GLOBAL 5G: IMPLICATIONS OF A TRANSFORMATIONAL TECHNOLOGY

5G AMERICAS REPORT PROVIDED BY RYSAVY RESEARCH

Key Conclusions (1)

Development	Summary
5G Deployment Has Begun	Operators globally have begun deploying 5G in a variety of bands, including low-band, mid-band, and mmWave bands. 5G smartphones are now available.
First 5G Standard Completed	Key aspects of the 5G NR have been determined, such as radio channel widths and use of OFDMA. The first version, specified in Release 15 in 2018, supports low-latency, beam-based channels, massive Multiple Input Multiple Output (MIMO) with large numbers of controllable antenna elements, scalable-width subchannels; carrier aggregation, cloud Radio-Access Network (RAN) capability; network slicing, and co-existence with LTE.
Subsequent 5G Standards in Development	3GPP is working on Release 16, with completion scheduled for 2020, adding mission-critical communications, integrated access and backhaul, vehicle communications, support for unlicensed bands, and various efficiency and performance enhancements. 3GPP this year will also define the features for Release 17, scheduled for release in 2021.
Harnessing Spectrum Never Before Feasible	Radio methods including massive MIMO and beamforming are enabling use of spectrum above 6 GHz that was never previously feasible for cellular networks. The huge amounts of spectrum above 6 GHz will result in wider channels with correspondingly faster data rates, capacity gains, or a combination thereof.

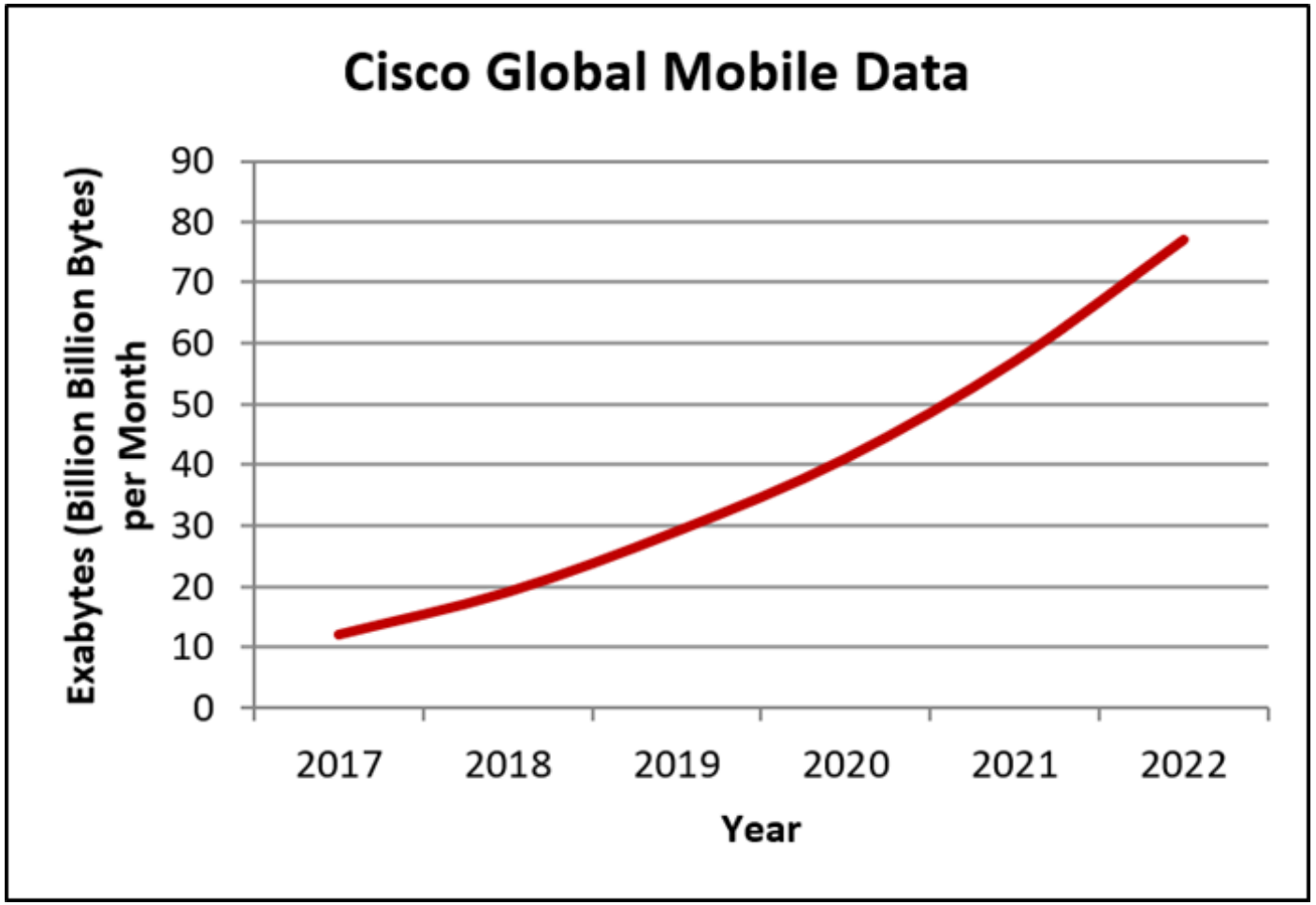
Key Conclusions (2)

Development	Summary
Spectrum Remains Essential	Spectrum in general, and licensed spectrum in particular, remains essential for the industry. Forthcoming new spectrum in the United States includes the 3.5 GHz Citizens Broadband Radio Service (CBRS), the first mmWave licenses at 24 GHz and 28 GHz, additional mmWave auctions in late 2019 (37, 39, 47 GHz), and mid-band spectrum within 3.7 GHz to 4.2 GHz (C-Band).
Unlicensed Spectrum Becomes More Tightly Integrated with Cellular	The industry has also developed and is now deploying versions of LTE that can operate in unlicensed spectrum, such as LTE-Unlicensed (LTE-U), LTE-Licensed Assisted Access (LTE-LAA), and MulteFire. NR support for unlicensed spectrum will be implemented in Release 16 of the 5G standard.
Internet of Things Poised for Wide-Scale Adoption	IoT, evolving from machine-to-machine (M2M) communications, is seeing rapid adoption, with tens of billions of new connected devices expected over the next decade. Drivers include improved LTE support, such as low-cost and low-power modems, enhanced coverage, higher capacity, and service-layer standardization, such as oneM2M. 5G IoT support includes higher density, greater reliability, longer battery life, and network slicing.

Key Conclusions (3)

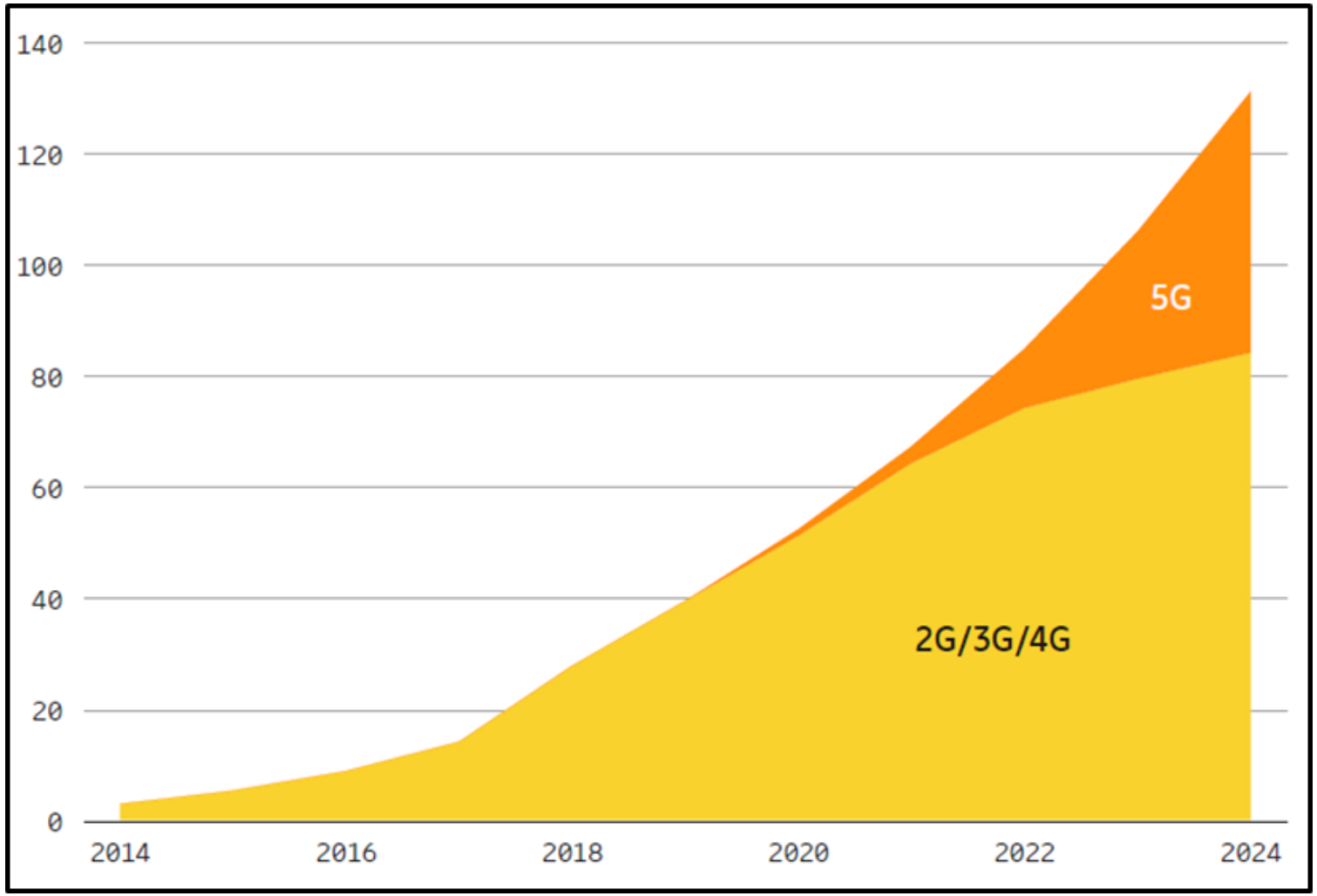
Development	Summary
Small Cells Accelerating	Operators have begun installing small cells, which now occupy over 100,000 outdoor sites in the United Sates. Eventually, hundreds of thousands, if not millions, of small cells will increase capacity and provide a viable alternative to wireline broadband. The industry is slowly overcoming challenges that include restrictive regulations, site acquisition, self-organization, interference management, power, and backhaul, but deployment remains a challenge.
Network Function Virtualization (NFV) Emerges and Proves Central to 5G	Network function virtualization (NFV) and software-defined networking (SDN) tools and architectures are enabling operators to reduce network costs, simplify deployment of new services, reduce deployment time, and scale their networks. Some operators are also virtualizing the radio-access network as well as pursuing a related development called cloud radio-access network (cloud RAN). NFV and cloud RAN are integral components of 5G.
5G Potential Synergistic with AI	Artificial intelligence will optimize network efficiency, make devices easier to use, enable new applications, and leverage a hybrid architecture of central cloud, edge clouds, and device computing capability.

Global Mobile Data 2017 to 2022



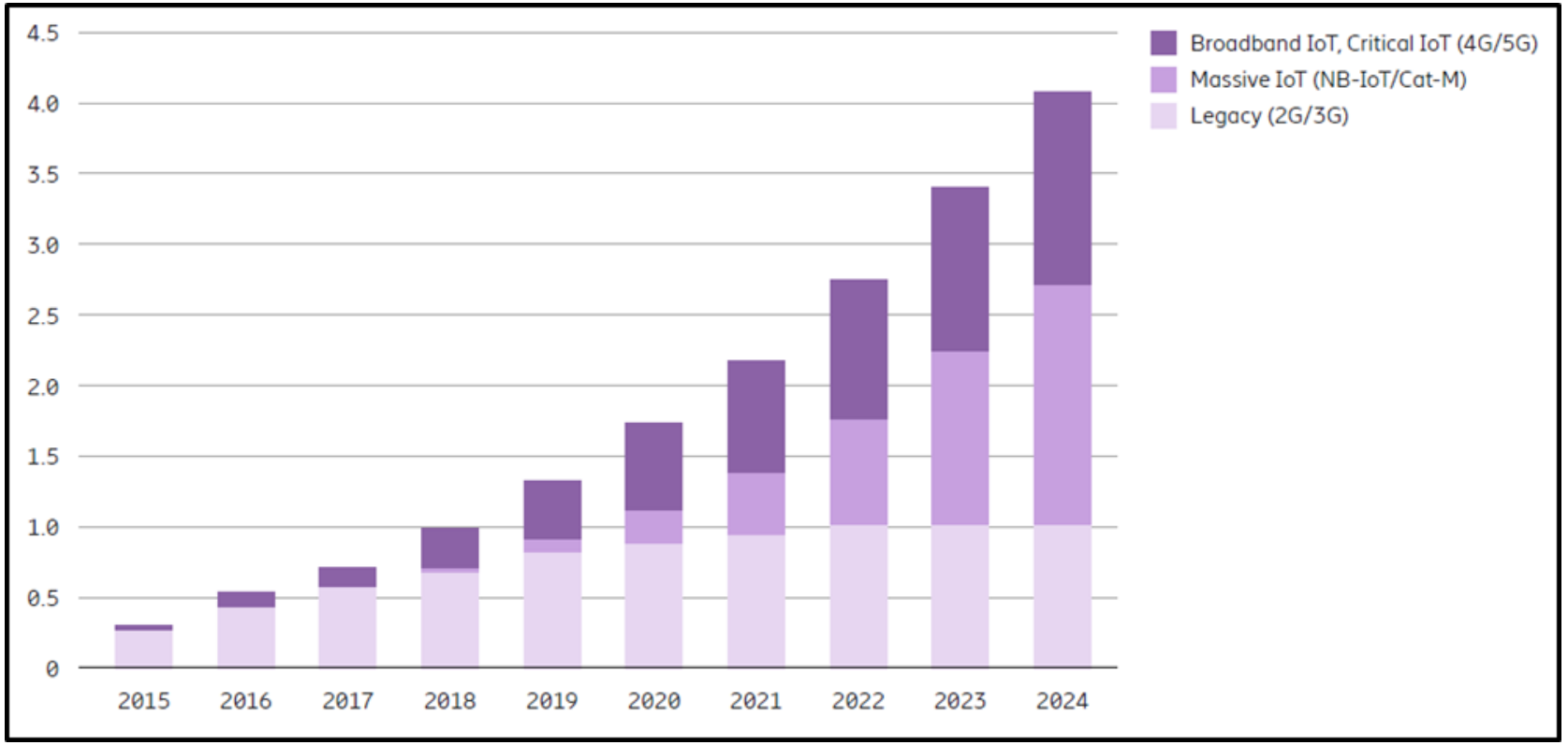
Cisco *Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2017-2022*, Feb. 2019.

Global Mobile Data Traffic (Exabytes/Month) 2014 to 2024



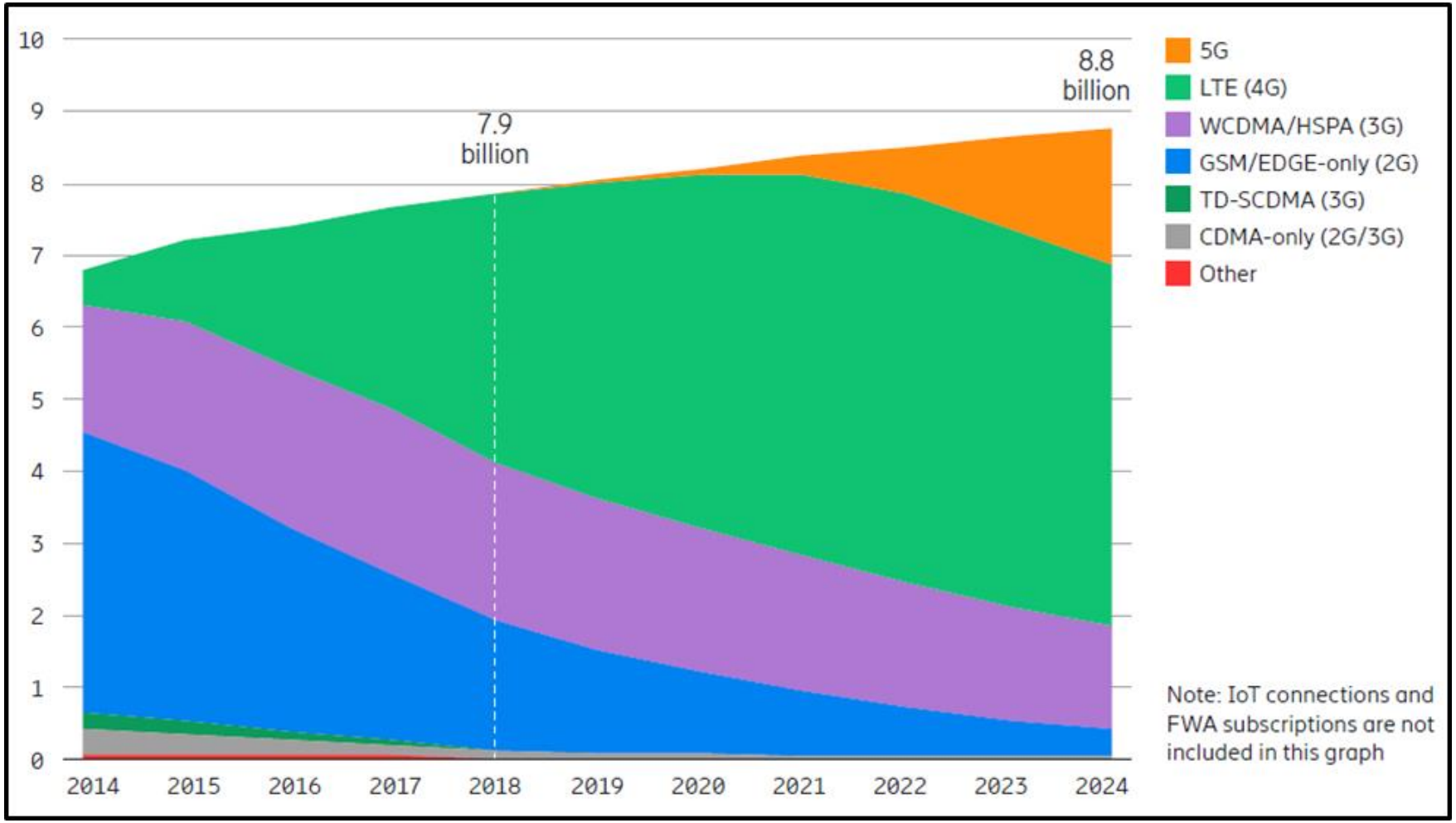
Ericsson Mobility Report, Jun. 2019.

Cellular IoT Connections by Segment and Technology (Billions)



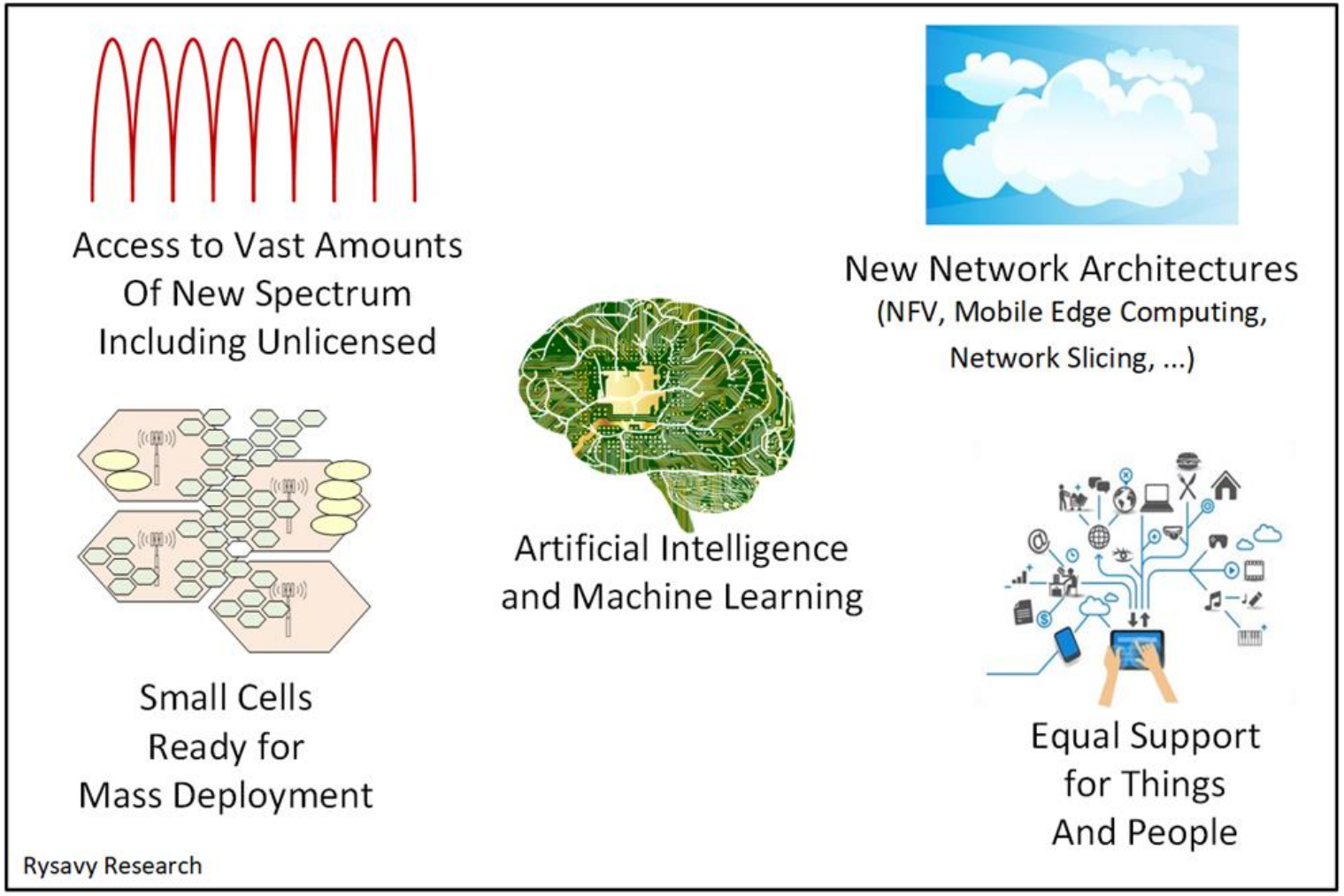
Ericsson Mobility Report, Jun. 2019.

Mobile Subscriptions by Technology (Billions)

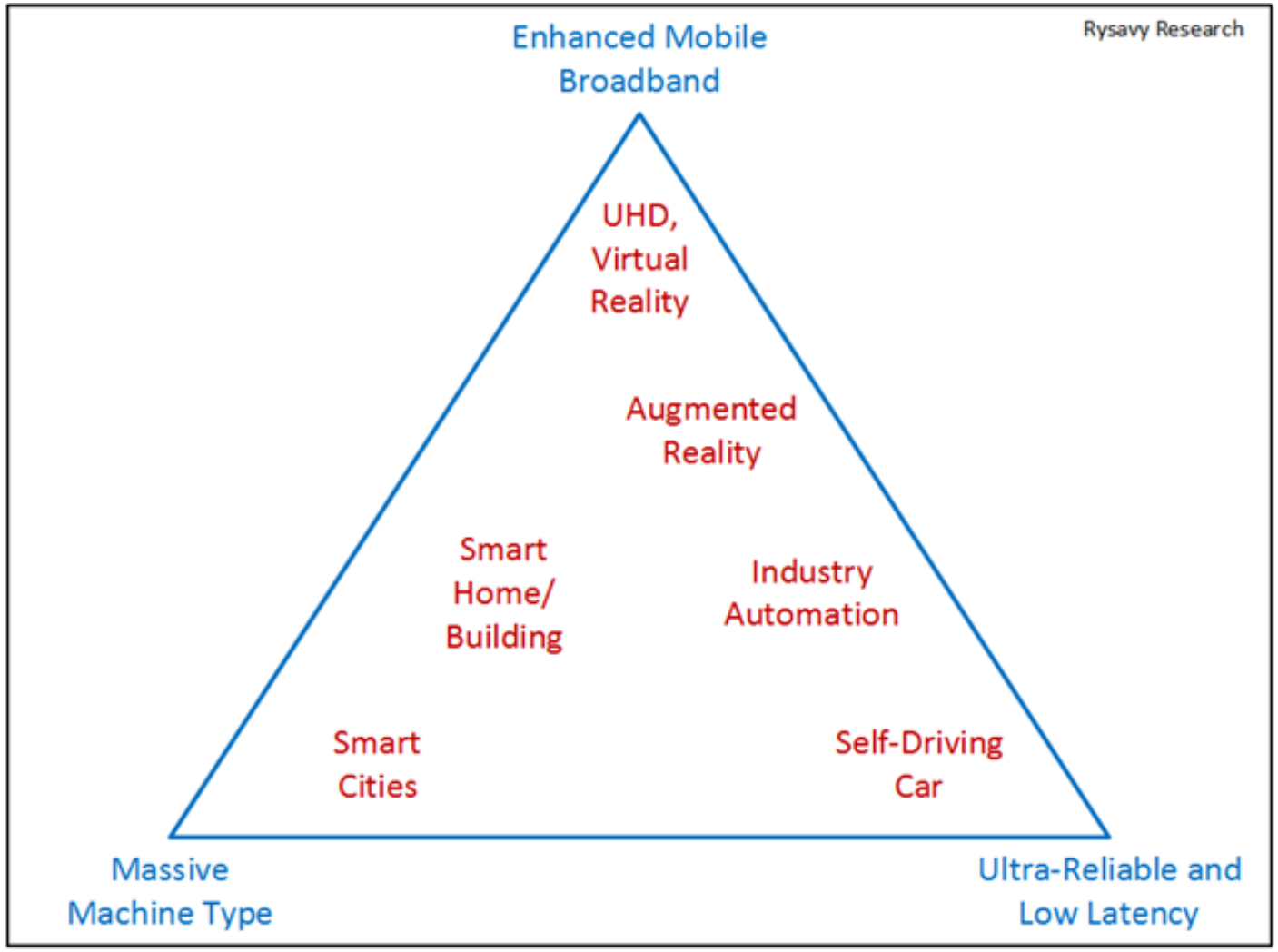


Ericsson Mobility Report, Jun. 2019.

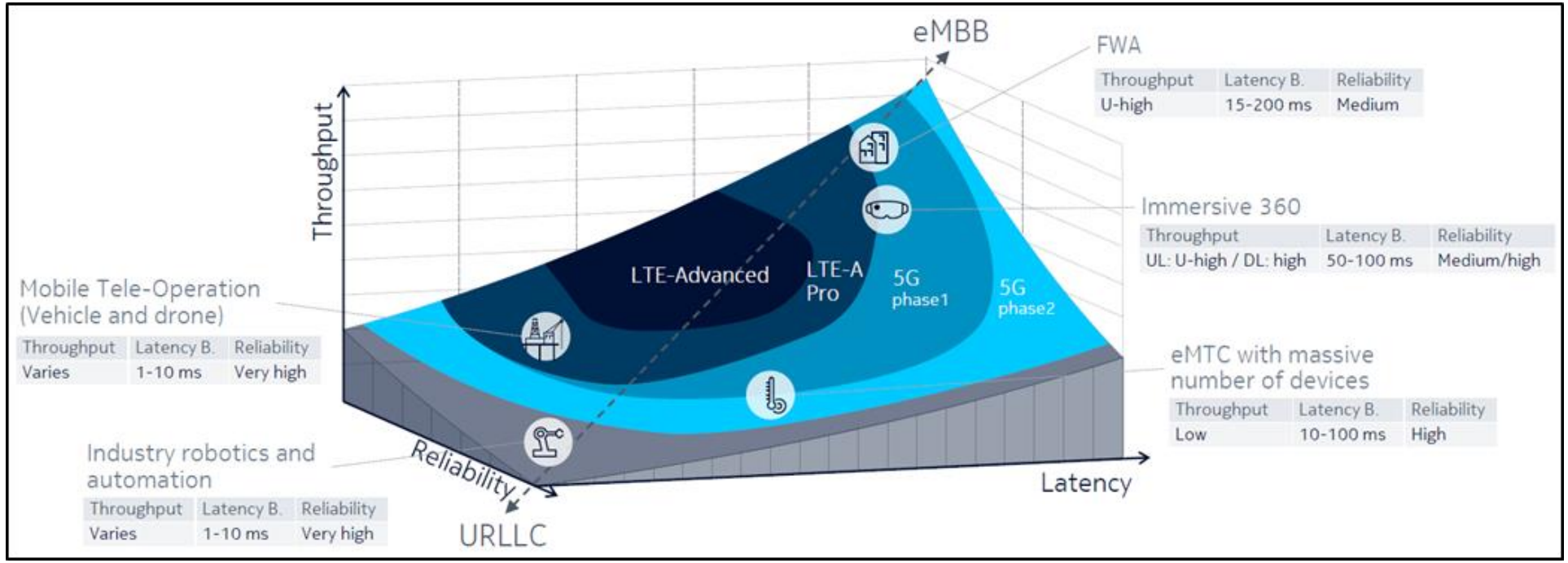
Mobile Broadband Transformational Elements



ITU Use Case Model

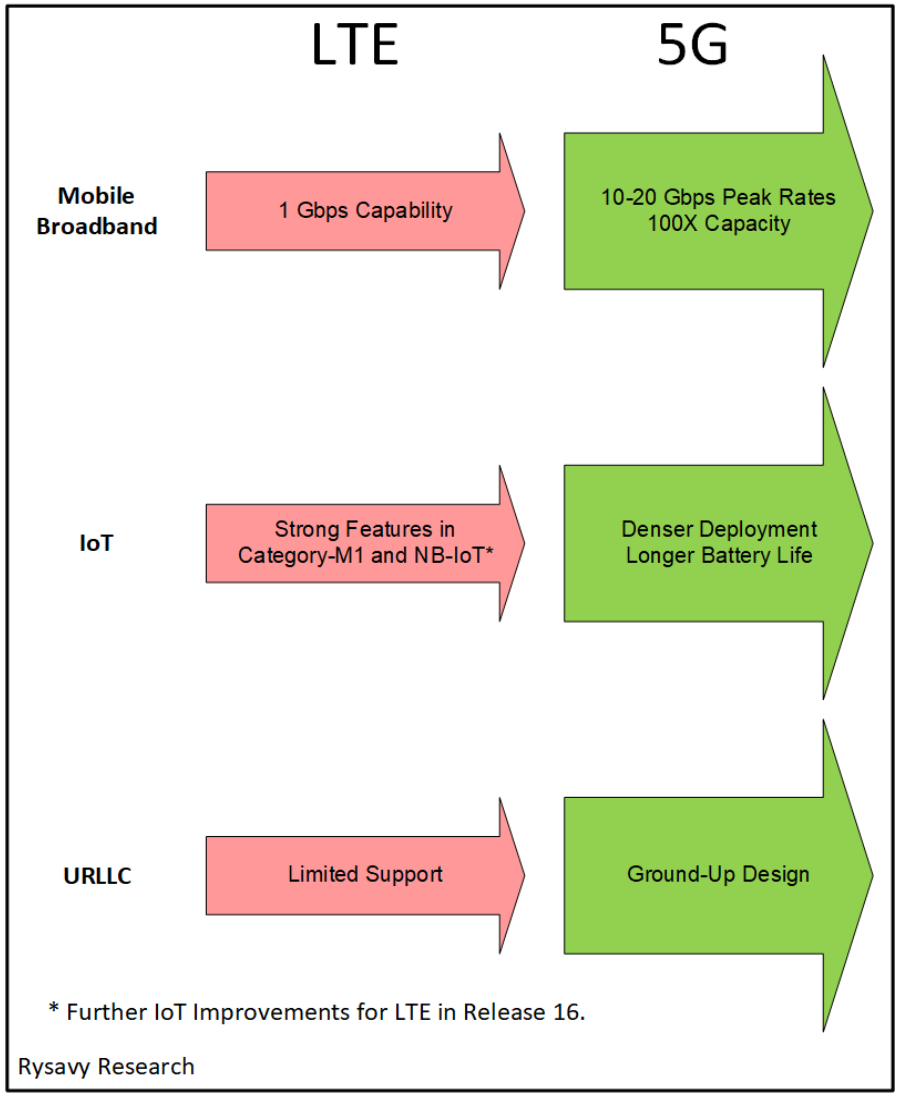


Requirements for Different 5G Use Cases

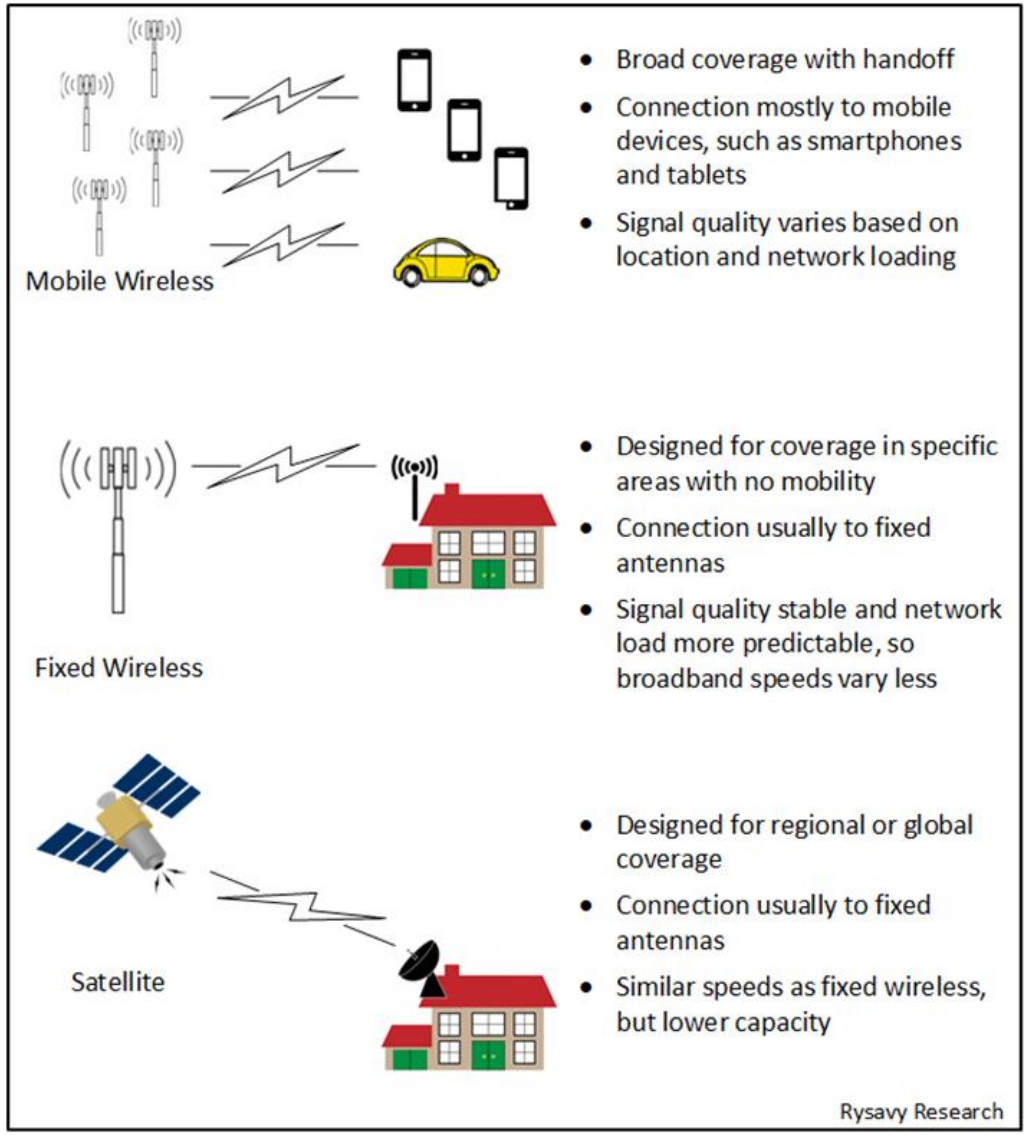


5G Americas Member contribution

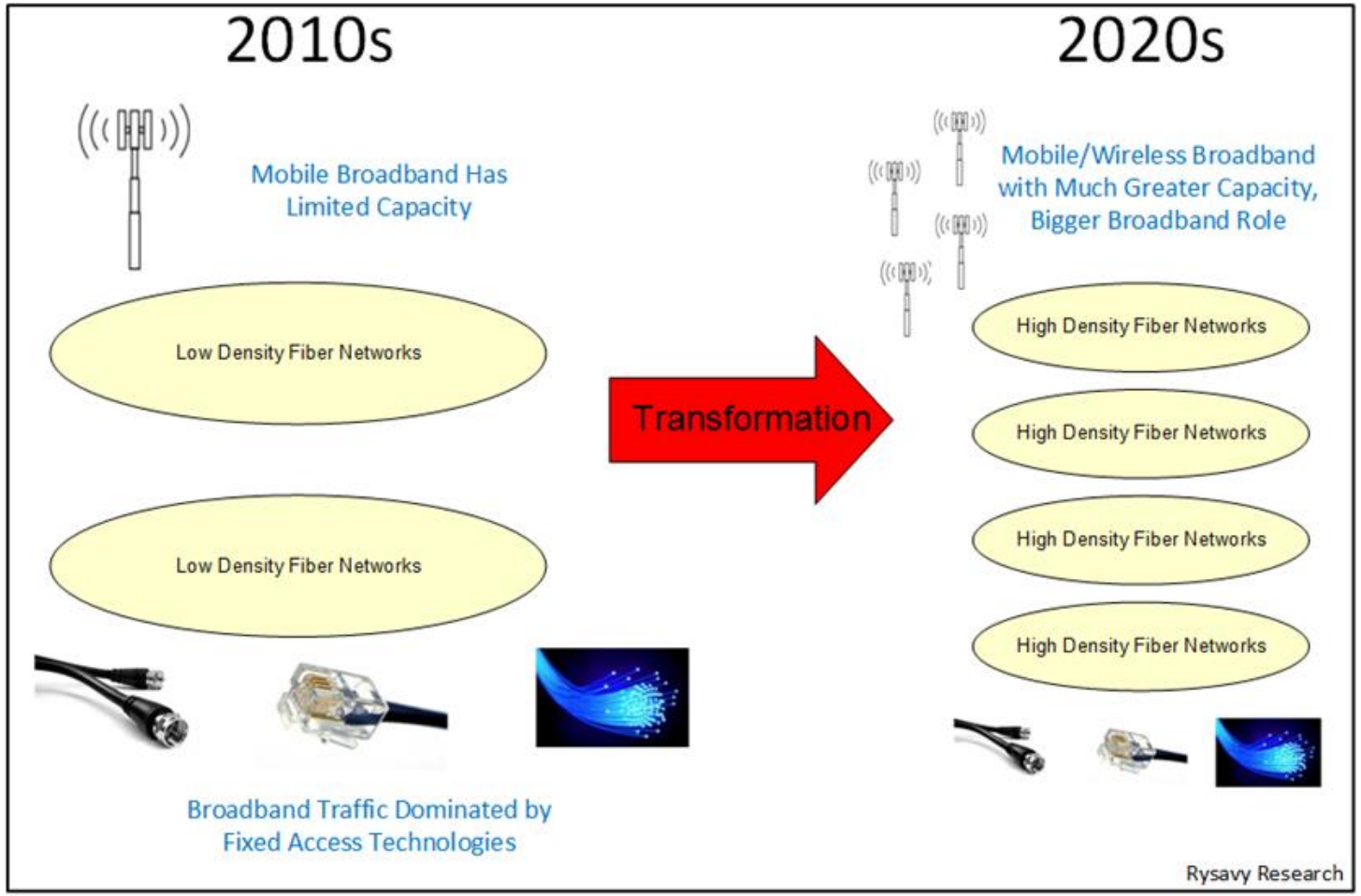
Comparison of Use Case Categories between LTE and 5G



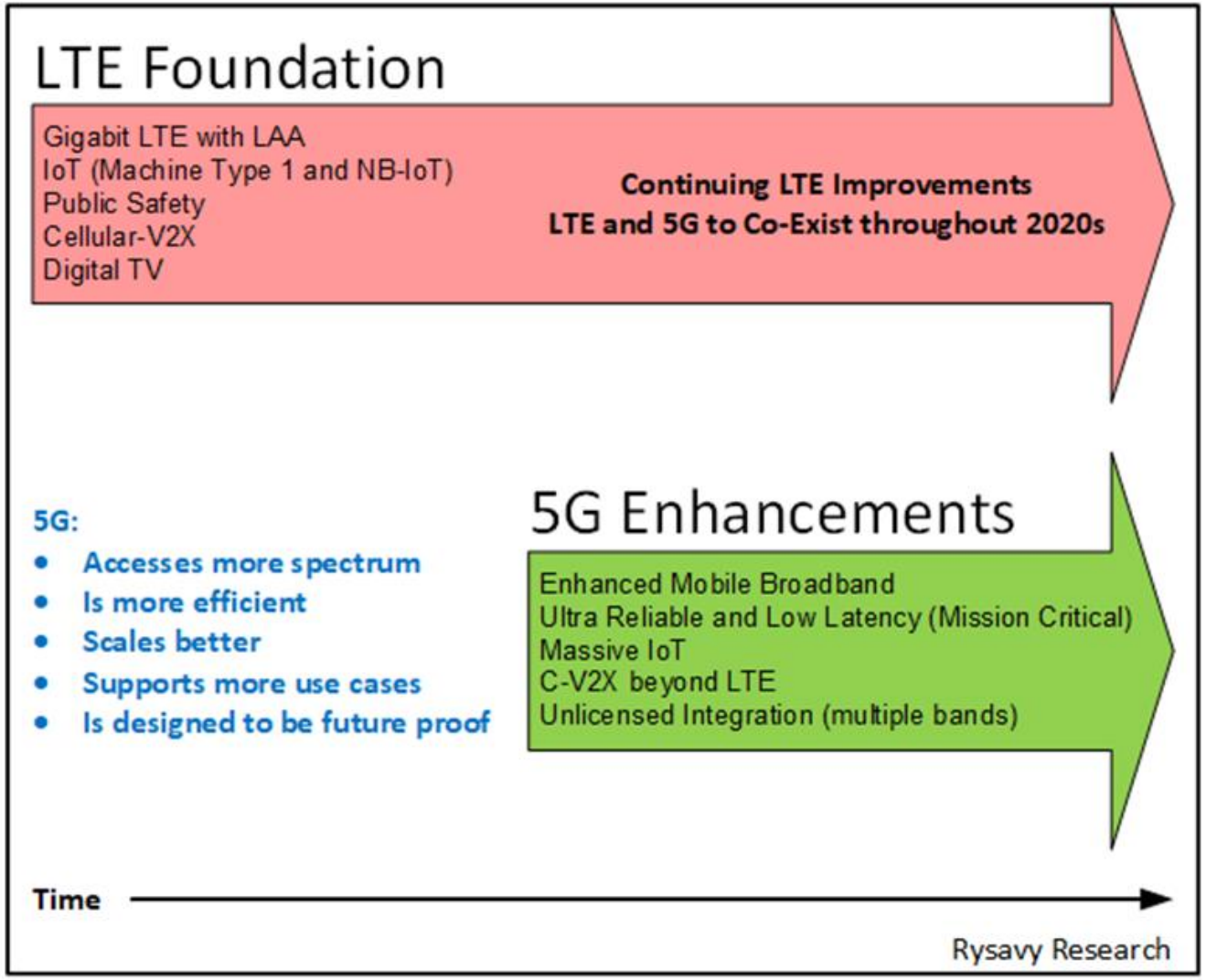
Fixed Wireless Access



Fiber Densification with Multiple Access Technologies, Including mmWave



Initial LTE as Foundation for 5G Enhancements



VR, AR, Mixed and Extended

Extended reality (XR) is a term referring to all real-and-virtual combined environments and human-machine interactions generated by computer technology and wearables. Examples: flying drones, underwater exploration.

