuming all resources utilized
Peak Spectral Efficiency	DL: **30 b/s/Hz** (assuming 8 streams) UL: 15 b/s/Hz (assuming 4 streams)	Single eMBB mobile in ideal scenarios assuming all resources utilized
User Experienced Data Rate	DL: 100 Mb/s UL: 50 Mb/s	5% CDF of the eMBB user throughput
Area Traffic Capacity	Indoor hotspot DL: 10 Mb/s/m^2	eMBB
User Plane Latency	eMBB: 4 ms URLLC: **1 ms**	Single user for small IP packets, for both DL and UL (eMBB and URLLC)
Control Plane Latency	20 ms (encouraged to consider **10 ms**)	Transition from Idle to Active (eMBB and URLLC)
Connection Density	1M devices per km^2	For mMTC
Reliability	99.9999% success prob.	32 L2 bytes within 1 ms at cell edge
Bandwidth	>100 MHz; up to **1 GHz in > 6 GHz**	Carrier aggregation allowed

https://spectrum.ieee.org/telecom/wireless/3gpp-release-15-overview

IMT 2020 Performance



ITU-R M-2083-0, “IMT-Vision − Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond“

Section 3:
5g Cellular Technology Overview

MILCOM

IEEE ComSoc
IEEE Communications Society

AFCEA

3GPP Overview

- The Third Generation Partnership Program (3GPP) is the effective cellular standard development organization (SDO) that defines cellular technology standards

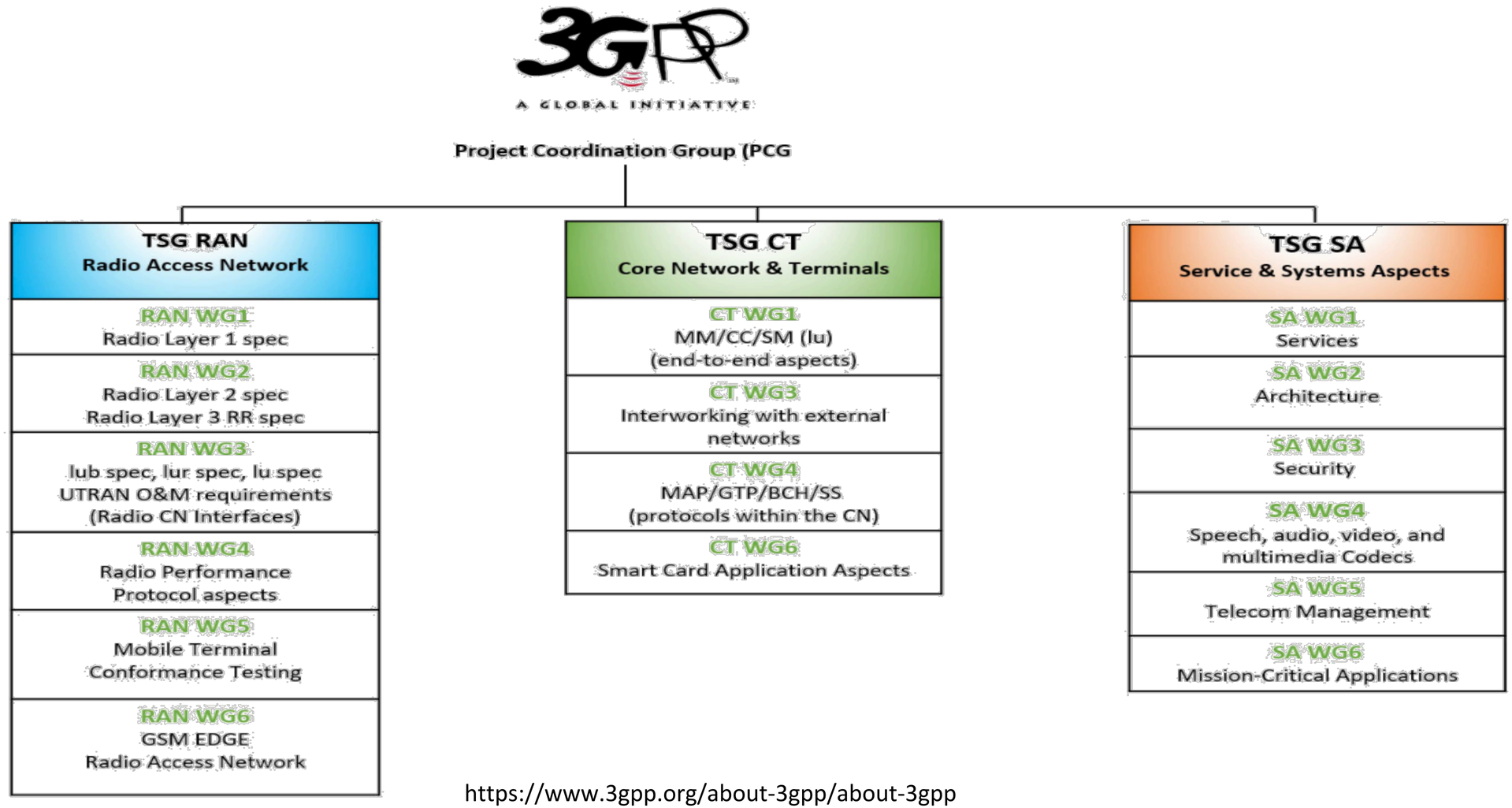
- Transforms visions put forth by ITU IMT into technology standards that can be implemented by industry

- 3GPP units seven telecommunications standard development organizations
  - ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC all Organizational Partners

- Three Technical Specification Groups (TSG)
  - Radio Access Networks (RAN)
  - Services and Systems Aspects (SA)
  - Core Network and Terminals (CT)

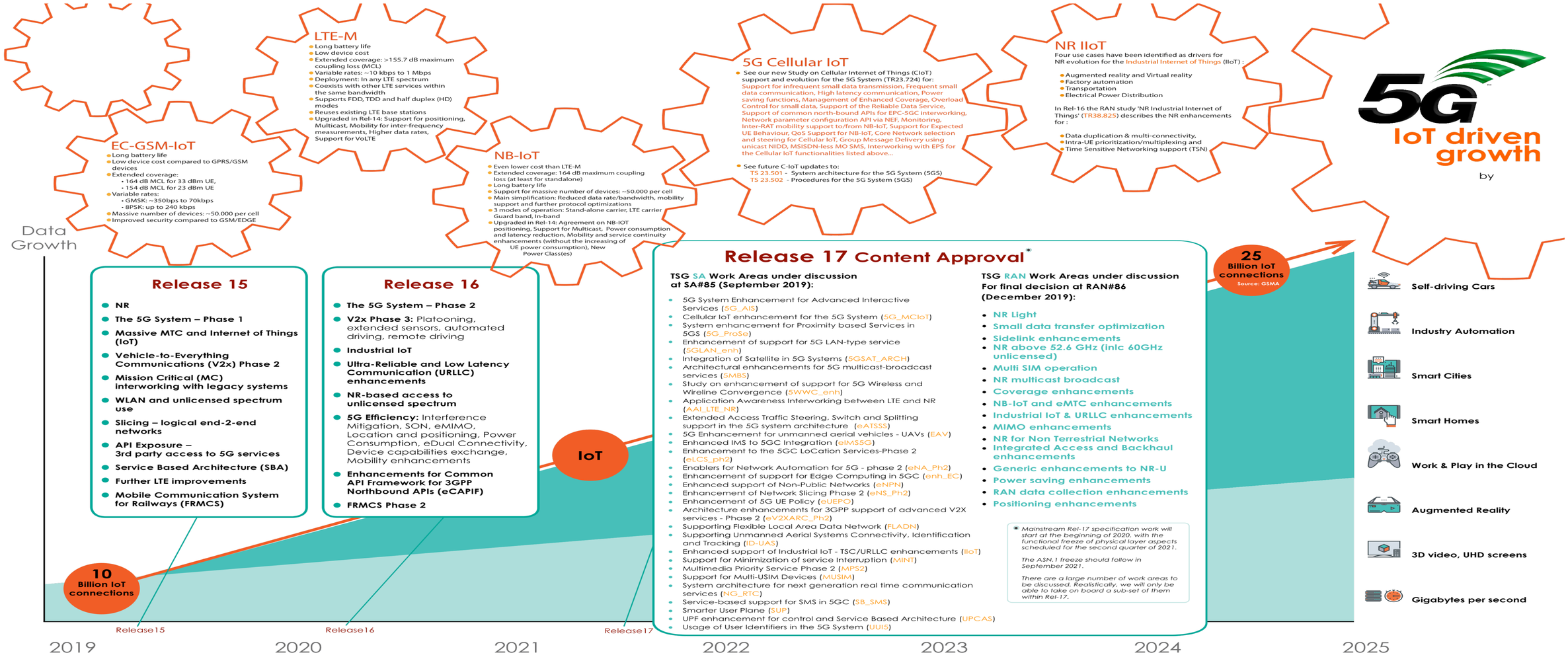
- Technical work is done within Working Groups (WG)
  - WGs reside within TSGs and meet regularly to present, discuss, and approve technical work

3GPP Organization



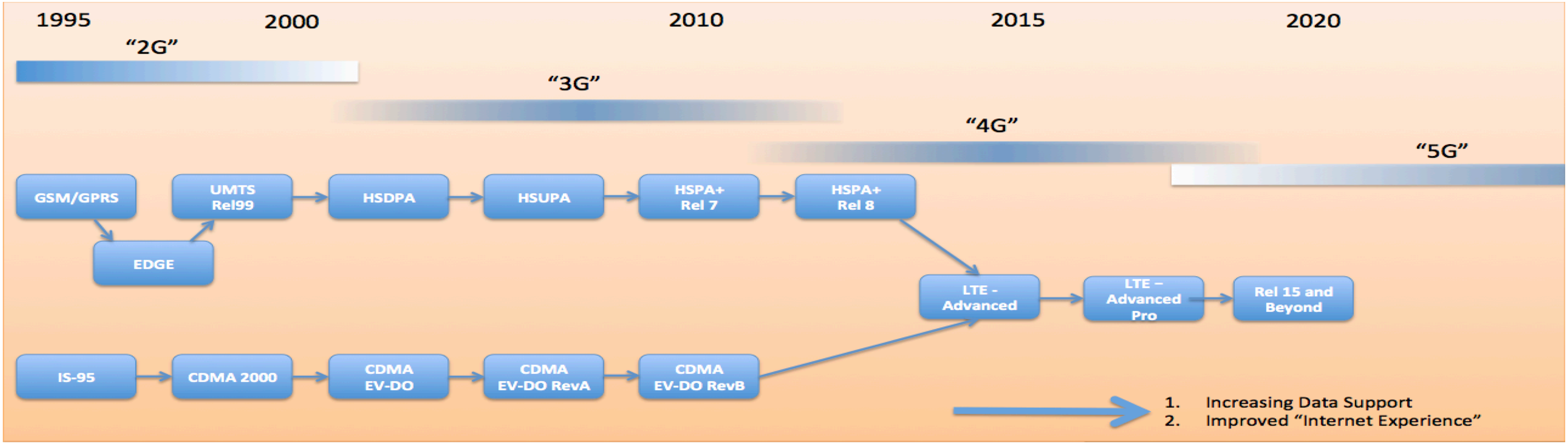
https://www.3gpp.org/about-3gpp/about-3gpp