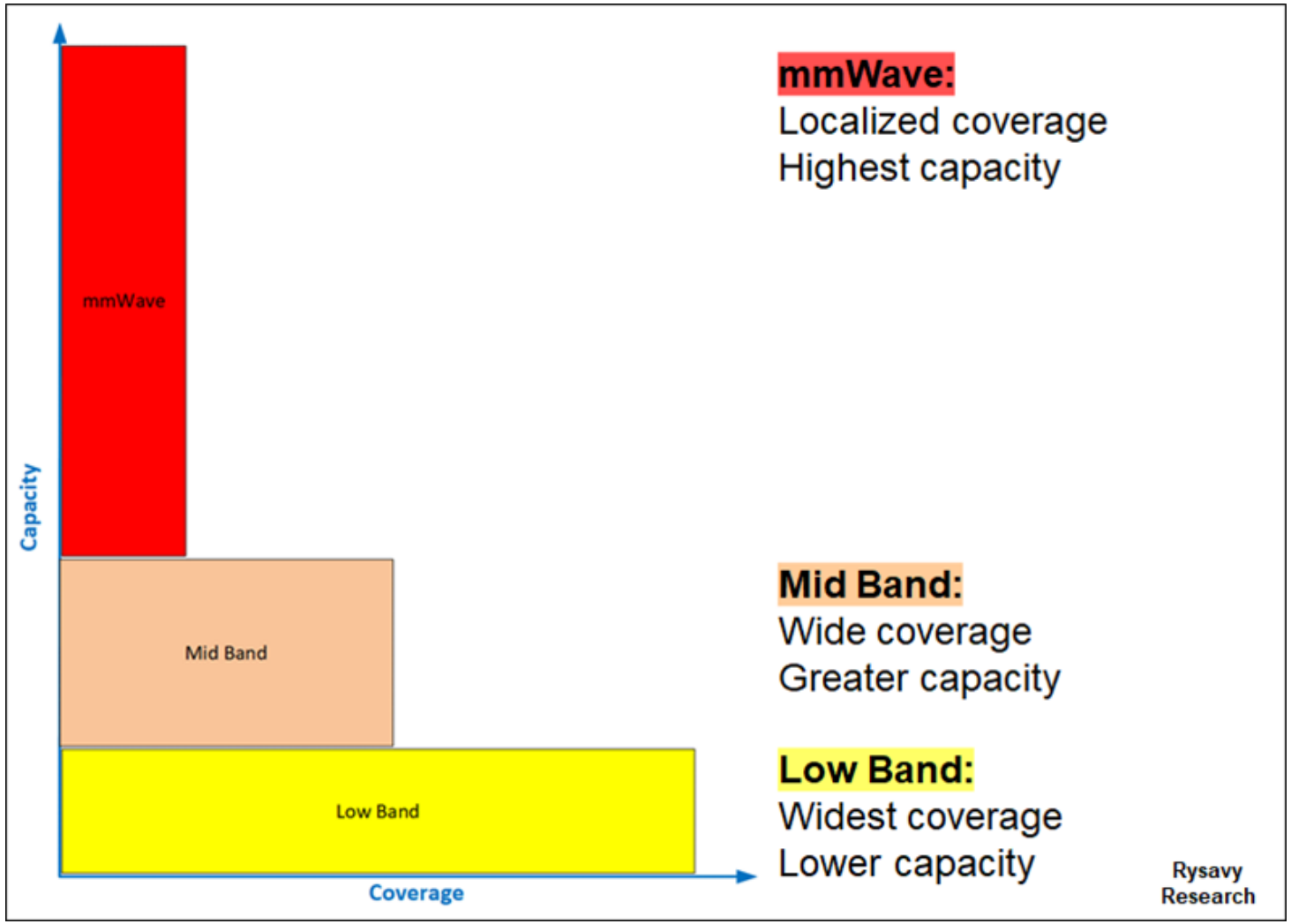
Mixed Reality: Mixed reality (MR), sometimes referred to as hybrid reality, is the merging of real and virtual worlds to produce new environments and visualizations where physical and digital objects co-exist and interact in real time.
Examples: entertainment industry.

Virtual reality (VR) is an immersive multimedia or computer simulated environment which allows one to interact with it. Examples: complete immersive gaming, virtual aviation training, medical/ surgical training, mental treatment.

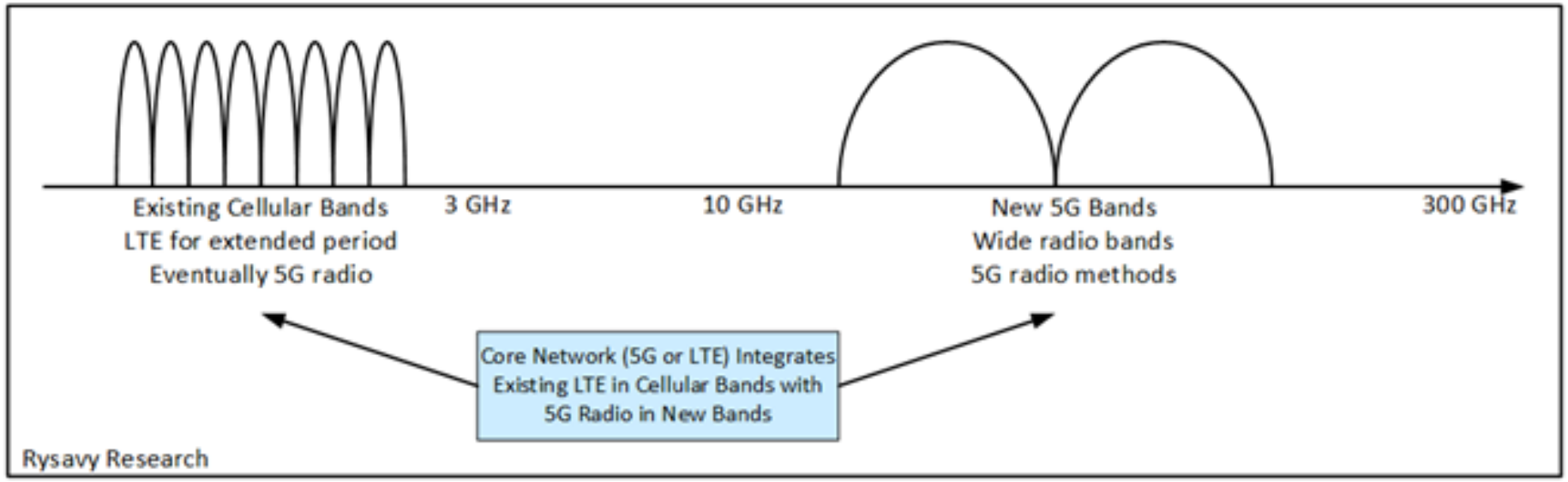
Augmented reality (AR) is a view of a real-world environment whose elements are supplemented and enhanced by computer-generated sensory input such as sound, video, or graphics
Examples: tourism, retail-furniture visualizers, clothes visualizer.

Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2017–2022, Feb. 2019.

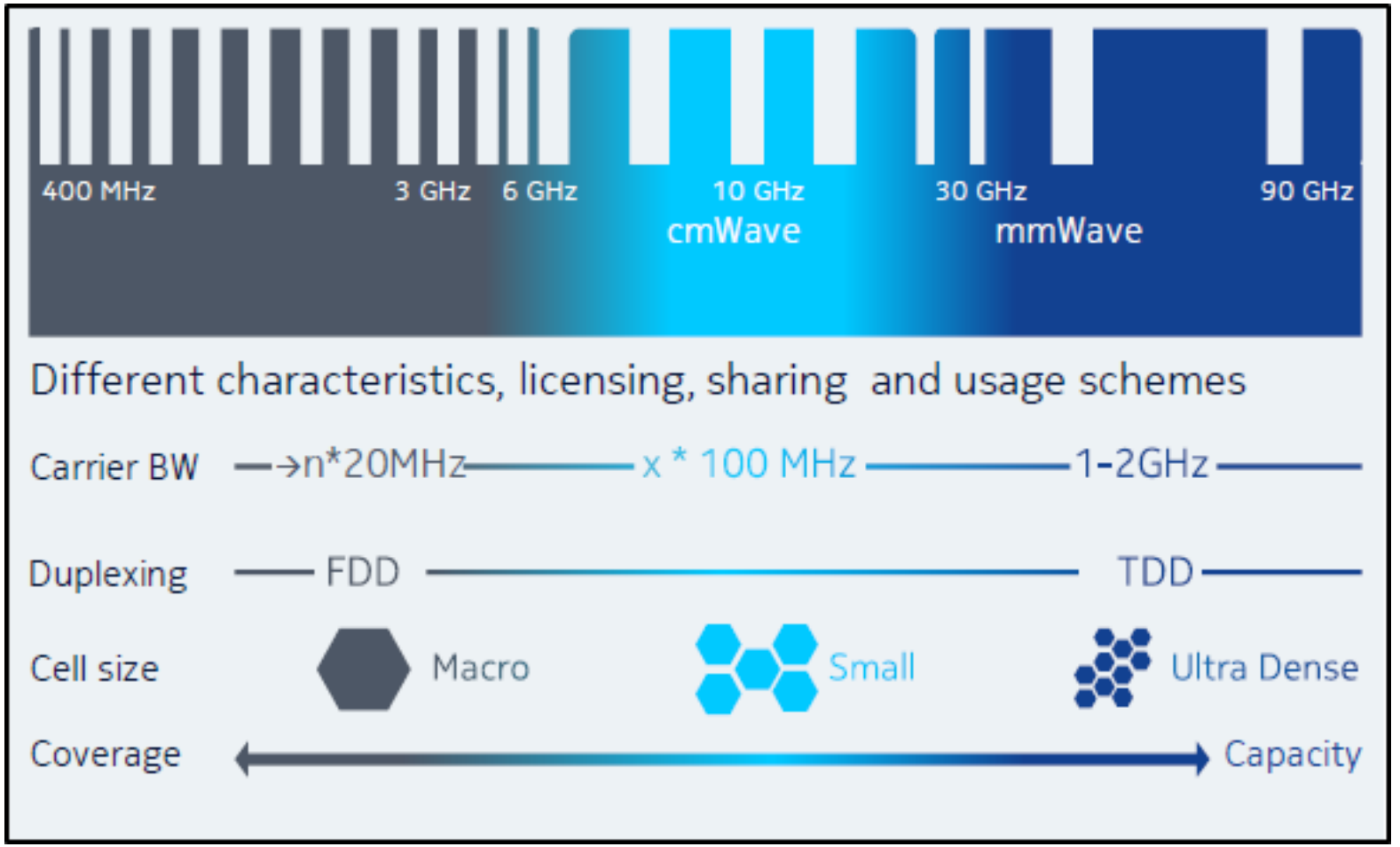
Three-Tier Spectrum Usage for 5G



5G Combining of LTE and New Radio Technologies

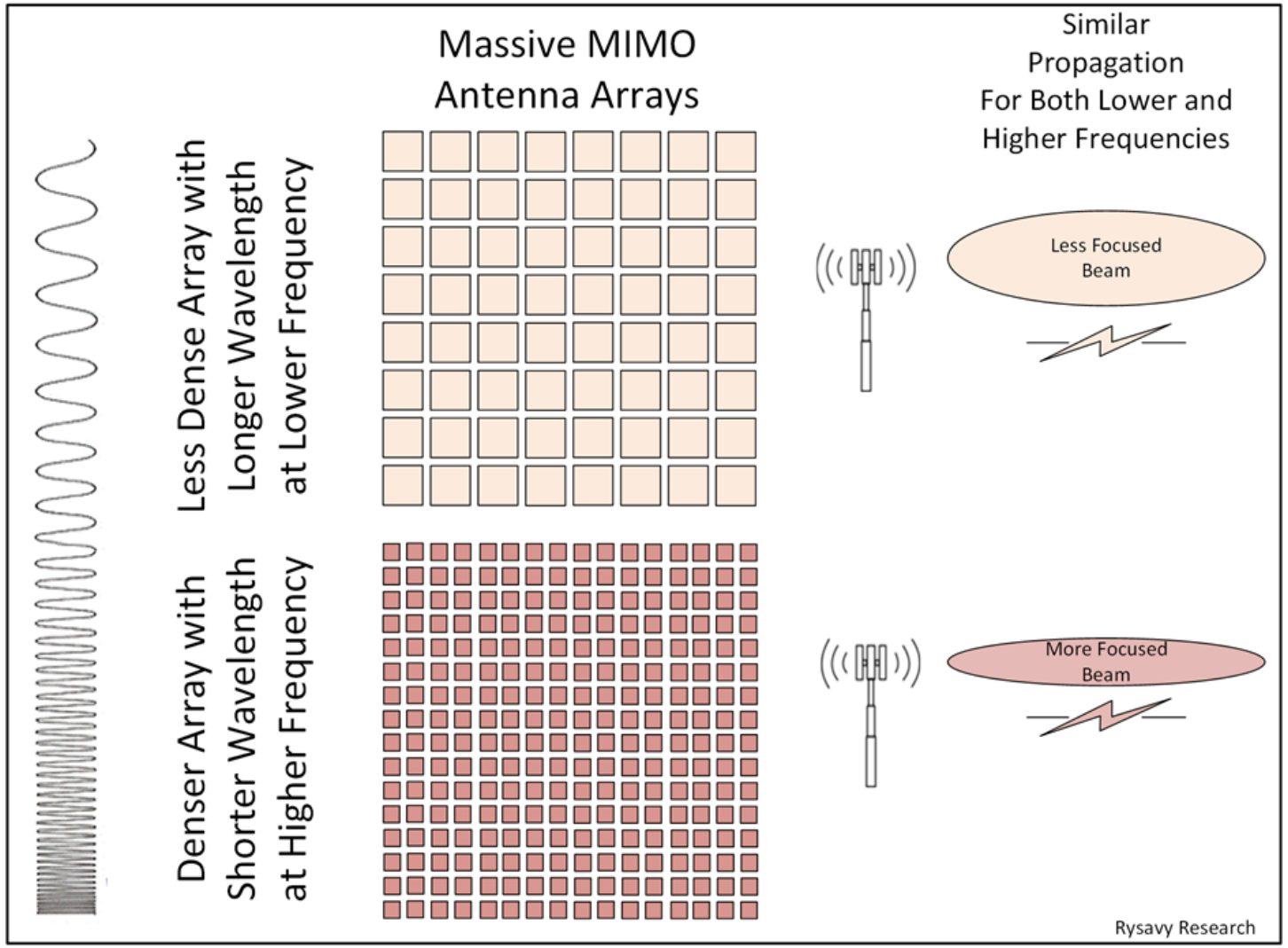


Characteristics of Different Bands

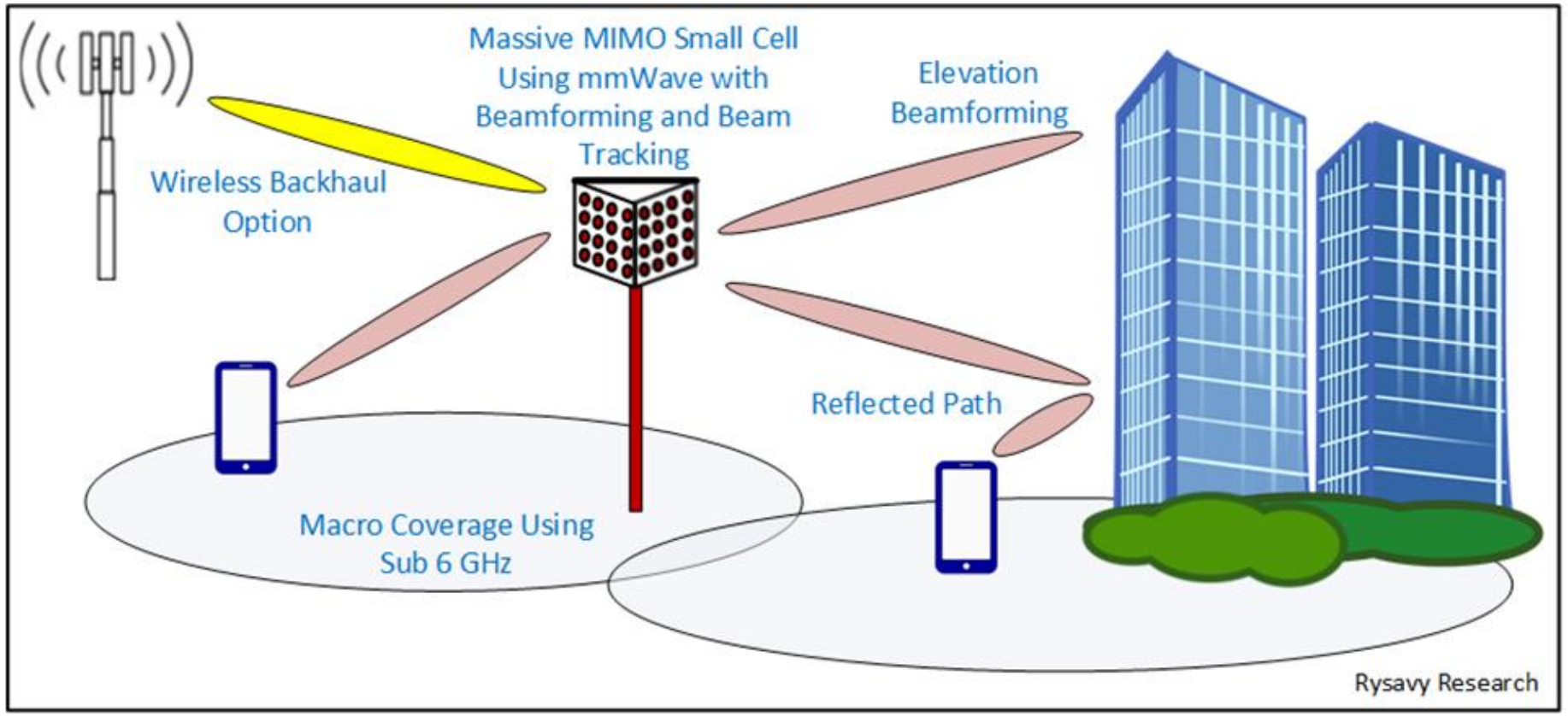


Nokia, *Vision & Priorities for Next Generation Radio Technology*,
3GPP RAN workshop on 5G, Sep. 17-18, 2015

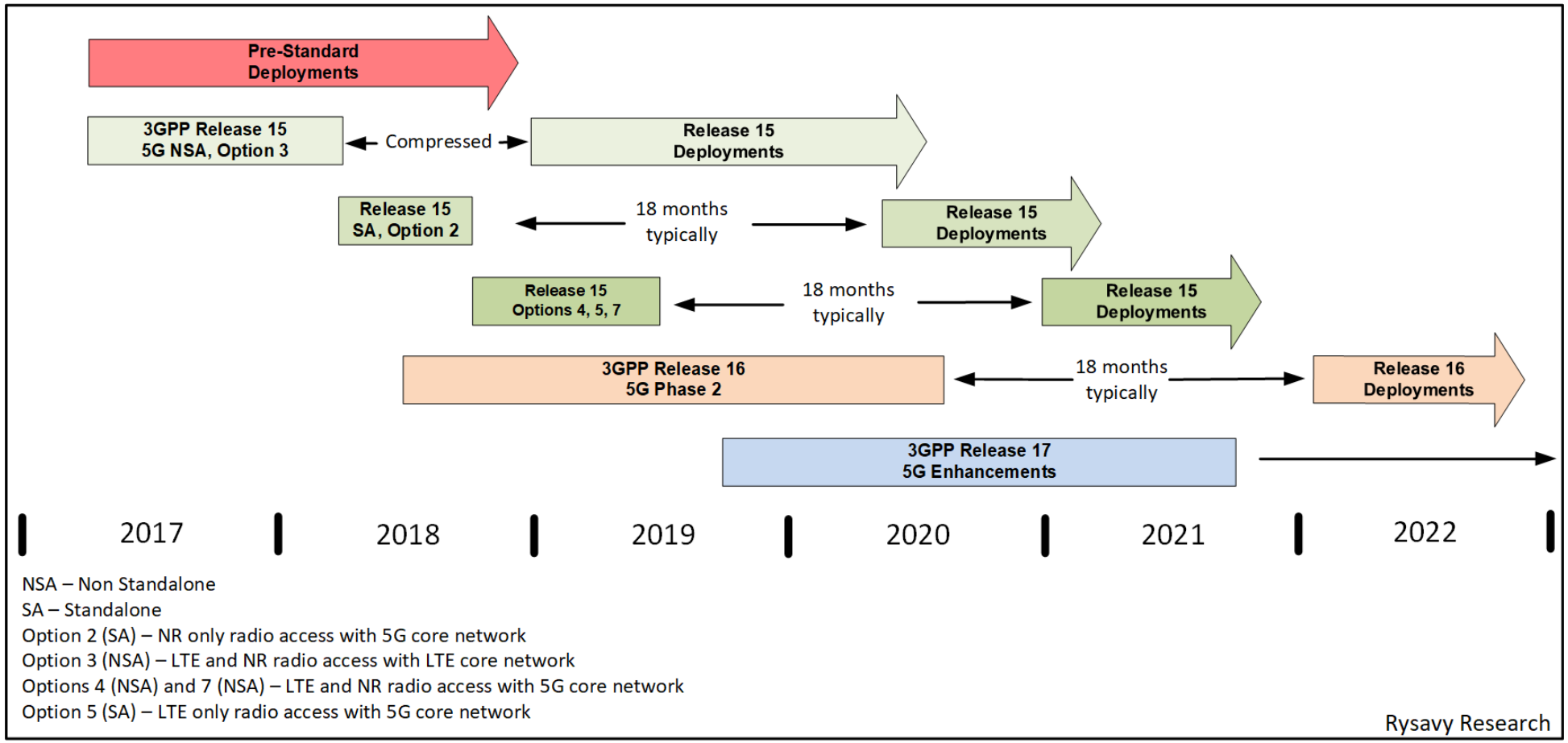
Higher-Order MIMO Compensation for Poorer Propagation



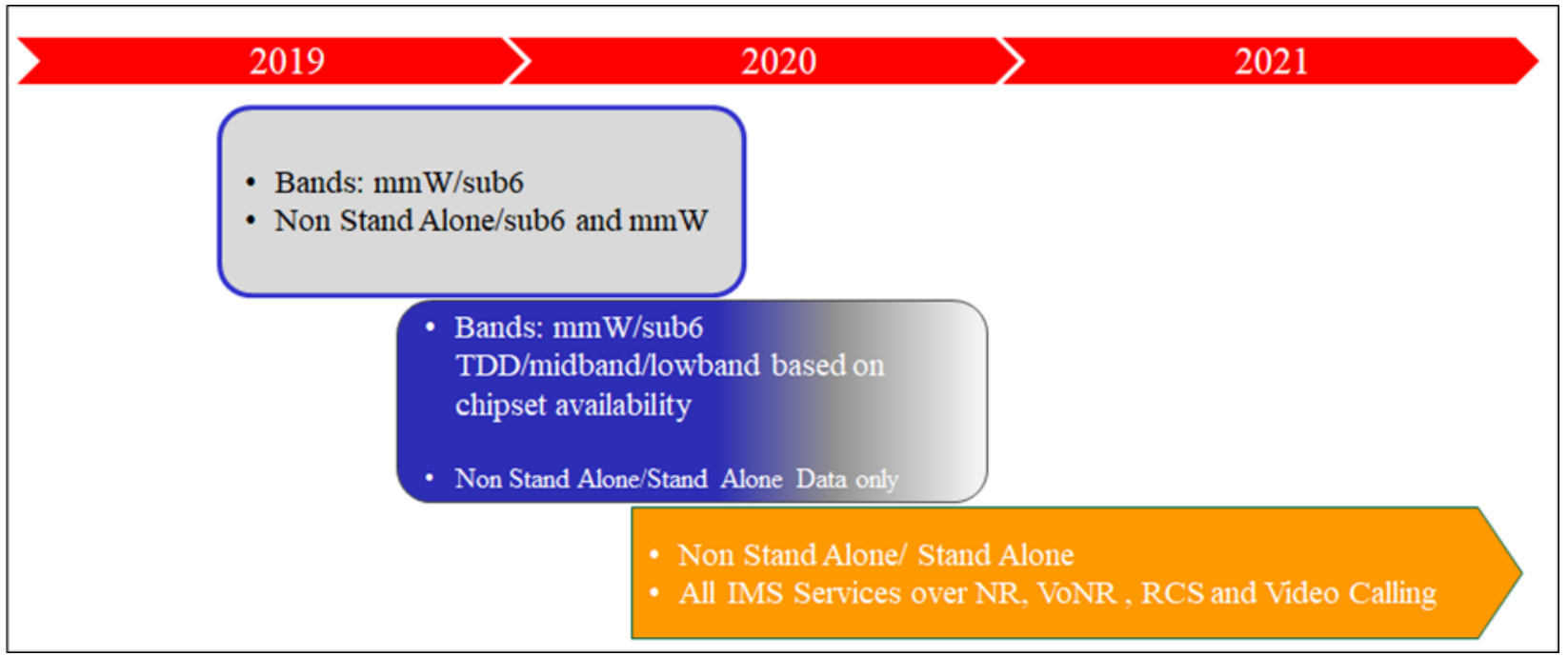
5G Architecture for Low-Band/High-Band Integration



5G Timeline

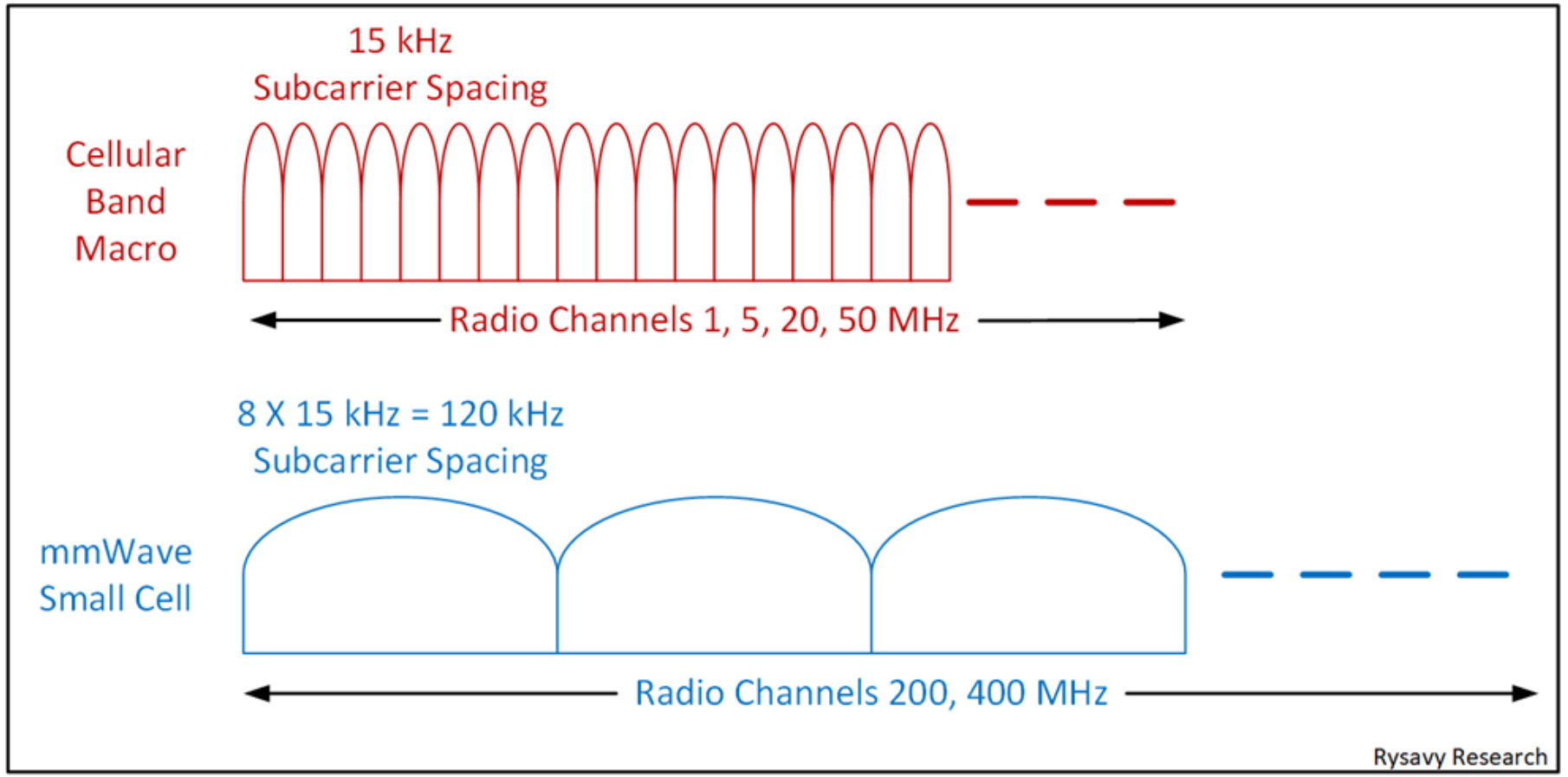

Pre-Standard Deployments
3GPP Release 15 5G NSA, Option 3
Compressed
Release 15 Deployments
Release 15 SA, Option 2
18 months typically
Release 15 Deployments
Release 15 Options 4, 5, 7
18 months typically
Release 15 Deployments
3GPP Release 16 5G Phase 2
18 months typically
Release 16 Deployments
3GPP Release 17 5G Enhancements
2017
2018
2019
2020
2021
2022
NSA – Non Standalone
SA – Standalone
Option 2 (SA) – NR only radio access with 5G core network
Option 3 (NSA) – LTE and NR radio access with LTE core network
Options 4 (NSA) and 7 (NSA) – LTE and NR radio access with 5G core network
Option 5 (SA) – LTE only radio access with 5G core network
Rysavy Research

5G Device Timeline



5G Americas member contribution.

Example of 5G Numerology



ITU Objectives

	IMT-Advanced	IMT-2020
Peak Data Rate	DL: 1 Gbps UL: 0.05 Gbps	DL: 20 Gbps UL: 10 Gbps
User Experienced Data Rate	10 Mbps	100 Mbps
Spectrum Efficiency	1 (normalized)	3X over IMT-Advanced
Peak Spectral Efficiency	DL: 15 bps/Hz UL: 6.75 bps/Hz	DL: 30 bps/Hz UL: 15 bps/Hz
Average Spectral Efficiency		DL eMBB indoor: 9 bps/Hz DL eMBB urban: 7.8 bps/Hz DL eMBB rural: 3.3 bps/Hz UL eMBB indoor: 6.75 bps/Hz UL eMBB urban: 5.4 bps/Hz UL eMBB rural: 1.6 bps/Hz
Mobility	350 km/h	500 km/h
User Plane Latency	10 msec	1 msec
Connection Density	100 thousand devices/sq.km.	1 million devices sq./km.
Network Energy Efficiency	1 (normalized)	100X over IMT-Advanced
Area Traffic Capacity	0.1 Mbps/sq. m.	10 Mbps/sq. m. (hot spots)
Bandwidth	Up to 20 MHz/radio channel (up to 100 MHz aggregated)	Up to 1 GHz (single or multipole RF carriers)

5G Phase One (Release 15)

- Ability to operate in any frequency band, including low, mid, and high bands.
- Network can support both LTE and 5G NR
- A system architecture that enables user services with different access systems, such as WLAN.
- 5 Gbps peak downlink throughput in initial releases, increasing to 50 Gbps in subsequent versions.
- Massive MIMO and beamforming. Data, control and broadcast channels are all beamformed.
- Ability to support either FDD or TDD modes for 5G radio bands.
- Numerologies of 2N X 15 kHz for subcarrier spacing up to 120 kHz or 240 kHz.
- Carrier aggregation for up to 16 NR carriers.
- Aggregation up to approximately 1 GHz of bandwidth.
- Standards-based cloud RAN support.
- A comprehensive security architecture.
- QoS support using a new model.
- Dynamic co-existence with LTE in the same radio channels.
- Network slicing.

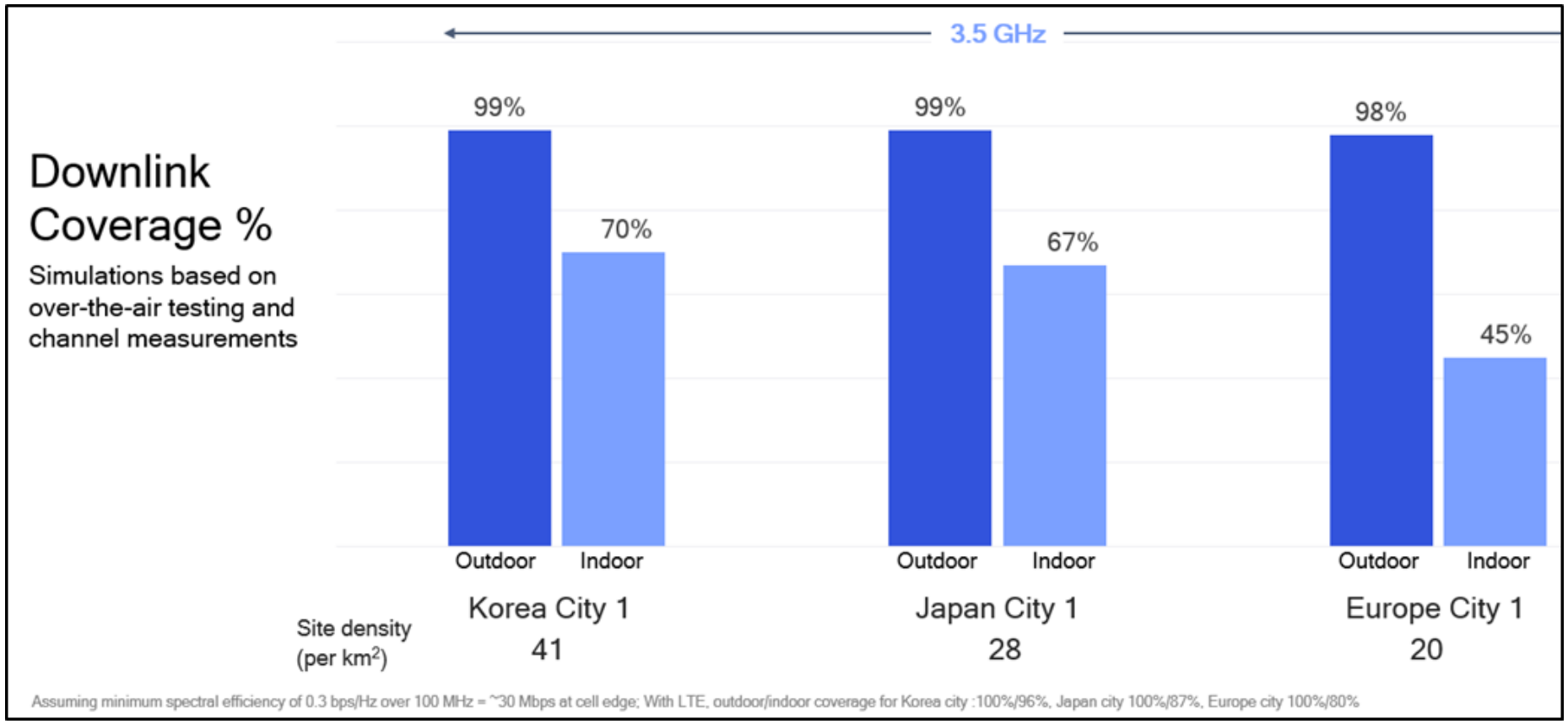
5G Phase Two (Release 16)

- URLLC.
- Unlicensed spectrum operation below 7 GHz.
- Integrated access and backhaul.
- Industrial IoT support, including URLLC and time-sensitive communications.
- NR-based C-V2X, including side-link communications.
- Positioning for both commercial and regulatory uses.
- Dual-connectivity, carrier-aggregation, and mobility enhancements.
- UE power consumption reduction.
- MIMO enhancements.
- Study on support for radio bands above 52.6 GHz.
- Study on non-orthogonal multiple access.
- Study on solutions for NR to support non-terrestrial (satellite) networks.
- Efficiency improvements, signaling improvements, and other enhancements.

5G Release 17

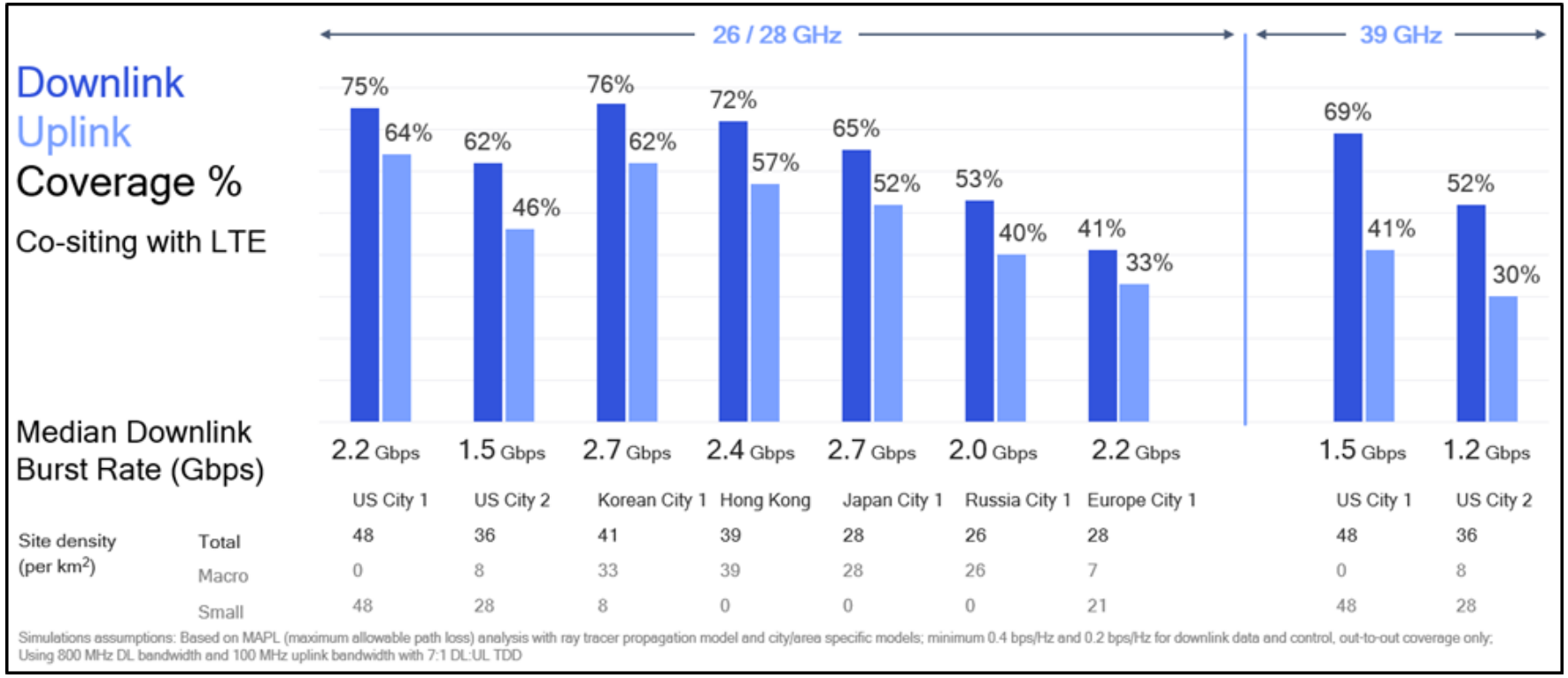
- NR-light to support devices such wearables and IoT with power saving.
- Operation above 52.6 GHz, including unlicensed bands.
- Support for multiple SIMs.
- NR multicast and broadcast, targeting V2X and public safety.
- Support for non-terrestrial networks (e.g., unmanned aerial vehicles [UAV], satellite).
- Industrial IoT (including URLLC) enhancements for wider use cases.
- Sidelink (device-to-device communications) enhancements for V2X, commercial, and critical communications.
- Multiple other enhancements, including ones for MIMO, coverage, IAB (including mobile IAB, such as on buses), unlicensed operation, positioning, and power saving.

Indoor 5G NR Coverage Co-Siting with Existing Outdoor LTE Sites



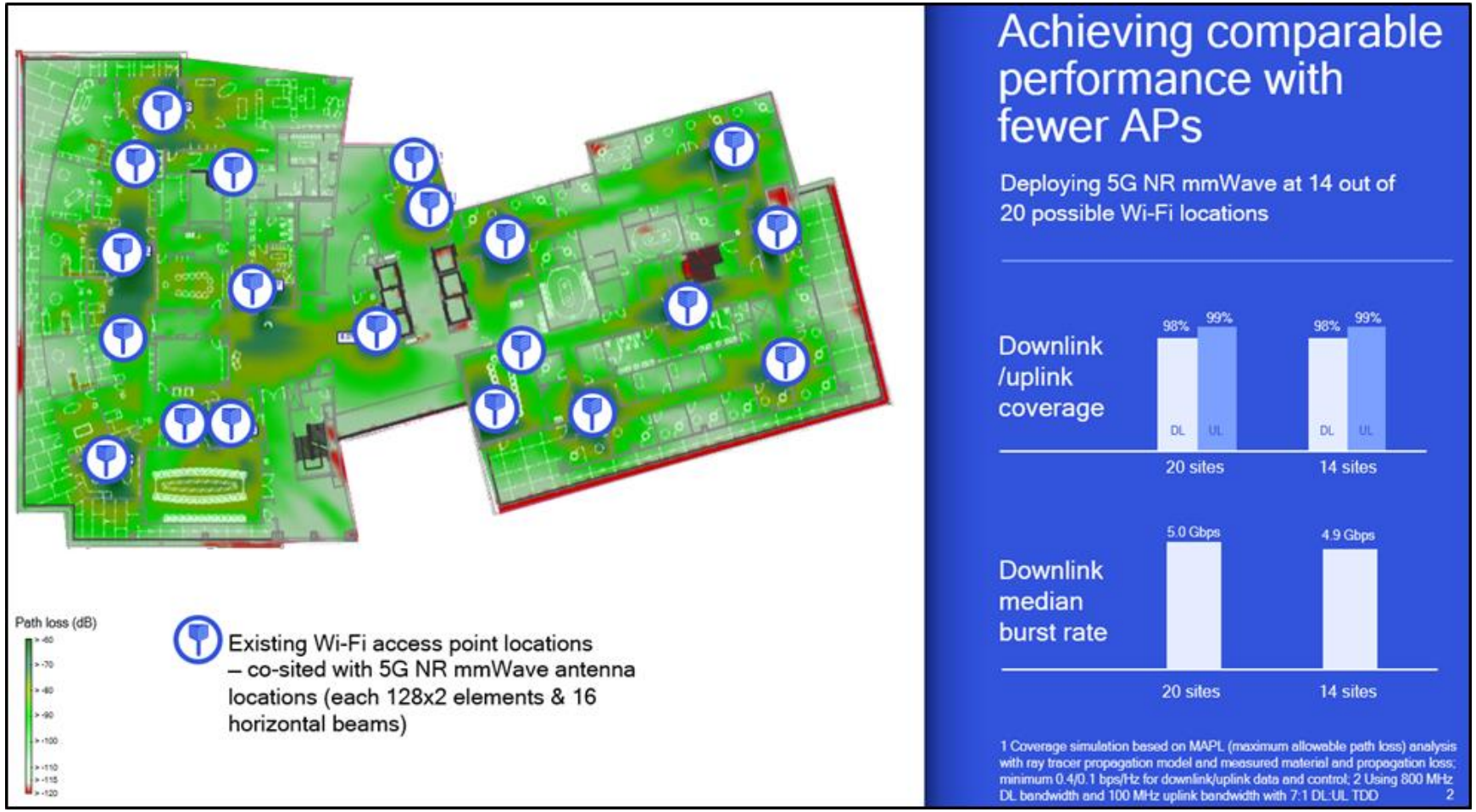
Qualcomm webinar, *How do we plan for 5G NR network deployments coming in 2019*? Nov. 2018.

mmWave Coverage Achieved by Co-Siting with LTE



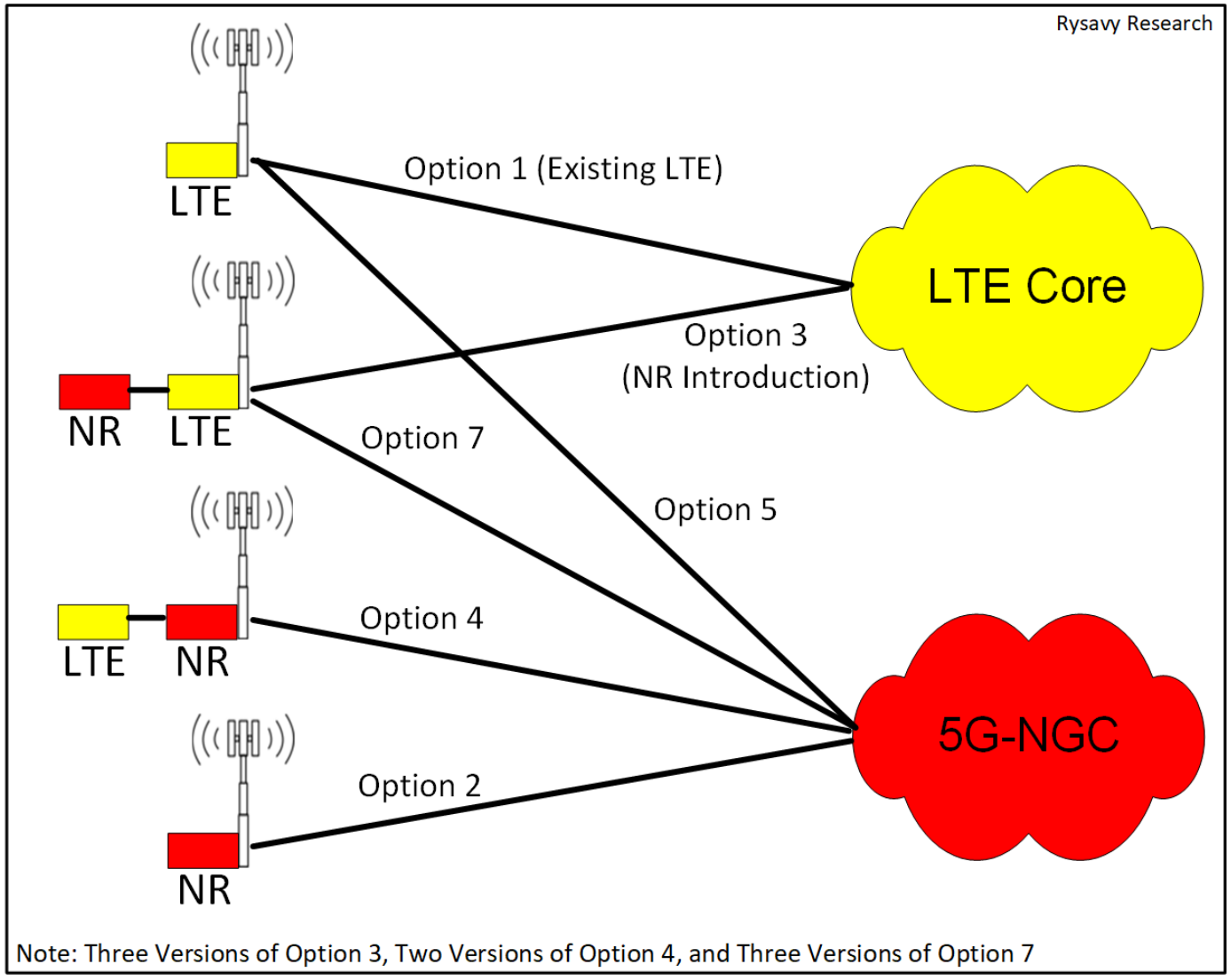
Qualcomm webinar, *What new indoor opportunity will 5G NR mmWave bring*? Feb. 2019.