3GPP 5G Work Plan

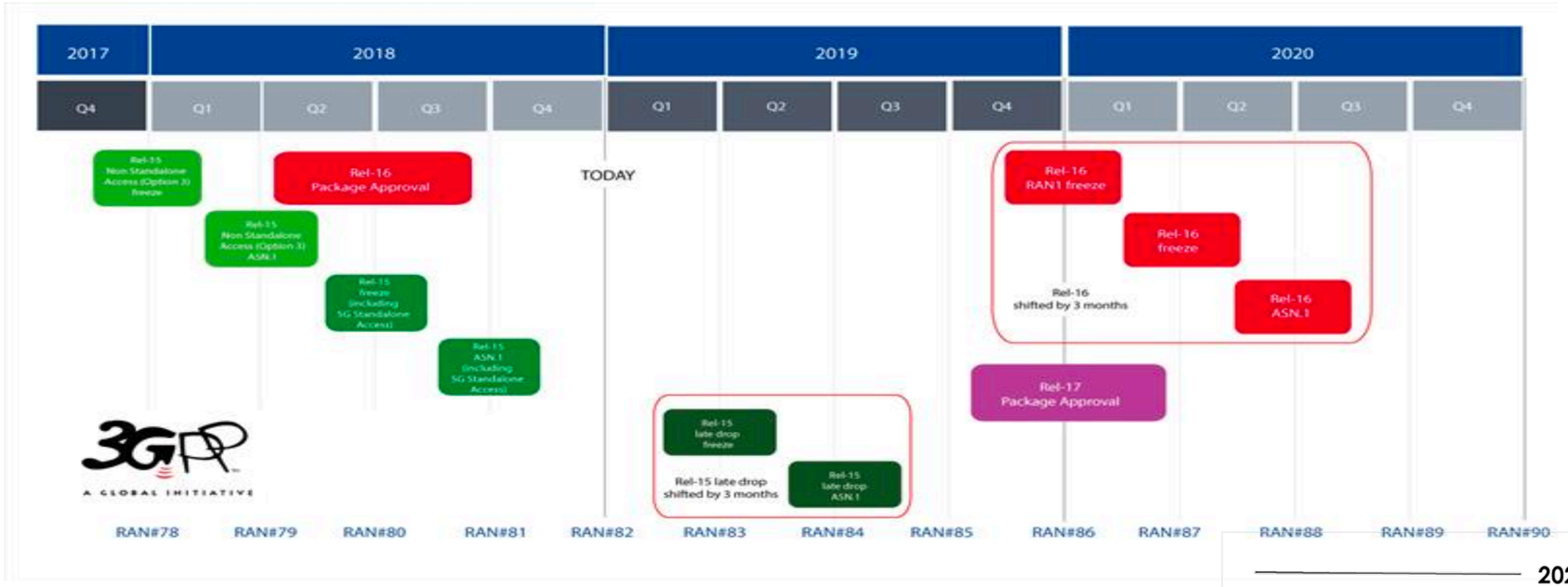


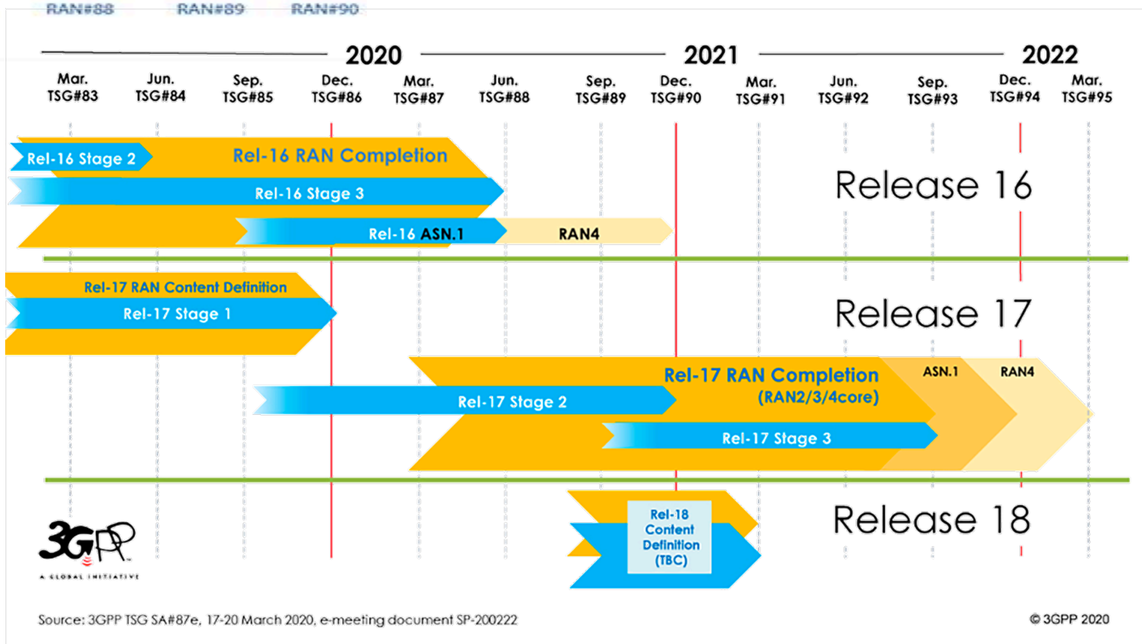
www.3gpp.org/specifications/work-plan

High-Level History of Cellular Standards



3GPP Release Timelines





Source: 3GPP TSG SA#87e, 17-20 March 2020, e-meeting document SP-200222

5G: A Phased Approach

- 5G is about three things:
  - Enhanced Mobile Broadband (eMBB)
  - Ultra-Reliable Low-Latency Communications (URLLC)
  - Massive Machine Type Communications (mMTC)
- Agreed upon early on that all three of these topics are far too much to be addressed in single Release
  - Phased approach was needed
- Phase 1: Primarily addressed by Release 15
  - Focus is on enhanced Mobile Broadband (eMBB)
  - Also introduces many of the mechanisms that will be needed to eventually achieve other goals
  - This is what is primarily deployed today
- Phase 2: Primarily addressed by Release 16 and 17
  - Focus on URLLC and mMTC
  - Many other key features

5G: A Phased Approach (continued)

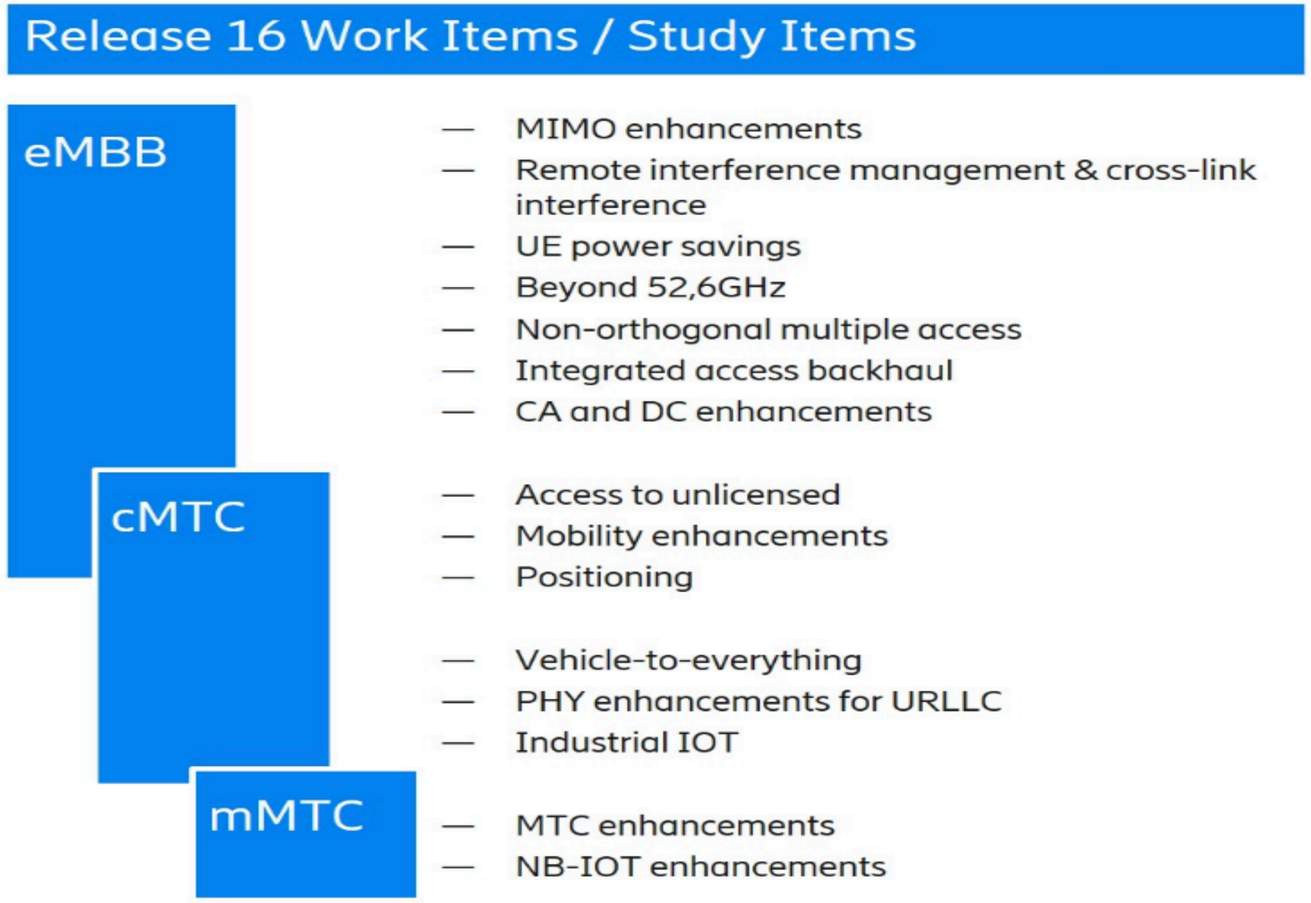
Phase 1

- NR
- New decomposed radio network architecture
- New modularized 5G core network
- Network slicing
- Multi-access Edge Computing (MEC)

Phase 2

- Integrated Access and Backhaul (IAB)
- Enhanced Vehicle-to-Everything (eV2X)
- NR-based use of unlicensed spectrum
- Non-Orthogonal Multiple Access (NOMA)
- Non-Terrestrial Systems

Release 16: Key Features



https://www.ericsson.com/en/blog/2018/9/5g-nr-release-16--start-of-the-5g-evolution

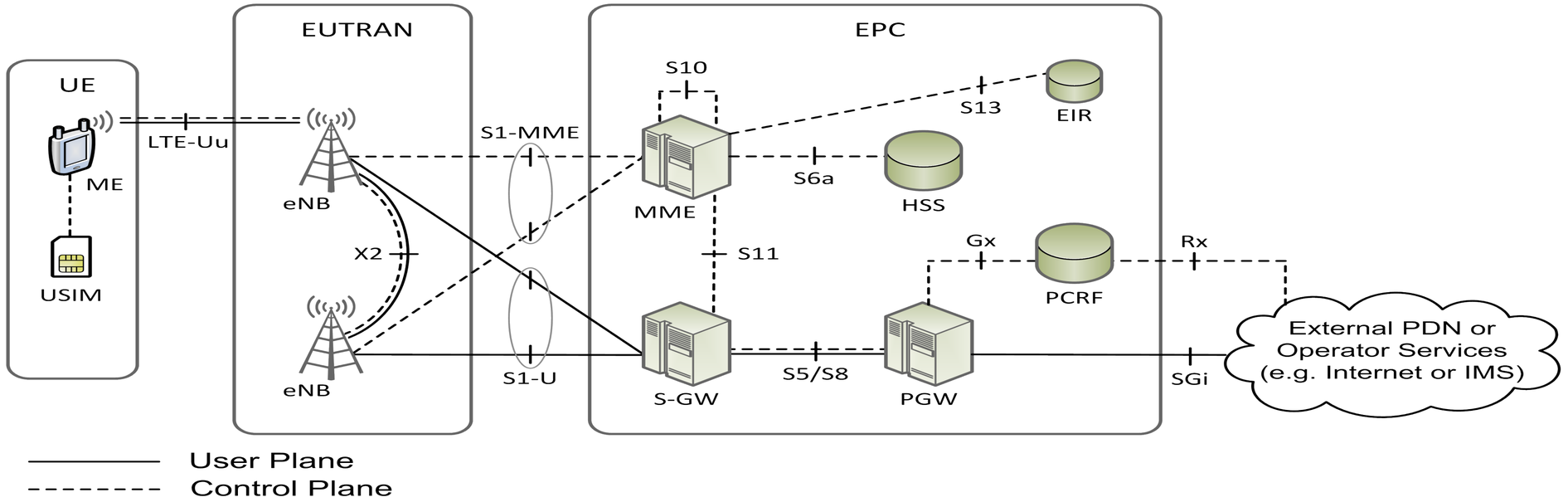
3GPP Release Schedule

3GPP Release	Date	Details
Release 99	Q1 2000	3G UMTS
Release 4	Q2 2001	UMTS all-IP Core
Release 5	Q1 2002	IMS and HSDPA
Release 6	Q4 2004	HSUPA, IMS Enhancements
Release 7	Q4 2007	HSPA+
Release 8	Q4 2008	LTE
Release 9	Q4 2009	LTE UMTS Interop.
Release 10	Q1 2011	LTE-Advanced
Release 11	Q3 2012	Hetnet, CoMP
Release 12	Q1-2015	Carrier Aggregation
Release 13	Q1 2016	LTE-U, LTE-LAA, LTE-M
Release 14	Mid 2017	CUPS
Release 15	End 2018	5G Phase 1
Release 16	End 2020	5G Phase 2 (URLLC)
Release 17	~Sept 2021	5G Enhancements