Co-Siting mmWave 5G NR with Wi-Fi Indoors for Effective Coverage

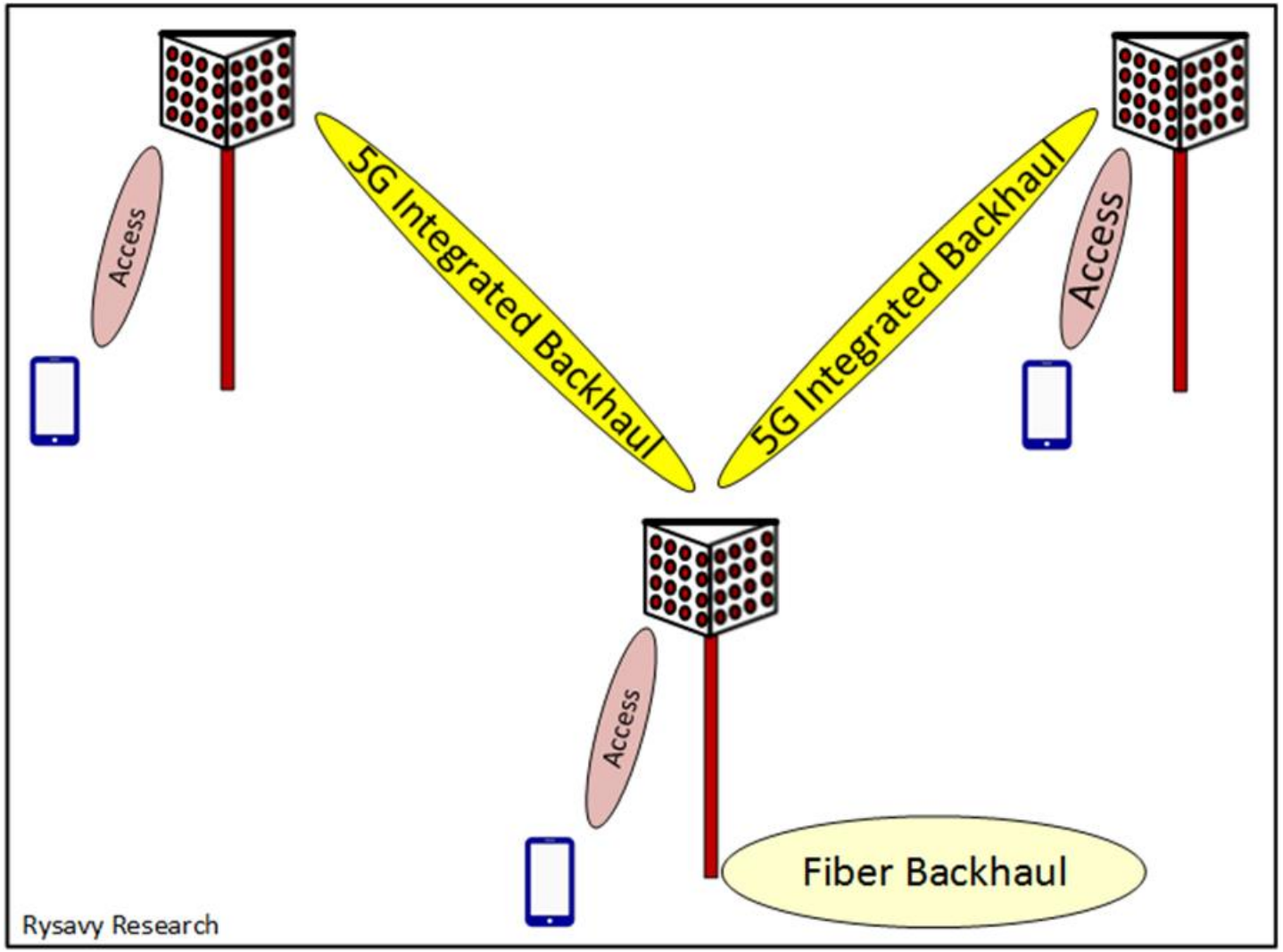


Qualcomm webinar, *What new indoor opportunity will 5G NR mmWave bring*? Feb. 2019.

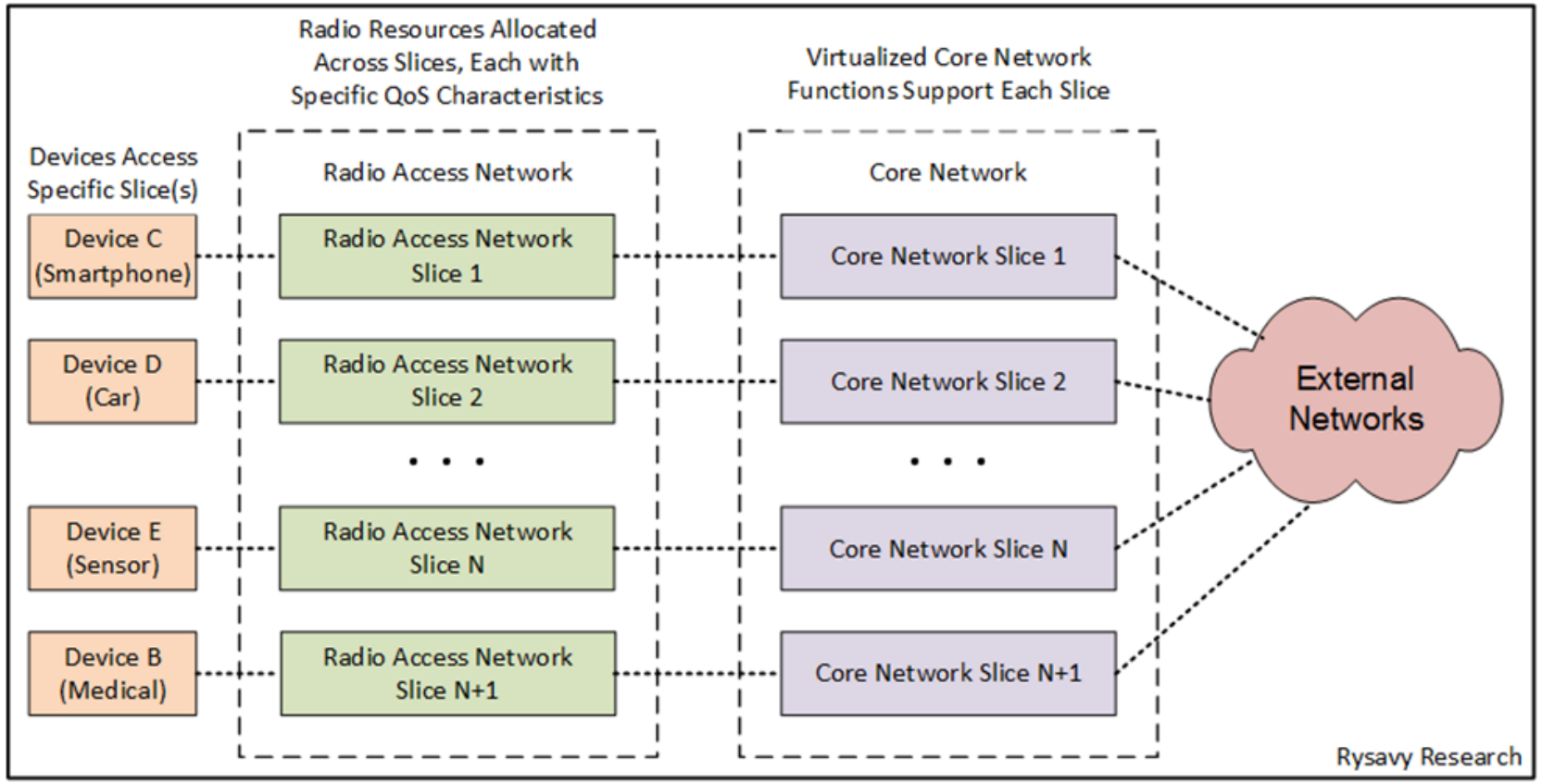
Release 15 Non-Standalone and Standalone Options



5G Integrated Access and Backhaul



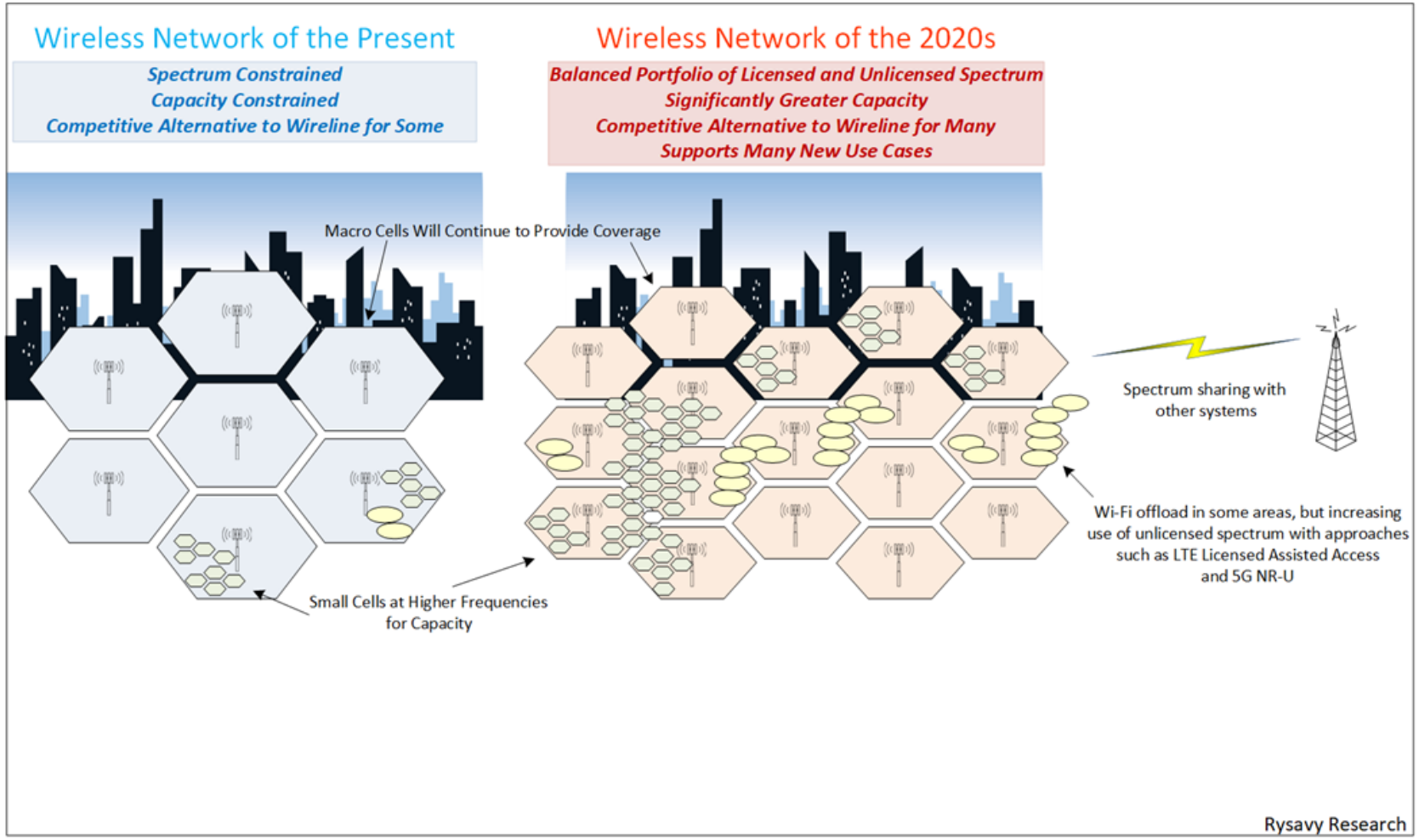
Network Slicing Architecture



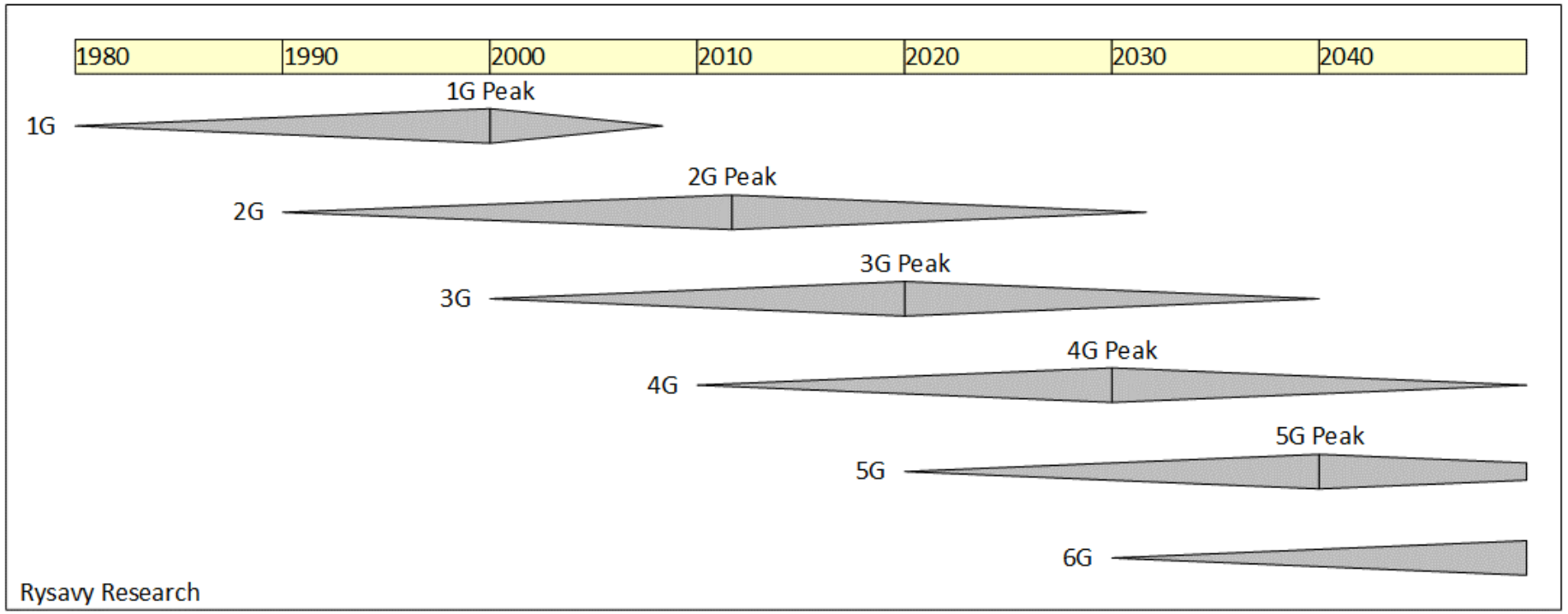
Evolution from 4G to Beyond 5G

	4G	5G	Future Technology Beyond 5G (Speculative)
Peak theoretical throughput	1 Gbps	20 Gbps	1 Tbps (1000 Gbps)
Typical throughputs	10s of megabits per second (Mbps)	100s of Mbps to over 1 Gbps	10s or 100s of Gbps
Wireline broadband replacement	Only viable for small percentage of users	Viable for many users	Viable for nearly all users
Video	Streaming video but with restrictions, HD possible	Fewer restrictions, UHD possible	Super-high resolution
Types of communications	Voice, interactive video	HD interactive, VR	Immersive telepresence and 3D holographic
Reliability	Networks mostly operates on best-effort basis	Designed for mission-critical applications (capable of six nines of reliability 99.9999%)	Nine nines of reliability
Latency (radio network delay)	As low as 10 msec.	As low as 1 msec.	Even greater timing precision

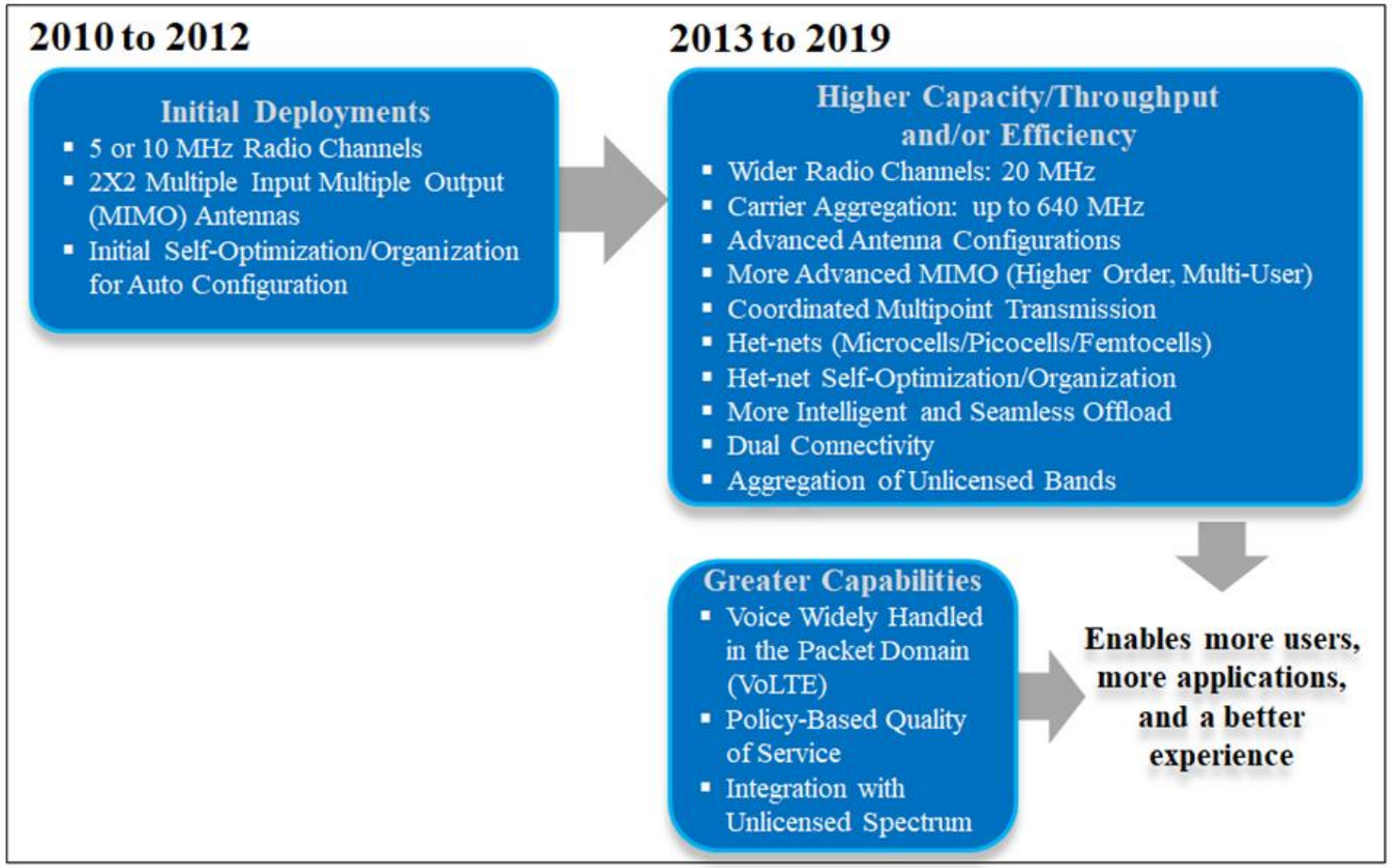
Network Transformation



Timeline of Cellular Generations



LTE to LTE-Advanced Pro Migration



LTE 1 Gbps Capability

Capability	Gain	Resulting Peak Throughput (Mbps)
LTE in 20 MHz with 64 QAM	Baseline	75
2X2 MIMO	100%	150
256 QAM	25%	200
4X4 MIMO	100%	400
3 Component Carrier Aggregation (For example, 10 MHz licensed carrier + 2 of 20 MHz unlicensed carriers)	250%	1000
Additional Carrier Aggregation	Additional gains	> 1000

Characteristics of 3GPP Technologies

Technology Name	Type	Characteristics	Typical Downlink Speed	Typical Uplink Speed
HSPA	WCDMA	Data service for UMTS networks. An enhancement to original UMTS data service.	1 Mbps to 4 Mbps	500 Kbps to 2 Mbps
HSPA+	WCDMA	Evolution of HSPA in various stages to increase throughput and capacity and to lower latency.	1.9 Mbps to 8.8 Mbps in 5+5 MHz 3.8 Mbps to 17.6 Mbps with dual-carrier in 10+5 MHz	1 Mbps to 4 Mbps in 5+5 MHz or in 10+5 MHz
LTE	OFDMA	New radio interface that can use wide radio channels and deliver extremely high throughput rates. All communications handled in IP domain.	6.5 to 26.3 Mbps in 10+10 MHz	6.0 to 13.0 Mbps in 10+10 MHz
LTE- Advanced	OFDMA	Advanced version of LTE designed to meet IMT-Advanced requirements.	Significant gains through carrier aggregation, 4X2 and 4X4 MIMO, and 256 QAM modulation.	
5G	OFDMA	Scalable radio interface designed for 5G able to support existing cellular bands as well as mmWave bands.	1 Gbps with 400 MHz radio channel in mmWave band.	500 Mbps with 400 MHz radio channel in mmWave band.

Key Features in 3GPP Releases

Release	Year	Key Features
99	1999	First deployable version of UMTS.
5	2002	High Speed Downlink Packet Access (HSDPA) for UMTS.
6	2005	High Speed Uplink Packet Access (HSUPA) for UMTS.
7	2008	HSPA+ with higher-order modulation and MIMO.
8	2009	Long Term Evolution. Dual-carrier HSDPA.
10	2011	LTE-Advanced, including carrier aggregation and eICIC.
11	2013	Coordinated Multi Point (CoMP).
12	2015	Public safety support. Device-to-device communications. Dual Connectivity. 256 QAM on the downlink.
13	2016	LTE-Advanced Pro features. LTE operation in unlicensed bands using LAA. Full-dimension MIMO. LTE-WLAN Aggregation. Narrowband Internet of Things.
14	2017	LTE-Advanced Pro additional features, such as eLAA (adding uplink to LAA) and cellular V2X communications. Study item for 5G "New Radio."
15	2018	Additional LTE-Advanced Pro features, such as ultra-reliable low-latency communications and high-accuracy positioning. Phase 1 of 5G. Emphasizes enhanced mobile broadband use case and operation to 52.6 GHz. Includes Massive MIMO, beamforming, and 4G-5G interworking, including ability for LTE connectivity to a 5G CN.
16	2020	Phase 2 of 5G. Full compliance with ITU IMT-2020 requirements. Will add URLLC, IAB, unlicensed operation, NR-based C-V2X, positioning, dual-connectivity, carrier aggregation, and multiple other enhancements.
17	2021	Further LTE and 5G enhancements not yet defined. Key items under discussion include NR-light, operation above 52.6 GHz, non-terrestrial networks, and multiple enhancements.

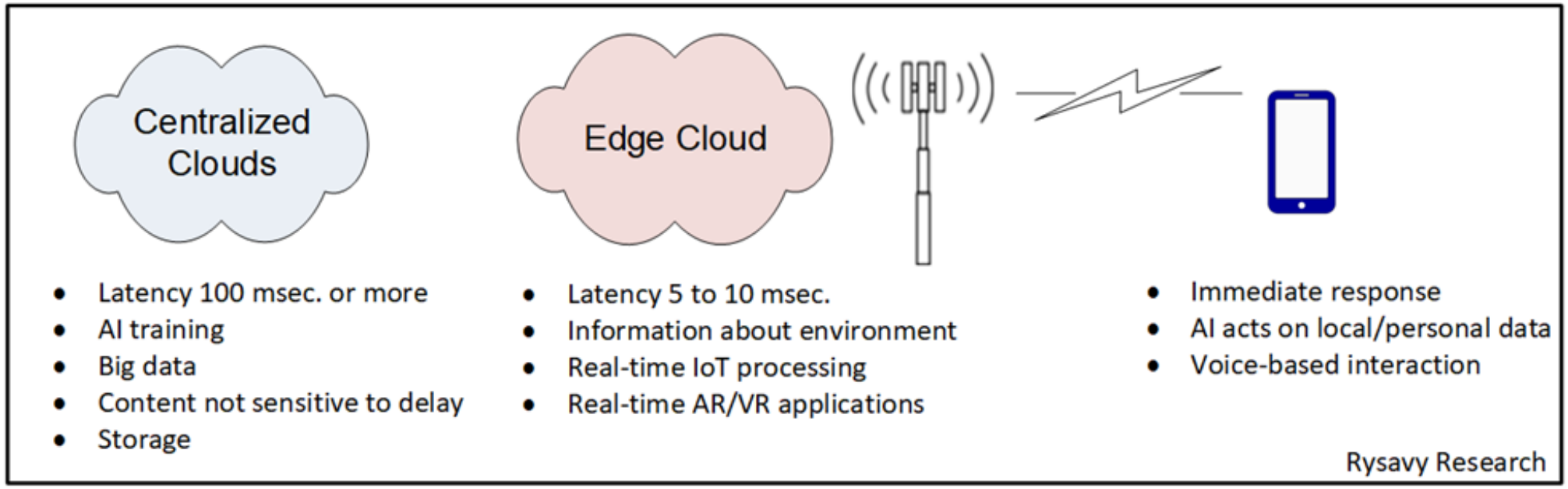
Wireless Networks for IoT

Technology	Coverage	Characteristics	Standardization/ Specifications
GSM/GPRS/EC-GSM-IoT	Wide area. Huge global coverage.	Lowest-cost cellular modems, risk of network sunsets. Low-throughput.	3GPP
HSPA	Wide area. Huge global coverage.	Low-cost cellular modems. Higher power, high throughput.	3GPP
LTE, NB-IoT	Wide area. Increasing global coverage.	Wide area, expanding coverage, cost/power reductions in successive 3GPP releases. Low to high throughput options.	3GPP
Wi-Fi	Local area.	High throughput, higher power.	IEEE
ZigBee	Local area.	Low throughput, low power.	IEEE
Bluetooth Low Energy	Personal area.	Low throughput, low power.	Bluetooth Special Interest Group
LoRa	Wide area. Emerging deployments.	Low throughput, low power. Unlicensed bands (sub 1 GHz, such as 900 MHz in the U.S.)	LoRa Alliance
Sigfox	Wide area. Emerging deployments.	Low throughput, low power. Unlicensed bands (sub 1 GHz such as 900 MHz in the U.S.)	Sigfox
Ingenu (previously OnRamp Wireless)	Wide area. Emerging deployments.	Low throughput, low power. Using 2.4 GHz ISM band. Uses IEEE 802.15.4.	Ingenu
Weightless	Wide area. Planned deployments.	Low throughput, low power. Unlicensed bands (sub 1 GHz such as TV White-Space and 900 MHz in the U.S.)	Weightless Special Interest Group

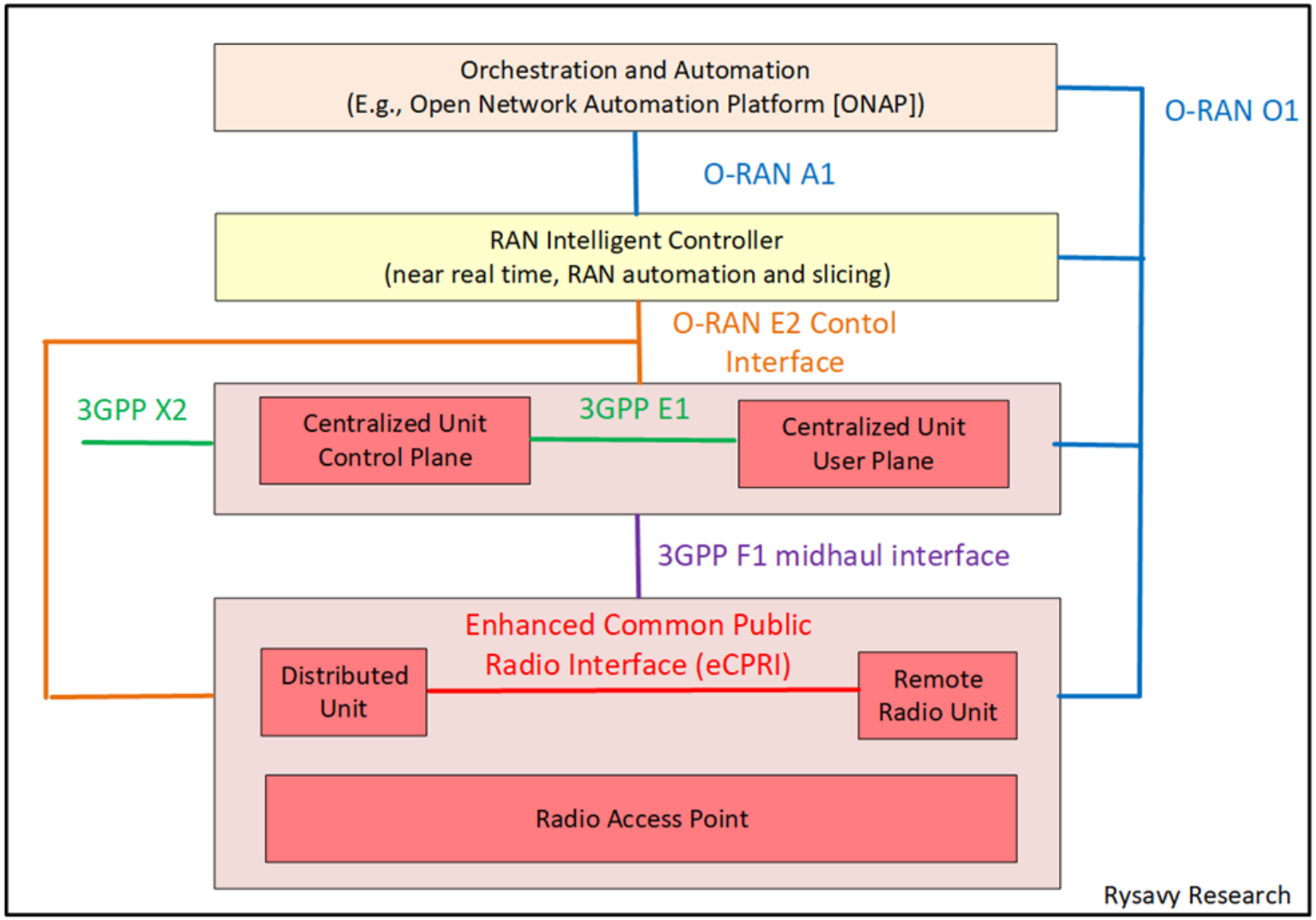
AI for Cellular Networks

- Optimize the network in real time by controlling connections, such as which base stations users connect with, whether to hand off from cellular to Wi-Fi, mesh configurations for wireless multi-hop backhaul, or load balancing.
- Handle increasing network complexity with an increased number of cell sites (especially small cells), number of devices, and speed of operation.
- Heal the network to work around failures, such as a base station that becomes inoperable.
- Organize the radio resources used by different 5G network slices.
- Reduce tower climbs by using drones with AI interpretation of video images to detect issues.
- Provide customer-support functions.
- Augment security functions, such as threat detection.

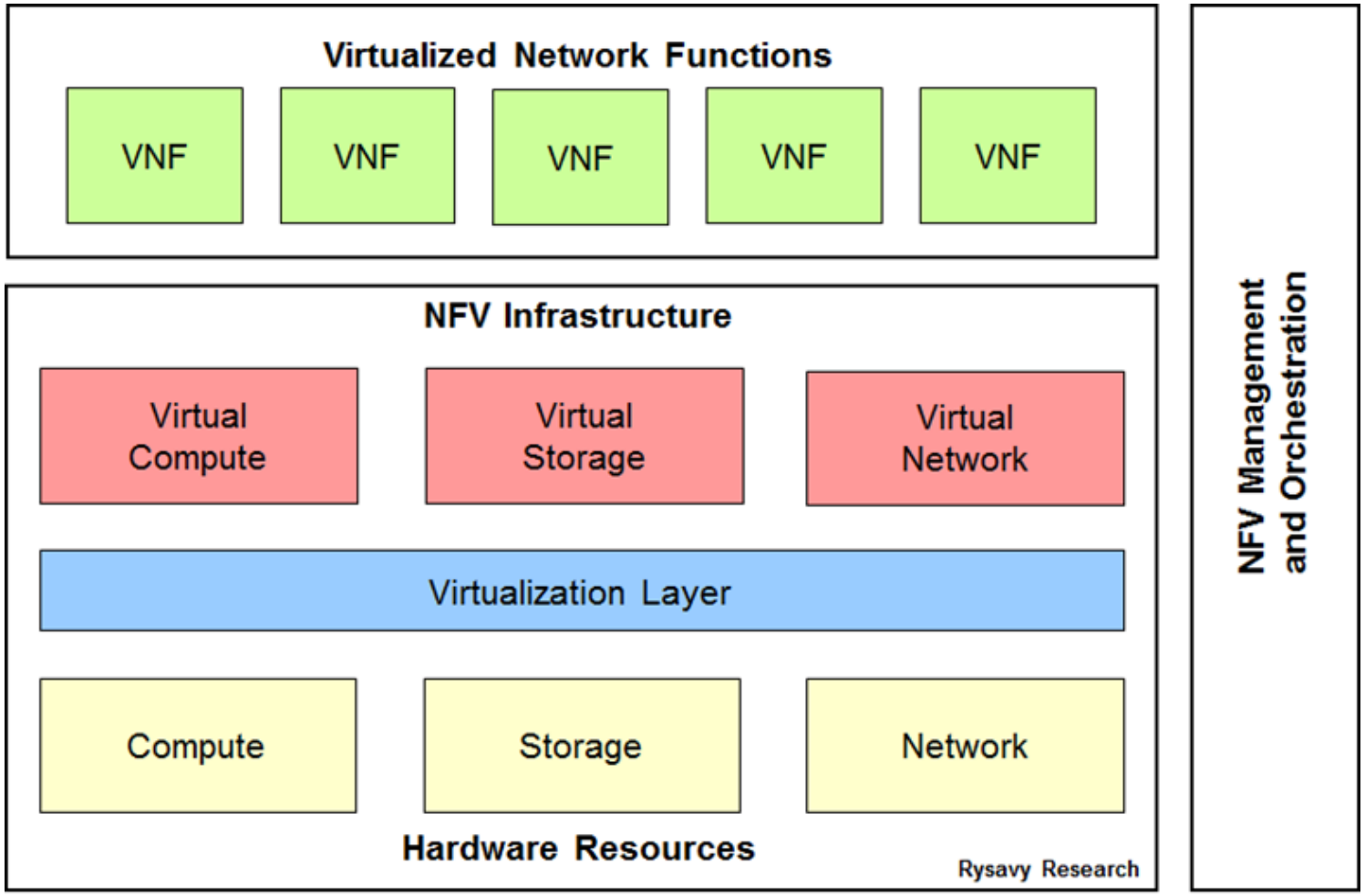
AI across Centralized Clouds, Edge Clouds, and Devices



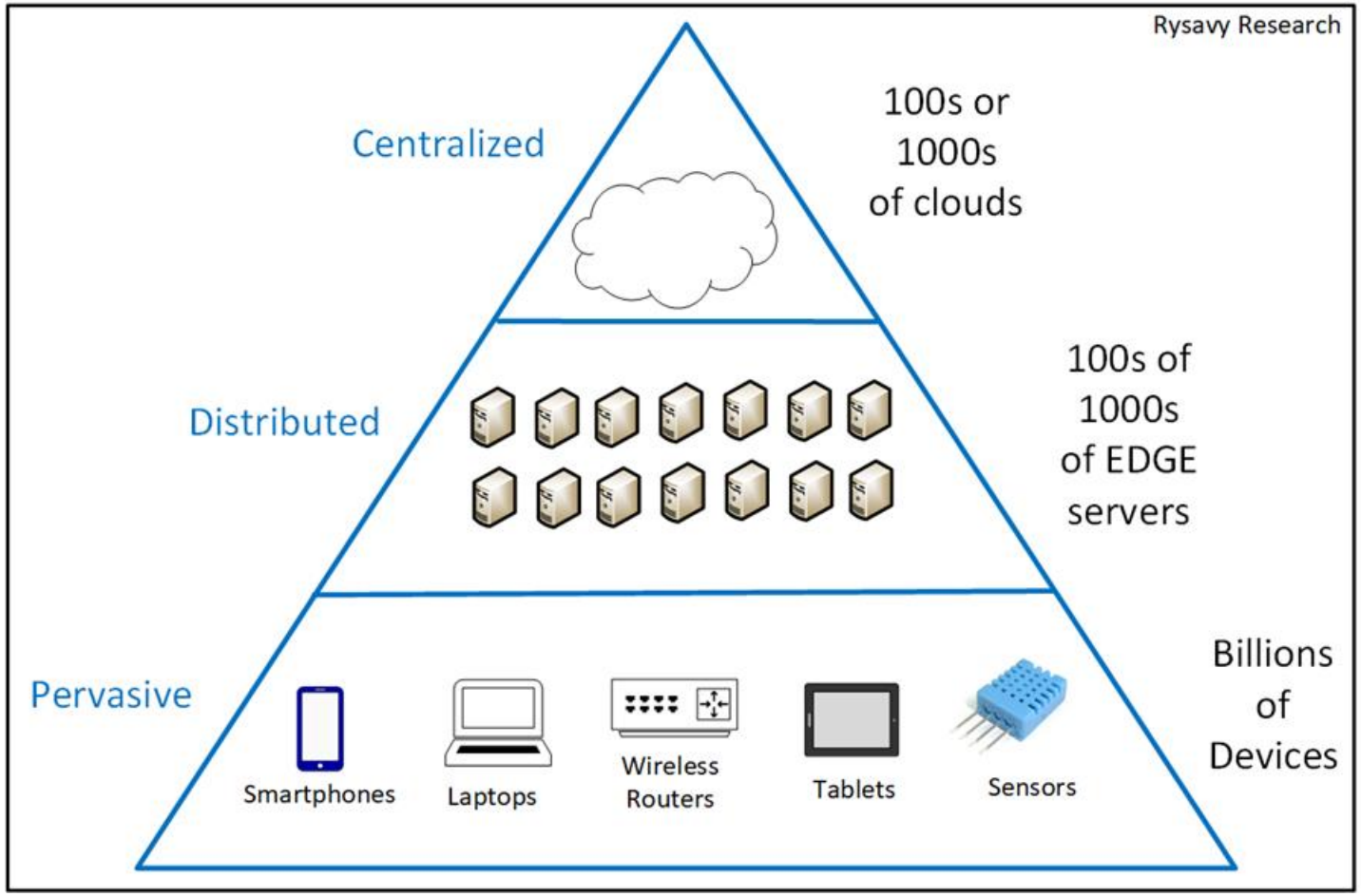
O-RAN Architecture



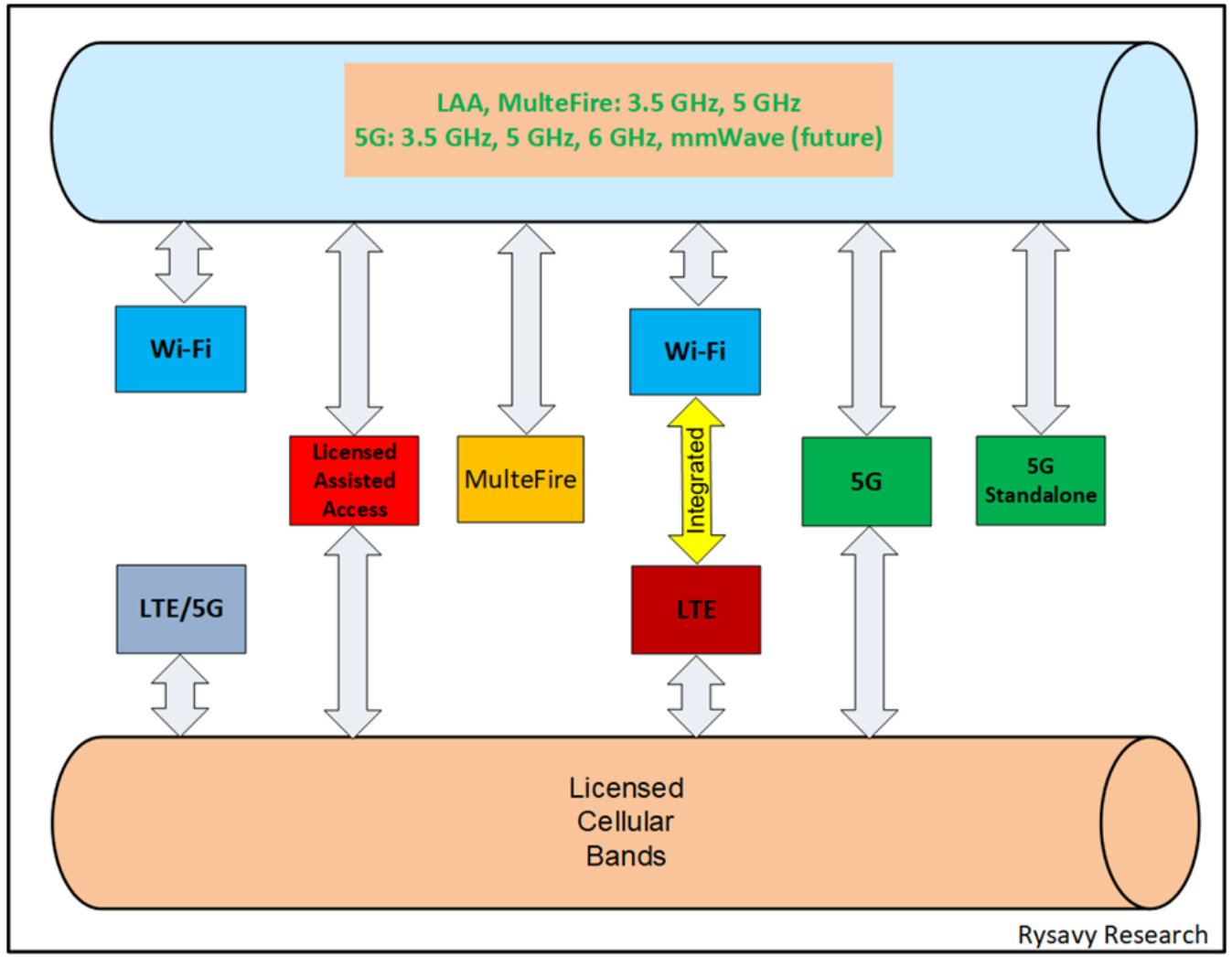
ETSI NFV High-Level Framework



Intelligence in the Cloud, the Edge, and in Devices



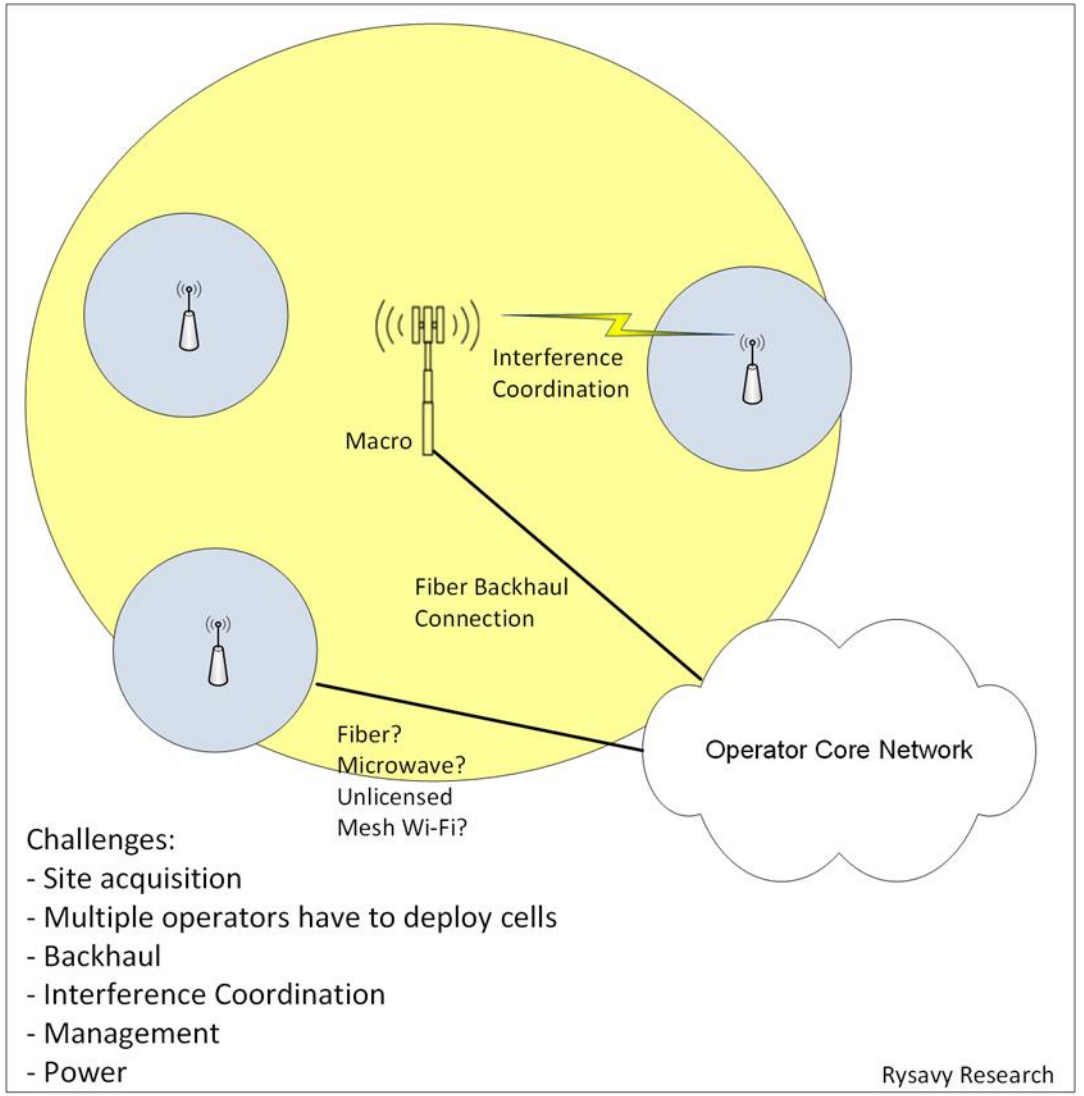
How Different Technologies Harness Spectrum



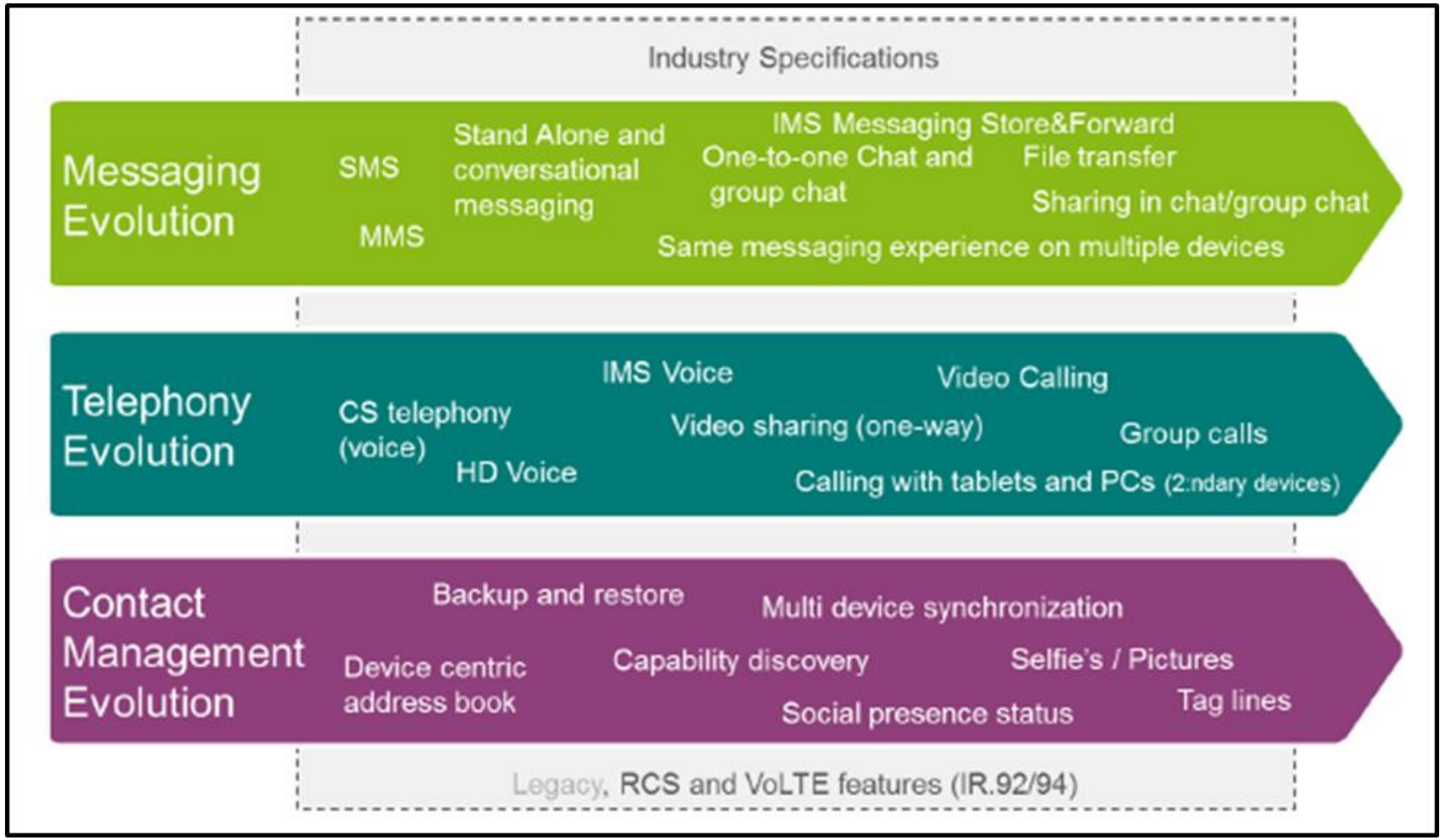
Approaches for Using Unlicensed Spectrum

	Technology	Attributes
Wi-Fi	Ever-more-sophisticated means to integrate Wi-Fi in successive 3GPP Releases.	Combining Wi-Fi with cellular increases capacity.
Release 13 RAN Controlled LTE WLAN Interworking	Base station can instruct the UE to connect to a WLAN for offload.	Available in late 2017 or 2018 timeframe.
Release 10-12 LTE-U Based on LTE-U Forum Specifications	LTE-U Forum-specified approach for operating LTE in unlicensed spectrum.	Available in 2017. More seamless than Wi-Fi. Cannot be used in some regions (e.g., Europe, Japan).
Release 13 Licensed-Assisted Access	3GPP-specified approach for operating LTE in unlicensed spectrum. Downlink only.	Available in 2018. Designed to address global regulatory requirements.
Release 14 Enhanced Licensed-Assisted Access	Addition of uplink operation.	Available in 2019.
5G Unlicensed Operation	To be addressed in Release 16. Will include license assisted and standalone versions.	Available in 2021-2022 timeframe.
MulteFire	Does not require a licensed anchor.	Potentially creates a neutral-host small cell solution.
LWA	Aggregation of LTE and Wi-Fi connections at PDCP layer.	Part of Release 13.
LWIP	Aggregation of LTE and Wi-Fi connections at IP layer.	Part of Release 13.

Small Cell Challenges

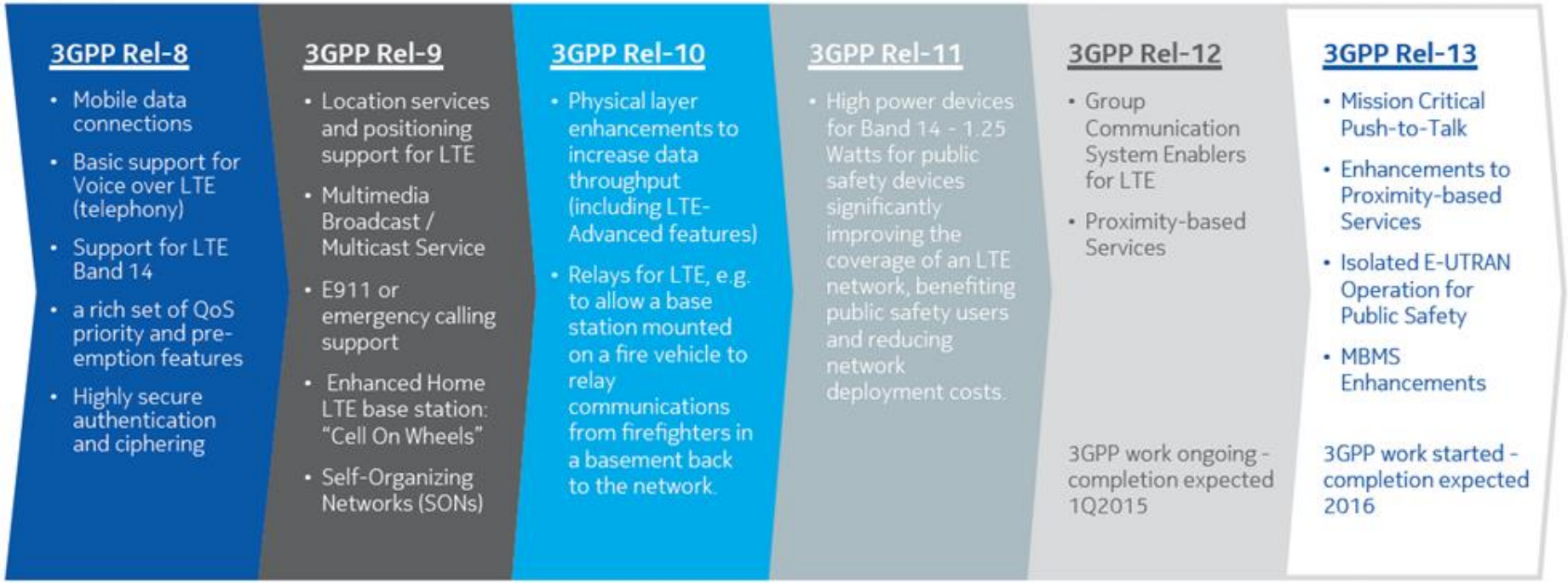


Evolution of RCS Capability



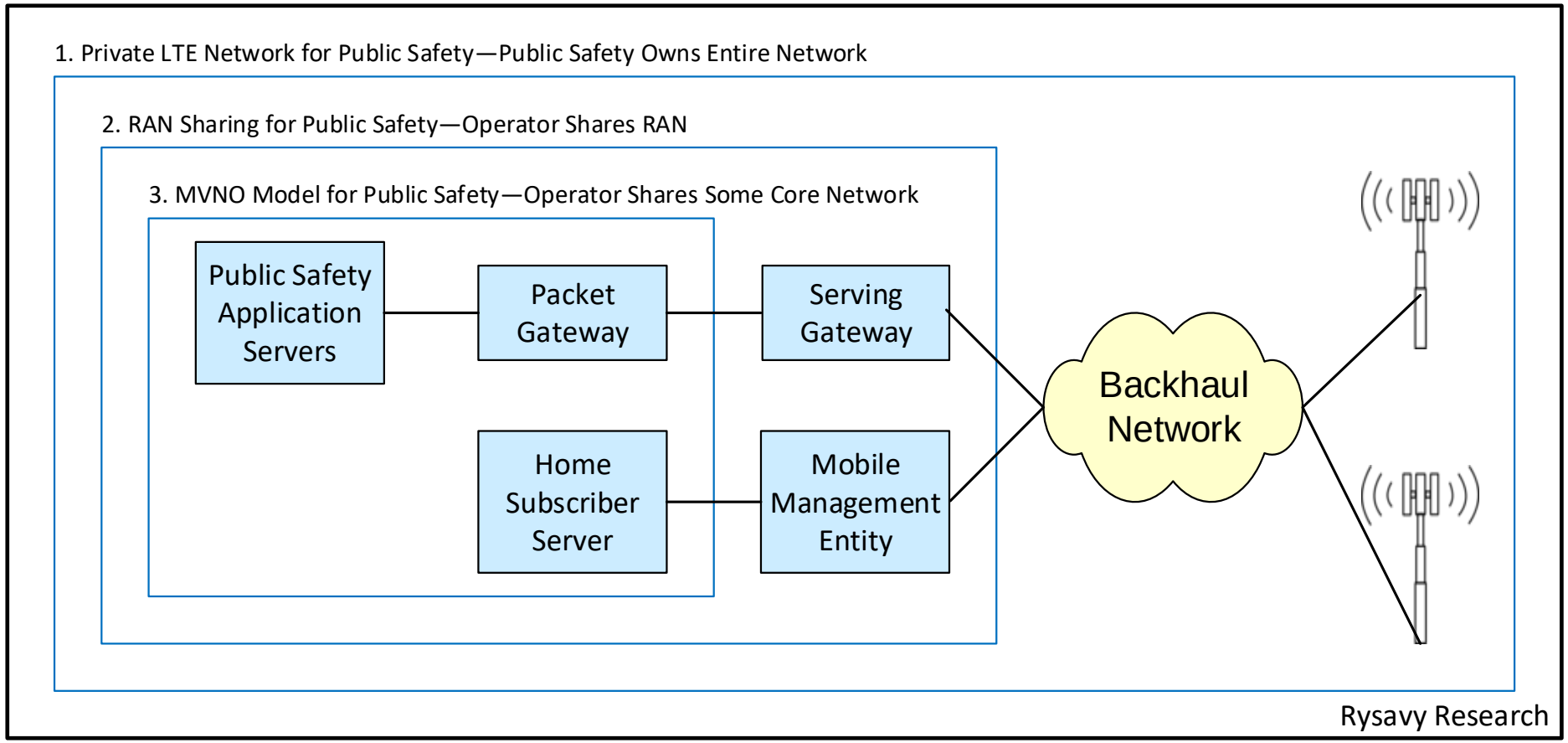
4G Americas white paper, *VoLTE and RCS Technology - Evolution and Ecosystem*, Nov. 2014.

Summary of 3GPP LTE Features to Support Public Safety

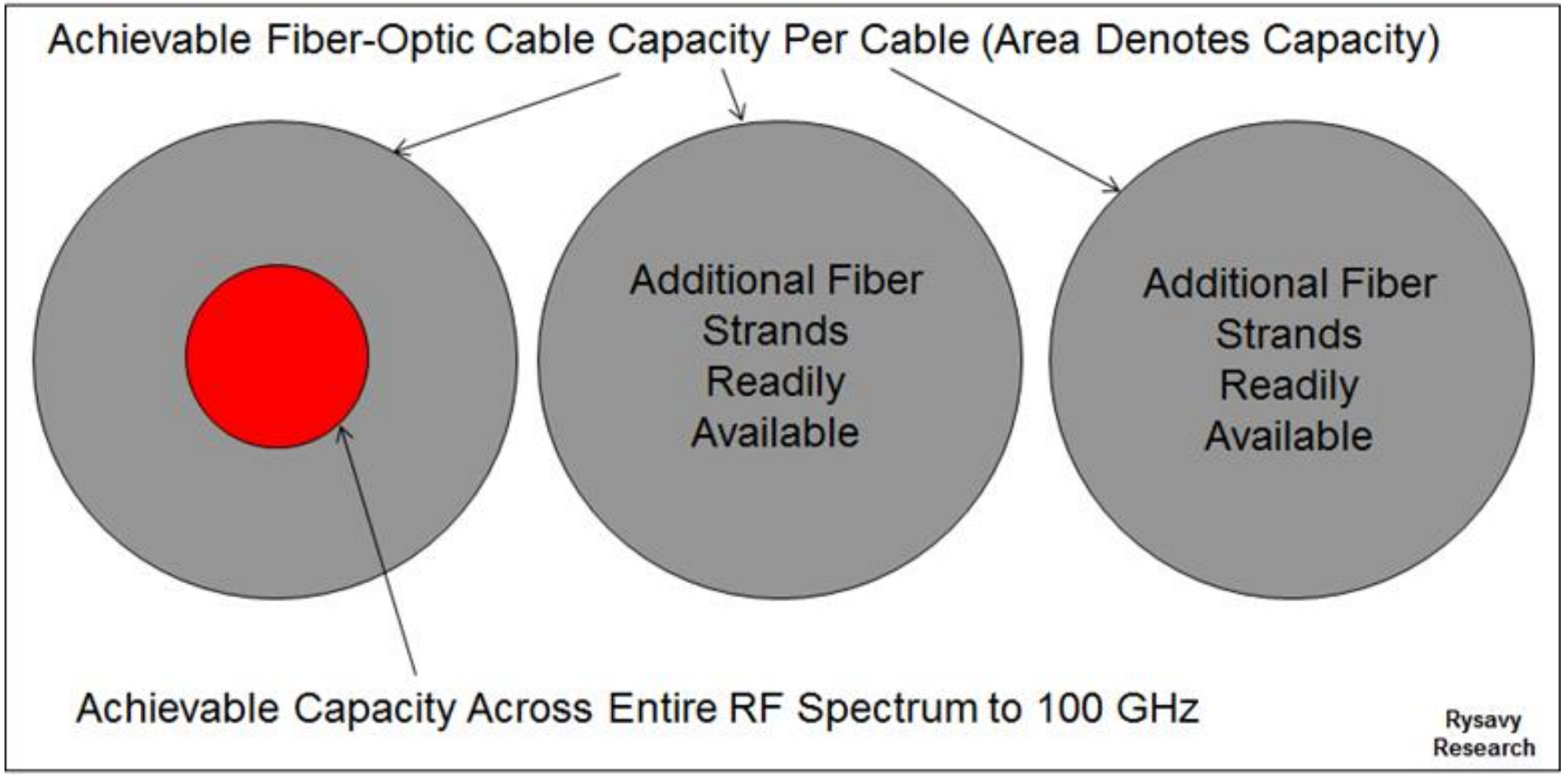


Nokia, *LTE networks for public safety services*, 2014

Sharing Approaches for Public Safety Networks

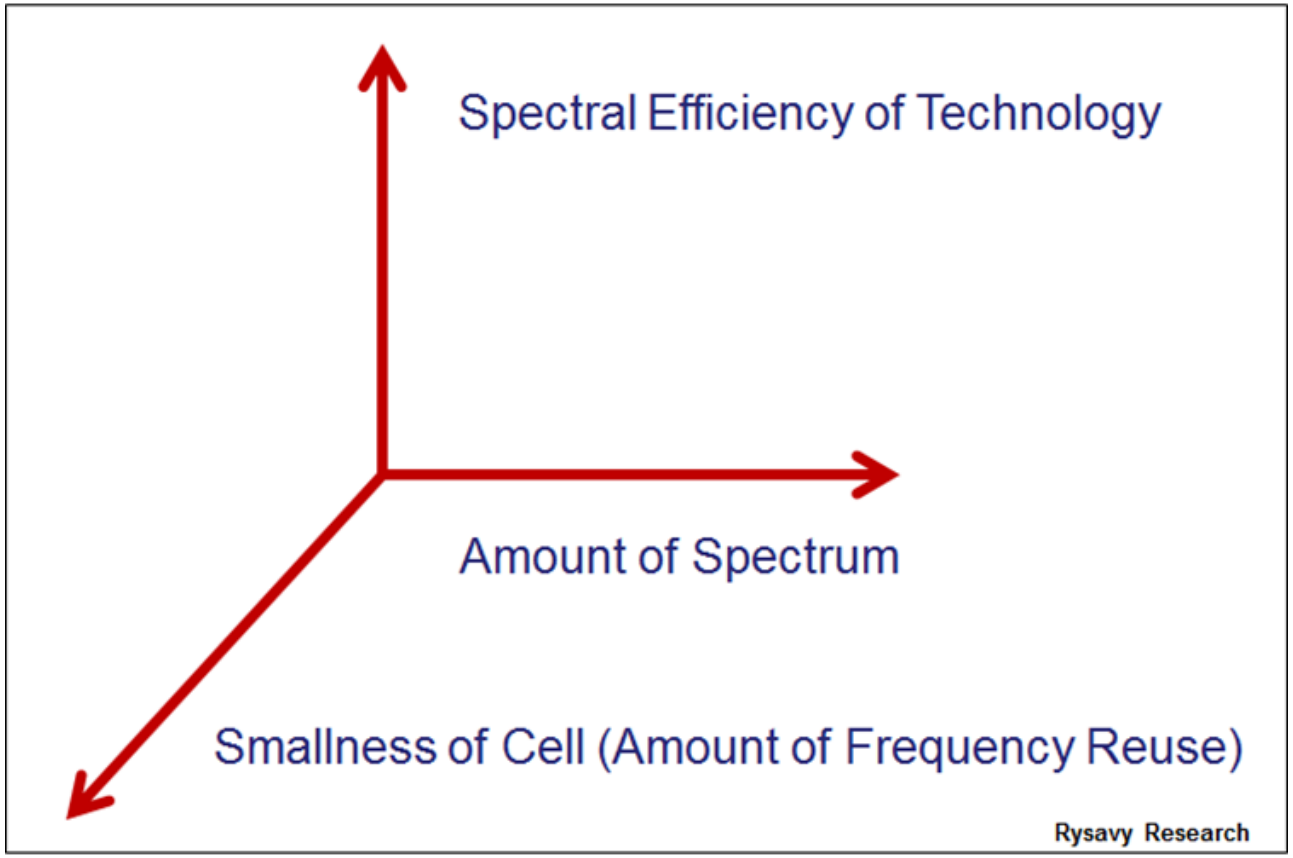


RF Capacity Versus Fiber-Optic Cable Capacity



Dimensions of Capacity

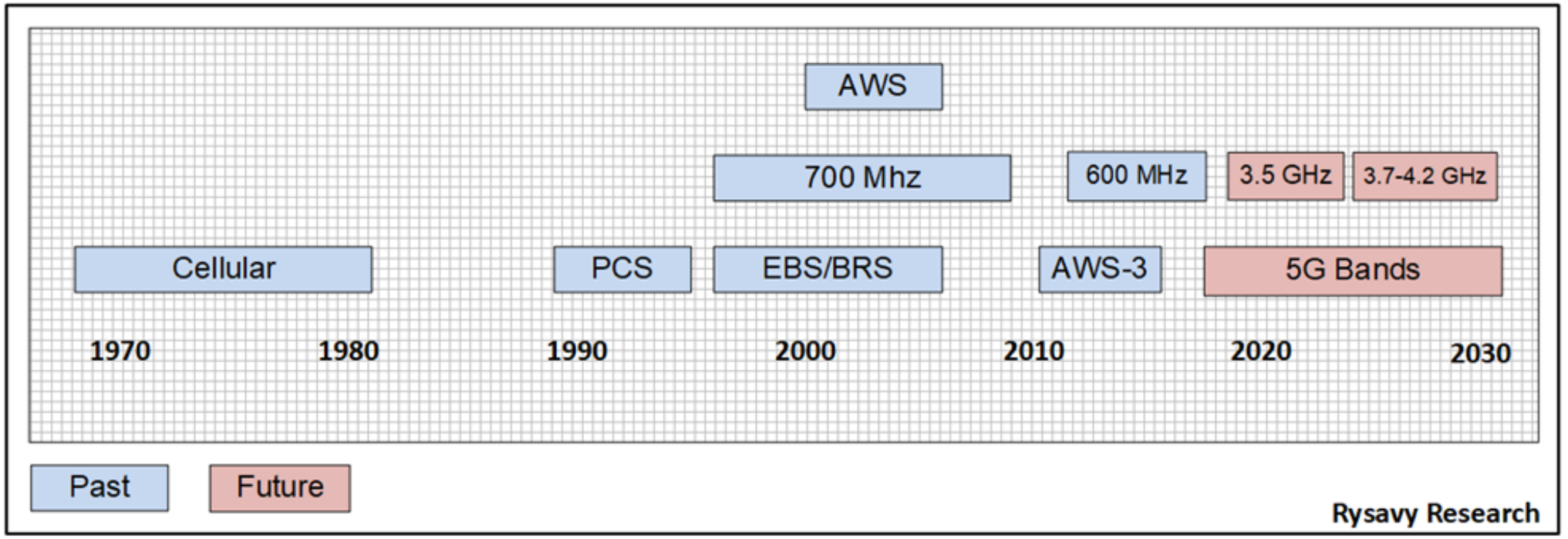
Rysavy Research Analysis:
Aggregate Wireless Network Capacity Doubles Every Three Years



Bandwidth Management

- More spectrum
- Unpaired spectrum
- Supplemental downlink
- Spectrum sharing
- Increased spectral efficiency
- Smart antennas
- Uplink gains combined with downlink carrier aggregation
- Small cells and heterogeneous networks
- Offload to unlicensed spectrum
- Higher-level sectorization
- Quality of service management
- Off-peak hours

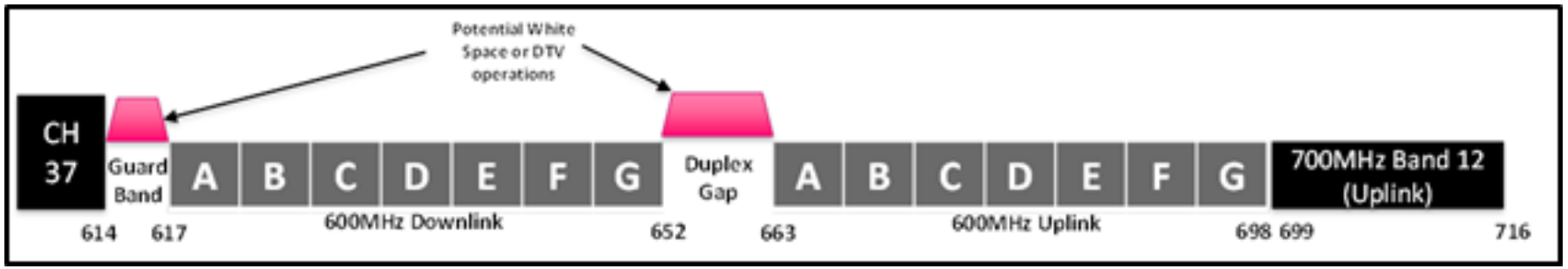
Spectrum Acquisition Time



United States Current and Future Spectrum Allocations

Frequency Band	Amount of Spectrum	Comments
600 MHz	70 MHz	Ultra-High-Frequency (UHF).
700 MHz	70 MHz	Ultra-High Frequency (UHF).
850 MHz	64 MHz	Cellular and Specialized Mobile Radio.
1.7/2.1 GHz	90 MHz	Advanced Wireless Services (AWS)-1.
1695-1710 MHz, 1755 to 1780 MHz, 2155 to 2180 MHz	65 MHz	AWS-3. Uses spectrum sharing.
1.9 GHz	140 MHz	Personal Communications Service (PCS).
2000 to 2020, 2180 to 2200 MHz	40 MHz	AWS-4 (Previously Mobile Satellite Service).
2.3 GHz	20 MHz	Wireless Communications Service (WCS).
2.5 GHz	194 MHz	Broadband Radio Service. Closer to 160 MHz deployable.
24 GHz	700 MHz	Second licensed mmWave spectrum in the United States.
28 GHz	850 MHz	First licensed mmWave spectrum in the United Sates.
FUTURE		
3.55 to 3.70 GHz	150 MHz	Will employ spectrum sharing and unlicensed options. CBRS GAA expected by end of 2019, and CBRS LAA license auction expected in 2020.
3.7 to 4.2 GHz	Up to 500 MHz with 200-to-300 MHz likely	Mid-band spectrum under discussion for 5G.
Other mmWave	Multi GHz	37 GHz, 39 GHz, 47 GHz auctions planned for 2019. Additional bands will be made available in the future.

600 MHz Band Plan

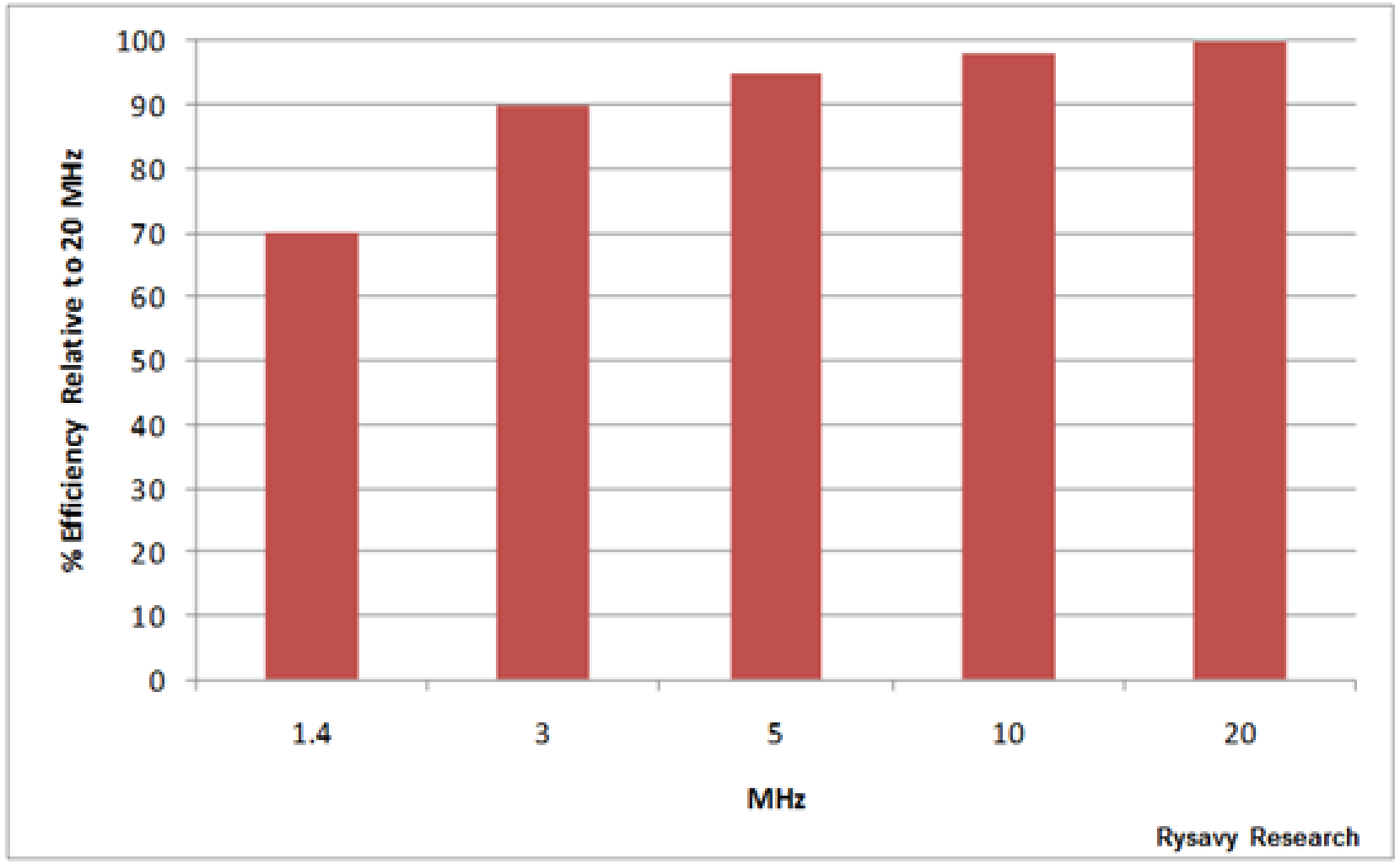


5G Americas member contribution

United States 5G mmWave Bands

Bands	Details
24 GHz Band (24.25-24.45 GHz and 24.75-25.25 GHz)	Identified for flexible use. Licensed in seven 100 MHz blocks.
28 GHz Band (27.5-28.35 GHz)	Currently licensed for Local Multipoint Distribution Service (LMDS). Licensed in two 425 MHz blocks by county.
39 GHz Band (38.6-40 GHz)	Currently licensed for fixed microwave in 50 MHz channels. Segment auctioned in 100 or 200 MHz blocks.
37 GHz Band (37-38.6 GHz)	Lower 37-37.6 GHz segment will be shared between federal and non-federal users. Upper 37.6-38.6 GHz segment auctioned in 100 or 200 MHz blocks.
47 GHz Band (47.2-48.2 GHz)	Identified for flexible use.
64-71 GHz Band	Available for unlicensed use with same Part 15 rules as existing 57-64 GHz band.

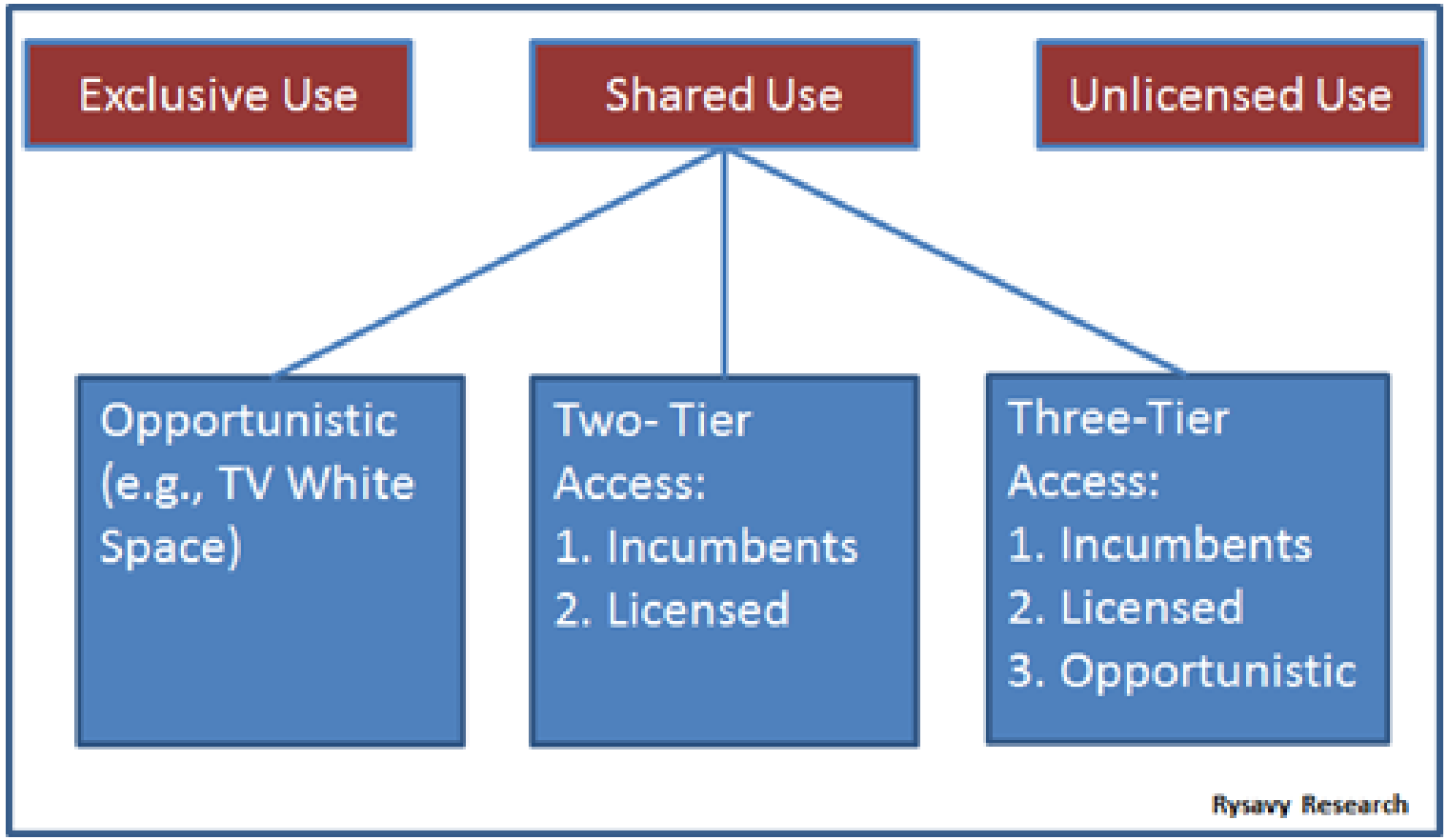
LTE Spectral Efficiency as Function of Radio Channel Size



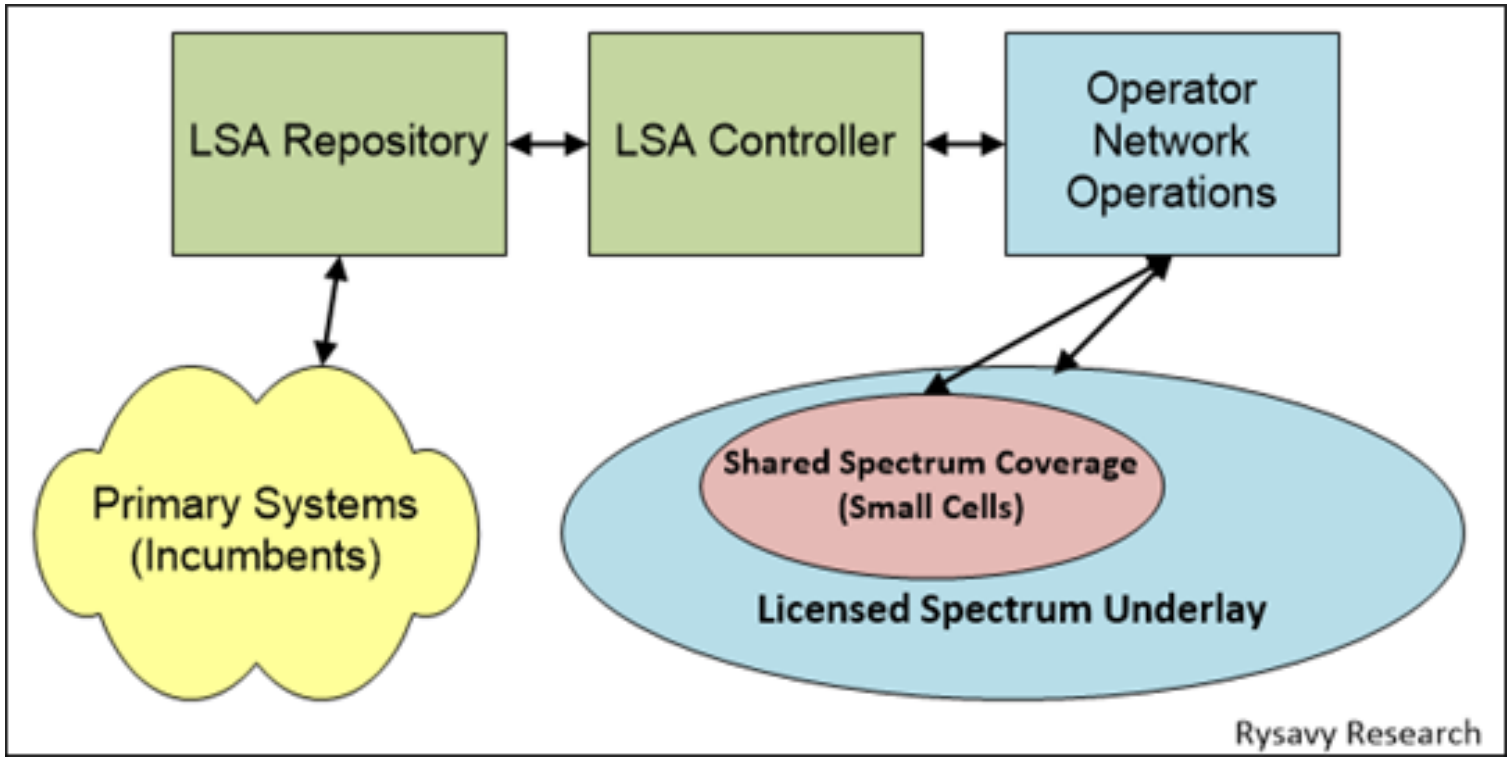
Pros and Cons of Unlicensed and Licensed Spectrum

Unlicensed Spectrum		Licensed Spectrum	
Pros	Cons	Pros	Cons
Easy and quick to deploy	Potential of other entities using same frequencies	Huge coverage areas	Expensive infrastructure
Low-cost hardware	Difficult to impossible to provide wide-scale coverage	Able to manage quality of service	Each operator has access to only a small amount of spectrum