Table 1: 3GPP 5G Release Schedule

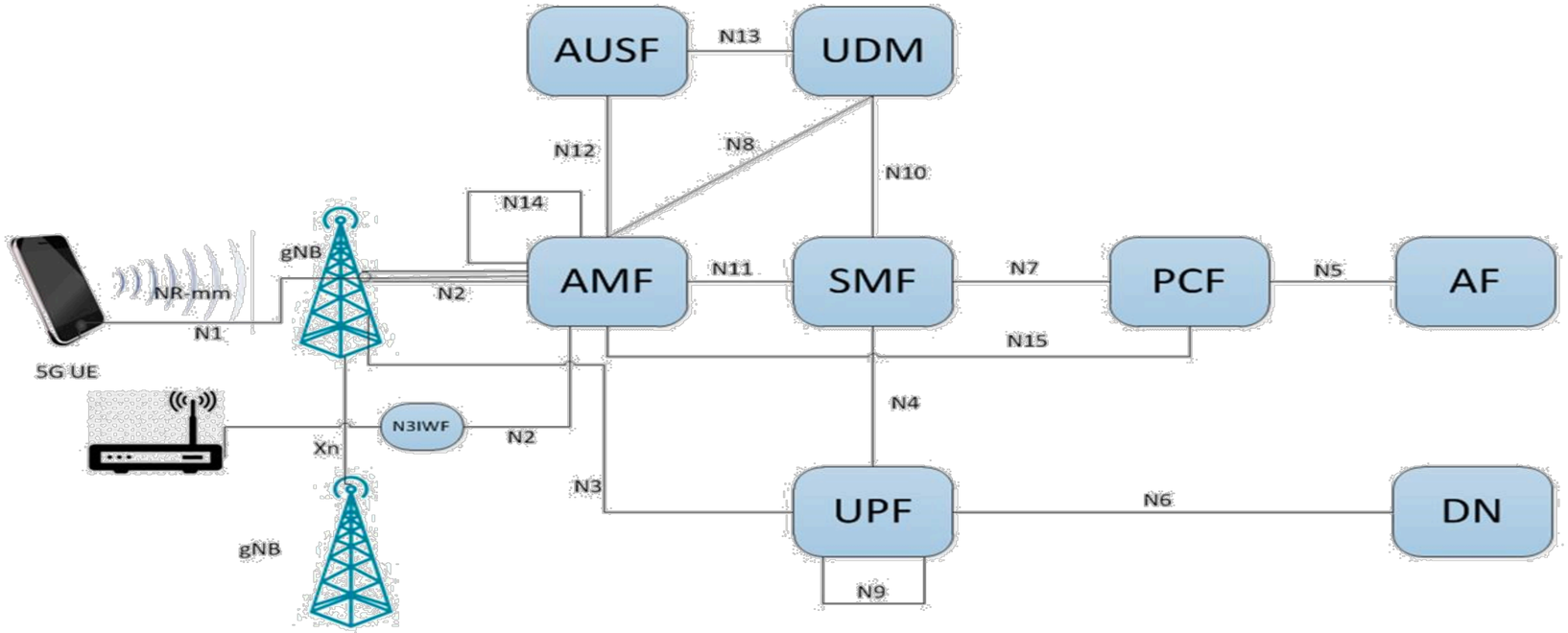
https://5g.security/5g-technology/5g-3gpp-releases-15-16-17/

Quick Review: 4G Network Architecture



Entity	Description
Serving Gateway	S-GW serves as user plane mobility anchor.
PDN Gateway	P-GW provides EPC connectivity with external systems
Mobility Management Entity	MME manage UE connections to the EPC
Home Subscriber Server	HSS stores user information (e.g. credential, roaming restrictions)
Policy Charging and Rules Function	PCRF responsible for policy control and flow-based charing control

5G Network Architecture



Component	Function
AMF	Access and Mobility Function
AUSF	Authentication Server Function
UDM	Unified Data Management
SMF	Session Management Function
UPF	User Plane Function
PCF	Policy Control Function
AF	Application Function
DN	Data Network
NG-RAN	Next-Generation RAN

- While previous trends were to condense network functions, the 5G network architecture emphasizes decomposition of functions and delineation of user plane and control plane functions
  - Goals:
    - Enable virtualization and software-defined approaches
    - Enable Network Slicing

5G Core (5GC) Network Elements

Component	Function	Closest 4G Equivalent
AMF	5G Core Access and Mobility Management Function	MME
AUSC	Subscriber authentication management	HSS
UDM	Stores Authentication Vectors	HSS
SMF	Session management, plus some control plane functions (allocation of IP addresses)	MME, S-GW, P-GW
UPF	User traffic transport functions. QoE Enforcement function	S-GW, P-GW
PCF	Provides policy rules for control plane function	PCRF
AF	Application influence policy and traffic routing	AF
DN	External Data Network	PDN

5GC vs. 4G EPC

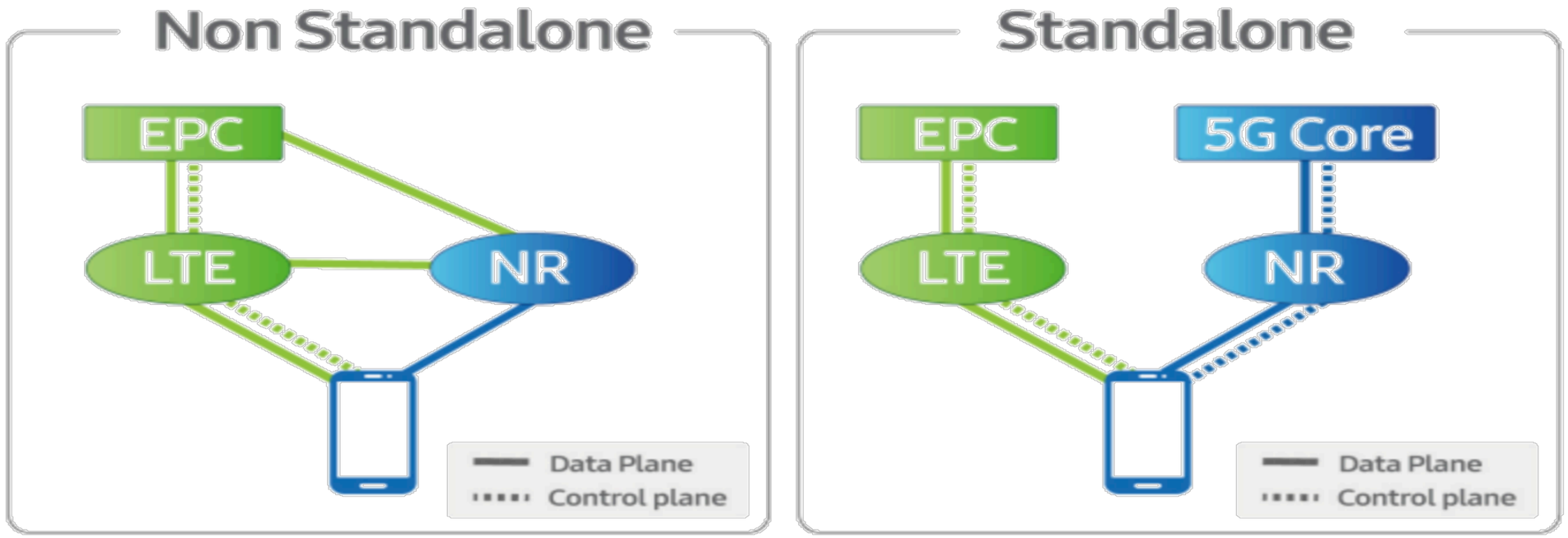
- Good paper describing the new 5GC and migration from 4G EPC to 5GC can be found at:
  - https://www.gsma.com/futurenetworks/wp-content/uploads/2018/04/Road-to-5G-Introduction-and-Migration_FINAL.pdf

Feature	EPC (4G Core)	5GC (5G Core)
Access Network interface	S1 with per UE assigned MME & SGW (in case of CUPS: single SGW-C and multiple SGW-U) & multiple PDN GWs ePDG and TWAG for non-3GPP access	N2/3 common to all access with per UE assigned AMF & multiple N3 to UPFs
Procedures	Access dependent procedures.	Unified registration, authentication, session management for 3GPP, non-3GPP access (including untrusted, trusted WLAN and in Rel 16 also fixed access), Common N1/N2/N3 for 3GPP and non-3GPP access, enabling seamless mobility
Network slicing	Single slice per UE with multiple PGW	E2E multiple slices per UE with shared AMF, slicing aware RAN and per slice SMF/UPF (potentially slice specific PCF, NRF, etc.)
QoS model	QCI based bearers	QoS flow based framework, including reflective QoS support
Cloud native	Possible but node based (box driven)	Native support for cloud based deployment with service based architecture and service-based interfaces within 5GC CP; Definition of NF services
Local applications	Support LIPA/SIPTO based deployment	Support for edge computing. Application influence on traffic routing.
Session/service continuity	Supports full IP address preservation for centralized GW or break before make solution for local GW (LIPA/SIPTO); service continuity with 2G/3G PS and SRVCC	Improved Session model including different Session and Service Continuity modes. Support for concurrent (e.g. local and central) access to a data network. No service continuity with 2G/3G PS and no support of SRVCC.
Policy framework	Support SM/QoS based policies	Unified Policy framework for Access and mobility control, QoS and charging enforcement, policy provisioning in the UE; introducing NWDA (Network Data Analytics) for data analytics support.
Services supported	SMS over NAS over 3GPP access, IMS services over 3GPP access and non-3GPP access, LCS, MPS, MCPTT, mobile broadband	SMS over NAS (including over Non- 3GPP), support of IMS services over 3GPP access and non-3GPP access, LCS, MPS, MCPTT, mobile broadband
Support for RRC INACTIVE state	Support not specified	Support for RRC inactive (RRC state machine includes 3 states: RRC IDLE, INACTIVE, CONNECTED)

The 5G Architecture: SA vs. NSA

- Non-Standalone (NSA): 5G Networks supported by existing 4G infrastructure
  - 5G UEs use 5G for data but use 4G for non-data functions

- Standalone (SA): 4G infrastructure not required



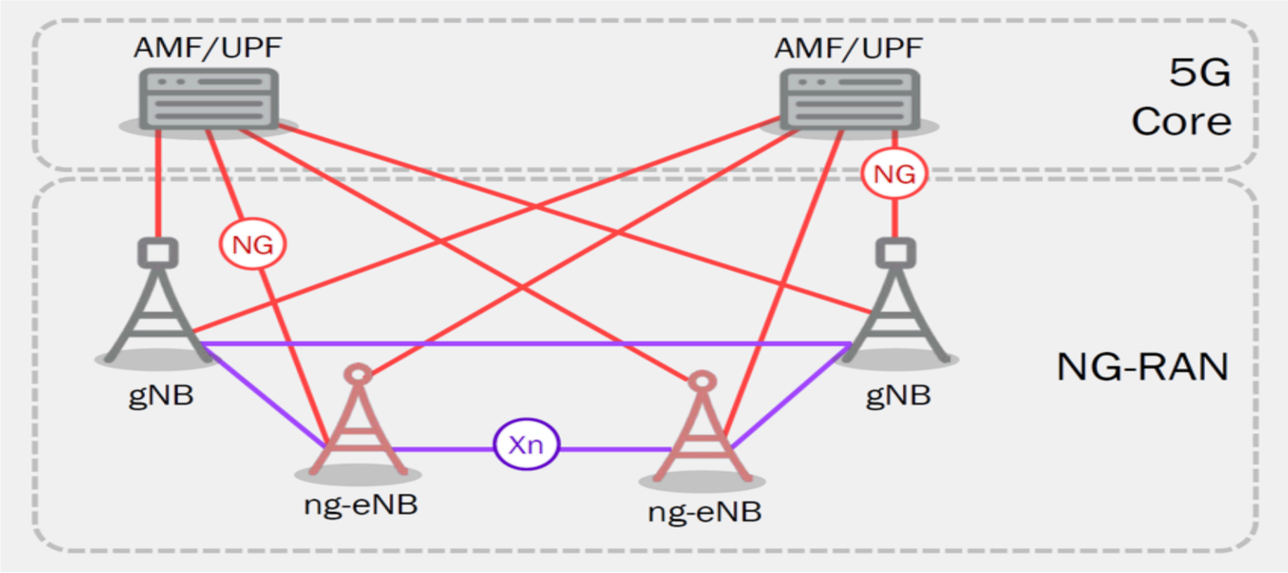
https://www.testandverification.com/5g-usage-scenarios-nsa-sa

The 5G Alphabet: G's, N's, and B's

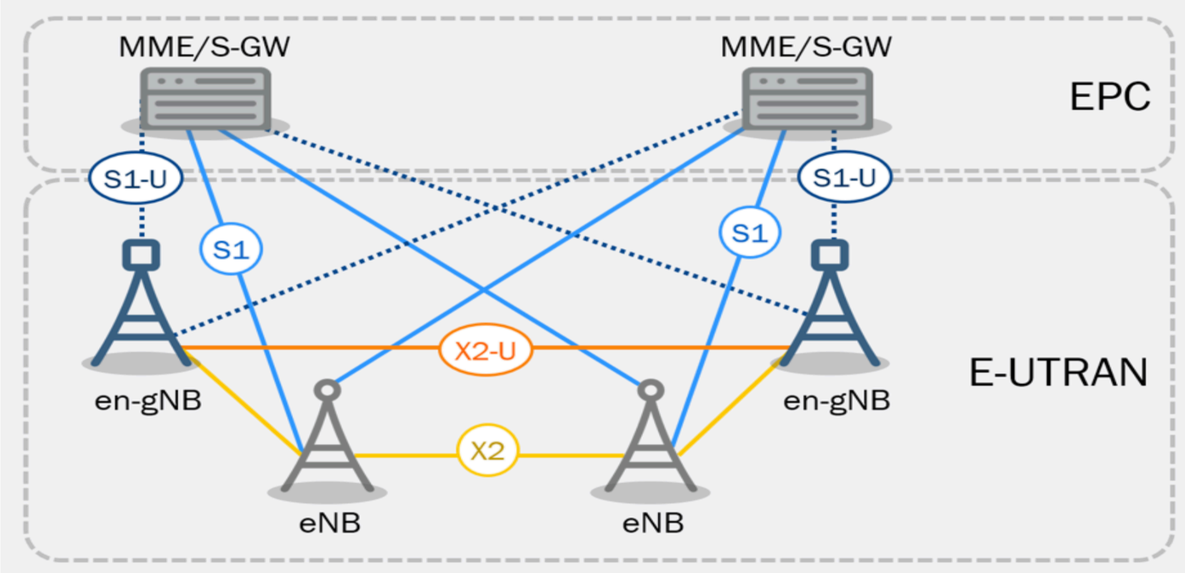
- Lots of different types of 5G cells in the 5G NG-RAN

Cell Type	Full Name	Description
gNB	Next-Generation Node B	Logical 5G Node B, equivalent of NodeB in 3G UMTS and eNB in 4G LTE
eNB	Evolved Node B	LTE-only cell
ng-eNB	Next-Generation eNB	Enhanced 4G eNB that connects to the 5GC Core Network
en-gNB	Session management, plus some control plane functions (allocation of IP addresses)	Supports dual-connectivity UEs
MeNB	Master Node	Controls UE radio connection. Supports dual-connectivity UEs
SgNB	Secondary Node	Supports dual-connectivity UEs
EN-DC	E-UTRA New Radio Dual Connectivity	Ues communicate with both cell types simultaneously.

Mixed 4G/5G RAN



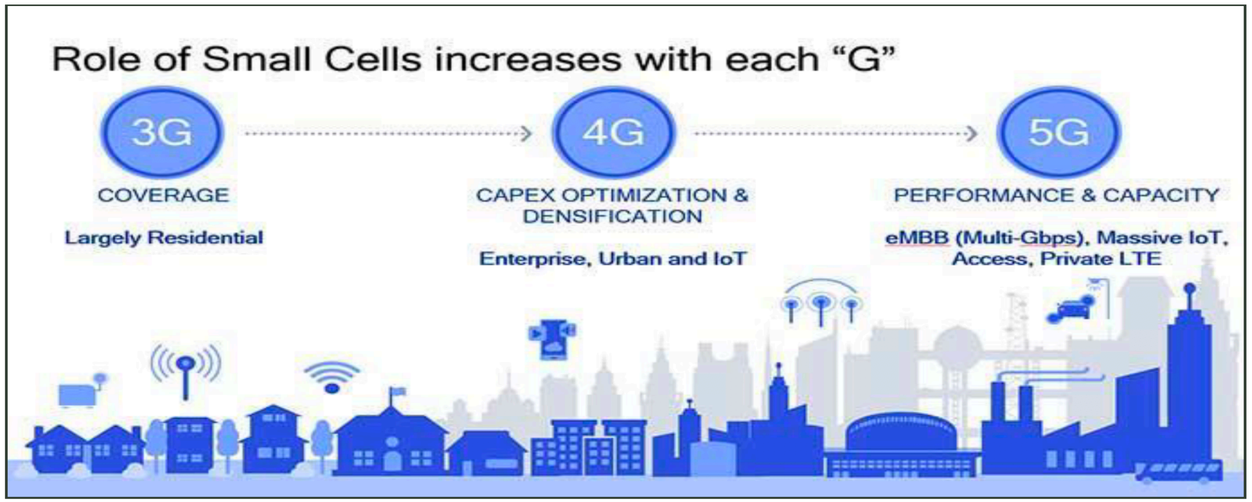
4G and 5G NBs communicating with the 5GC



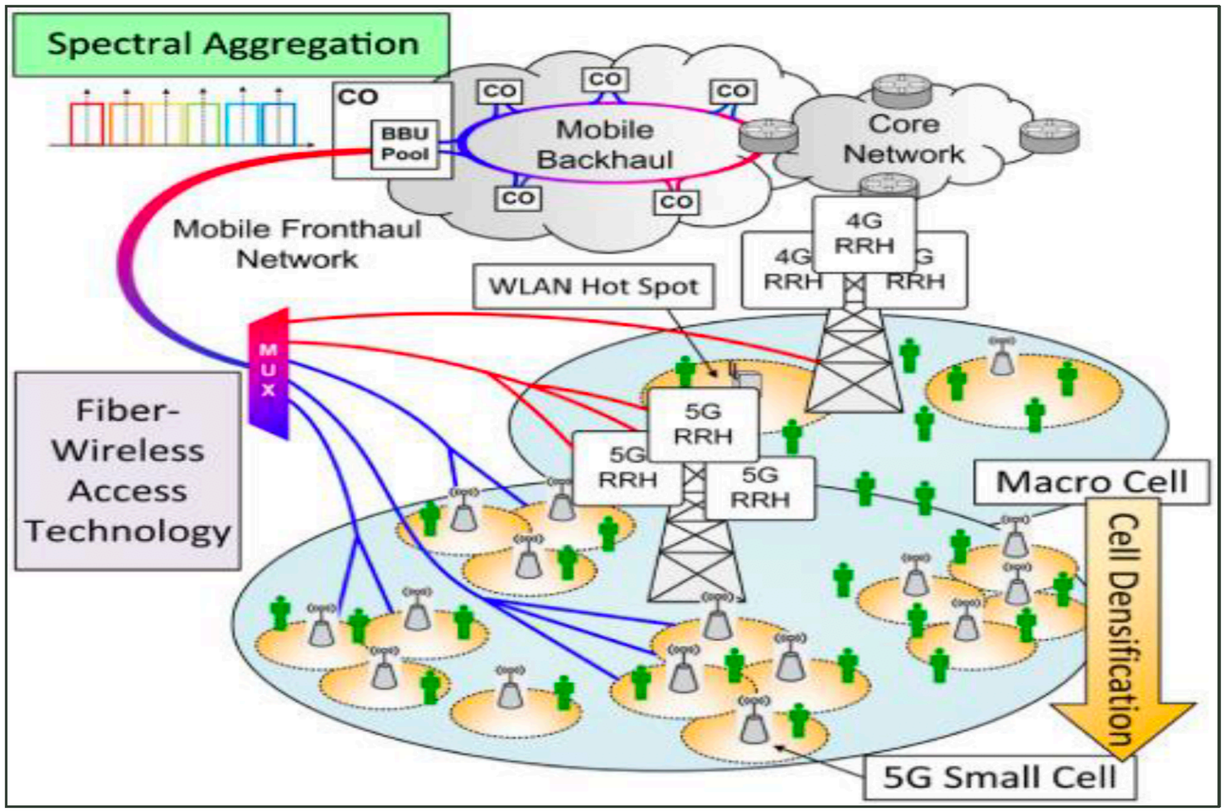
Dual Connectivity

Small Cell Networking

- Small cell networking allows for densification of networks for improved performance and capacity
  - 5G will use small cells for more than just filling in coverage gaps



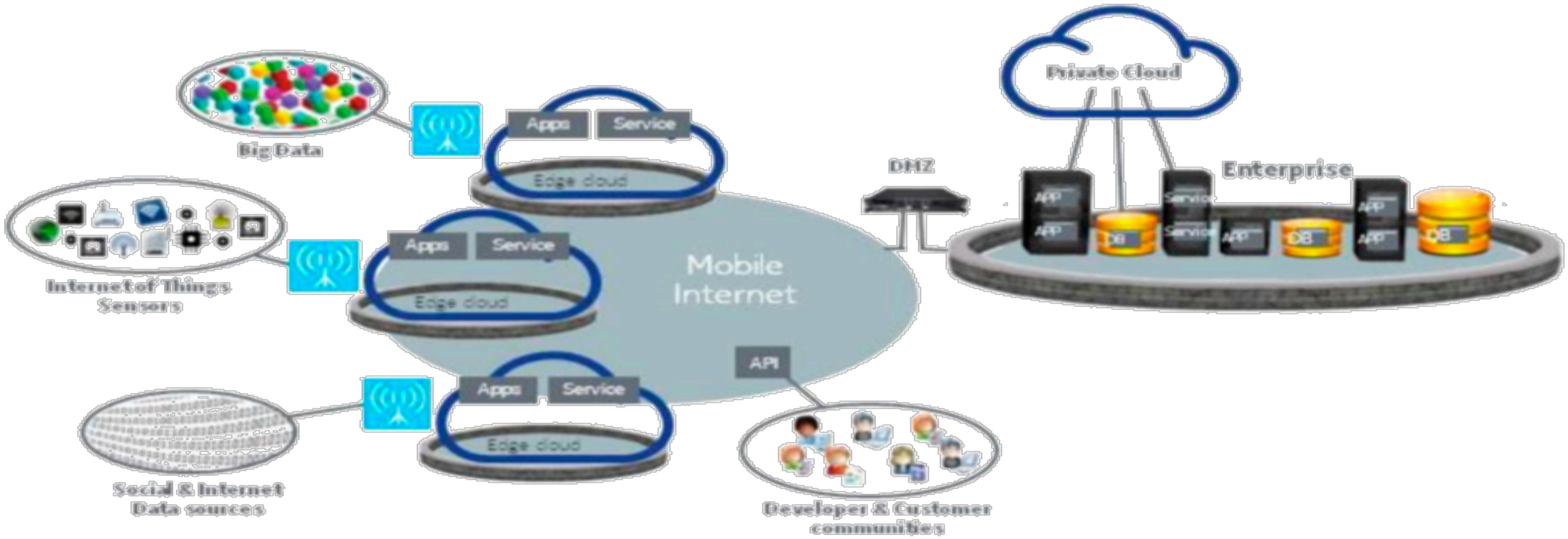
http://qualcomm.com/news/onq/2018/10/15/ubiquitous-5g-experiences-small-cells



M. Xu et al., "Bidirectional Fiber-Wireless Access Technology for 5G Mobile Spectral Aggregation and Cell Densification," IEEE Journal of Optical Communications and Networking, Vol. 8, Issue 12, 2016.