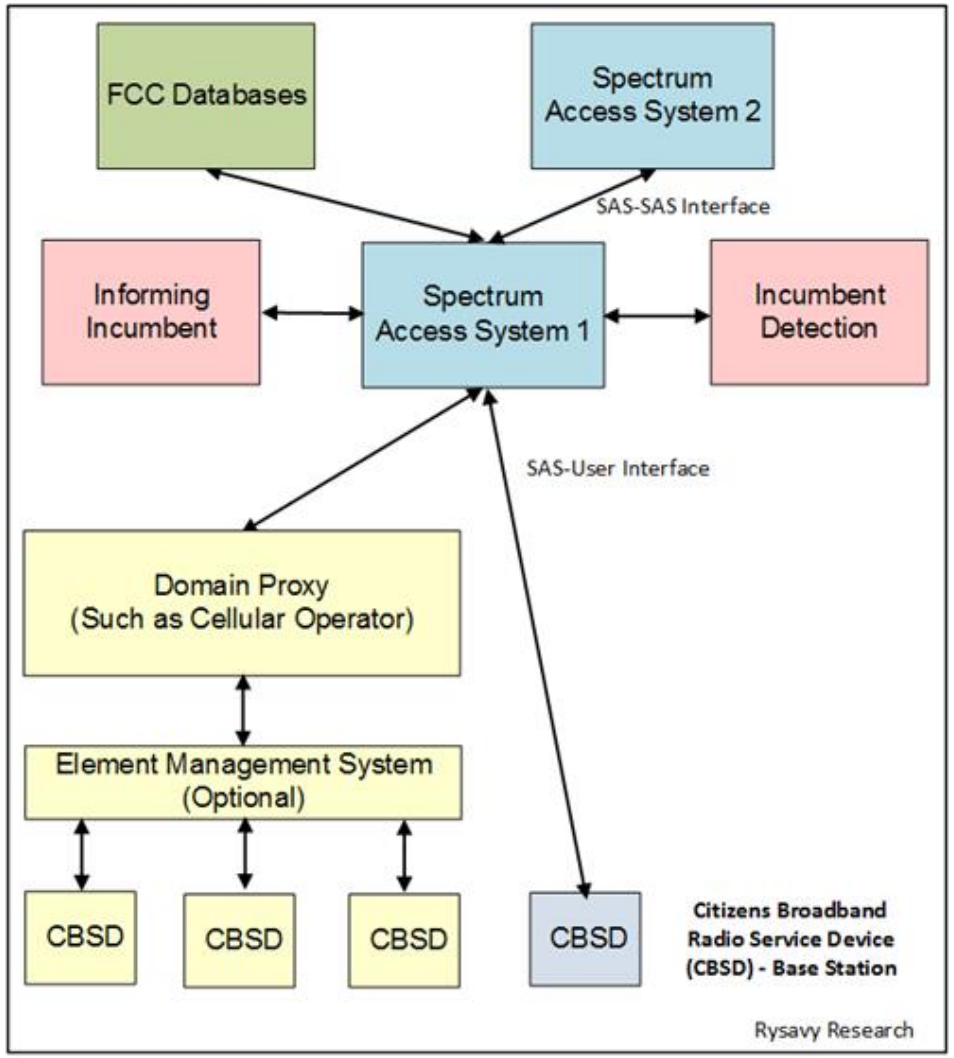
Spectrum Use and Sharing Approaches



Licensed Shared Access

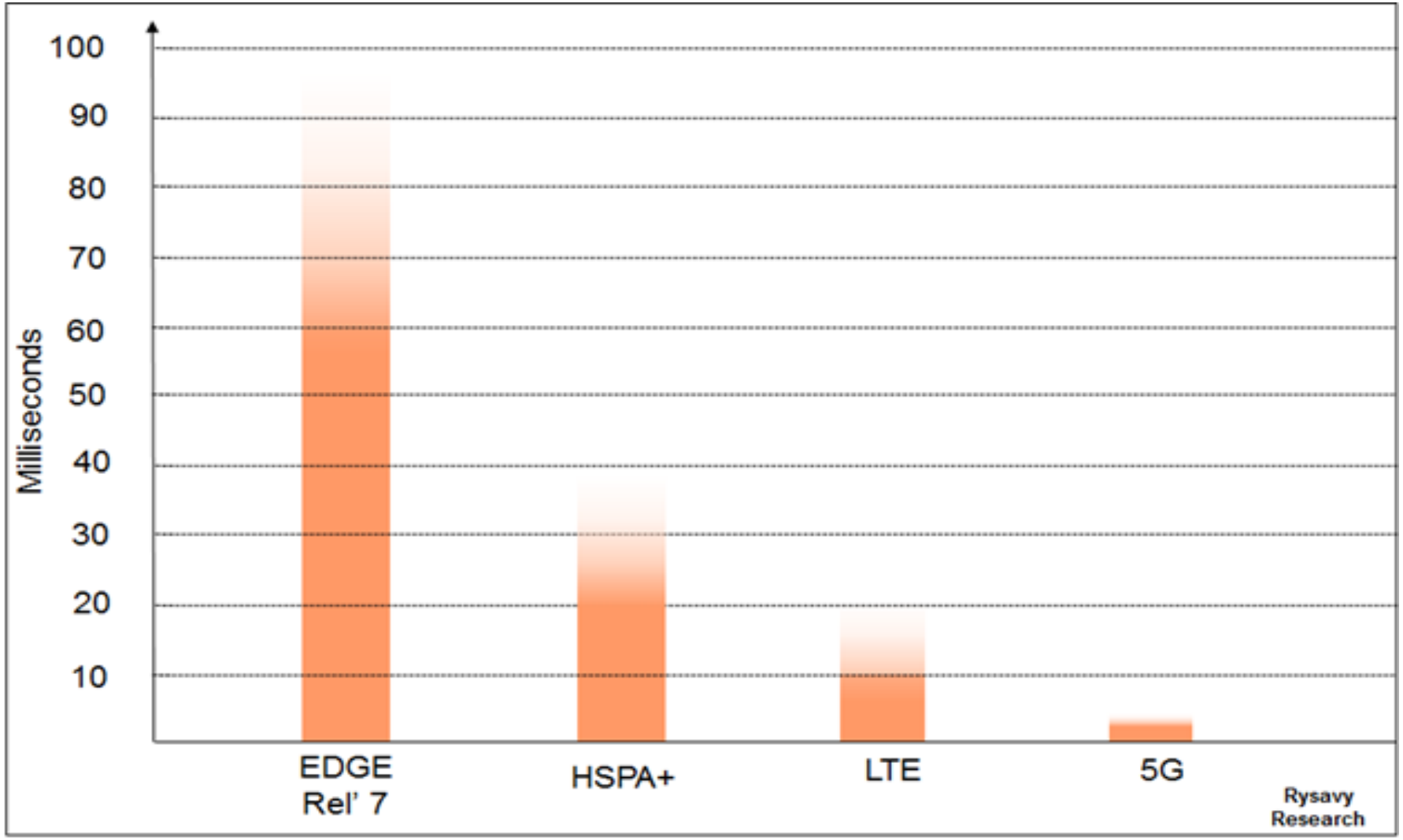


CBRS Architecture

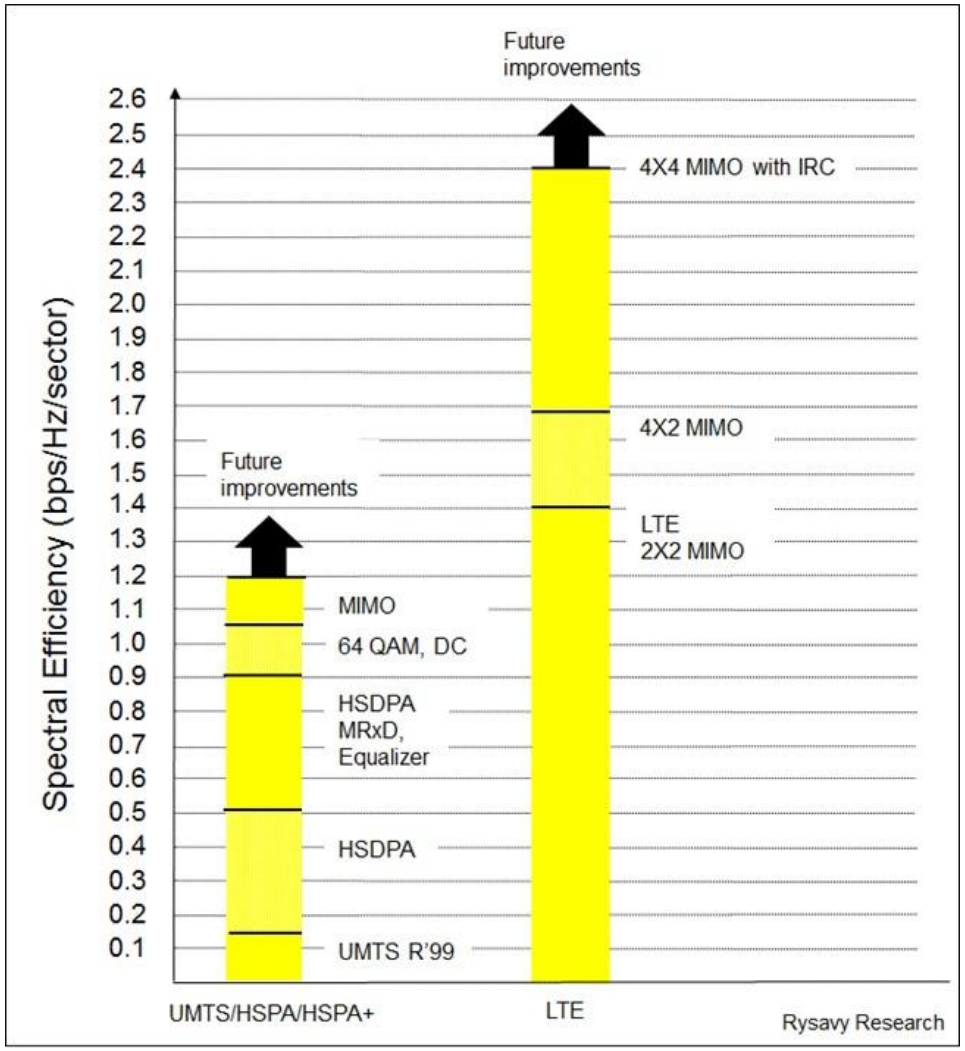


Appendix section with additional technical details

Latency of Different Technologies



Comparison of Downlink Spectral Efficiency



Massive MIMO Capacity Gains

Deployment of active antenna systems for 3.5 GHz

Active antenna system performance depends on:

# of supported sync. & reference signals[1]	Users distribution	Infrastructure implementation

Key considerations include:

of elements: more elements enable better beamforming but tradeoff with cost/weight

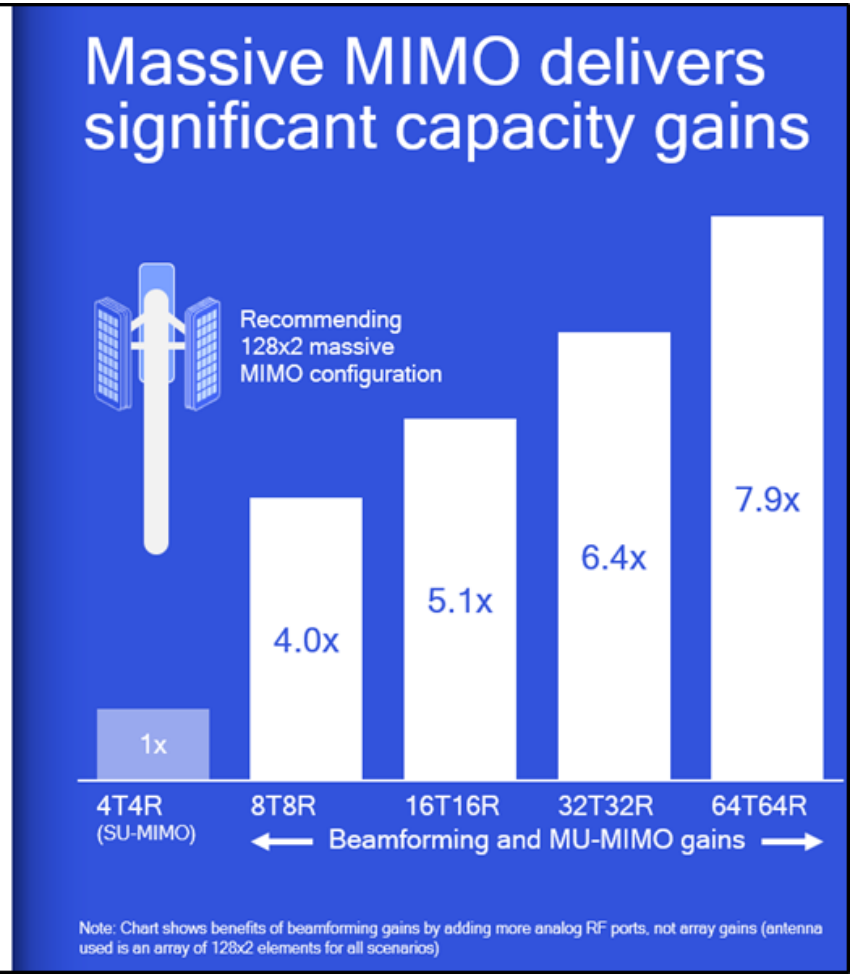
Square-shape: supporting horizontal & vertical traffic distribution

Inter-beam overlap impacts MU-MIMO

Recommendations:

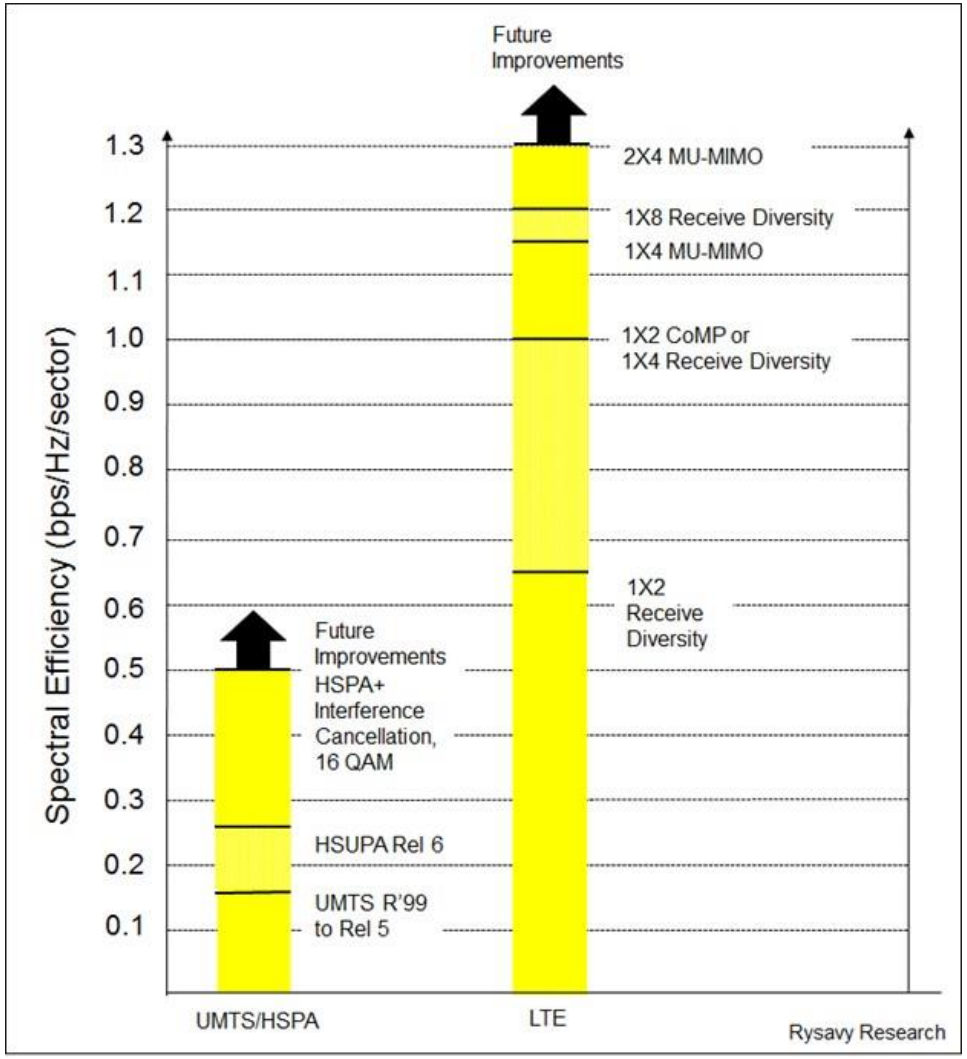
Massive MIMO with 128x2 elements with configuration of 8(h) x 16(v) x 2(x-pol.) for urban, dense urban deployments

1. SSB: Synchronization Signal Blocks and CSI-RS: Channel State Information Reference Signal

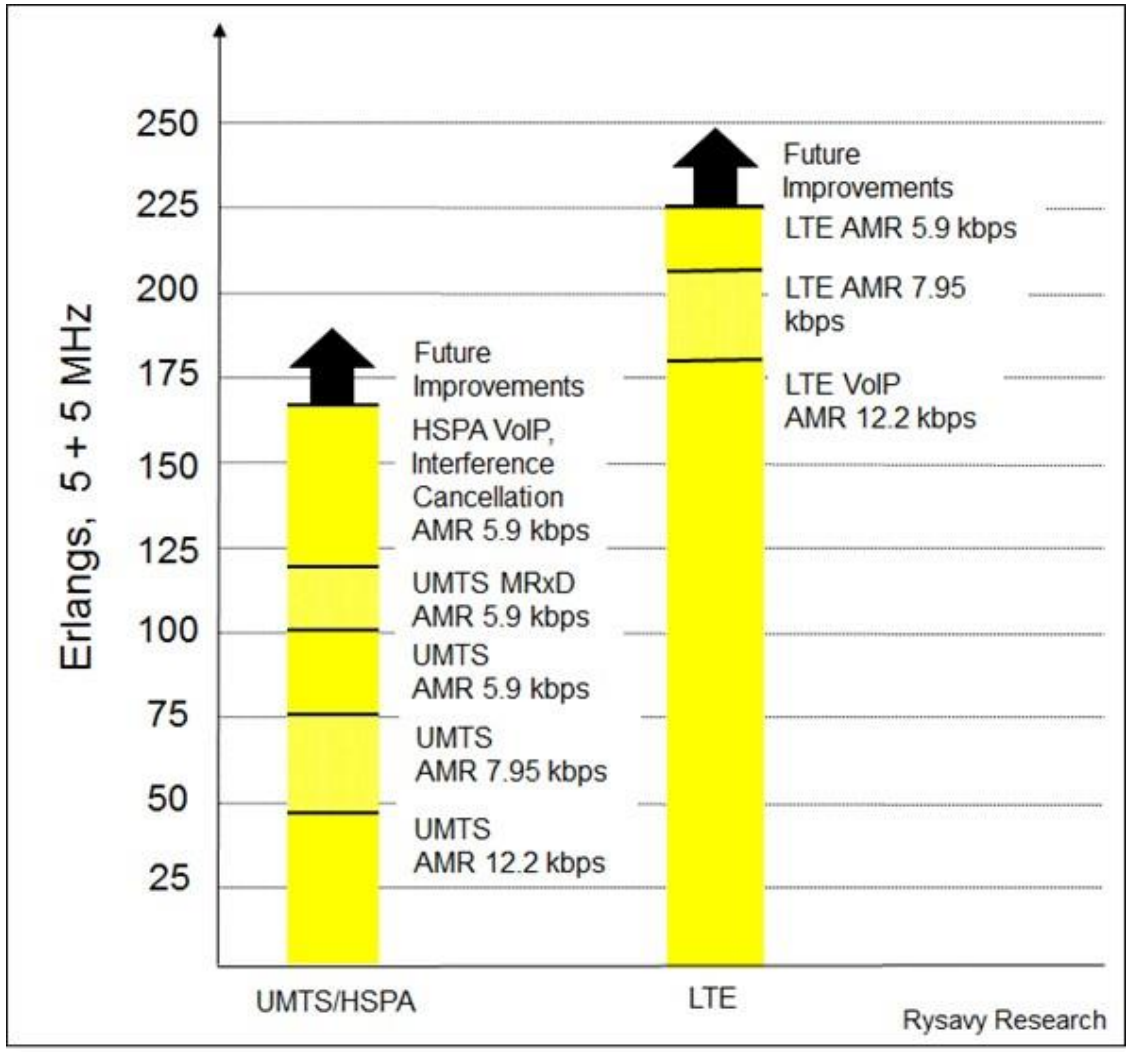


Qualcomm webinar, *How do we plan for 5G NR network deployments coming in 2019*? Nov. 2018.

Comparison of Uplink Spectral Efficiency



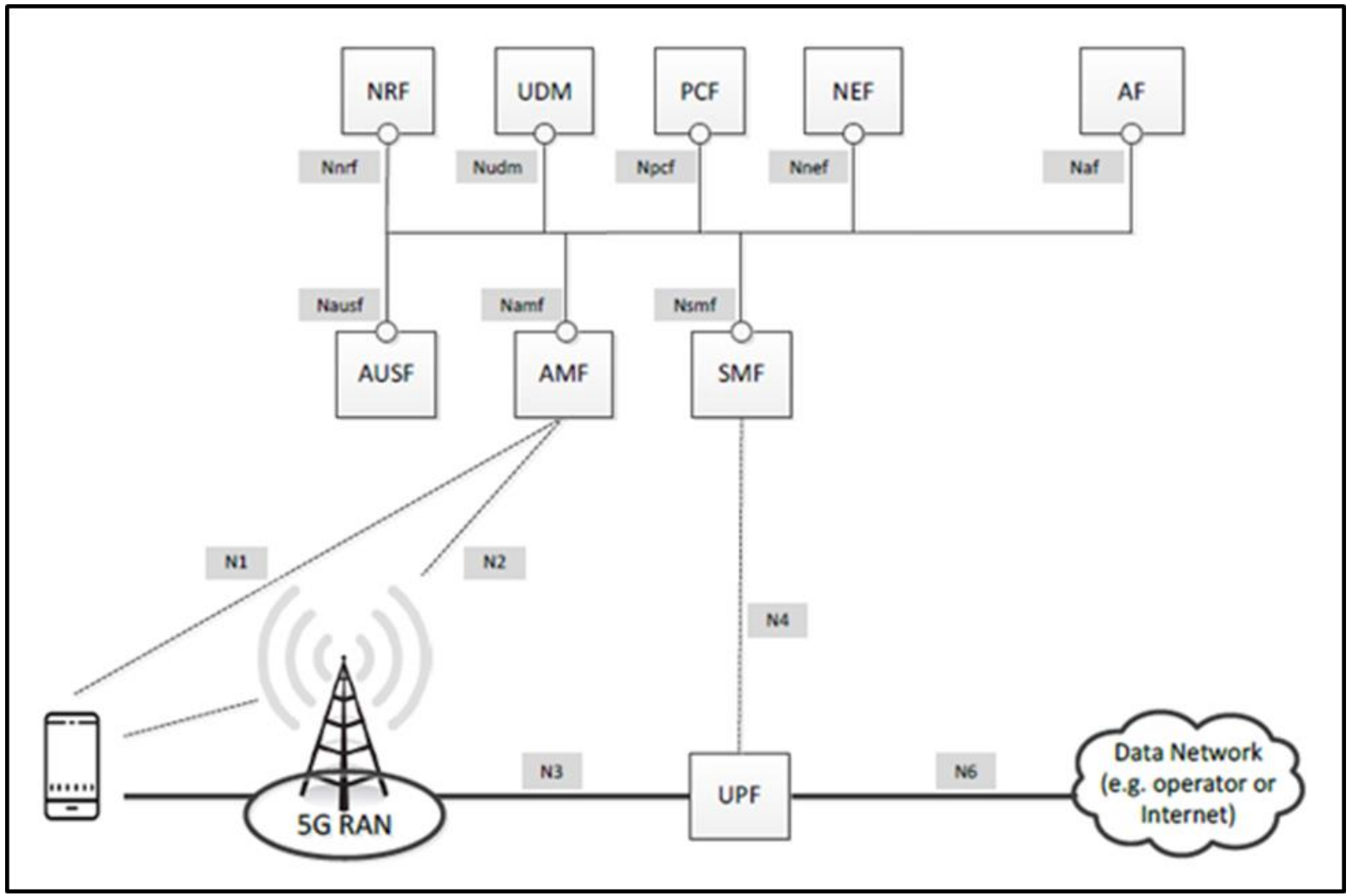
Comparison of Voice Spectral Efficiency



Data Consumed by Streaming and Virtual Reality

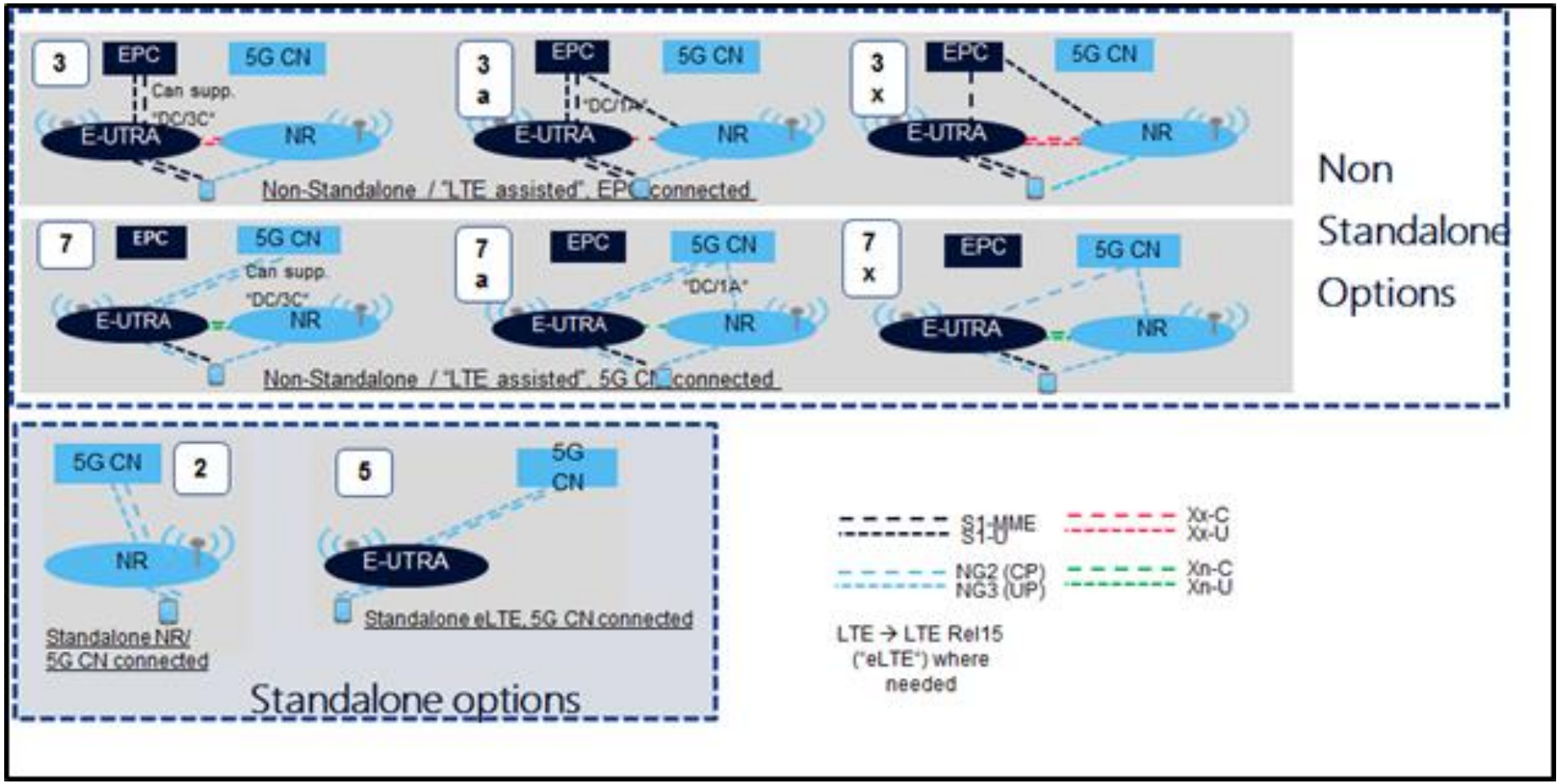
Application	Throughput (Mbps)	MByte/hour	Hrs./day	GB/month
Audio or Music	0.1	58	0.5	0.9
			1.0	1.7
			2.0	3.5
			4.0	6.9
Small Screen Video (e.g., Feature Phone)	0.2	90	0.5	1.4
			1.0	2.7
			2.0	5.4
			4.0	10.8
Medium Screen Video (e.g., Smartphone, Tablet, Laptop)	1.0	450	0.5	6.8
			1.0	13.5
			2.0	27.0
			4.0	54.0
Larger Screen Video (e.g., 720p medium definition)	3.0	1350	0.5	20.3
			1.0	40.5
			2.0	81.0
			4.0	162.0
High Definition (e.g., 1080p Netflix HD)	5.0	2250	0.5	33.8
			1.0	67.5
			2.0	135
			4.0	270
4K Ultra-High Definition (Rates will range 12 to 30 Mbps)	20.0	9000	0.5	135
			1.0	270
			2.0	540
			4.0	1080
4G, 30 FPS, Virtual Reality (Rates will range 10 to 50 Mbps)	25.0	11250	0.5	169
			1.0	338
			2.0	675
			4.0	1350
8K, 90 FPS, Virtual Reality (Rates will exceed 200 Mbps)	200.0	90000	0.5	1350
			1.0	2700
			2.0	5400
			4.0	10800
6 Degrees Freedom VR (Rates will range 200 to 1,000 Mbps)	500.0	225000	0.5	3375
			1.0	6750
			2.0	13500
Rysavy Research			4.0	27000

5G Core Service Based Architecture



5G Americas white paper, *5G Network Transformation*, Dec. 2017

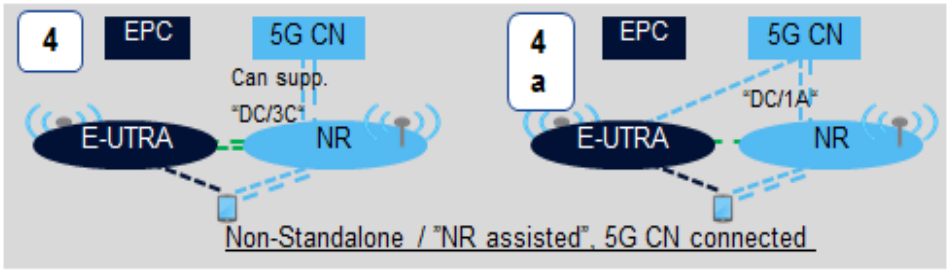
5G Architecture Options in Release 15



5G Americas Member Contribution

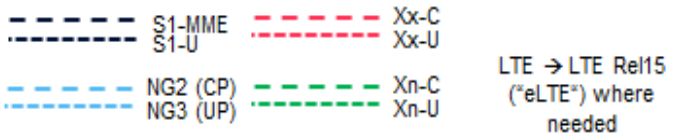
De-Prioritized 5G Network Architecture Options in 3GPP Release 15

Work on Option 4/4A will be started after the work on Option 2, 3 series and 7 series are completed. This is logical as Option 4/4A would be only used for dual connectivity with 5G lower frequency band than LTE



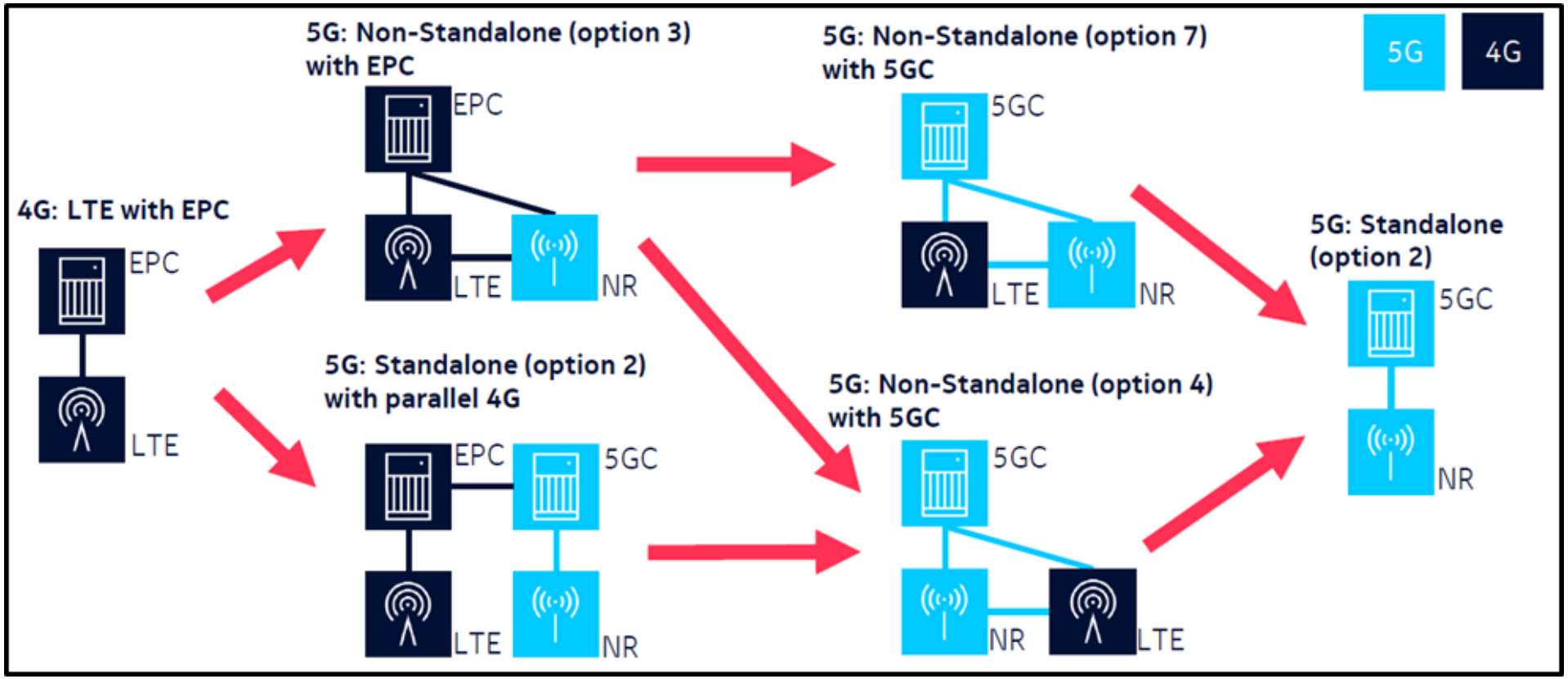
Non Standalone Option

Work on Option 5 (LTE connecting to 5G core) is covered in a separate work item (as no 5G impacts). This requires devices to also be upgraded (as e.g. broadcast of core network type), thus legacy devices need still connection to EPC



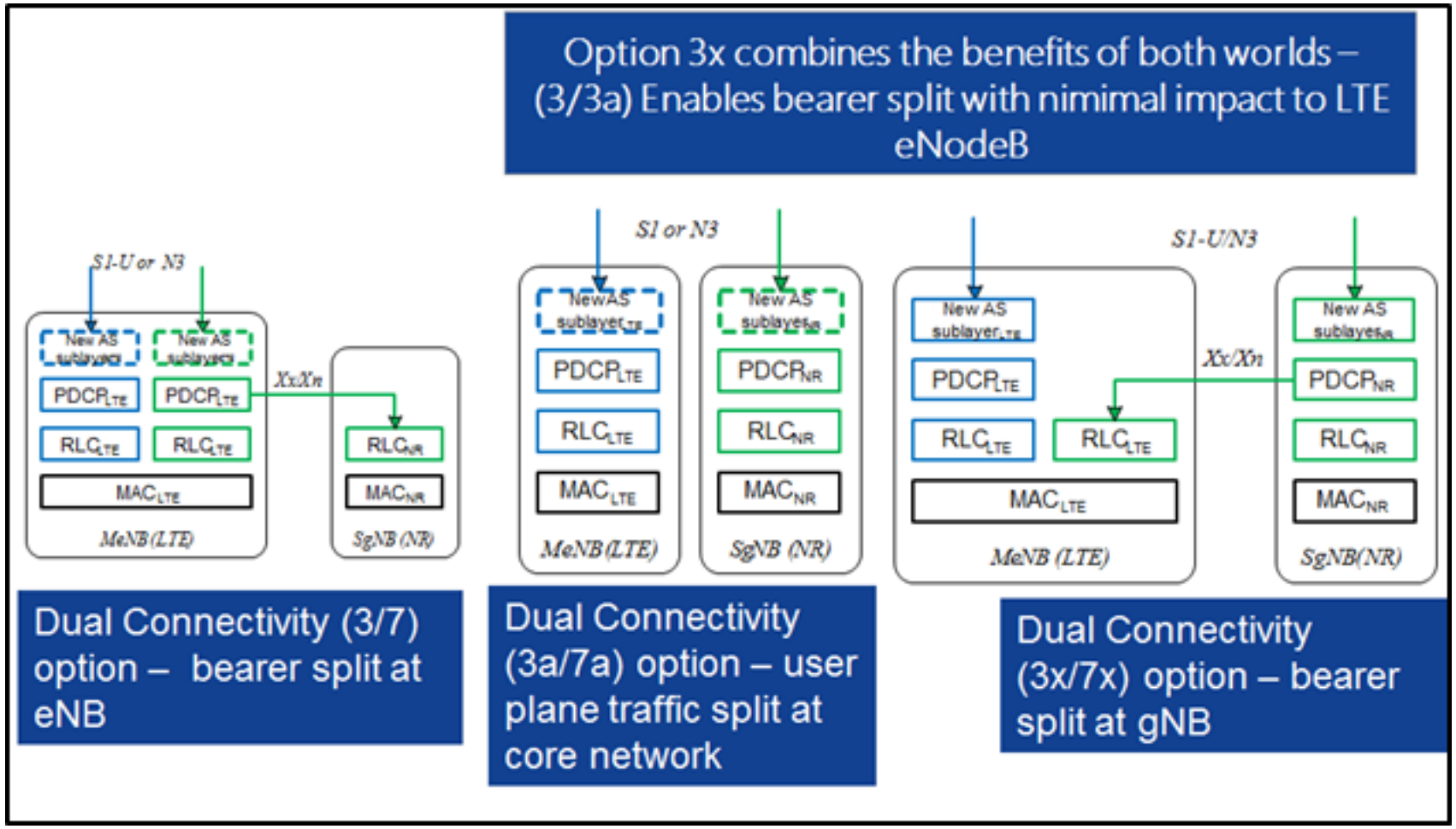
5G Americas Member Contribution

Different Migration Paths for LTE to 5G



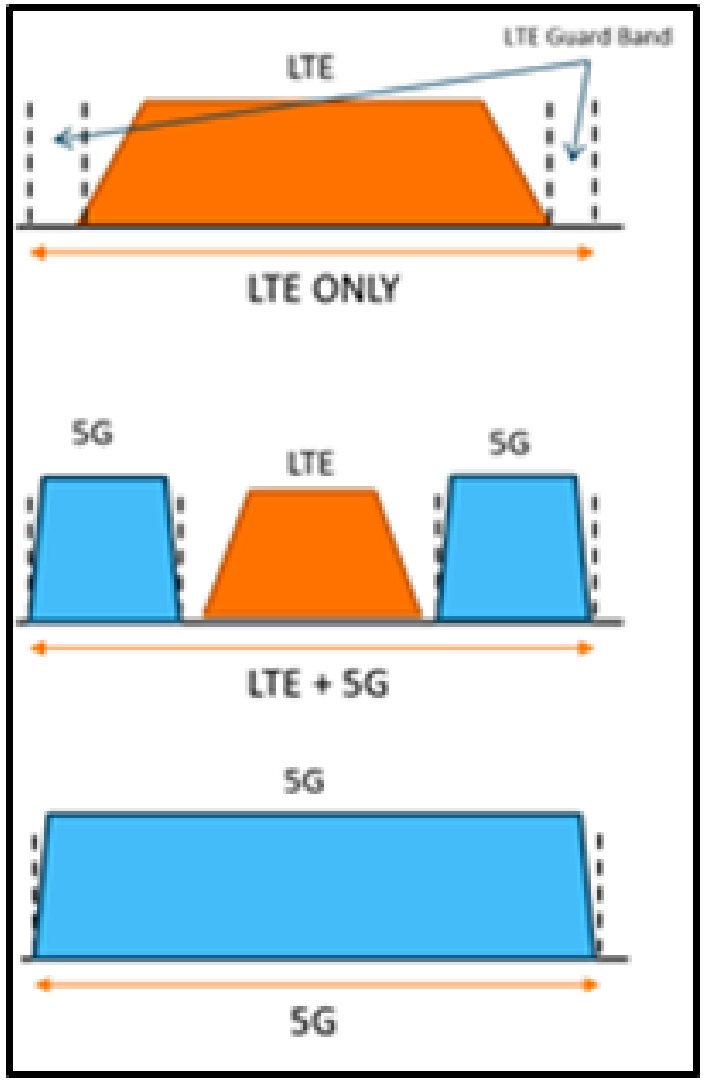
5G Americas Member Contribution

Dual-Connectivity Options with LTE as Master

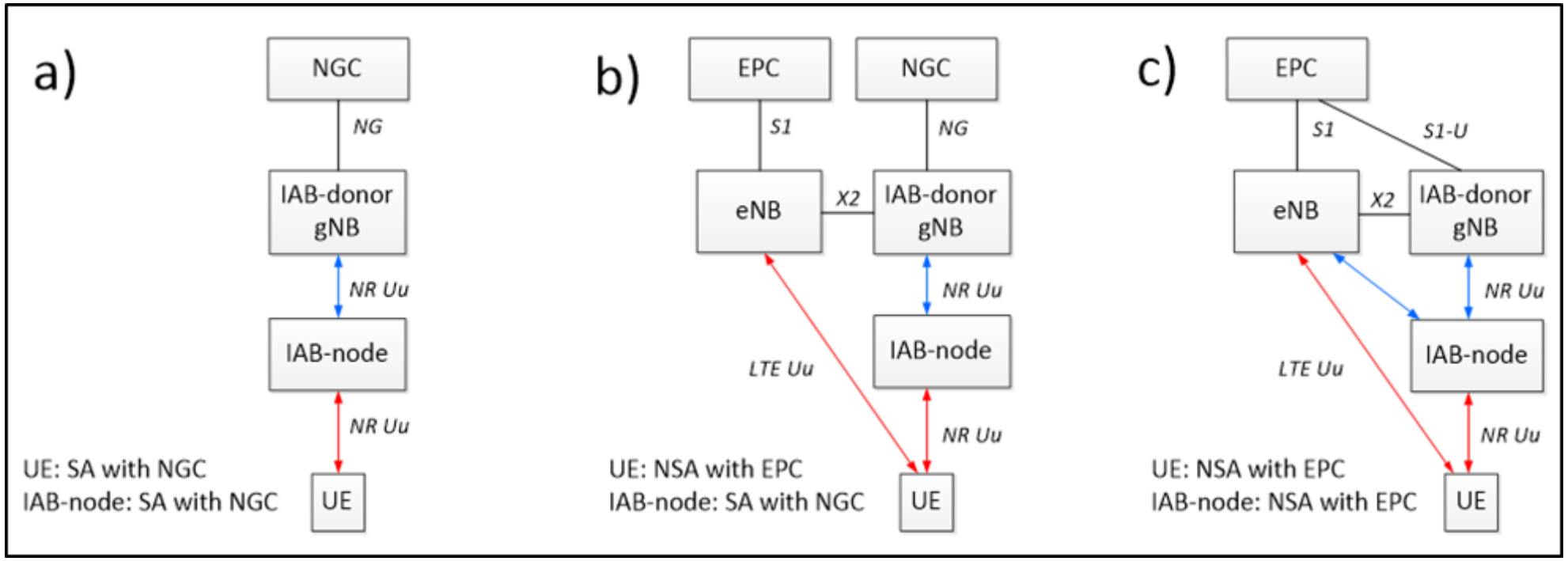


5G Americas Member Contribution

Frequency Domain Coexistence of LTE and NR

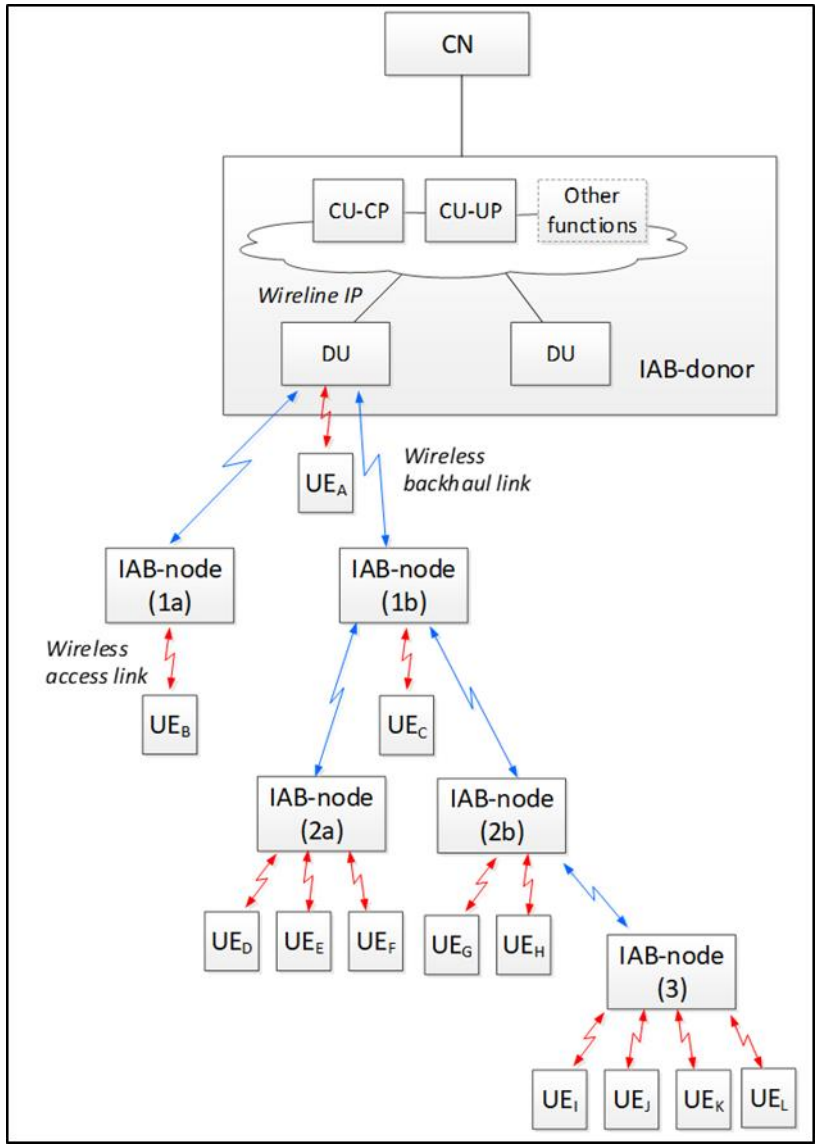


Examples for Operation in SA and NSA Modes



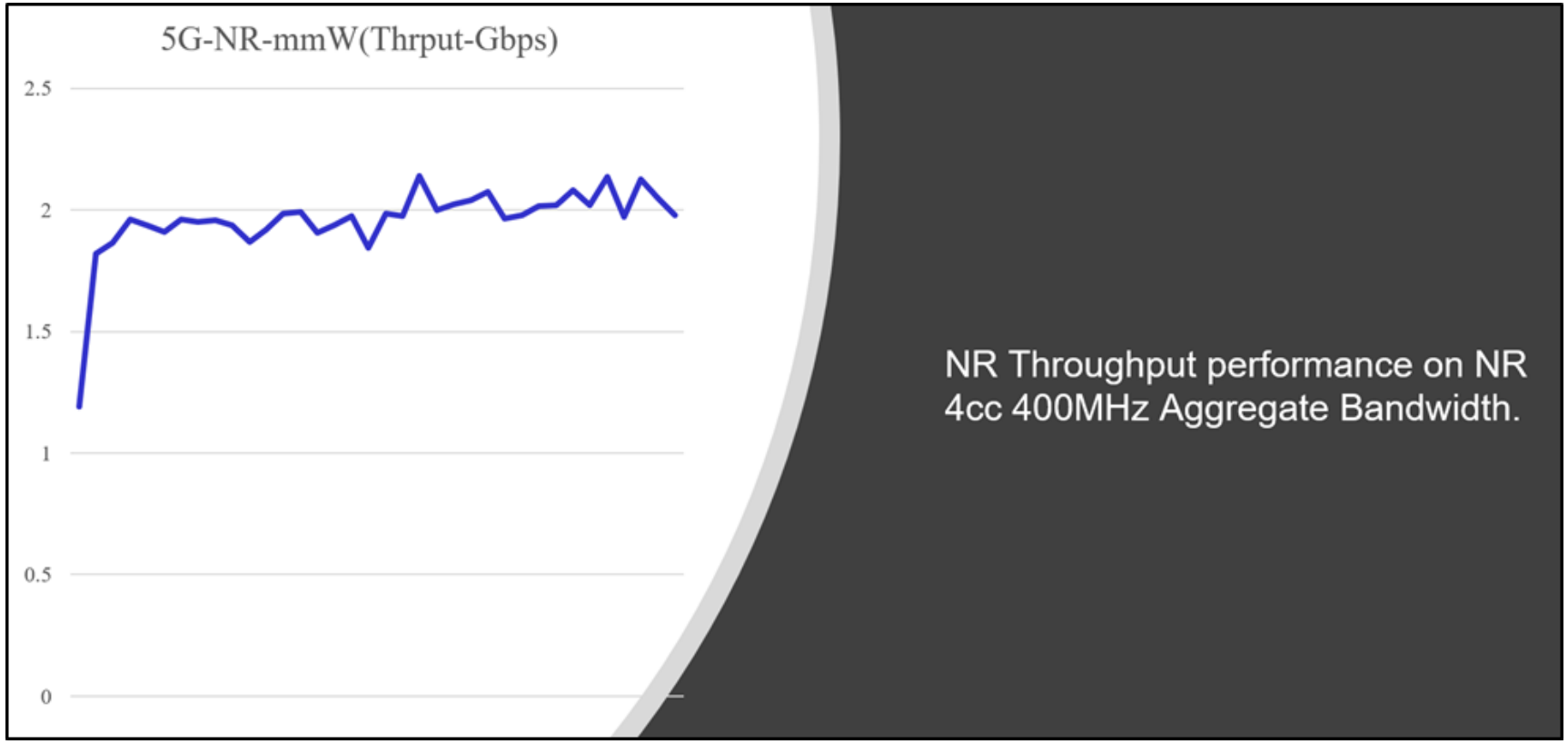
3GPP, *Study on Integrated Access and Backhaul*, Release 16, 3GPP TR 38.874 V16.0.0