Multi-Access Edge Computing

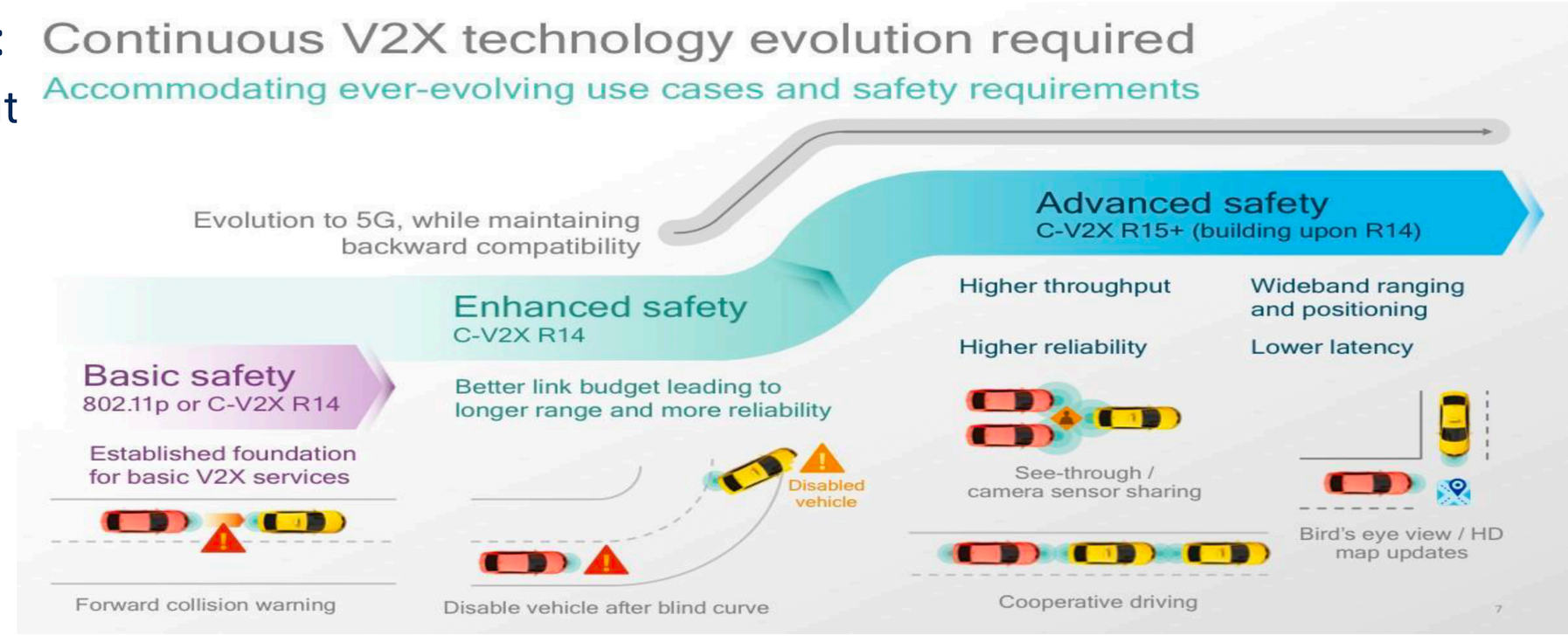
- The movement of applications closer to the edge (i.e. users)
  - Improves E2E latency performance
  - Improves user experience



Y. Hu et al., "Mobile Edge Computing: A Key Technology towards 5G," ETSI White Paper, September 2015.

Vehicle-to-Everything

- V2X technology being developed to provide:
  - Improved throughput
  - Higher reliability
  - Lower latency
- Key enabler for autonomous vehicles

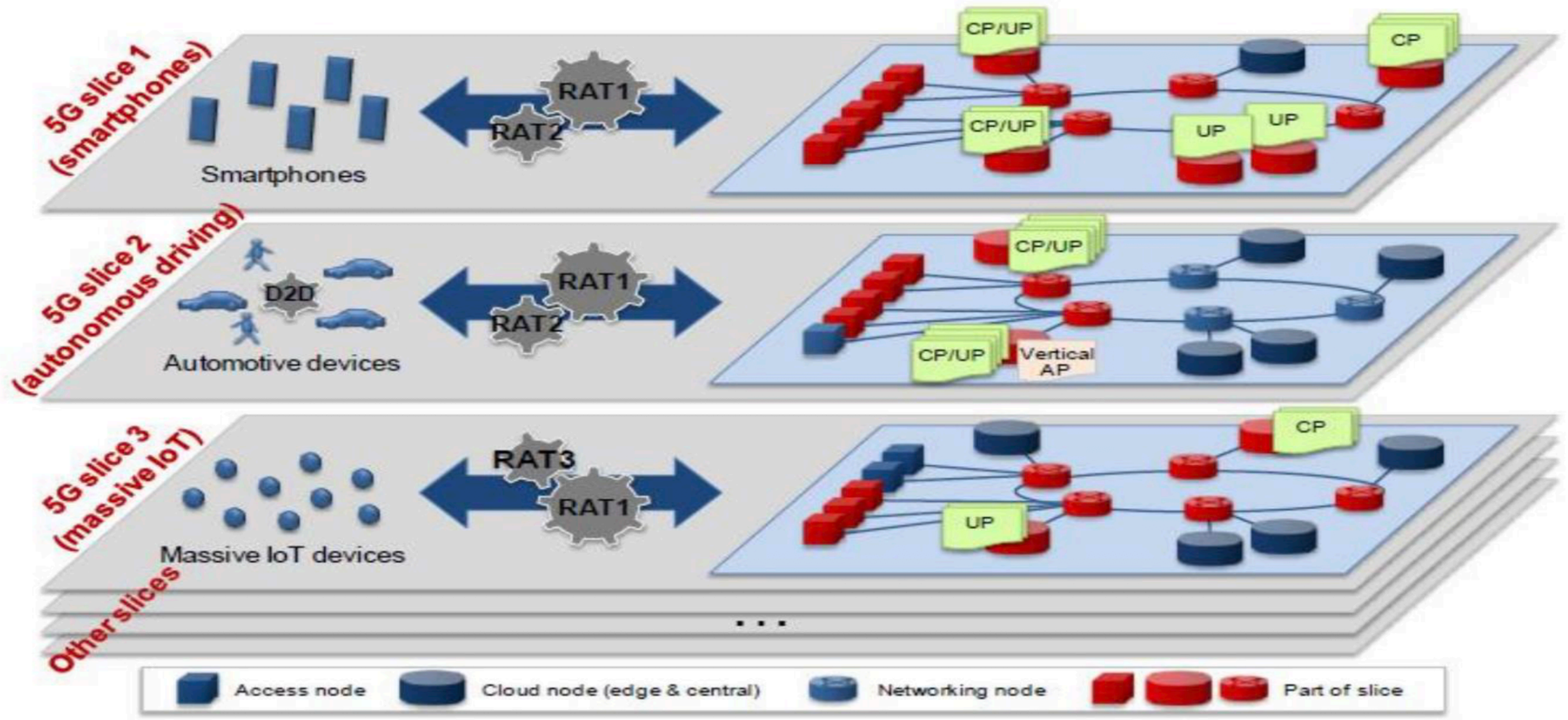


http://qualcomm.com/news/onq/2017/02/24/accelerating-c-v2x-toward-5g-autonomous-driving

- Great V2X tutorial can be found at:
  - https://site.ieee.org/swe-ctw/files/2019/06/20190611-5GCAR-Summer-School-5GCAR-Presentation_public.pdf

Network Slicing

- “Providing dedicated virtual networks with functionality specific to the service or customers over a common network infrastructure”



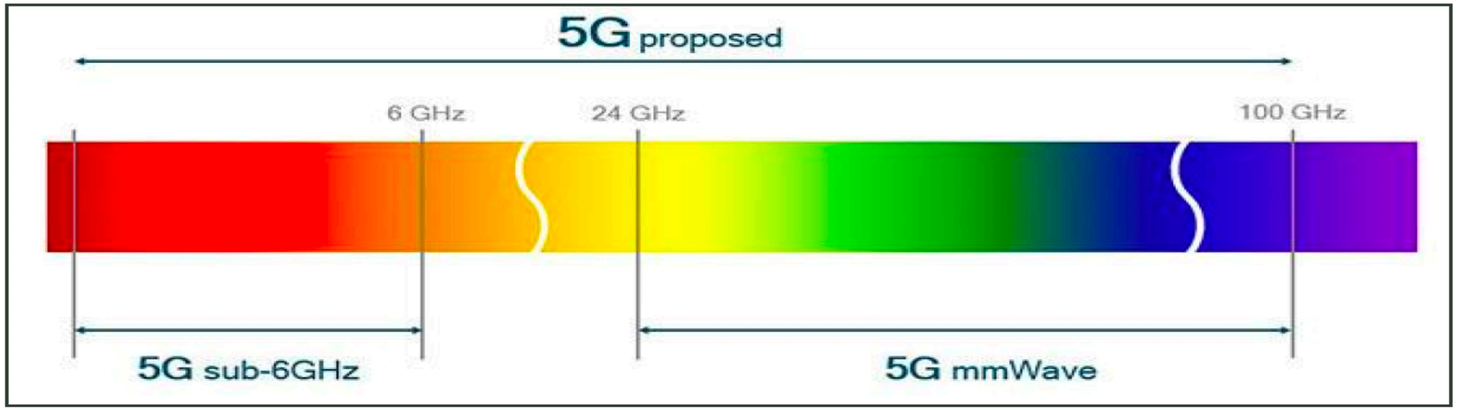
“TSN Profile for Network Slicing,” Huawei presentation, http://www.ieee802.org/1/files/public/docs2018/new-tsn-wangtt-TSN-profile-for-network-slicing-0718.pdf

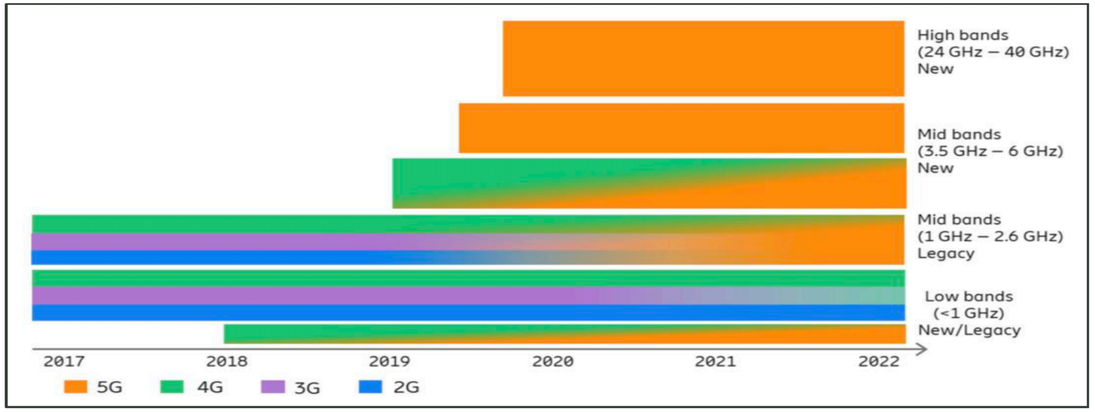
The 5G NG RAN: New Radio (NR)

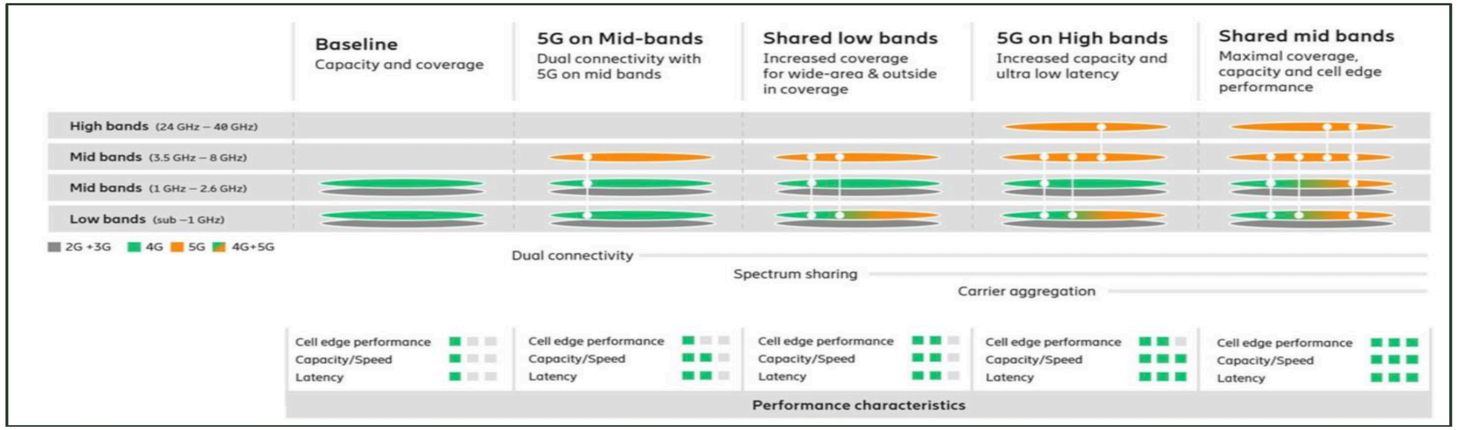
- New spectrum – sub-6 GHz and mmWave
- Massive MIMO and Beamforming
- Flexible Frame Structure
- Scalable OFDM
- Scalable numerology

5G Spectrum

- New spectrum opportunities for 5G
  - Millimeter wave (mmW)
  - New sub-6 GHz opportunities







http://www.ericsson.com/en/networks/trending/hot-topics/5g-spectrum-strategies-to-maximize-all-bands

5G Spectrum (continued)

- More available spectrum
- New shared spectrum models
- New unlicensed spectrum models

Range	Band	Frequency Band	Bandwidth	Frequency Range
Low	71	600 MHz	81 MHz	617MHz - 698MHz
	44	700 MHz	100 MHz	703 MHz - 803 MHz
Mid	66	(AWS) 1700.2100 MHz	100 MHz	1710-1780 and 2110-2200 MHz
	40	2.3 GHz	100 MHz	2.3 – 2.4 GHz
	41	2.5 GHz BRS/EBS in US	194 MHz	2496 - 2690 MHz
	42	3.5 GHz	200 MHz	3400 - 3600 MHz
	43	3.6 GHz	200 MHz	3600 - 3800 MHz
	C-band	4.4 GHz	590 MHz	4400 - 4499 MHz
High	n258	24 GHz mmWave	3.25 GHz	24.25 - 27.5 GHz
	n257	26 GHz mmWave	3.00 GHz	26.5 - 29.5 GHz
	n261	28 GHz mmWave	850 MHz	27.5 - 28.35 GHz
	n260	37 GHz mmWave	1 GHz	37.0 - 38.6 GHz
	n260	39 GHz mmWave	2 Ghz	38.0 – 40.0 GHz
	n257	47 GHz mmWave	1 GHz	47.2 - 48.2 GHz