IAB Network with Three hops and 12 UEs



3GPP, *Study on Integrated Access and Backhaul*, Release 16, 3GPP TR 38.874 V16.0.0

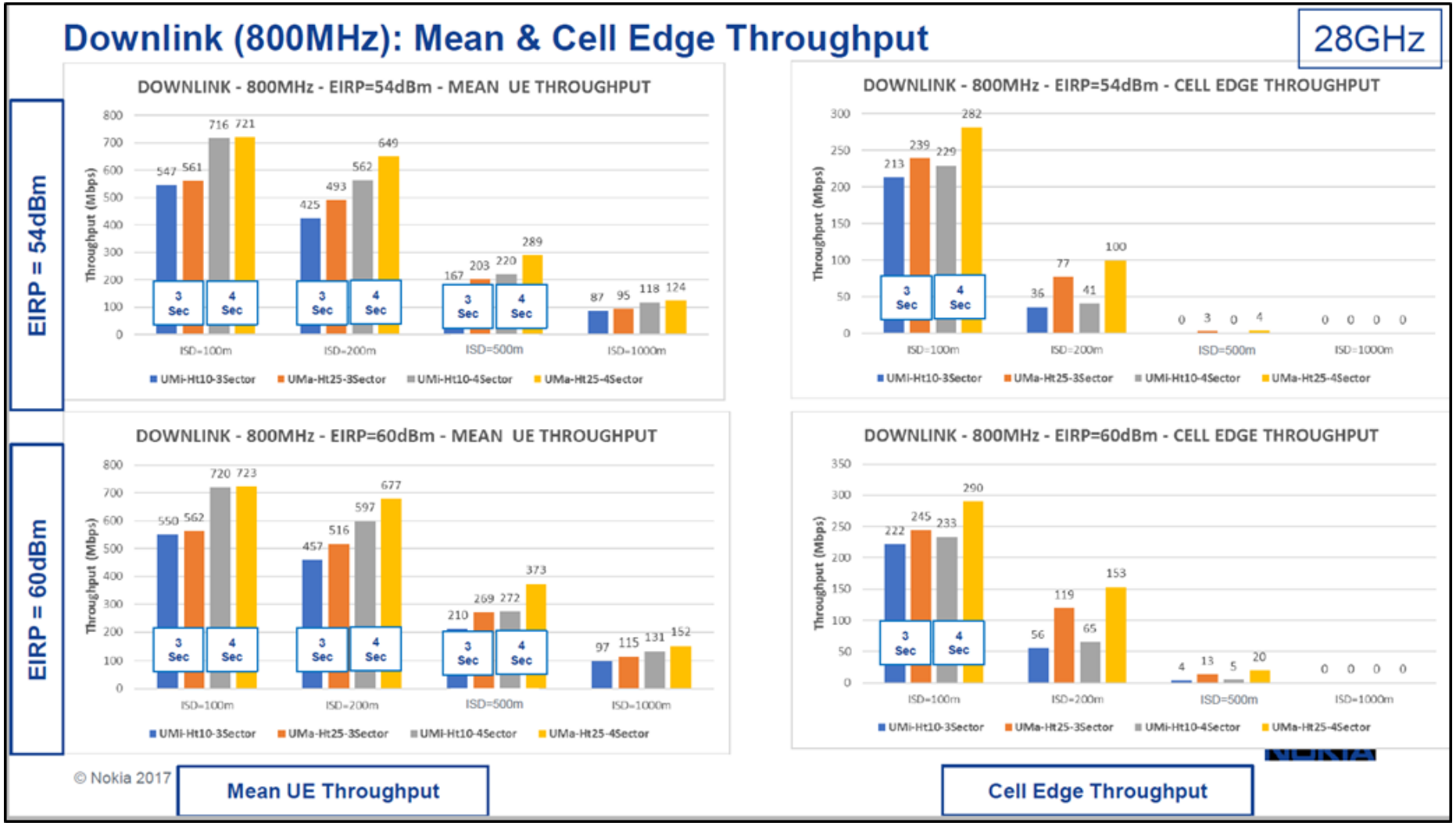
5G NR Downlink Measured Performance



Horizontal axis is time. Additional test configuration information: direct line of sight with 85° angle of arrival, beam reference signal received power of -82dbm, 2x2 MIMO, 64 QAM, 8 wide beams, 64 narrow beams.

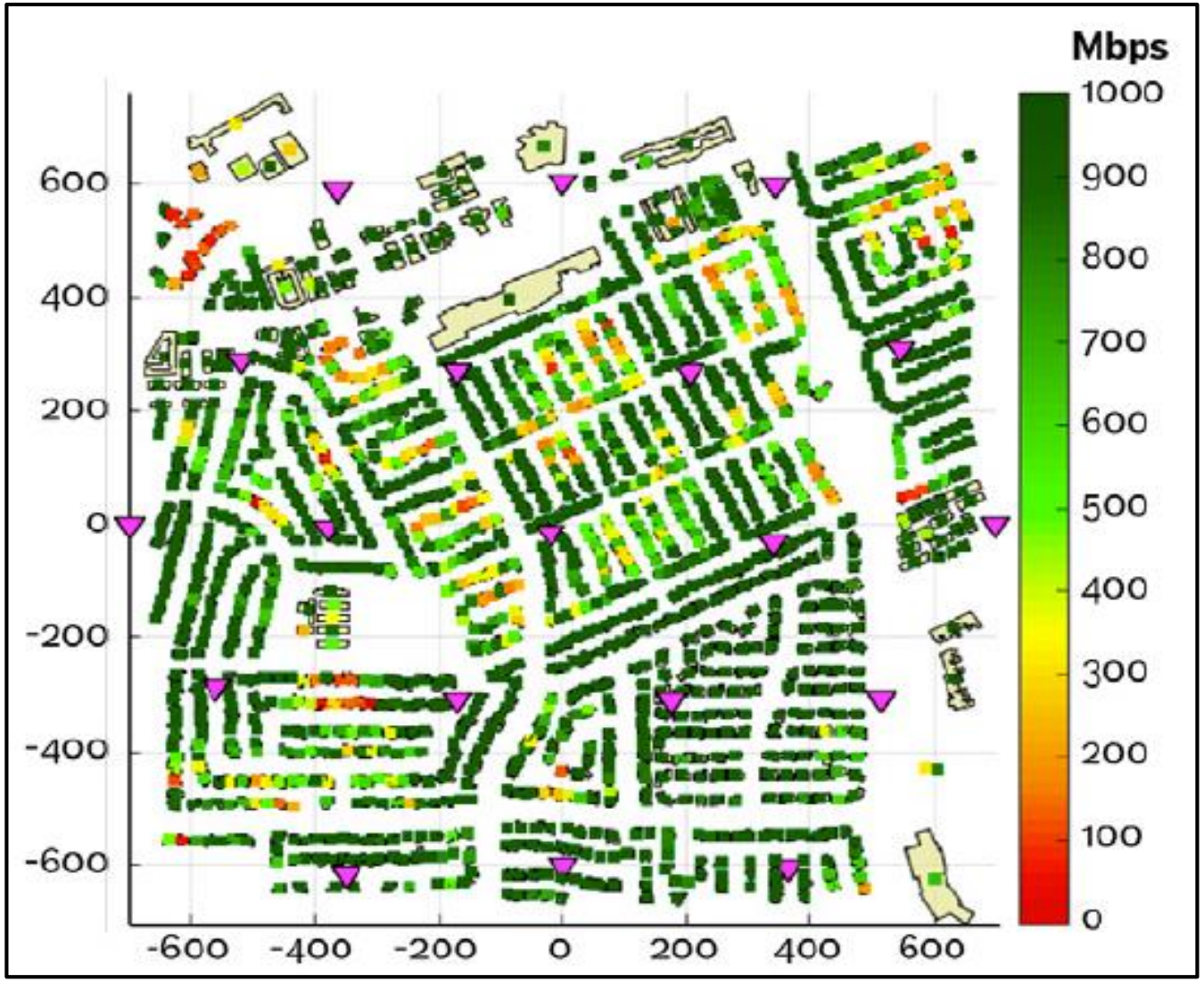
5G Americas Member Contribution

Downlink Performance, Different ISDs



5G Americas Member Contribution
Refer to white paper for assumptions.

Throughput Map of Suburban Area at Low Load



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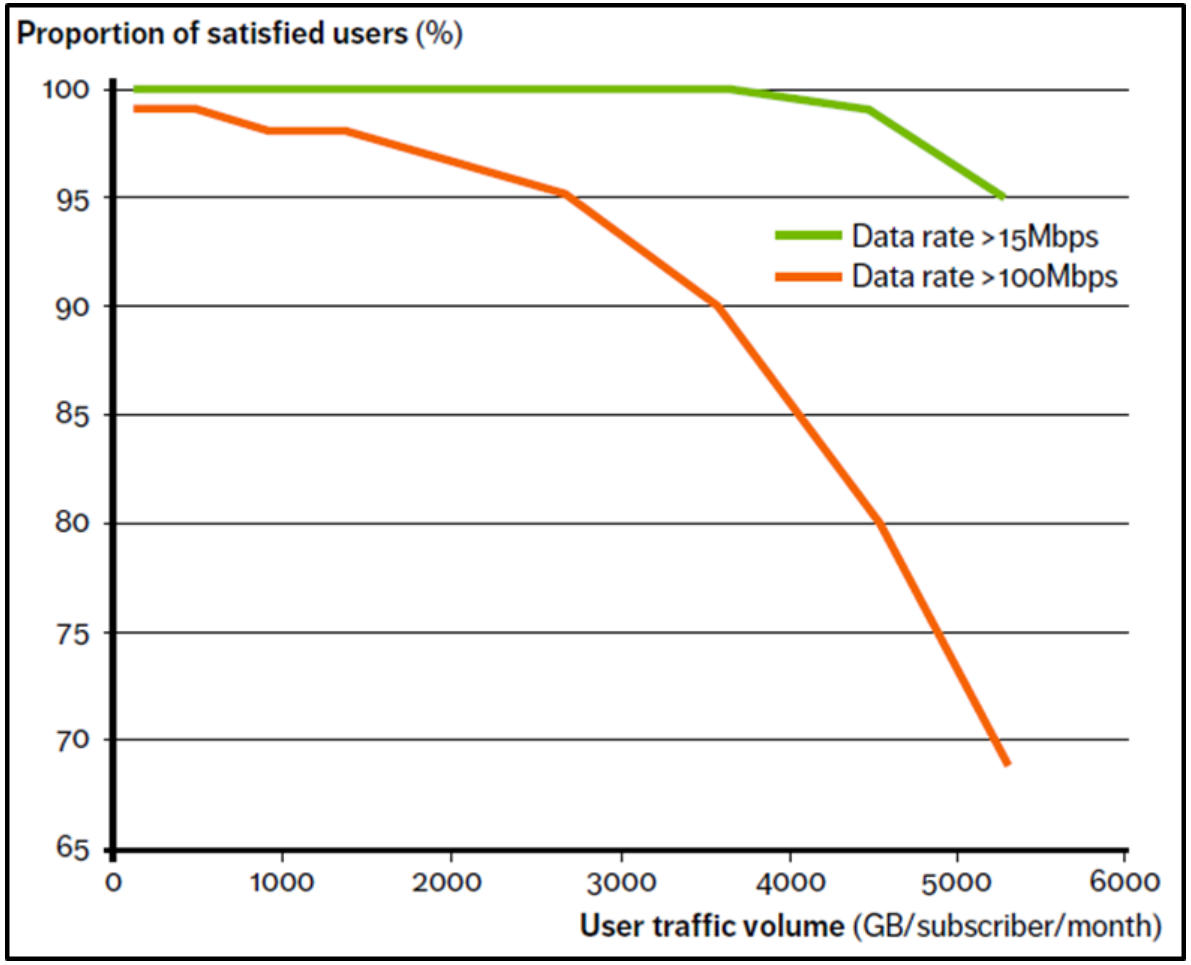
Proportion of Satisfied Users Relative to Monthly Usage



5G Americas Member Contribution

5G Fixed Wireless Simulation with Different Loading and Densities

DL	Scenario 1 (3 APs per 40 homes)				Scenario 2 (6 APs per 40 homes)			
	10% loading		50% loading		10% loading		50% loading	
	Cell-edge (Mbps)	Average (Mbps)	Cell-edge (Mbps)	Average (Mbps)	Cell-edge (Mbps)	Average (Mbps)	Cell-edge (Mbps)	Average (Mbps)
100 MHz, 64x8	5	200	4	160	50	290	45	230
100 MHz, 128x16	22	280	20	210	150	370	145	275
400 MHz, 128x16	88	1,120	80	840	600	1,480	580	1,100

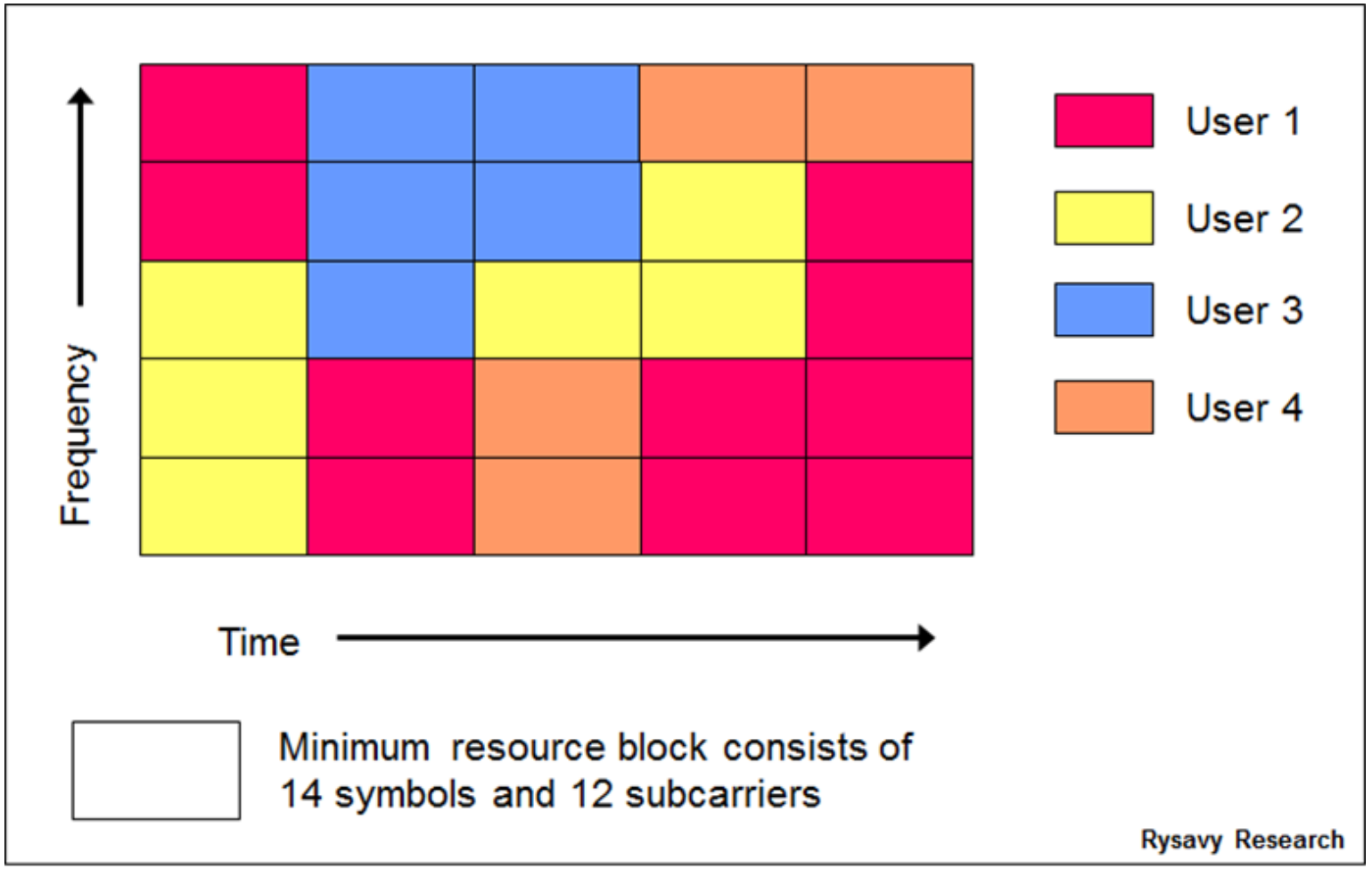
UL	Scenario 1 (3 APs per 40 homes)				Scenario 2 (6 APs per 40 homes)			
	10% loading		50% loading		10% loading		50% loading	
	Cell-edge (Mbps)	Average (Mbps)	Cell-edge (Mbps)	Average (Mbps)	Cell-edge (Mbps)	Average (Mbps)	Cell-edge (Mbps)	Average (Mbps)
100MHz, 16x64	2	85	1	75	35	120	30	100
100MHz, 16x128	4	95	2	80	50	140	40	110
100MHz, 32x64	7	100	4	85	70	150	60	115

5G Americas Member Contribution

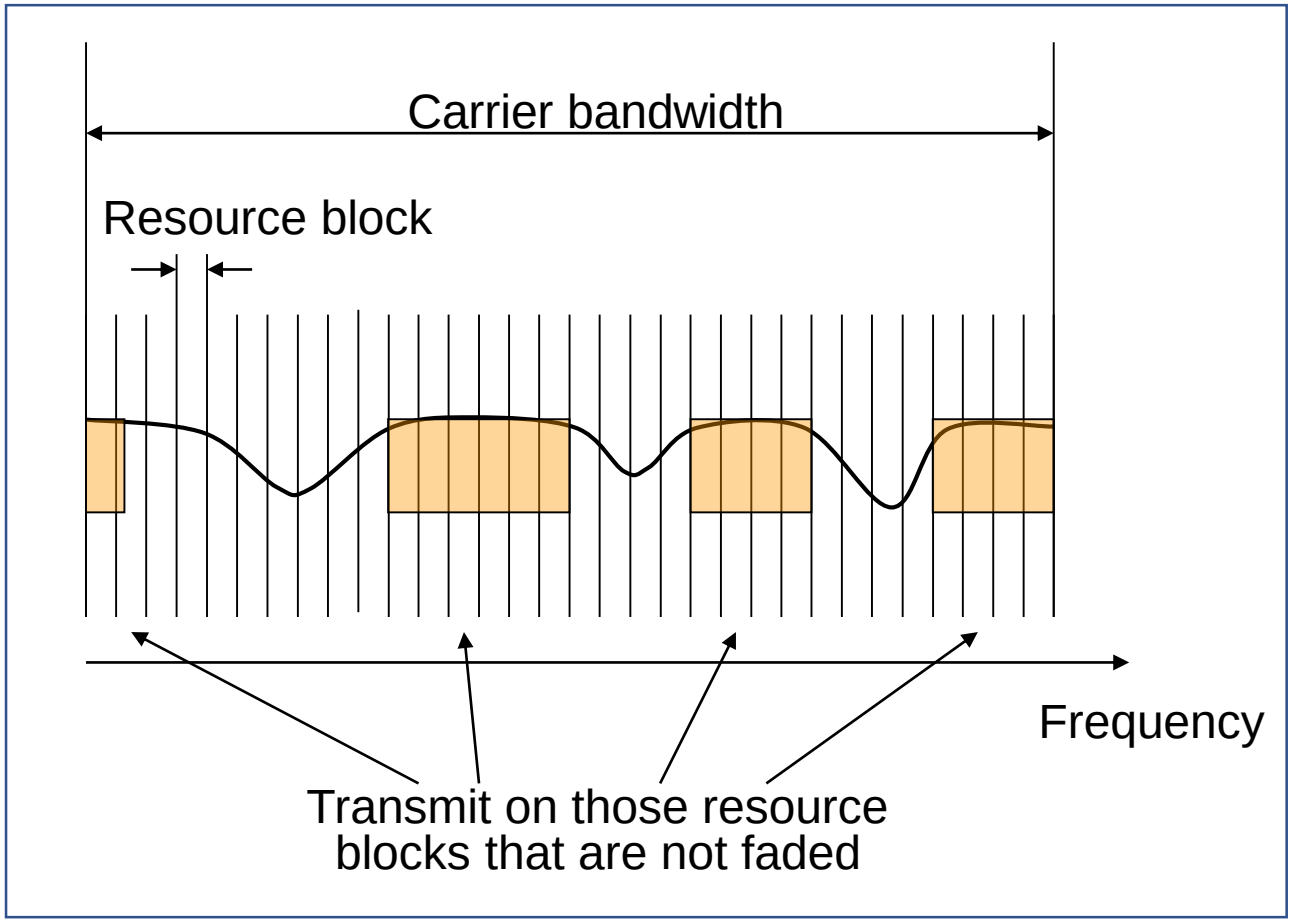
LTE Capabilities

- Downlink peak data rates up to 300 Mbps with 20+20 MHz bandwidth in initial versions, increasing to over 1 Gbps in subsequent versions through carrier aggregation, higher-order modulation, and 4X4 MIMO.
- Uplink peak data rates up to 71 Mbps with 20+20 MHz bandwidth in initial versions, increasing to over 1 Gbps in subsequent versions.
- Operation in both TDD and FDD modes.
- Scalable bandwidth up to 20+20 MHz covering 1.4, 3, 5, 10, 15, and 20 MHz radio carriers.
- Increased spectral efficiency over HSPA by a factor of two to four.
- Reduced latency, to 15 msec round-trip times between user equipment and the base station, and to less than 100 msec transition times from inactive to active.
- Self-organizing capabilities under operator control and preferences that will automate network planning and will result in lower operator costs.

LTE OFDMA Downlink Resource Assignment



Frequency Domain Scheduling in LTE



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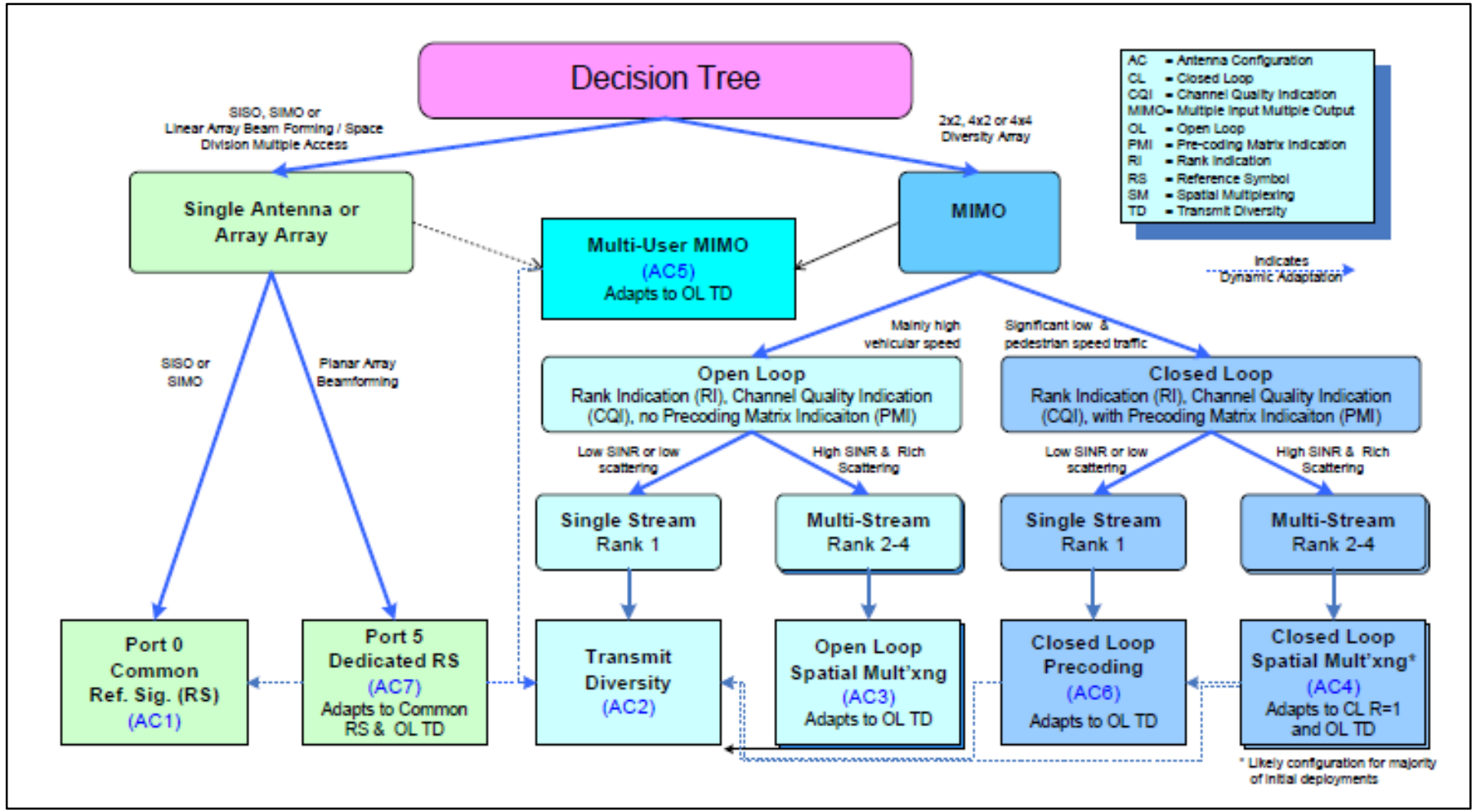
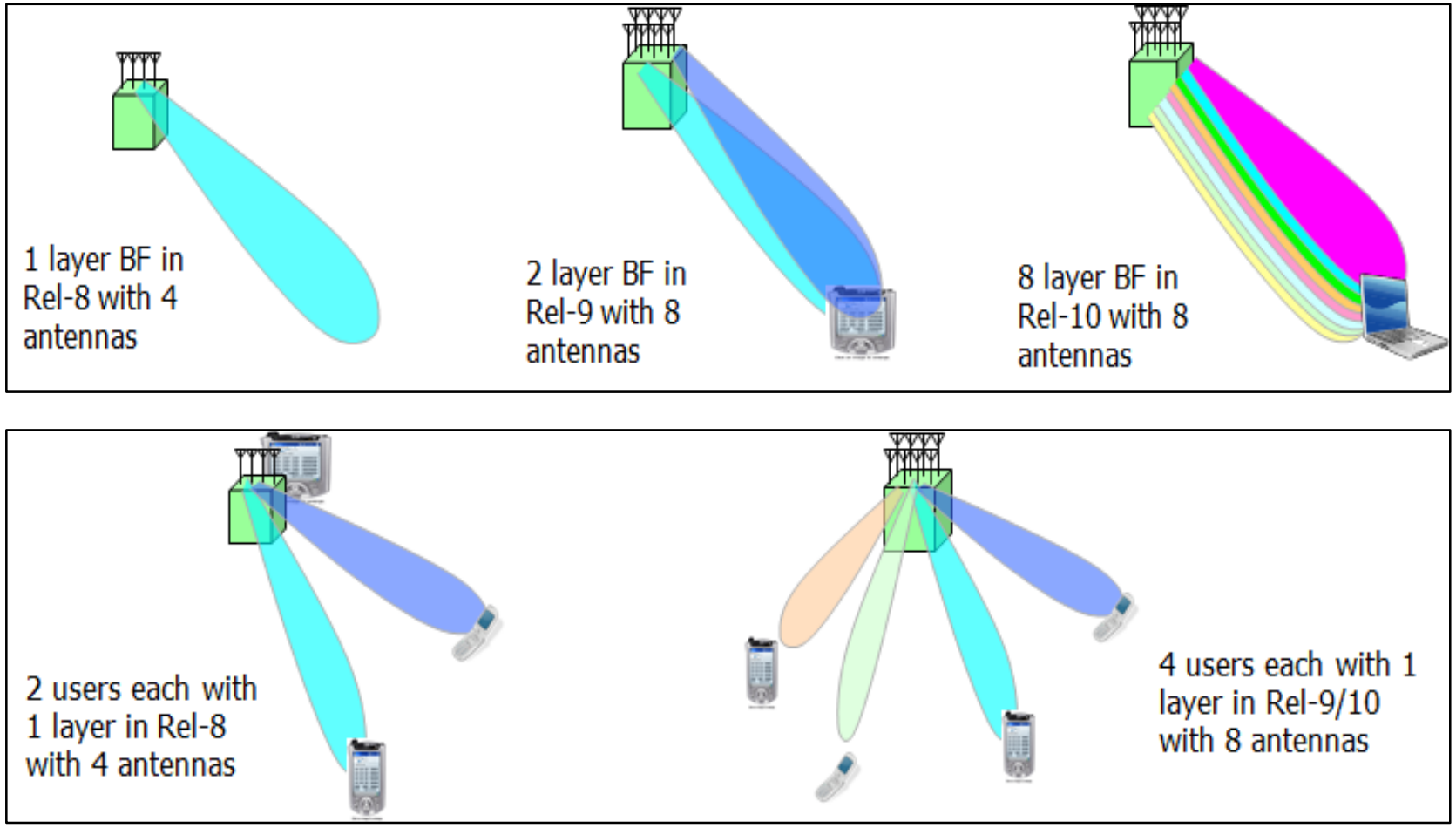
LTE Antenna Schemes



3G Americas' white paper, *MIMO and Smart Antennas for 3G and 4G Wireless Systems – Practical Aspects and Deployment Considerations*, May 2010

Single-User and Multi-User MIMO



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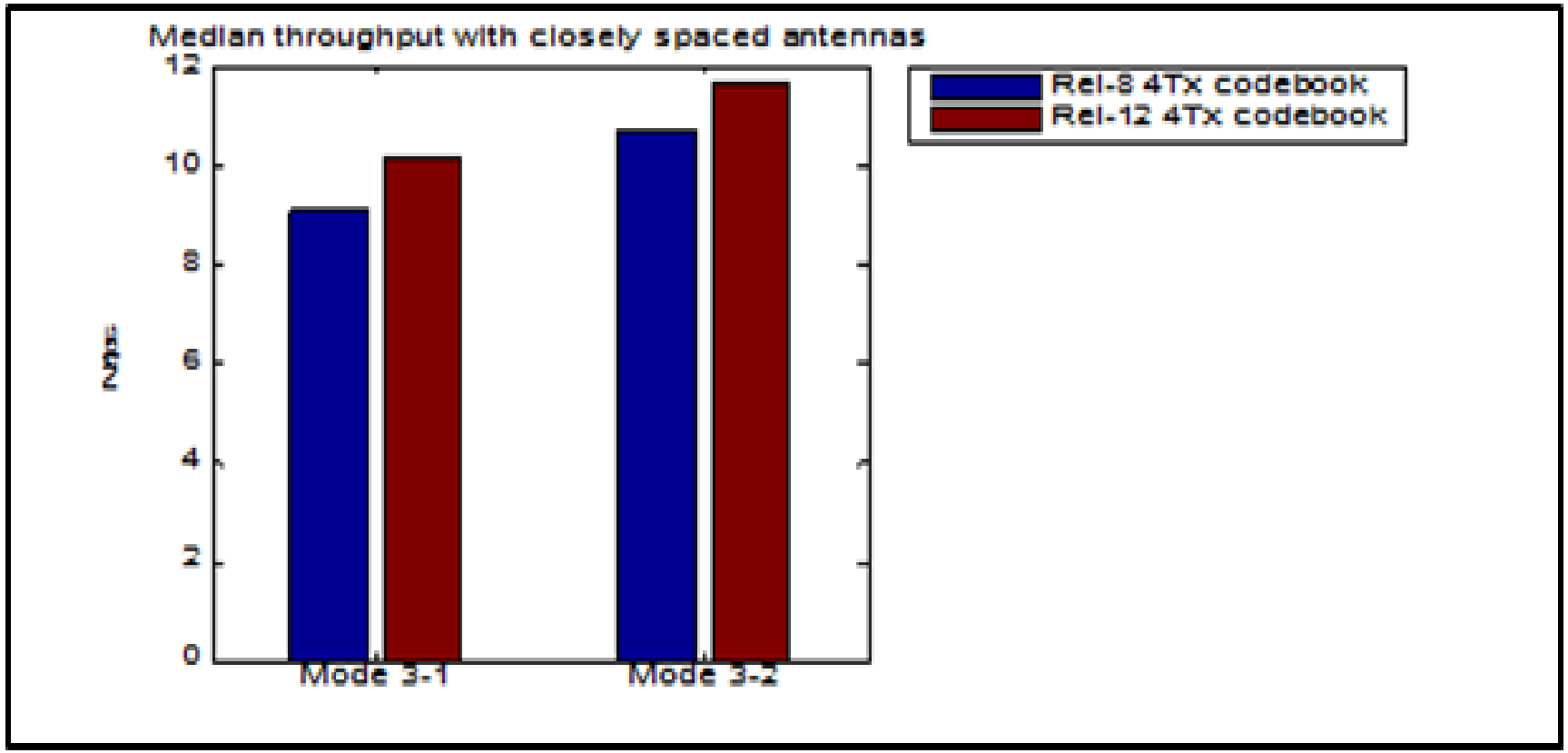
Median Throughput of Feedback Mode 3-2 and New Codebook



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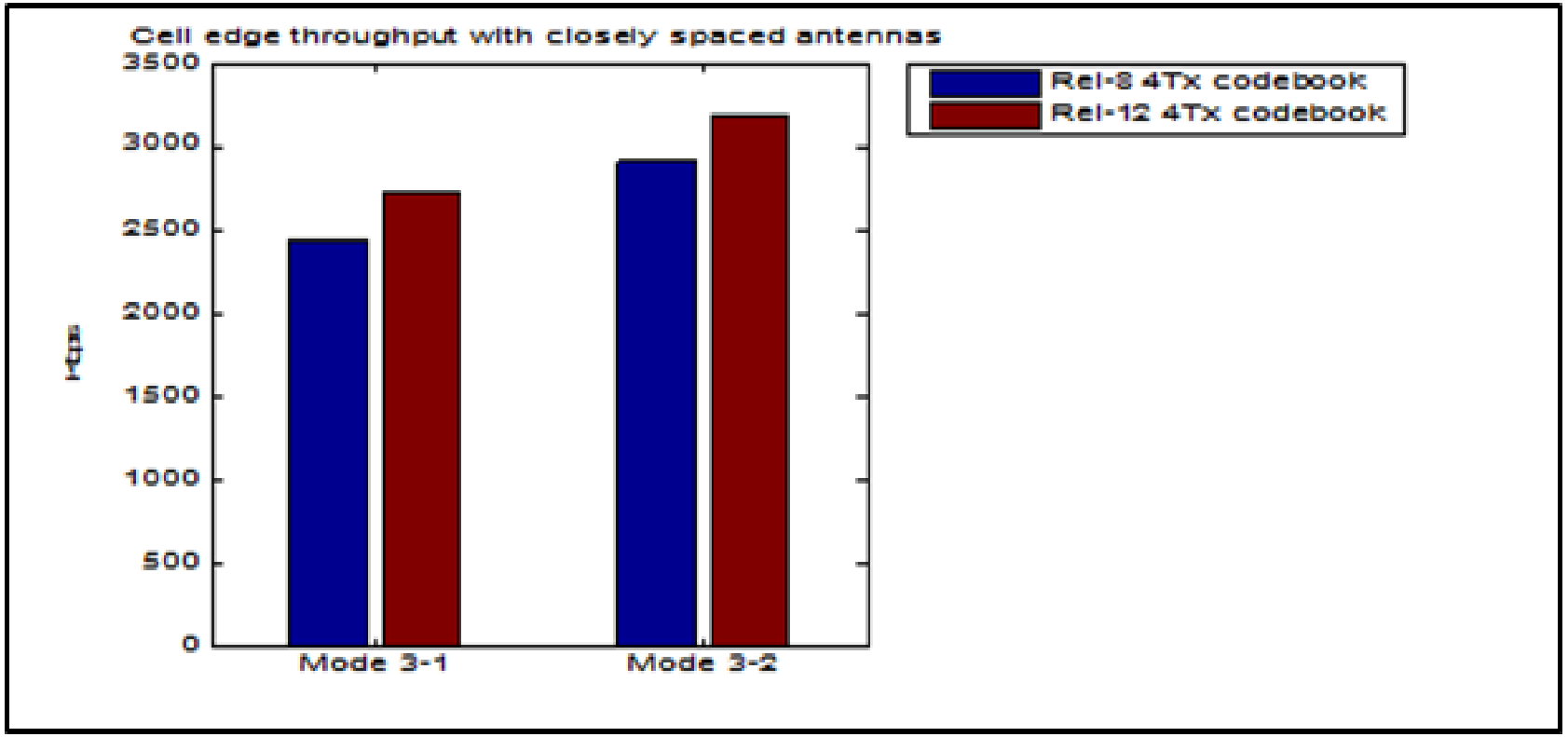
Cell-Edge Throughput of Feedback Mode 3-2 and New Codebook



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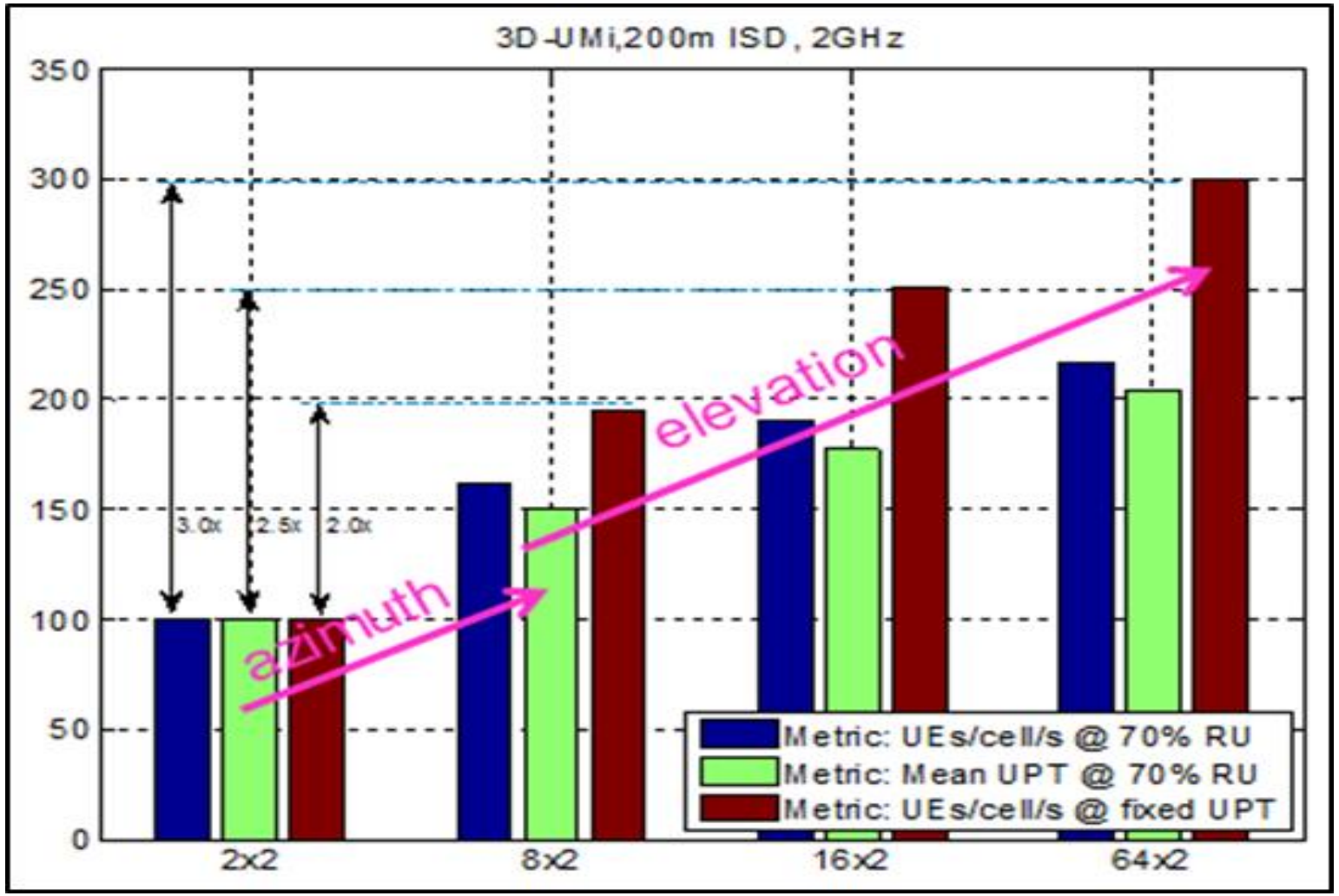
Performance Gains with FD-MIMO Using 200 Meter ISD