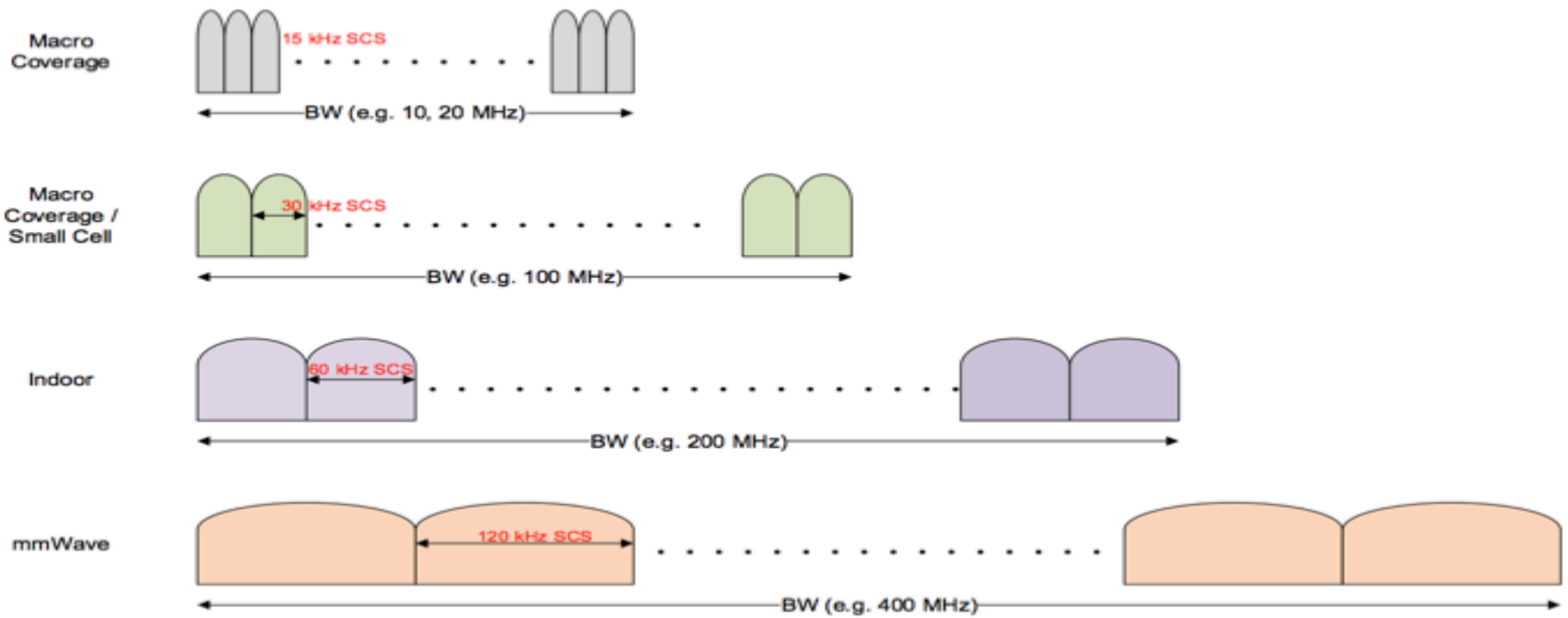
Source: 5G Americas, 3GPP 5GNR NSA specification and Wireless 20/20, December 2018

Spectrum Bands	Licensed	Shared	Unlicensed
Low-band ***Below 1 GHz*** *Limited capacity with large area coverage and indoor penetration*	*600 MHz US* *700 MHz EU*		
Mid-band ***1 – 6 GHz*** *Good for urban deployment with increased capacity*	*AWS (Band 66)* *2.5 GHz* *3.3 - 4.3 GHz* *4.4 - 4.99 GHz*	*3.5 GHz CBRS US* *3.7-4.2 GHz US* *5.9-7.1 GHz US.*	*5-5.9 GHz*
High-band ***Above 20 GHz*** *Limited coverage with potential for very high capacity*	*4.25 - 29.5 GHz* *27.5-28.35 GHz* *37-38.6 GHz* *38.6-40 GHz*	*37-37.6 GHz* *57-71 GHz*	*64-71 GHz*

Source: Wireless 20/20, December 2018

Scalable Numerology

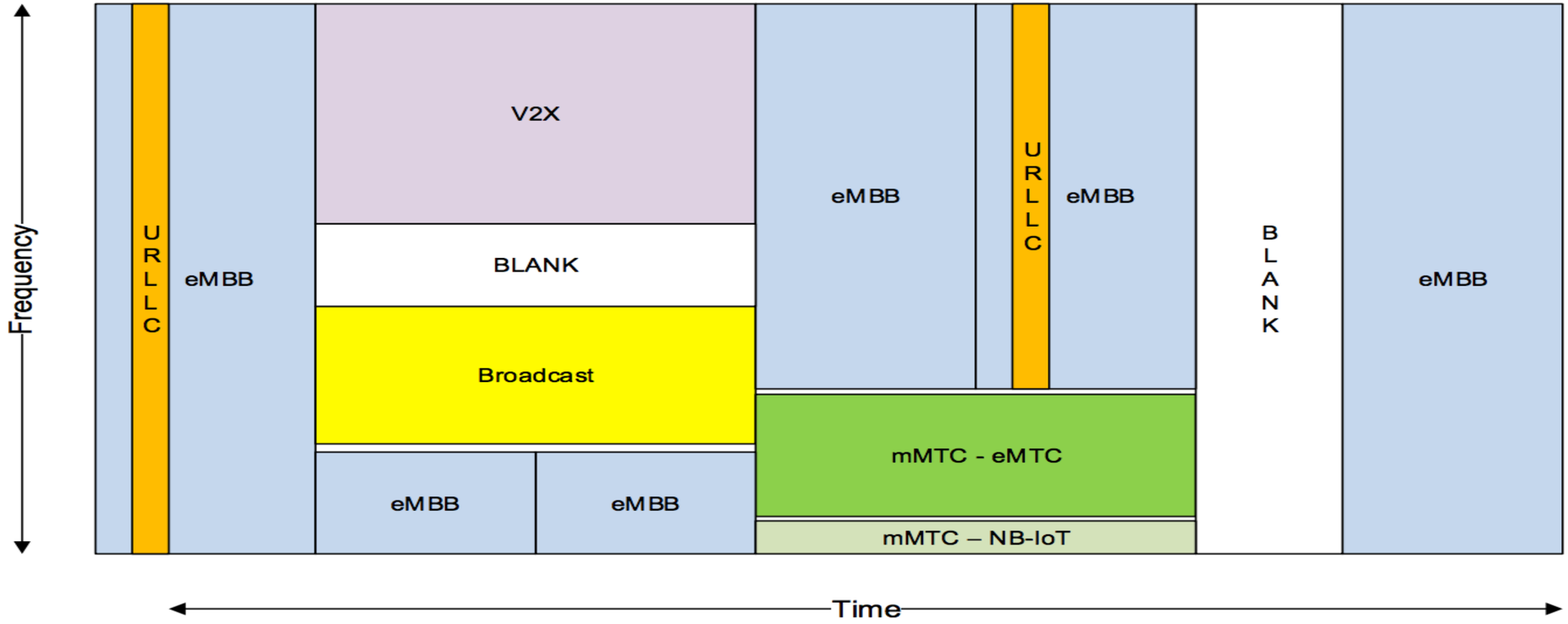
- The NR interface supports variable OFDM sub-carrier spacings to address different circumstances (e.g. spectrum, bandwidth, deployment)
  - 15 kHz, 30 kHz, 60 kHz, 120 kHz



A. Ghosh, Nokia Networks, "5G NR: Physical Layer Overview and Performance," IEEE Communications Theory Workshop, May 2018.

Flexible Resource Allocation

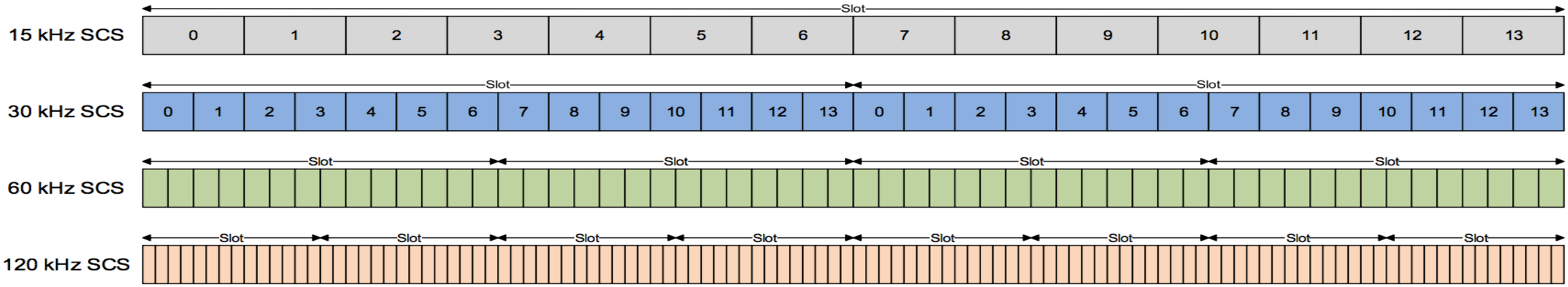
- The 5G NG air interface allows for flexible allocation of resources to support different service types and QoS requirements
  - Scalable slot duration
  - Traffic preemption for URLLC



A. Ghosh, Nokia Networks, “5G NR: Physical Layer Overview and Performance,” IEEE Communications Theory Workshop, May 2018.

Scalable Slot Durations

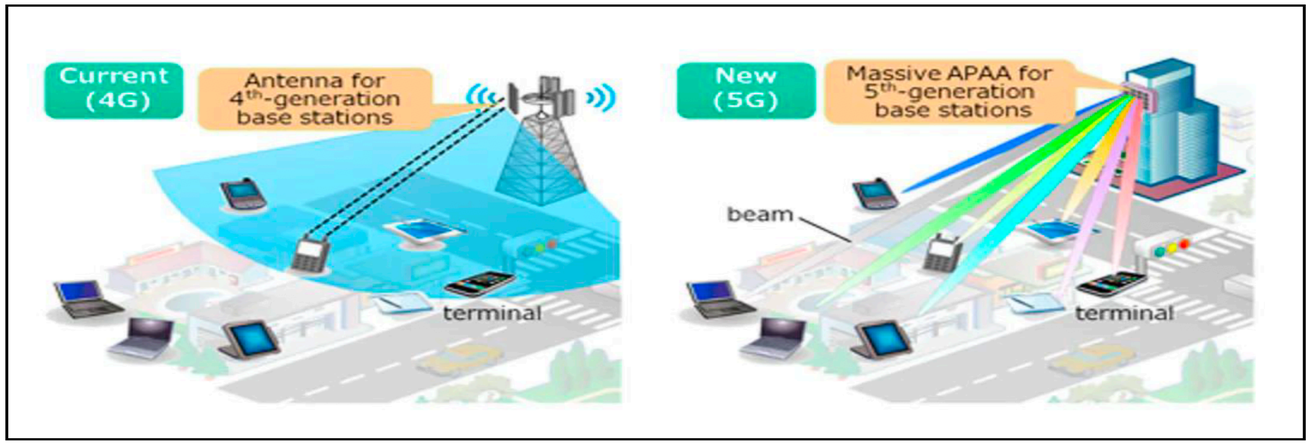
- The 5G NG air interface provides flexible slot duration structure for different transmission types
  - One slot is 14 symbols – slot length depends on sub-carrier spacing
  - Mini-slots can be allocated for shorter transmissions
  - Slots can be aggregated for longer transmissions



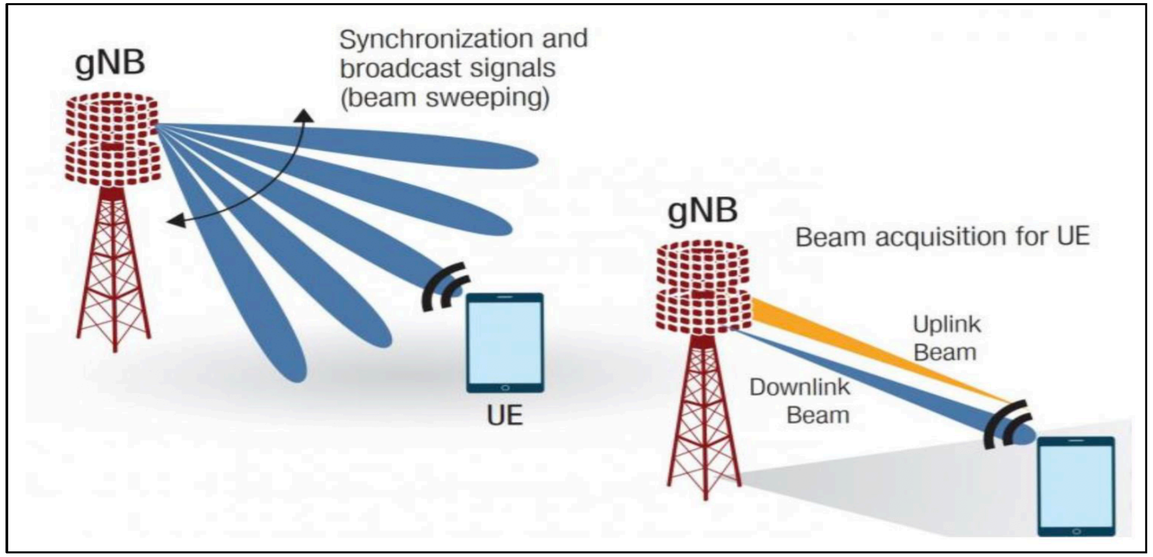
A. Ghosh, Nokia Networks, "5G NR: Physical Layer Overview and Performance," IEEE Communications Theory Workshop, May 2018.

Massive MIMO

- Massive MIMO enables higher data rates and improved RF link performance
- Beamforming allows for improved co-cell interference management



http://www.inverse.com/article/53624-do-cell-phones-cause-cancer-maybe-maybe-not



http://www.ecnmag.com/article/2018/05/fact-or-fiction-whats-real-5g-new-radio

Massive MIMO in 5G NR

Release 8	Release 9	Release 10	Release 11
• 4x4MIMO • 4x2MIMO • 8RX uplink • Uplink CRAN	• 8TX TM8	• 8TX TM9	• Downlink CoMP (TM10)

Release 12	Release 13	Release 14	Release 15+
• Downlink eCoMP • New 4TX codebook	• Massive MIMO 16TX	• Massive MIMO 32TX	• 5G / NR Massive MIMO 32TX+

A. Ghosh, Nokia Networks, “5G NR: Physical Layer Overview and Performance,” IEEE Communications Theory Workshop, May 2018.

High-Level Comparison between NR and LTE

	LTE	NR
Frequency of Operation	Up to 6 GHz	Up to 6 GHz, ~28 GHz, ~39 GHz, other mmWave bands (Upto 52 GHz)
Carrier Bandwidth	Max: 20 MHz	Max: 100 MHz (at <6 GHz) Max: 1 GHz (at >6 GHz)
Carrier Aggregation	Up to 32	Up to 16
Analog Beamforming (dynamic)	Not Supported	Supported
Digital Beamforming	Up to 8 Layers	Up to 12 Layers
Channel Coding	Data: Turbo Coding Control: Convolutional Coding	Data: LDPC Coding Control: Polar Coding
Subcarrier Spacing	15 kHz	15 kHz, 30 kHz, 60 kHz, 120 kHz, 240 kHz
Self-Contained Subframe	Not Supported	Can Be Implemented
Spectrum Occupancy	90% of Channel BW	Up to 98% of Channel BW

https://spectrum.ieee.org/telecom/wireless/3gpp-release-15-overview

The 5G Security Architecture

- Primarily defined by TS 33.501
- Key differences from 4G LTE security model
  - Less exposure of user ID (IMSI / SUPI)
  - Migration towards PKI approach rather than symmetric shared secret key approaches
  - Minimization of information in pre-authentication signaling
  - Mandatory integrity protection on the user plane
- 5G authentication procedure utilizes Extensible Authentication Protocol (EAP)
  - Used for both primary authentication procedure and secondary authentication
    - Secondary authentication used for user plane connections
- Community divided on impact of network slicing on security
  - Some believe it allows opportunity for advanced quarantine response procedures
  - Some believe it provides larger attack surface

The 5G Security Architecture

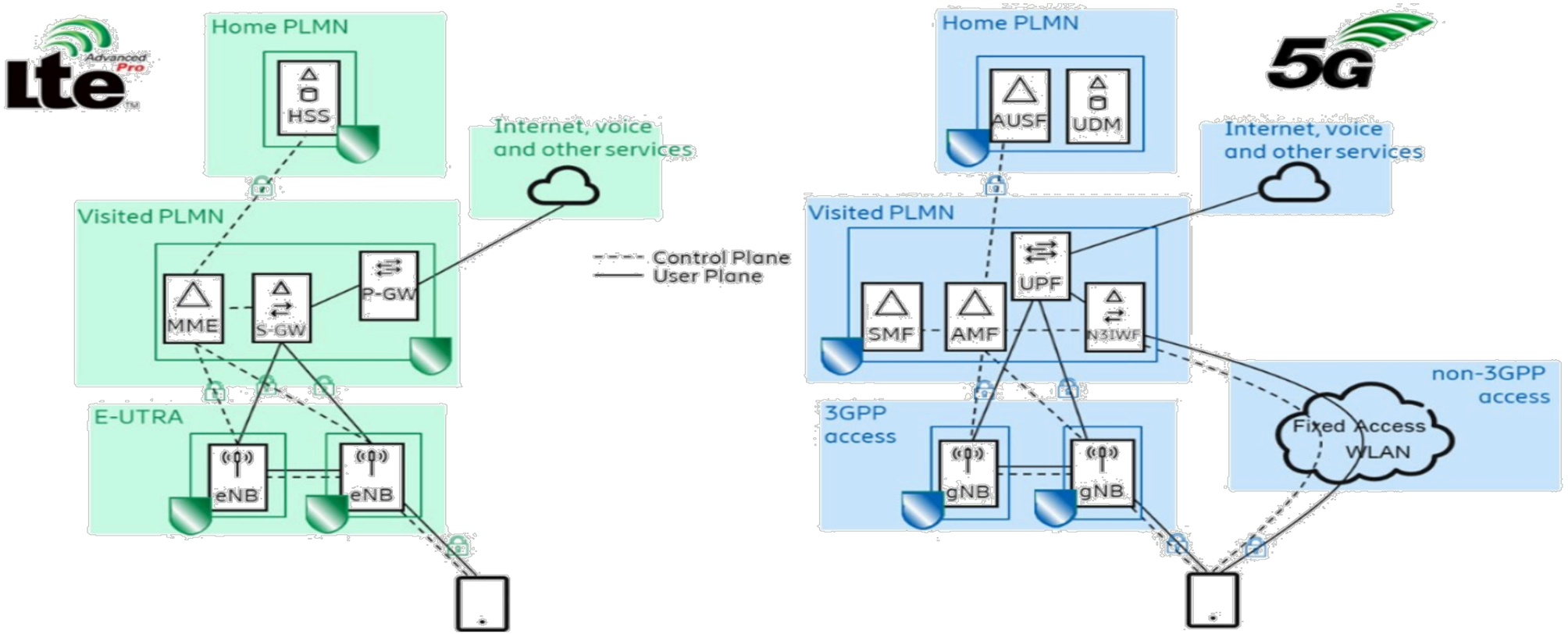


Figure 1: Simplified security architectures of LTE and 5G showing the grouping of network entities that needs to be secured in the Home Network and Visited Network and all the communication links that must be protected.

https://www.ericsson.com/en/blog/2019/7/3gpp-5g-security-overview

The 5G Security Architecture

- Security Edge Protection Proxy: SEPP: All signaling traffic across operator networks will transit through these security proxies
- Authentication between SEPPs is mandatory: Enables effective traffic filtering through the interconnect
- New N32 interface application layer security solution: Aims to protect information while still allowing inter-networking

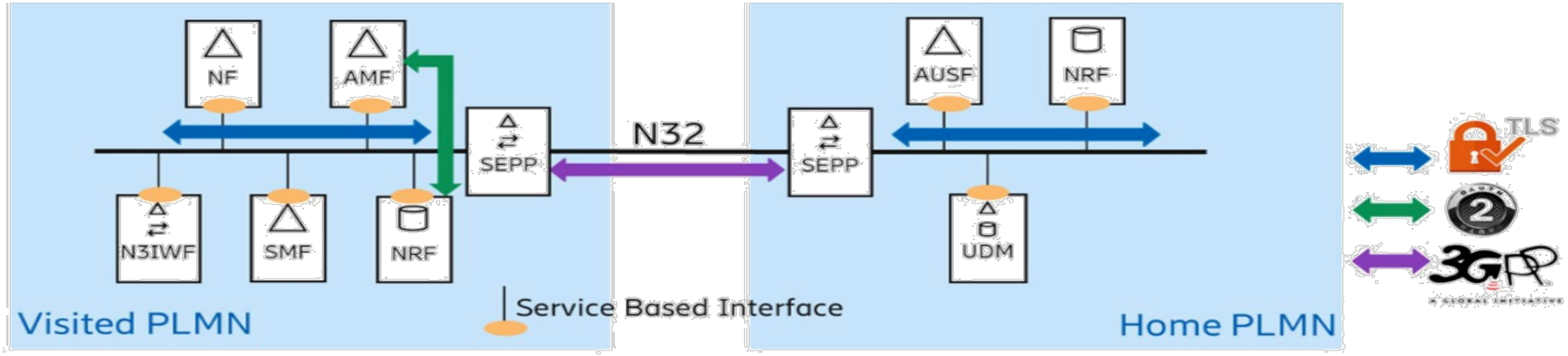


Figure 2: Simplified service-based architecture for the 5G system in the roaming case

https://www.ericsson.com/en/blog/2019/7/3gpp-5g-security-overview

Section 4:
Next-generation WLANS

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Overview of IEEE 802

- IEEE 802 is the “Local Area Network (LAN) and Metropolitan Area Network (MAN) standards committee”
  - Working-group based
  - Parliamentary procedure
  - Develops PAN/LAN/MAN/WAN standards

- Ethernet (IEEE 802.3)
- Token Ring (IEEE 80.5)
- Wireless Local Area Networks (WLAN) (IEEE 802.11)
- Wireless Personal Area Networks (WPAN) (IEEE 802.15)
- Wireless Regional Area Networks (WRAN) (IEEE 802.16)

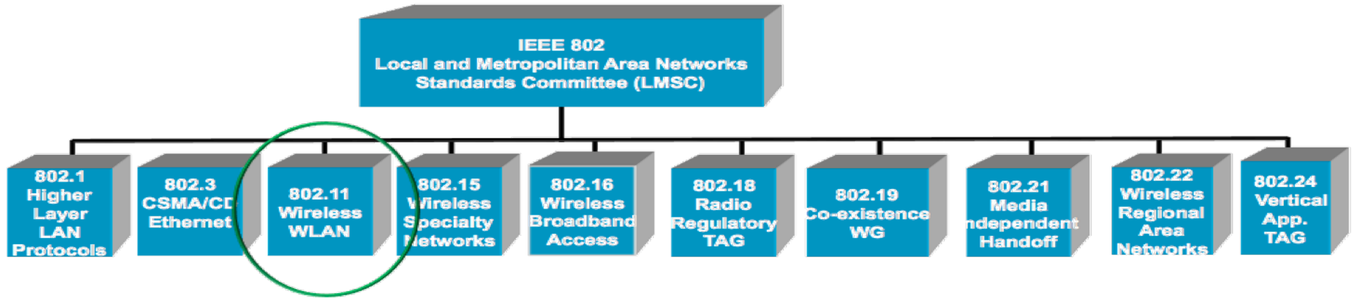
- All working groups can be found at http:www.ieee802.org