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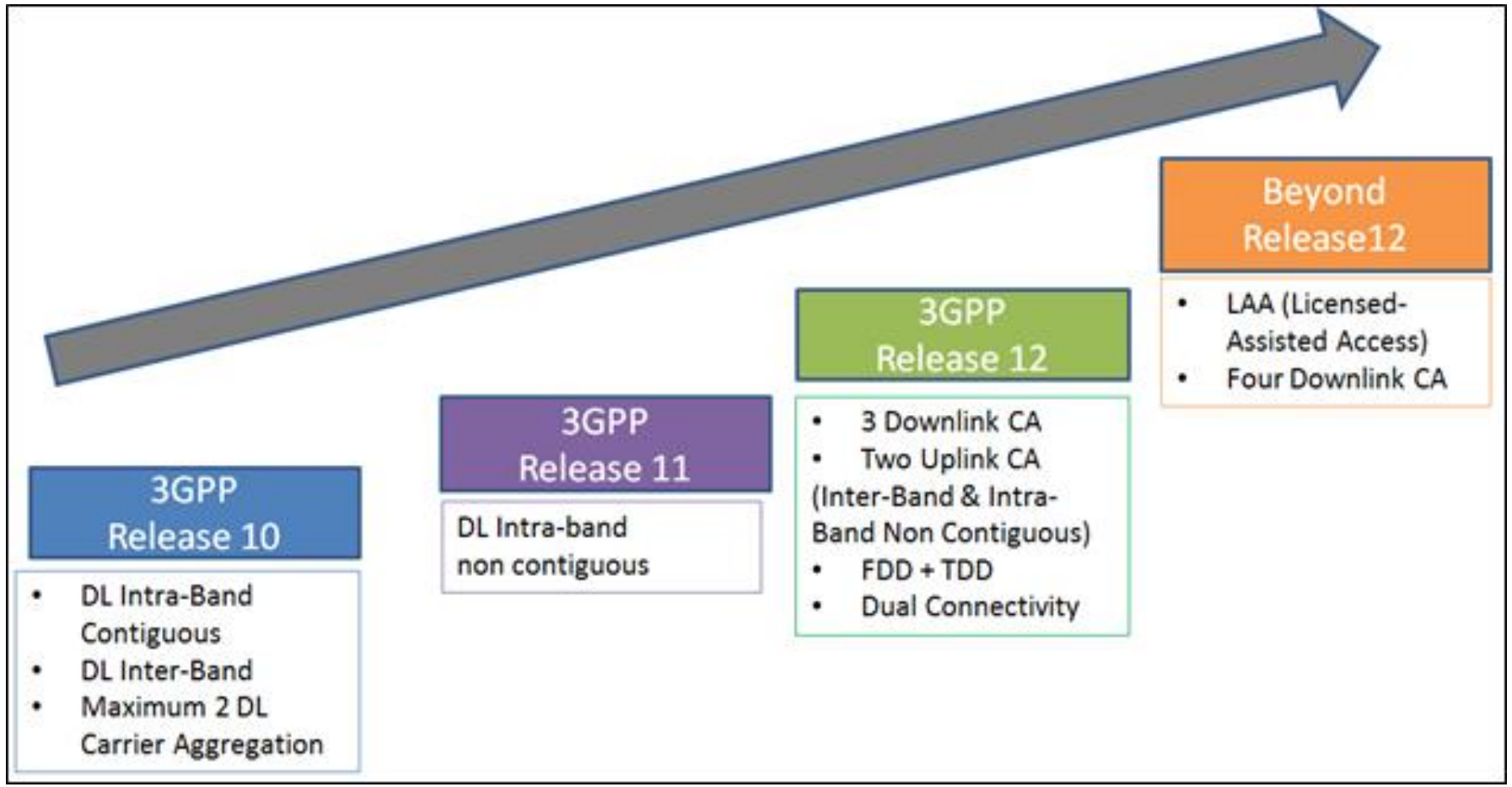
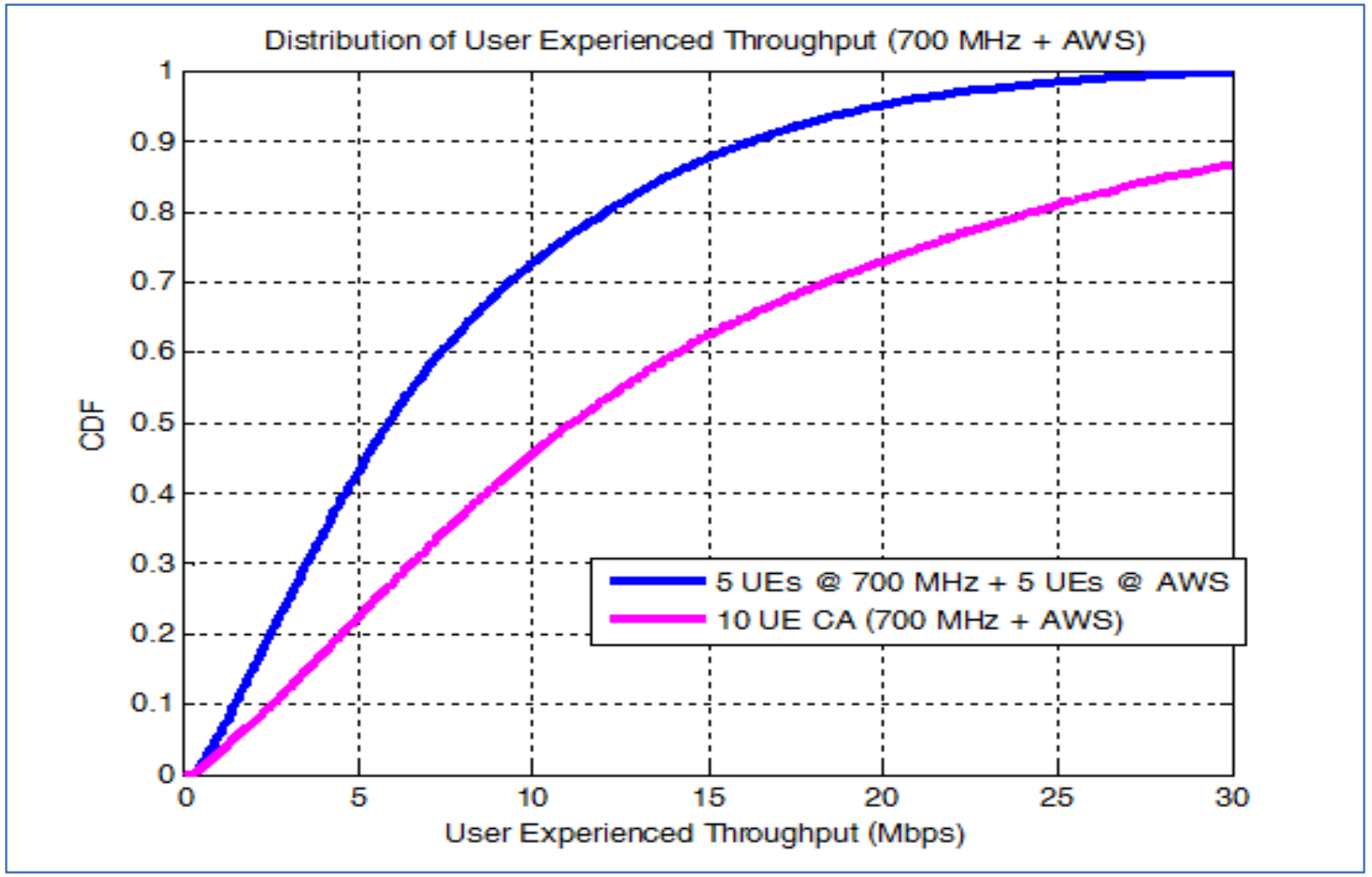
Carrier Aggregation Capabilities across 3GPP Releases



4G Americas White Paper, *Mobile Broadband Evolution: Rel-12 & Rel-13 and Beyond*, 2015

Gains From Carrier Aggregation



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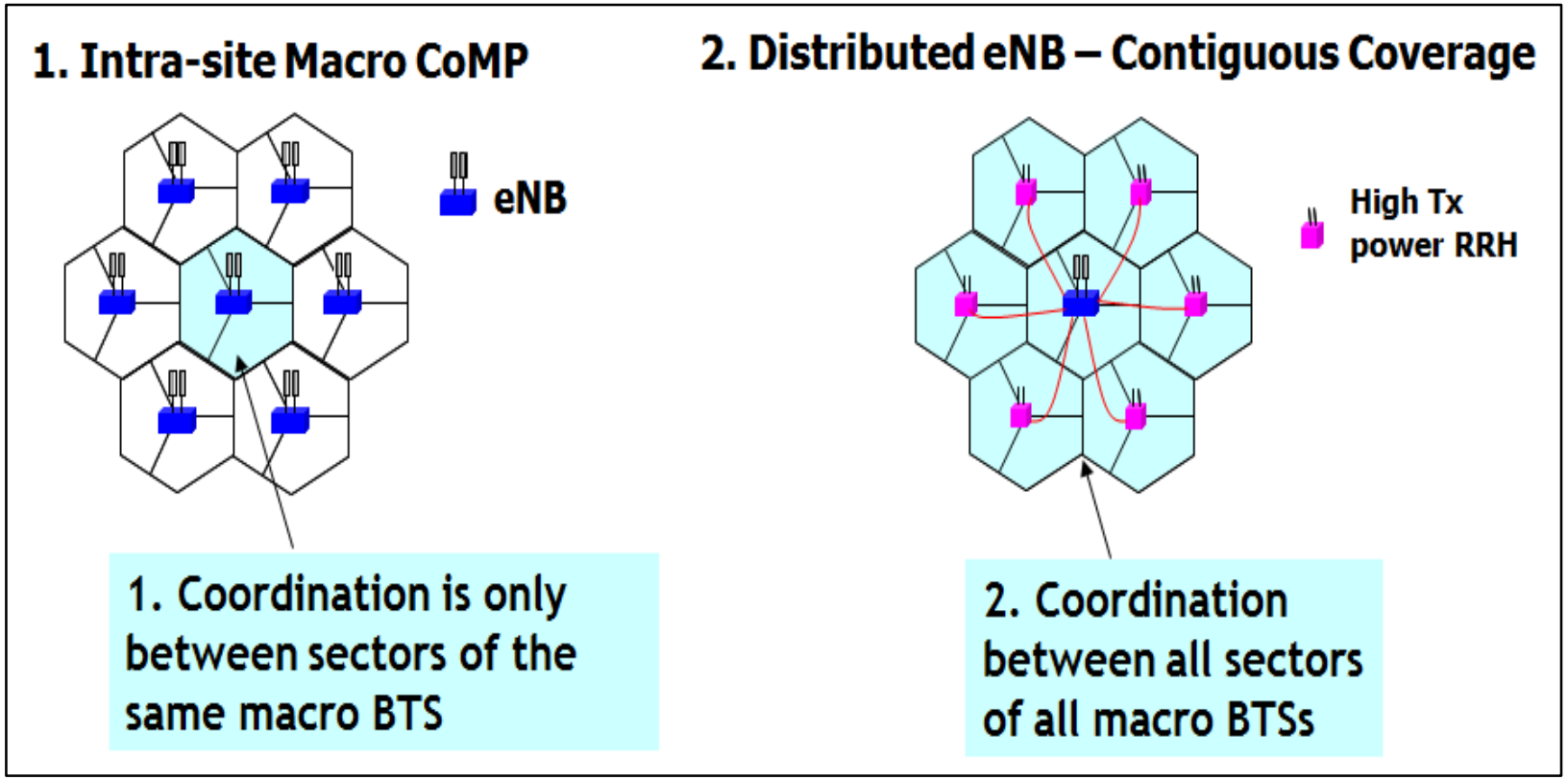
CoMP Levels



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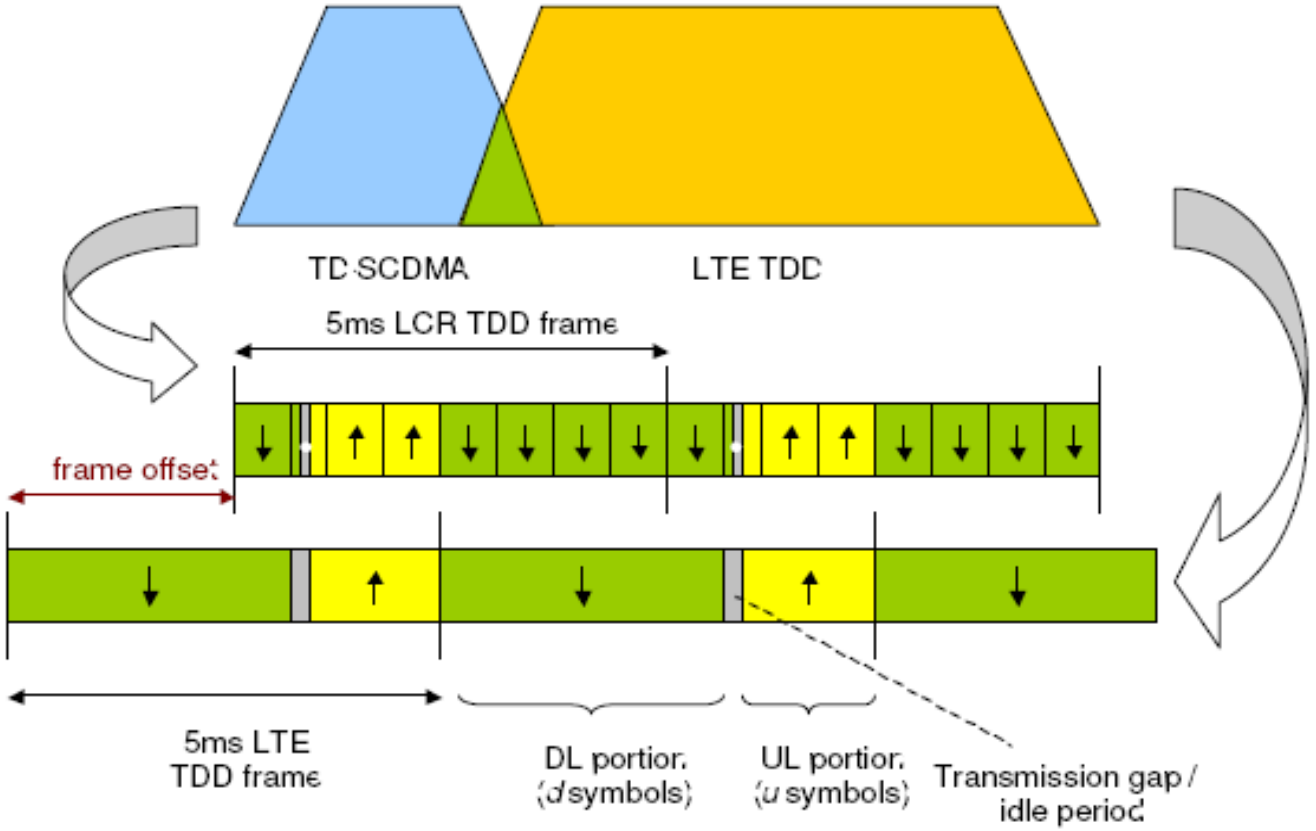
TDD Frame Co-Existence Between TD-SCDMA and LTE TDD



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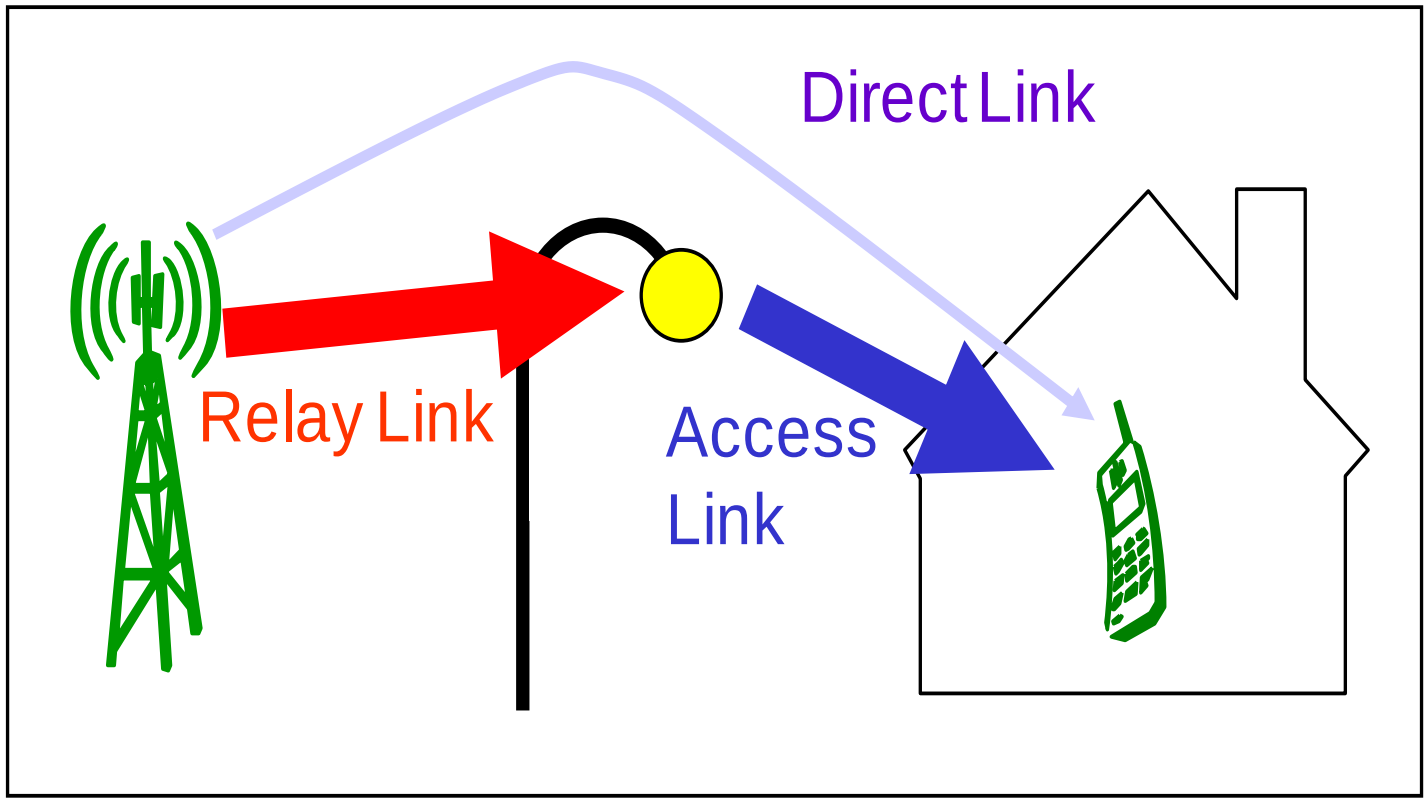
LTE UE Categories

UE Category	Max DL Throughput	Maximum DL MIMO Layers	Maximum UL Throughput
1	10.3 Mbps	1	5.2 Mbps
2	51.0 Mbps	2	25.5 Mbps
3	102.0 Mbps	2	51.0 Mbps
4	150.8 Mbps	2	51.0 Mbps
5	299.6 Mbps	4	75.4 Mbps
6	301.5 Mbps	2 or 4	51.0 Mbps
7	301.5 Mbps	2 or 4	102.0 Mbps
8	2998.6 Mbps	8	1497.8 Mbps
9	452.3 Mbps	2 or 4	51.0 Mbps
10	452.3 Mbps	2 or 4	102.0 Mbps
11	603.0 Mbps	2 or 4	51.0 Mbps
12	603.0 Mbps	2 or 4	102.0 Mbps
13	391.6 Mbps	2 or 4	150.8 Mbps
14	3916.6 Mbps	8	9587.7 Mbps
15	798.8 Mbps	2 or 4	226.1 Mbps
16	1051.4 Mbps	2 or 4	105.5 Mbps
17	2506.6 Mbps	8	2119.4 Mbps
18	1206.0 Mbps	2 or 4 (or 8)	211.0 Mbps
19	1658.3 Mbps	2 or 4 (or 8)	13563.9 Mbps
20	2019.4 Mbps	2 or 4 (or 8)	316.6 Mbps
21	1413.1 Mbps	2 or 4	301.5 Mbps

LTE-Advanced Relay



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LTE FDD User Throughputs Based on Simulation Analysis

Configuration	User Throughput, Mbps			
	Downlink (DL)		Uplink (UL)	
	Median	Average	Median	Average
LTE FDD: Low Band, 2x2 MIMO-DL, 1x2 SIMO-UL, 10+10 MHz, R8	8.6	10.9	4.5	5.0
LTE FDD: High Band, 4x2 MIMO-DL, 1x4 SIMO-UL, 10+10 MHz, R8	10.6	12.2	5.4	6.4
LTE FDD: High Band, 2x2 MIMO-DL, 1x2 SIMO UL, 20+20 MHz, R8	15.2	17.9	5.4	7.0
LTE FDD: High Band, 4x4 MIMO-DL, 1x4 SIMO UL, 20+20 MHz, R12	25.4	29.2	6.9	9.1

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LTE FDD User Throughputs Based on Simulation Analysis – Key Assumptions

- Traffic is FTP-like at a 50% load with a 75/25 mix of indoor/outdoor users.
- Throughput is at the medium-access control (MAC) protocol layer.
- The configuration in the first row corresponds to low-frequency band operation, representative of 700 MHz or cellular, while the remaining configurations assume high-frequency band operation, representative of PCS, AWS, or WCS. (Higher frequencies facilitate higher-order MIMO configurations and have wider radio channels available.)
- The downlink value for the first row corresponds to Release 8 device receive capability (Minimum Mean Square Error [MMSE]), while the values in the other rows correspond to Release 11 device receive capability (MMSE – Interference Rejection Combining [IRC]).
- The uplink value for the first row corresponds to a Maximal Ratio Combining (MRC) receiver at the eNodeB, while the remaining values correspond to an IRC receiver.
- Low-band operation assumes 1732 meter inter-site distance (ISD), while high-band operation assumes 500 meter ISD. The remaining simulation assumptions are listed in Table 11.
- Refer to white paper for additional assumptions.

Drive Test of Commercial European LTE Network, 10+10 MHz

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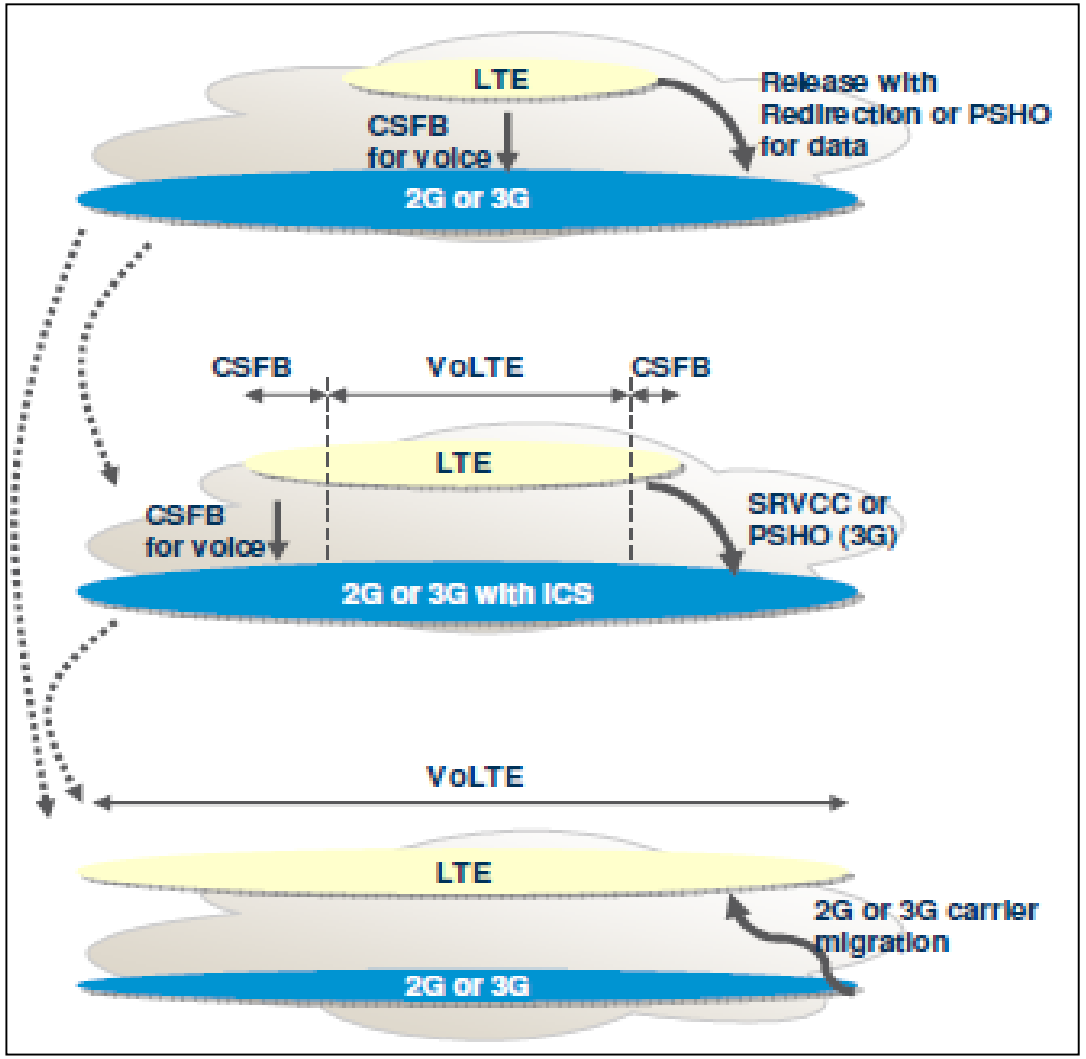
Evolution of Voice in LTE Networks



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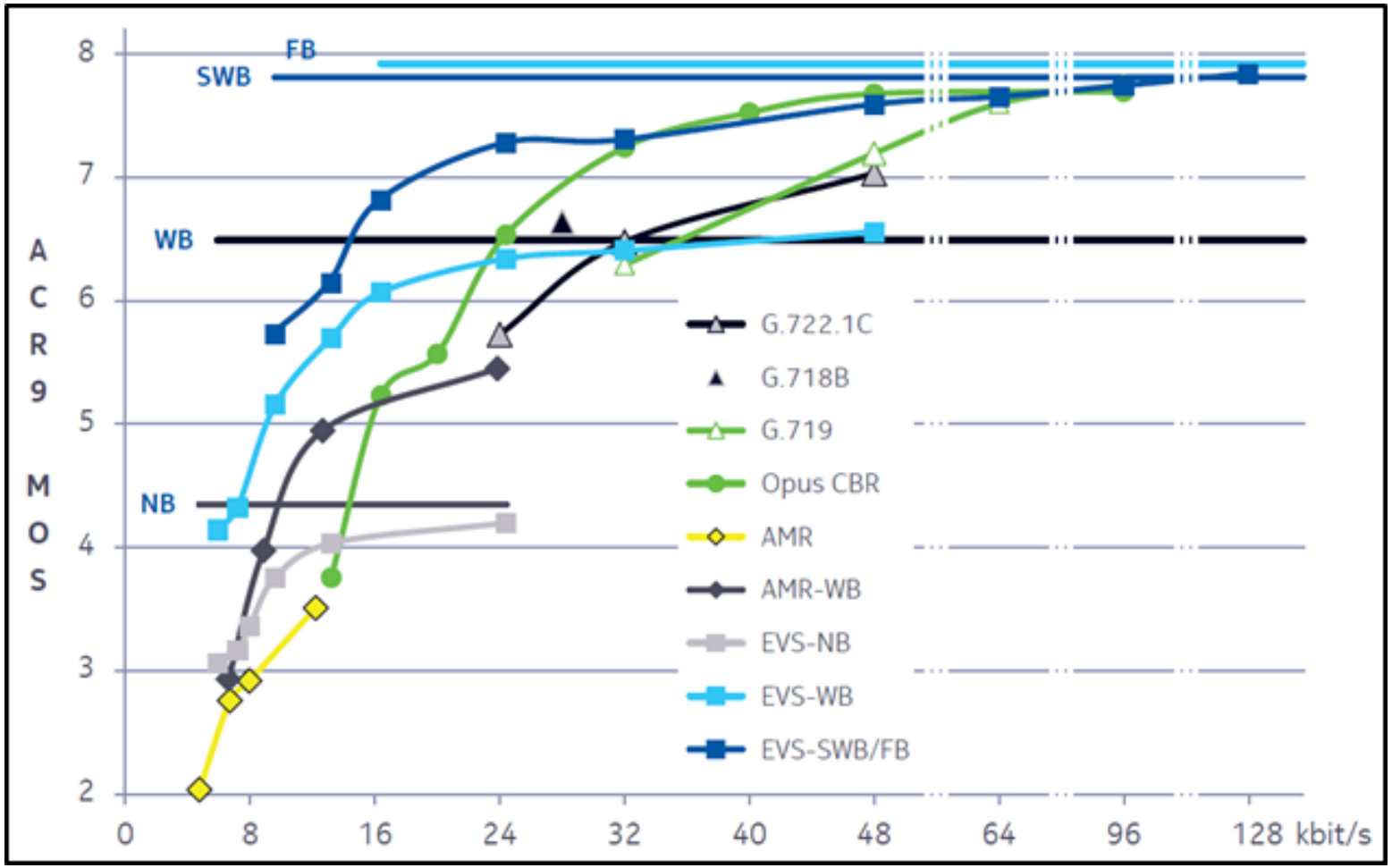
Comparison of AMR, AMR-WB and EVS Codecs

Features	AMR	AMR-WB	EVS
Input and output sampling frequencies supported	8KHz	16KHz	8KHz, 16KHz, 32KHz, 48 KHz
Audio bandwidth	Narrowband	Wideband	Narrowband, Wideband, Super-wideband, Fullband
Coding capabilities	Optimized for coding human voice signals	Optimized for coding human voice signals	Optimized for coding human voice and general-purpose audio (music, ringtones, mixed content) signals
Bit rates supported (in kb/s)	4.75, 5.15, 5.90, 6.70, 7.4, 7.95, 10.20, 12.20	6.6, 8.85, 12.65, 14.25, 15.85, 18.25, 19.85, 23.05, 23.85	5.9, 7.2, 8, 9.6 (NB and WB only), 13.2 (NB, WB and SWB), 16.4, 24.4, 32, 48, 64, 96, 128 (WB and SWB only)
Number of audio channels	Mono	Mono	Mono and Stereo
Frame size	20 ms	20 ms	20 ms
Algorithmic Delay	20-25 ms	25 ms	Up to 32 ms

Combined Mean Opinion Score Values



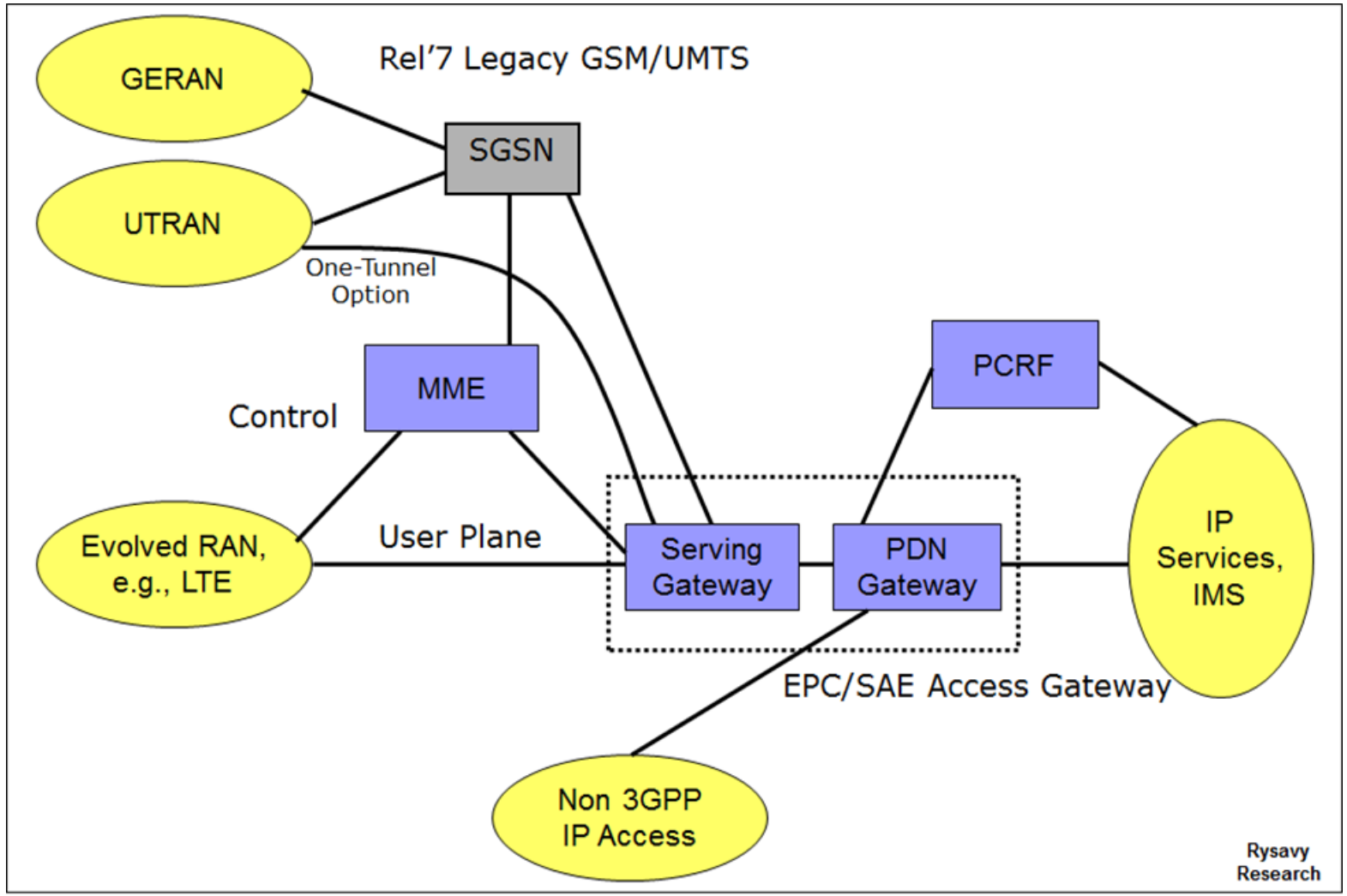
Nokia, *The 3GPP Enhanced Voice Services (EVS) codec*, 2015

EVS Compared to AMR and AMR-WB

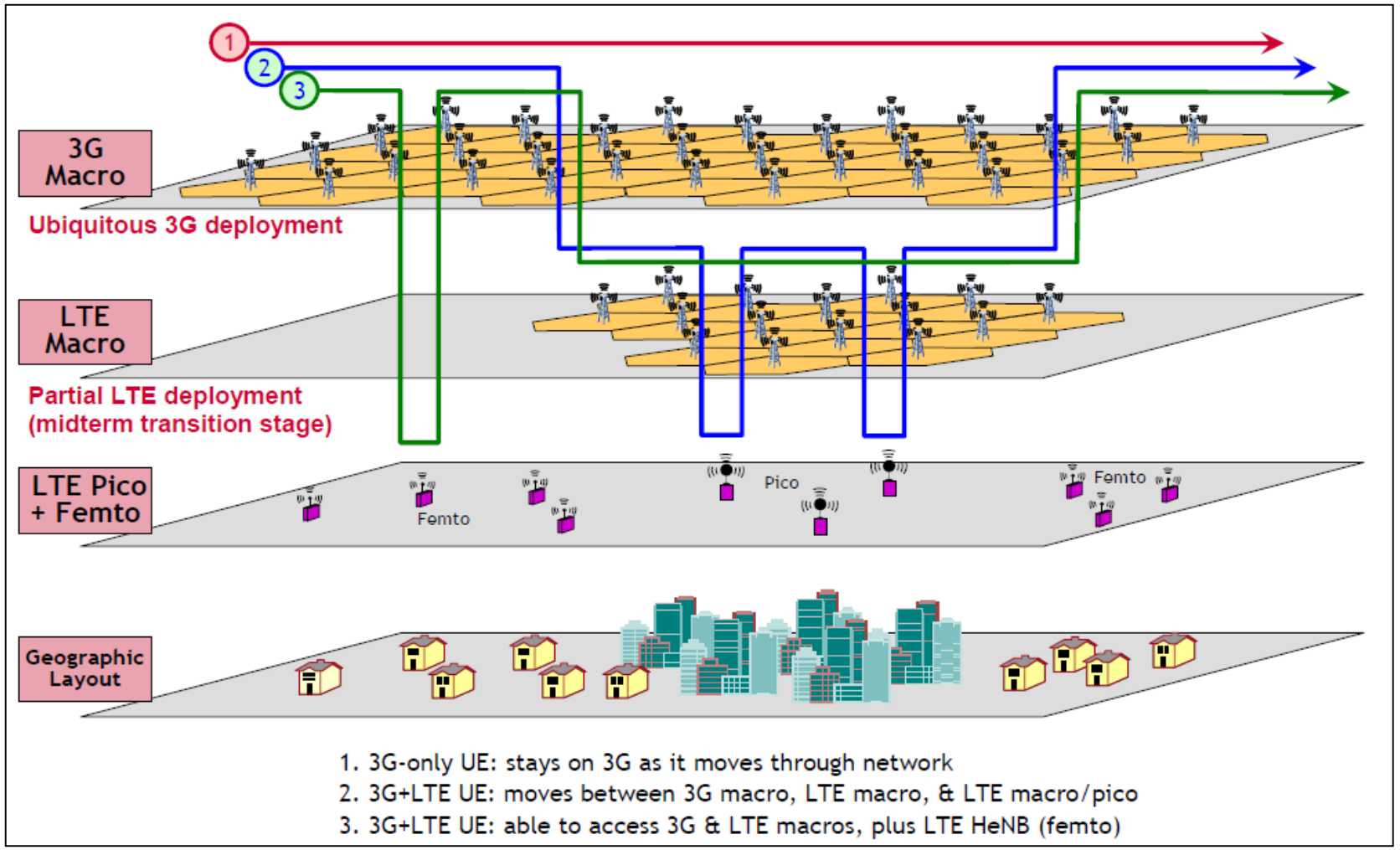
Reference	Equal bandwidth	Wider bandwidth
AMR 12.2 kbit/s	EVS-NB 8.0 kbit/s	EVS-WB 5.9 kbit/s
AMR-WB 12.65 kbit/s	EVS-WB 9.6 kbit/s	EVS-SWB 9.6 kbit/s
AMR-WB 23.85 kbits/s	EVS-WB 13.2 kbit/s	EVS-SWB 9.6 kbit/s

Nokia, *The 3GPP Enhanced Voice Services (EVS) codec*, 2015

Evolved Packet System



Load Balancing with Heterogeneous Networks



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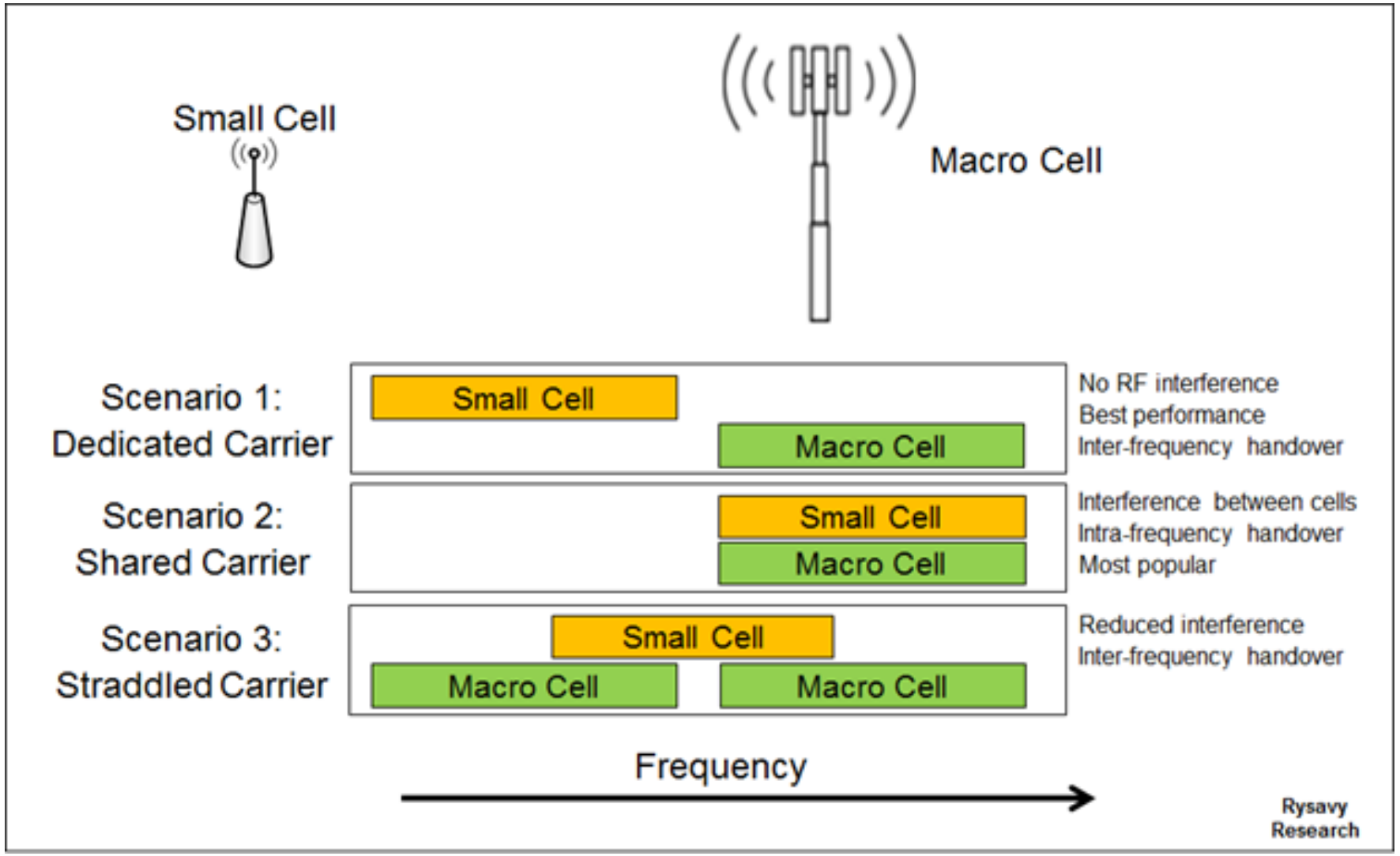
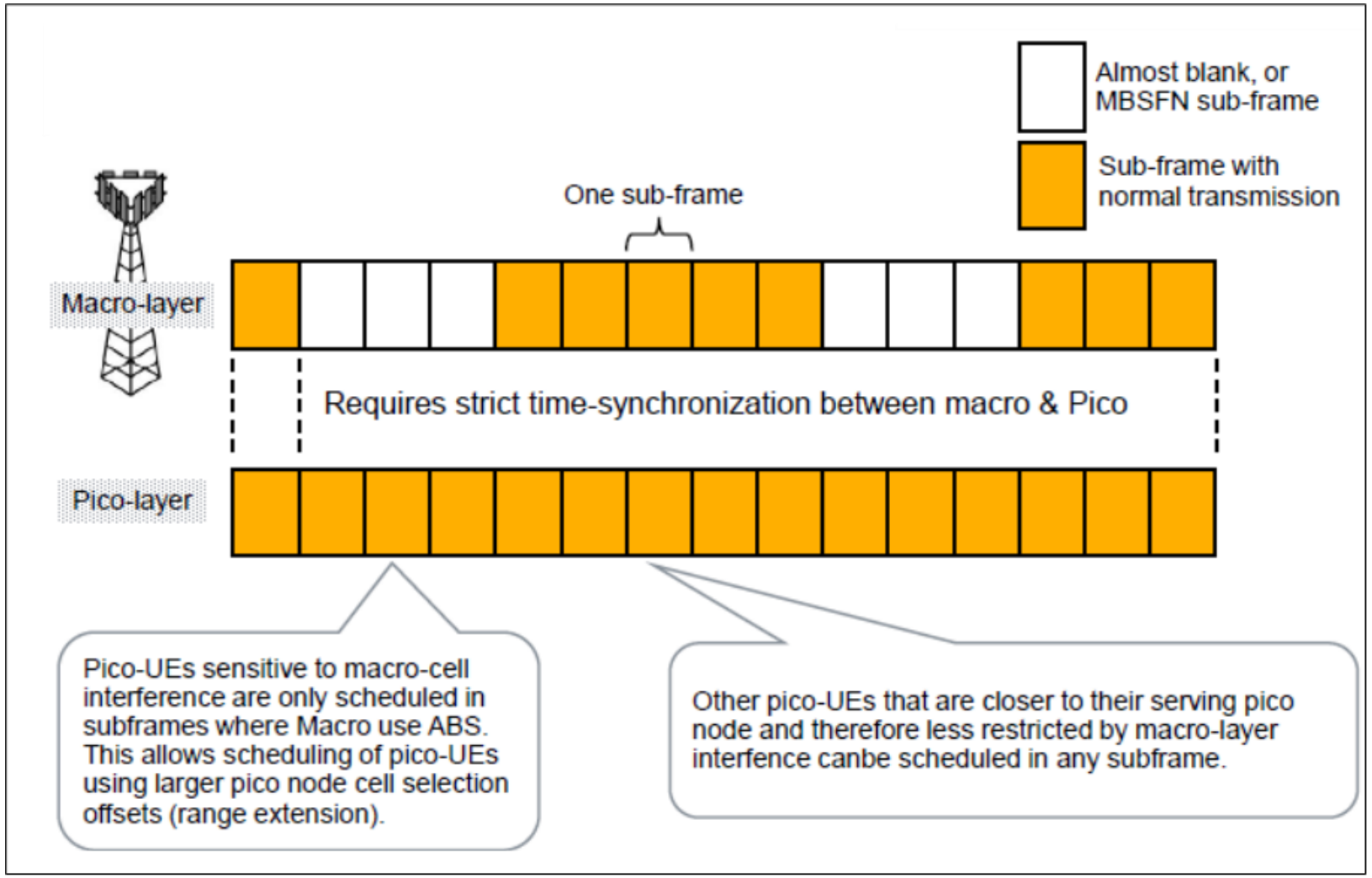
Scenarios for Radio Carriers in Small Cells