The IEEE 802 Standards Process

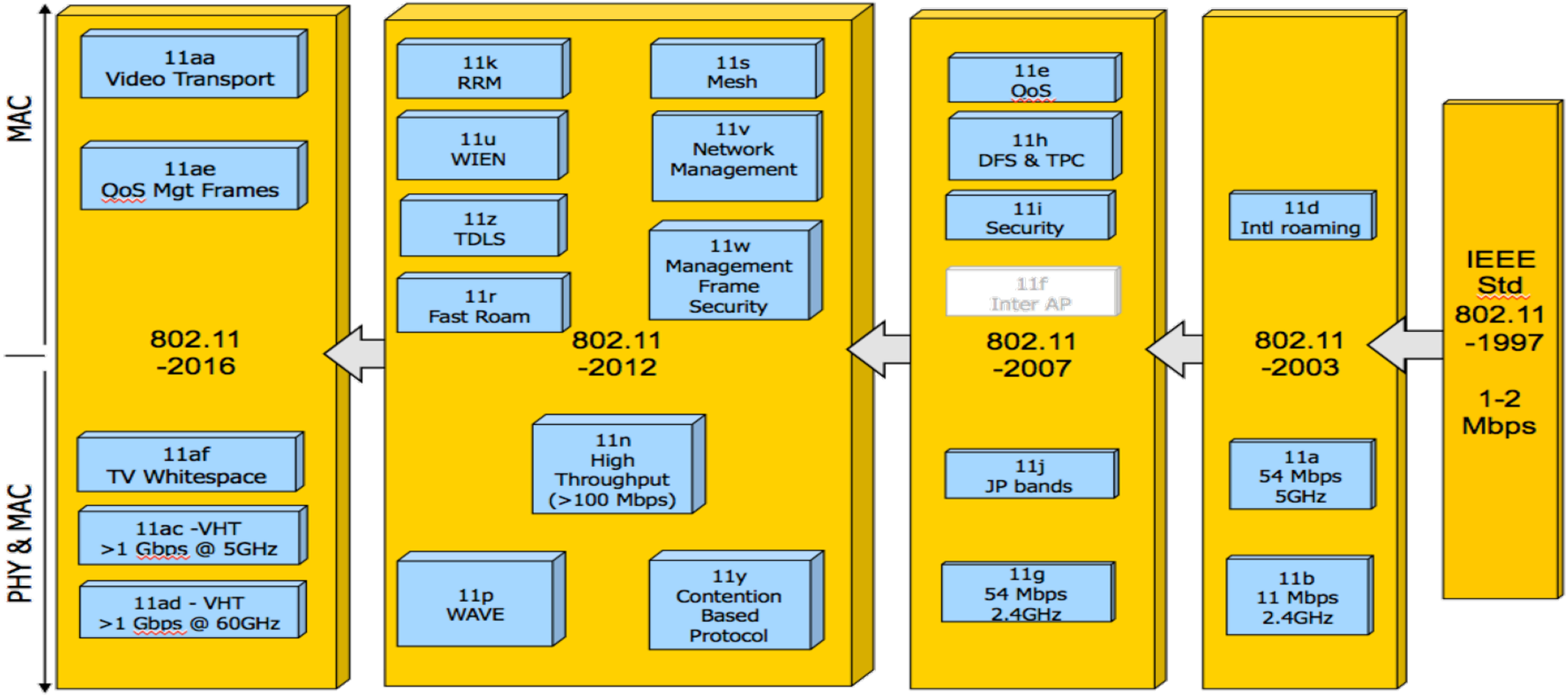
- Standards development activity begins in the form of a Study Group
- The members of the study group then decide if it wants to standardize a technology
- If so, it can then become a Task Group (TG)
- Before a TG can be formed, formal IEEE approval must be obtained
- IEEE approval requires two documents that have achieved working group consensus
  - Project Authorization Request (PAR)
    - Delineates scope of proposed TG, goals, deliverables, etc.
  - ‘5 Criteria’
    - There are five criteria that must be met before a formal technology standards process can begin
      - Broad Market Potential
      - Compatibility
      - Distinct Identity
      - Technical Feasibility
      - Economic Feasibility
- A typical timeline for a technology to become an 802 standard is typically 5 years

Overview of IEEE 802.11

- Defines PHY and MAC layer protocols for WLANS
- “Task Groups” define different PHY implementations of the protocol, clarifications to current IEEE 802.11 standards, address Quality-of-Service (QoS), security, etc.
- Current Task Groups:
  - ME – Maintenance / Revision
  - AX – High Efficiency Wireless LAN
  - AY – Next-Generation 60 GHz
  - AZ – Next-Generation Positioning
  - BA – Wake-up Radio
  - BB – Light Communications
  - BC – Enhanced Broadcast Service
  - BD – Enhancements for Next-Generation V2X
  - BE – Extremely High Throughput
  - BF – WLAN Sensing (SENS)
  - BH – Randomized and Changing MAC Addresses (RCM)
  - BI – Enhanced Data Privacy (EDP)



IEEE 802.11 Standards



"IEEE 802.11 Overview and Amendments under Development," http://grouper.ieee.org/groups/802/11/IEEE%20802-11-Overview-and-Amendments-Under-Development.pptx

The Wi-Fi Alliance

- "Wi-Fi" is an 802.11 marketing term that has become synonymous with 802.11 WLANs

- The Wi-Fi Alliance was formed in 1999 as a non-profit international organization to certify interoperability of IEEE 802.11 WLAN products
  - Acts as an advocate for IEEE 802.11-based technology

- Hundreds of member companies
- Over 50,000 certifications issued to date
- "Wi-Fi Certified" logos are found on 802.11 product packages

- More information at: http://www.wi-fi.org

Wi-Fi Generational Names

- Wi-Fi 4: IEEE 802.11n-based products
- Wi-Fi 5: IEEE 802.11ac-based products
- Wi-FI 6: IEEE 802.11ax-based products

IEEE 802.11ax

- IEEE 802.11ax aims to increase spectral efficiency over previous IEEE 802.11 specifications and to provide increased throughput in the 2.4 GHz, 5 GHz, and 6 GHz bands

- IEEE 802.11ax places emphasis on performance in extremely dense environments
  - Targets at least 4x throughput performance compared to 802.11n and 802.11ac

- PHY and MAC layer modification to the base IEEE 802.11-2016 specification

IEEE 802.11ax

Spectral Efficiency & Area Throughput

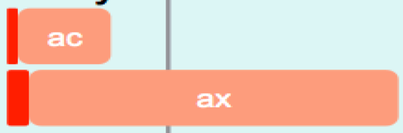
1024 QAM
25% increase
in data rate

DL/UL MU-MIMO
w/ 8 clients

8x8 AP

2x increase
in throughput

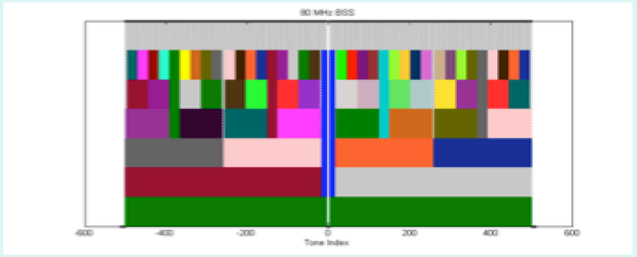
Long OFDM Symbol



Up to 20%
increase
in data rate

High Density

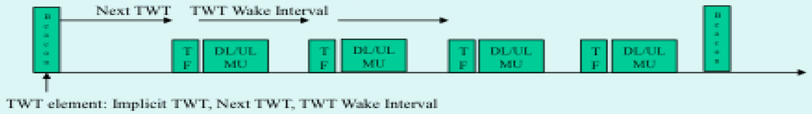
OFDMA



Spatial Reuse

Power Saving

Scheduled sleep and wake times

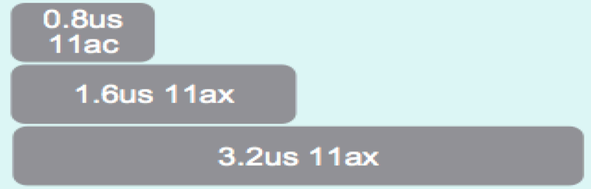


20 MHz-only clients

Outdoor / Longer range

Extended range packet structure

Enhanced delay spread protection- long guard interval



"IEEE 802.11 Overview and Amendments under Development," http://grouper.ieee.org/groups/802/11/IEEE%20802-11-Overview-and-Amendments-Under-Development.pptx

IEEE 802.11ax – 5G Indoor HotSpot

	Metric	ITU-R Evaluation Method	Minimum Requirement	802.11ax Performance
1	Peak data rate	Analytical	DL/UL : 20/10 Gbps	DL/UL : 20.78 Gbps [Note 1]
2	Peak spectral efficiency	Analytical	DL/UL : 30/15 bits/s/Hz	DL/UL : 58.01 bits/s/Hz [Note 2]
3	User experienced data rate	Analytical for single band and single layer; Simulation for multi-layer	Not applicable for Indoor Hotspot	Not applicable
4	5th percentile user spectral efficiency	Simulation	DL/UL : 0.3/0.21 bits/s/Hz	DL/UL : 0.45/0.52 bits/s/Hz [Note 3]
5	Average spectral efficiency	Simulation	DL/UL : 9/6.75 bits/s/Hz/TRxP	DL/UL : 9.82/13.7 bits/s/Hz/TRxP [Note 3]
6	Area traffic capacity	Analytical	DL : 10 Mbit/s/m^2	Required DL bandwidth = 170 MHz with 3 TRxP/ site. [Note 4]
7	Mobility	Simulation	UL : 1.5 bits/s/Hz	UL : 9.4 bits/s/Hz
8	Bandwidth	Inspection	100 MHz, scalable	20/40/80/80+80/160 MHz
9	User plane latency	Analytical	DL/UL : 4 ms	DL/UL : 80 us [Note 5]

“IEEE 802.11 Overview and Amendments under Development,” http://grouper.ieee.org/groups/802/11/IEEE%20802-11-Overview-and-Amendments-Under-Development.pptx

IEEE 802.11be

- Amendment that builds on IEEE 802.11ax
- Extremely high throughput – up to 30 Gbps
- Extremely low-latency communications
- Operations in the 2.4 GHz, 5 GHz, and 6 GHz bands
- Use Cases: AR/VR, 4K/8K video streaming, cloud computing
- Targeted Completion: 2023

IEEE 802.11bd

- IEEE 802.11bd is defining MAC and PHY enhancements from IEEE 802.11n, ac, and ax to provide a backwards compatible next-generation V2X protocol

- Aims to eventually be basis of next-generation DSRC technology
  - DSRC – Dedicated Short Range Communications (DSRC): current vehicular network standard
  - Currently based on IEEE 802.11p

- Key goals:
  - Higher throughput (2x) than IEEE 802.11p
  - Longer range
  - Support for positioning
  - Backwards compatibility with IEEE 802.11p

Finally…

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Concluding Statements

5G technologies such as 3GPP NR and WiFi 6 represent a significant evolution in wireless communications

5G technologies offer several key performance capabilities

- Extremely high data rates
- Extremely low latency
- Extremely high reliability
- Extreme scalability

Capabilities offered by 5G will likely enable an entire new generation of applications

- Autonomous vehicles
- Internet of Things
- Distributed Machine Learning
- Distributed / Remote Everything...

Commercial momentum is strong

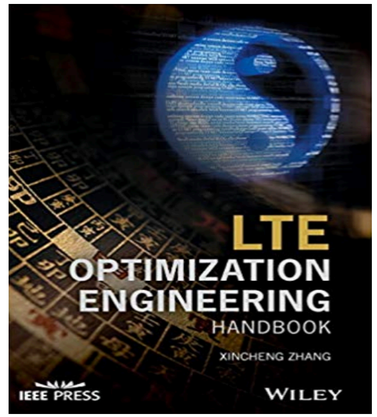
- Healthy eco-system
- Quickly growing product base

However, 5G is surrounded by confusion and hype

Market will determine final form of 5G

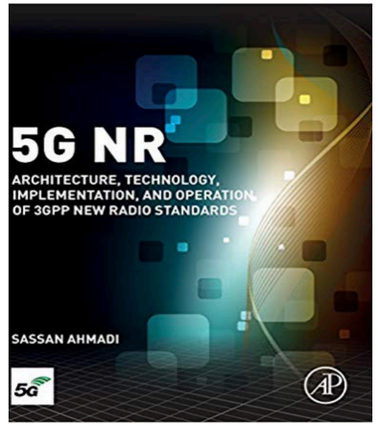
Resources

- LTE Optimization Engineering Handbook, X. Zhang, Wiley/IEEE Press, January 2018.

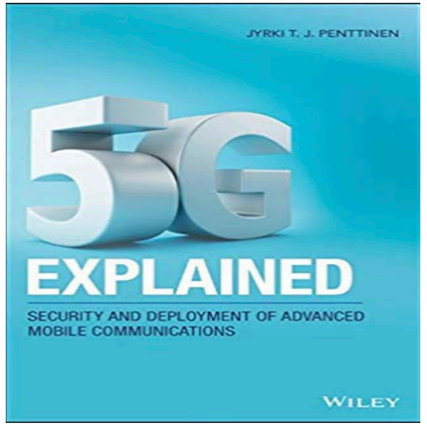


- 5G New Radio in Bullets by C. Johnson, Independently published, July 2019.

- 5G NR: Architecture, Technology, Implementation, and Operation of 3GPP New Radio Standards, 1st Edition, by S. Ahmadi, by B. Ramsundar and R. Zadeh, O'Reilly, June 2019.



- 5G Explained: Security and Deployment of Adbanced Mobile Communications, 1st Edition, J. Penttinen, April 2019.



http://www.rfindustries.com/resources/articles/how-RFIndustries-is-building-5G-wireless-networks.php