Enhanced Intercell Interference Cancellation



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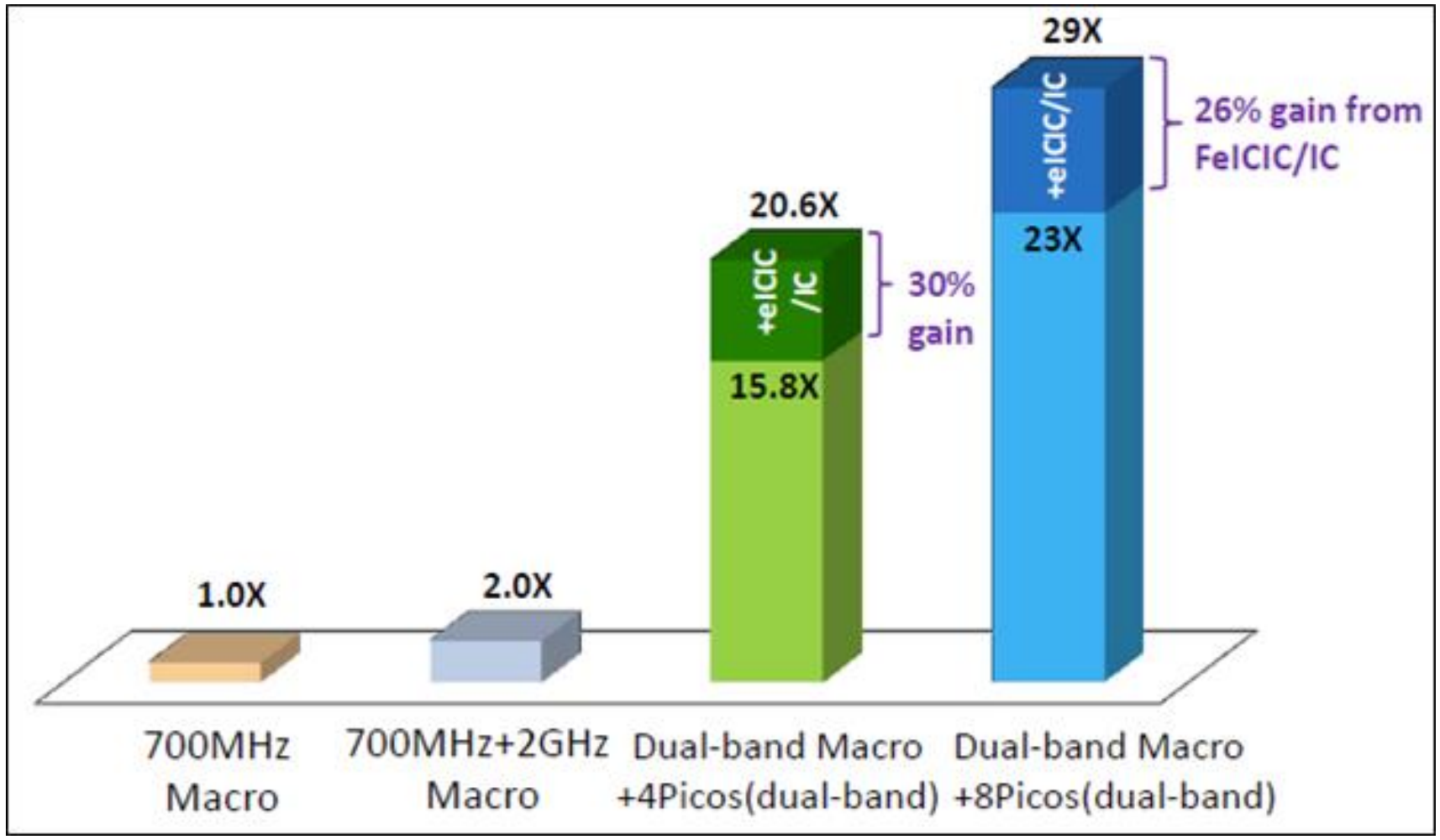
Median Throughput Gains Hotspot Scenarios



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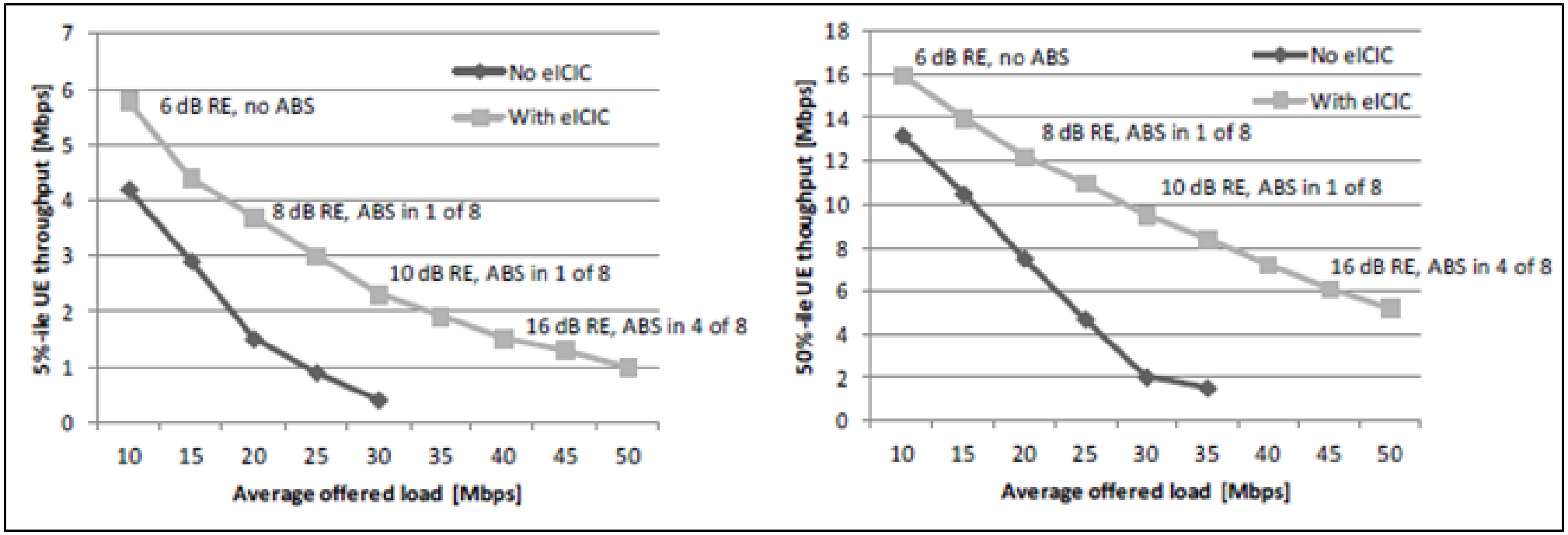
User Throughput Performance



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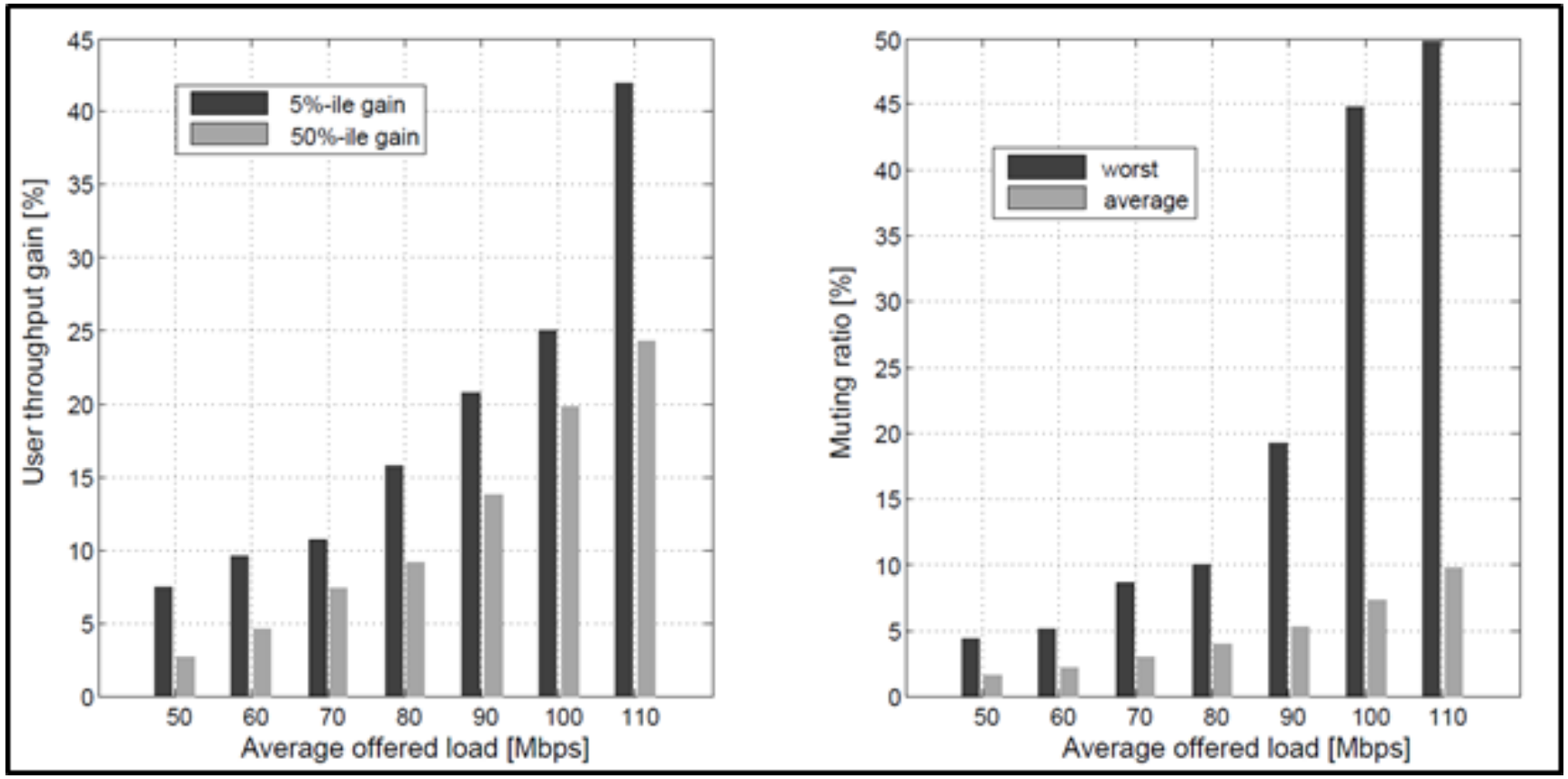
Throughput Gain of Time-Domain Interference Coordination



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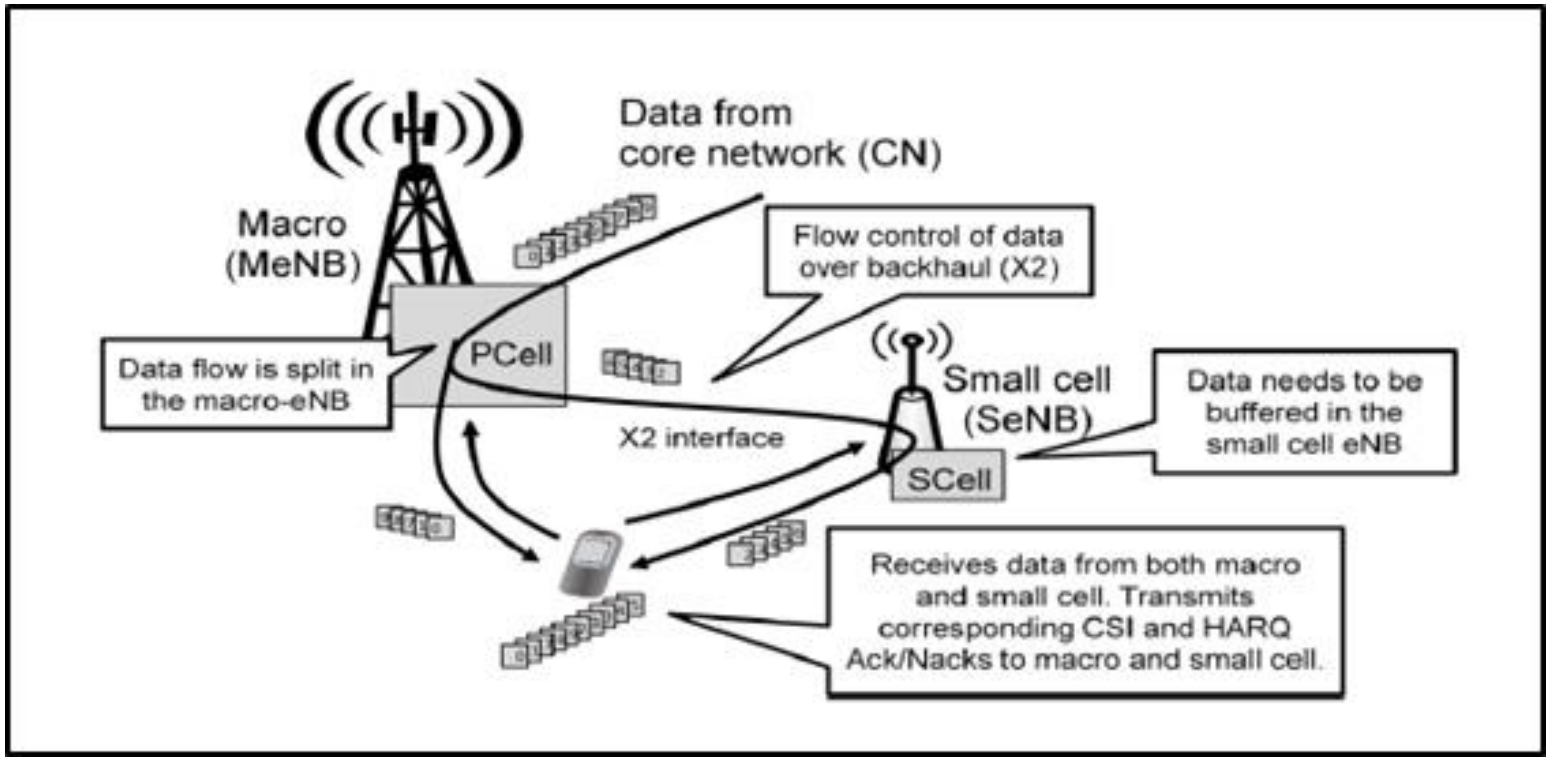
Dual Connectivity



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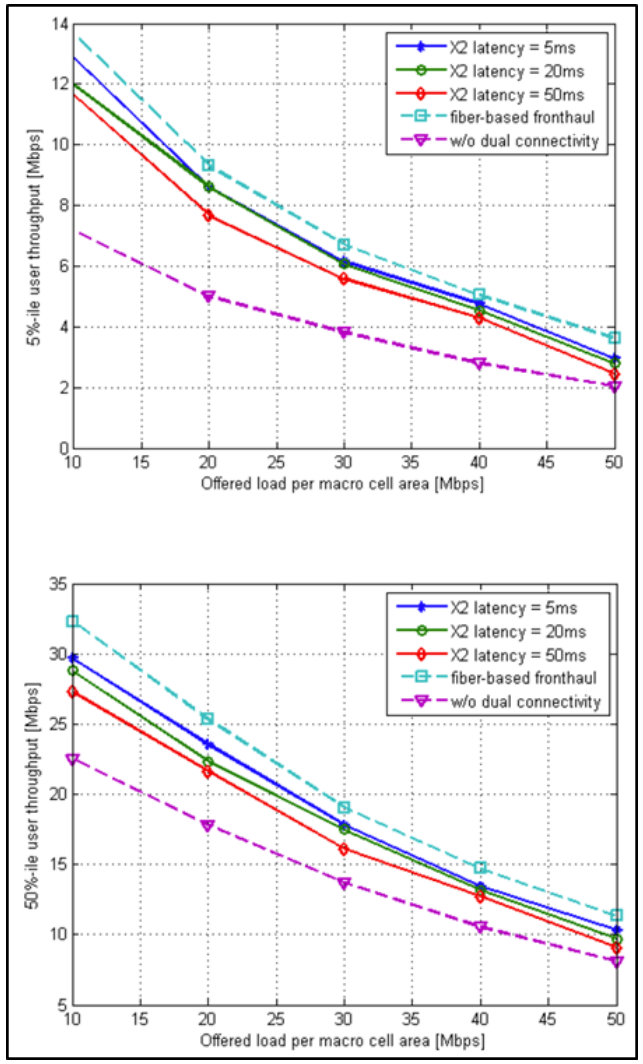
Dual Connectivity User Throughputs



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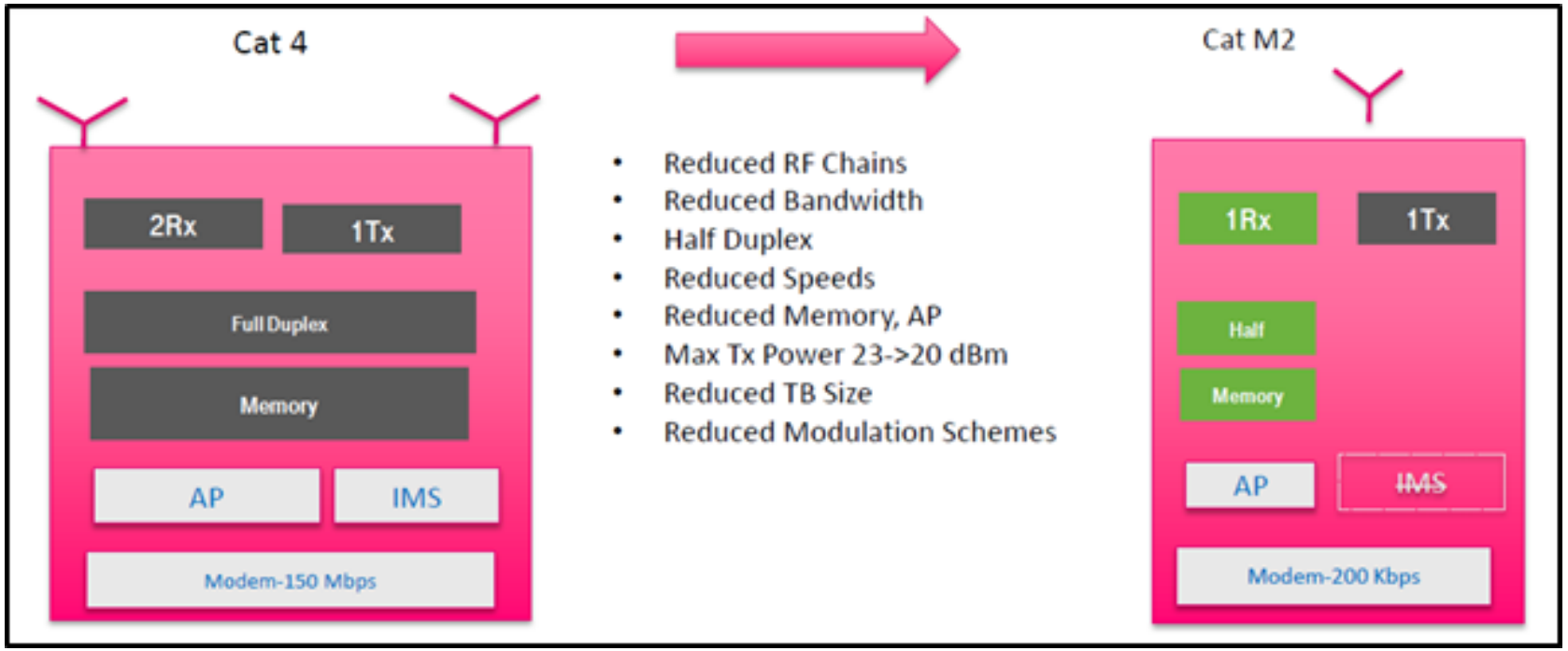
Means of Achieving Lower Cost in IoT Devices



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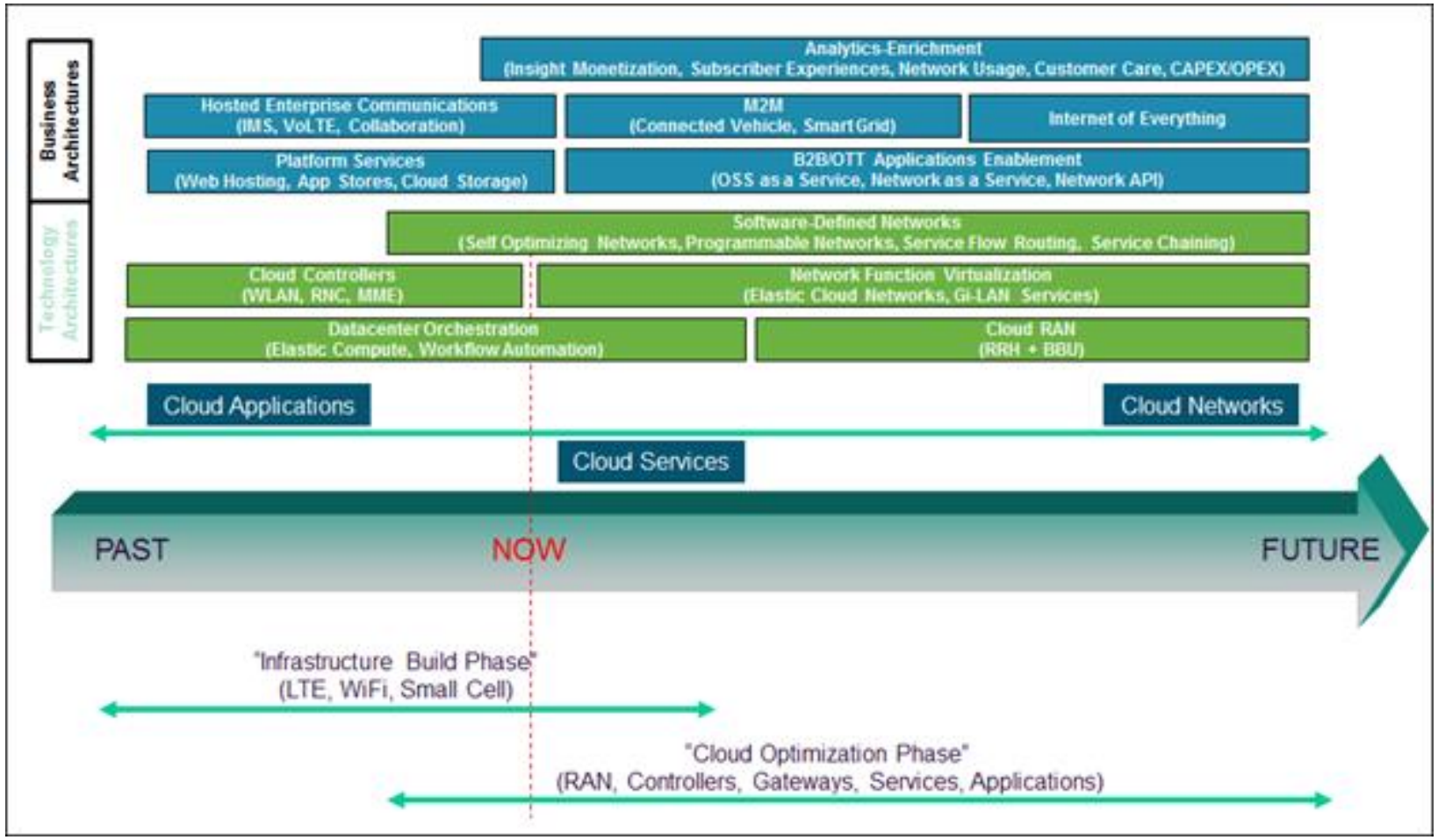
Summary of IoT Features in LTE Devices

Device Category	Category 3	Category 1	Category 0	Category M-1	Category NB-1	EC-GSM-IoT
3GPP Release	10	11	12	13	13	13
Max. Data Rate Downlink	100 Mbps	10 Mbps	1 Mbps	1 Mbps	200 Kbps	74 Kbps
Max. Data Rate Uplink	50 Mbps	5 Mbps	1 Mbps	1 Mbps	200 Kbps	74 Kbps
Max. Bandwidth	20 MHz	20 MHz	20 MHz	1.08 MHz	0.18 MHz	0.2 MHz
Duplex	Full	Full	Optional half-duplex	Optional half-duplex	Half	Half
Max. Receive Antennas	Two	Two	One	One	One	One
Power		Power Save Mode	Power Save Mode	Power Save Mode		
Sleep				Longer sleep cycles using Idle Discontinuous Reception (DRX)		
Coverage				Extended through redundant transmissions and Single Frequency Multicast		

Partially Centralized Versus Fully Centralized C-RAN

	Fully Centralized	Partially Centralized
Transport Requirements	Multi-Gbps, usually using fiber	20 to 50 times less
Fronthaul Latency Requirement	Less than 100 microseconds	Greater than 5 milliseconds.
Applications	Supports eICIC and CoMP	Supports centralized scheduling
Complexity	High	Lower
Benefit	Capacity gain	Lower capacity gain

Software-Defined Networking and Cloud Architectures



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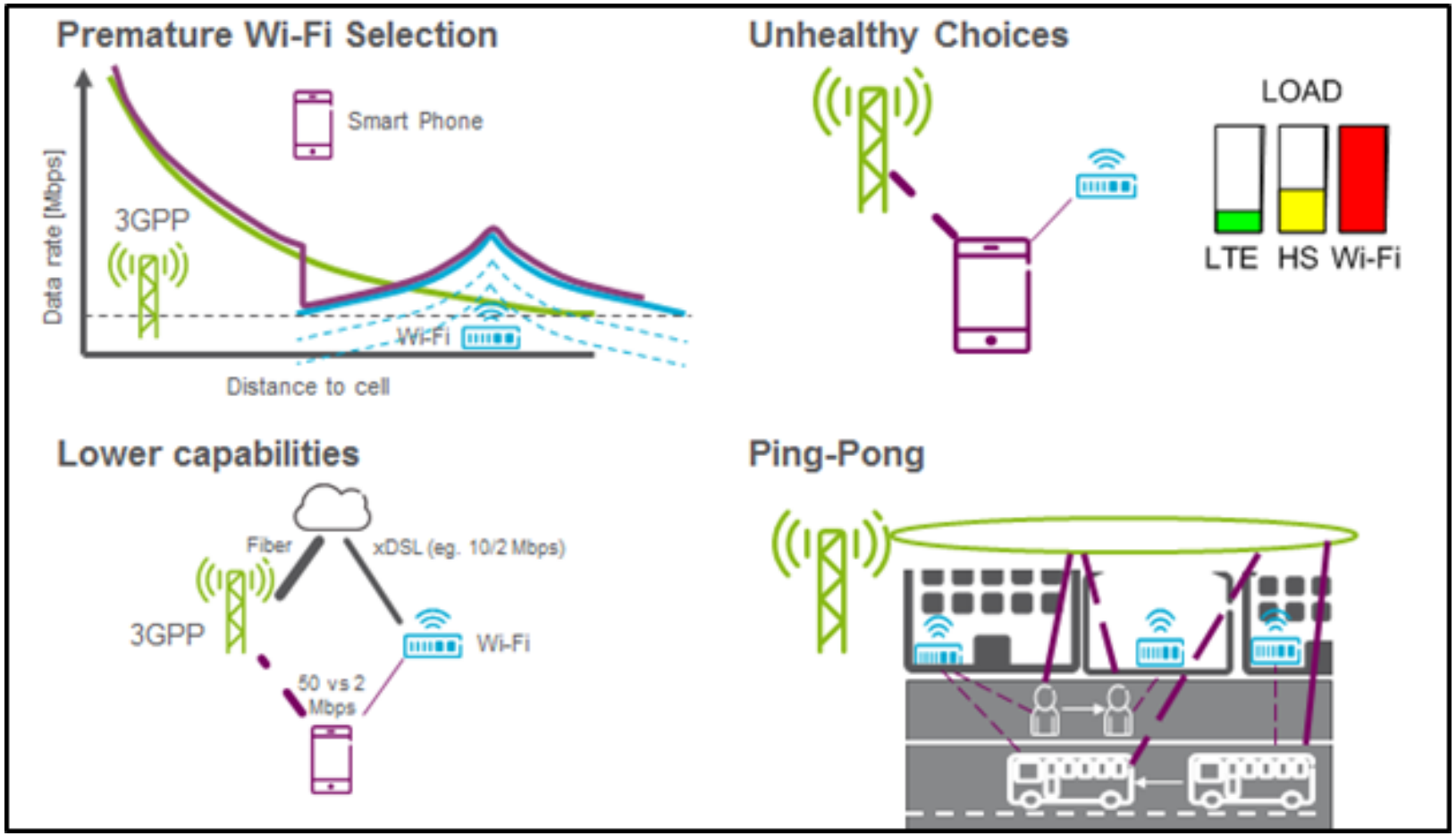
Bidirectional-Offloading Challenges



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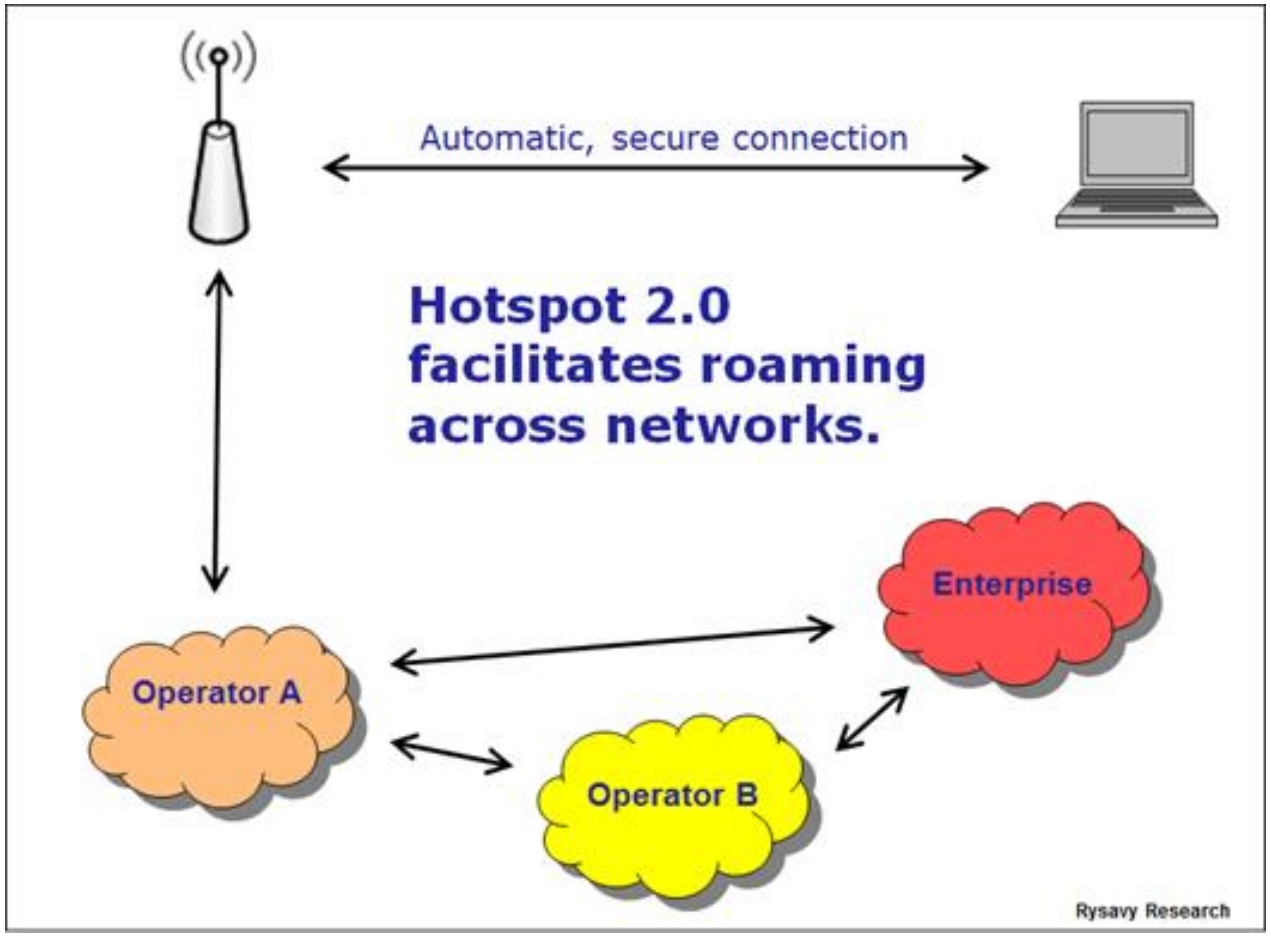
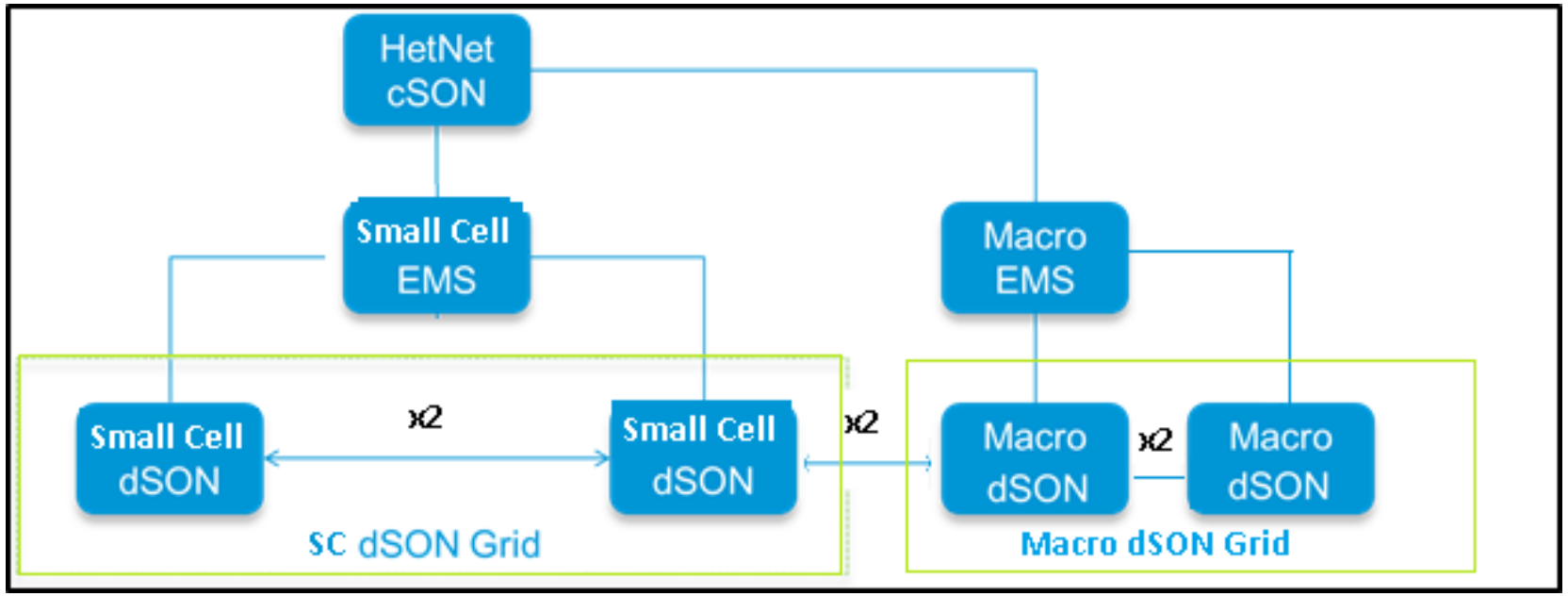
Roaming Using Hotspot 2.0



Hybrid SON Architecture



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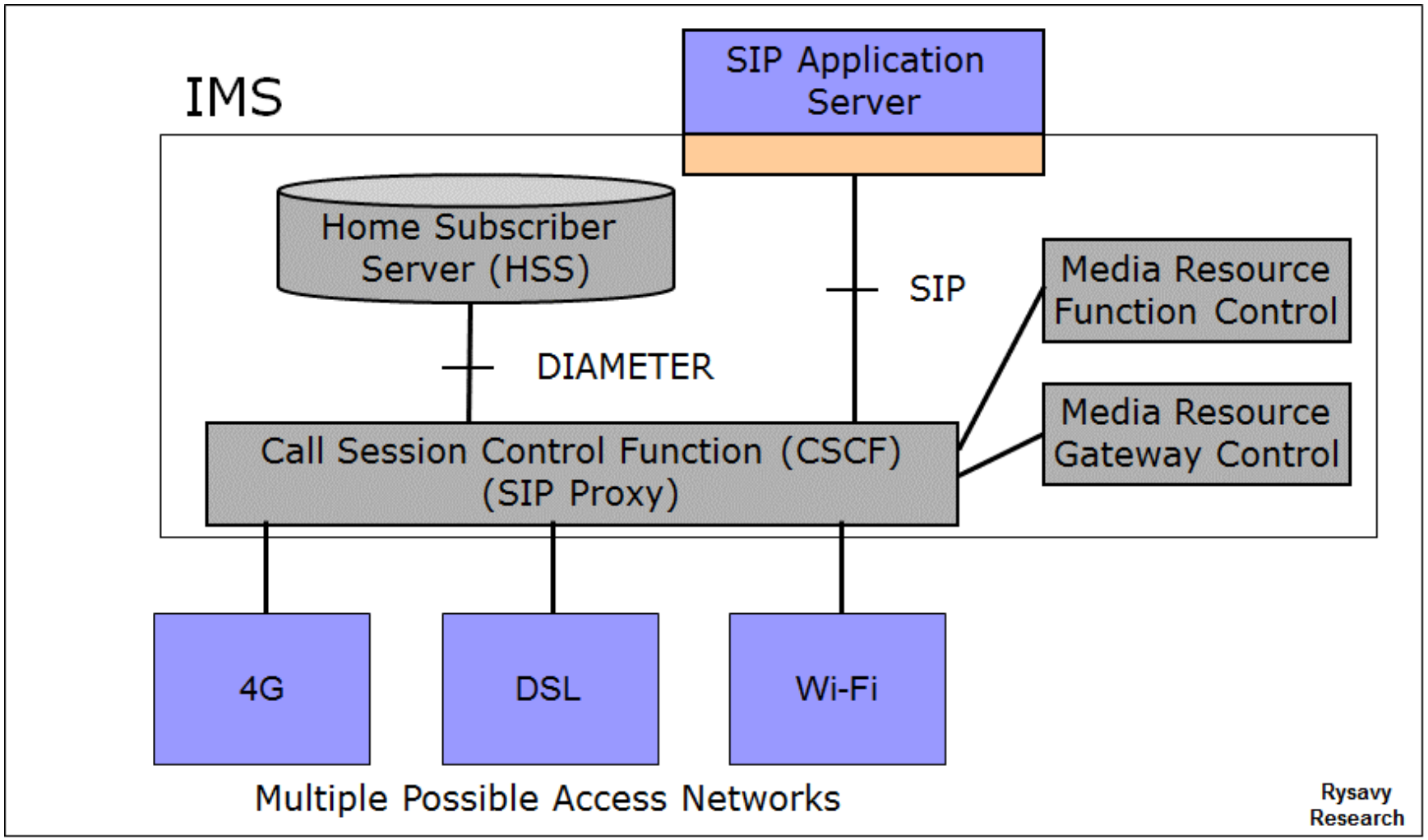
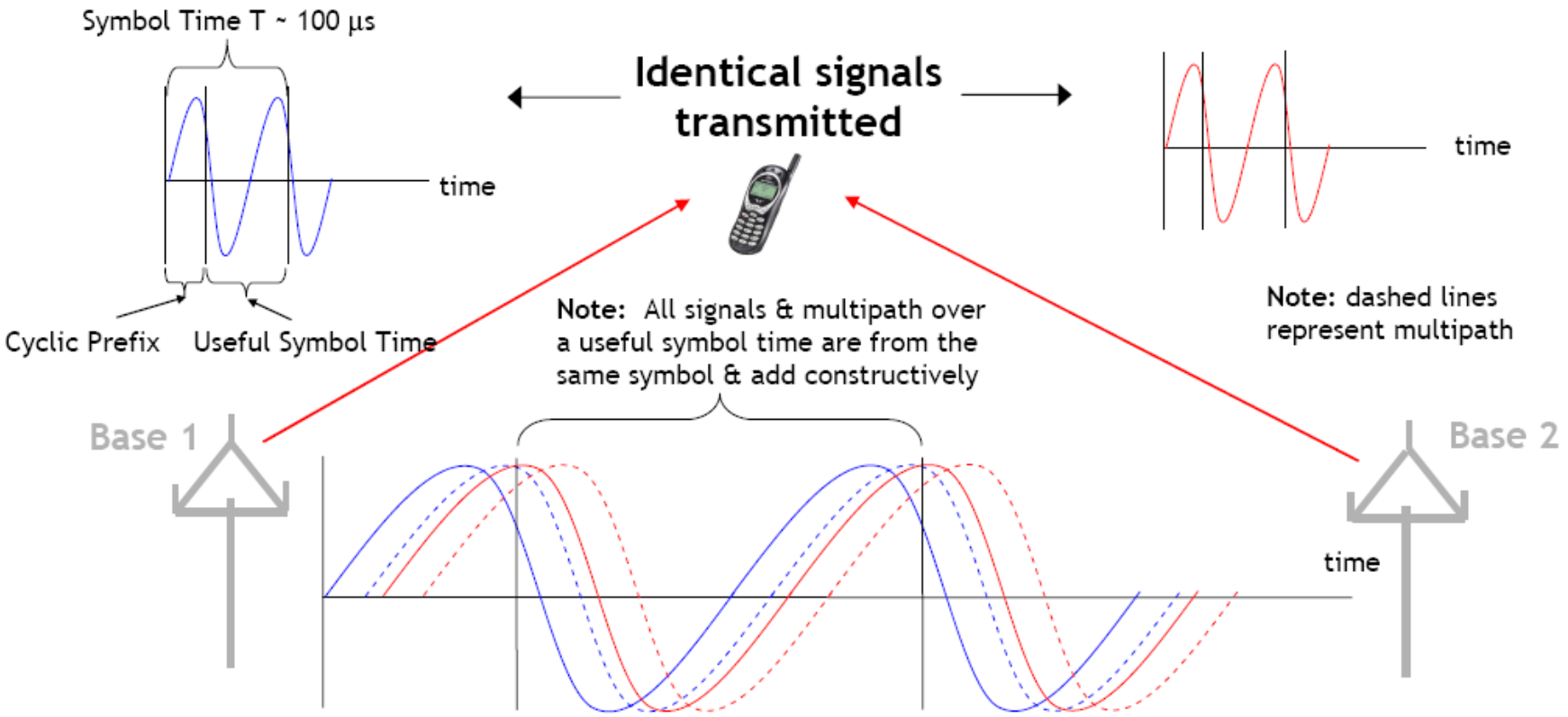
IP Multimedia Subsystem

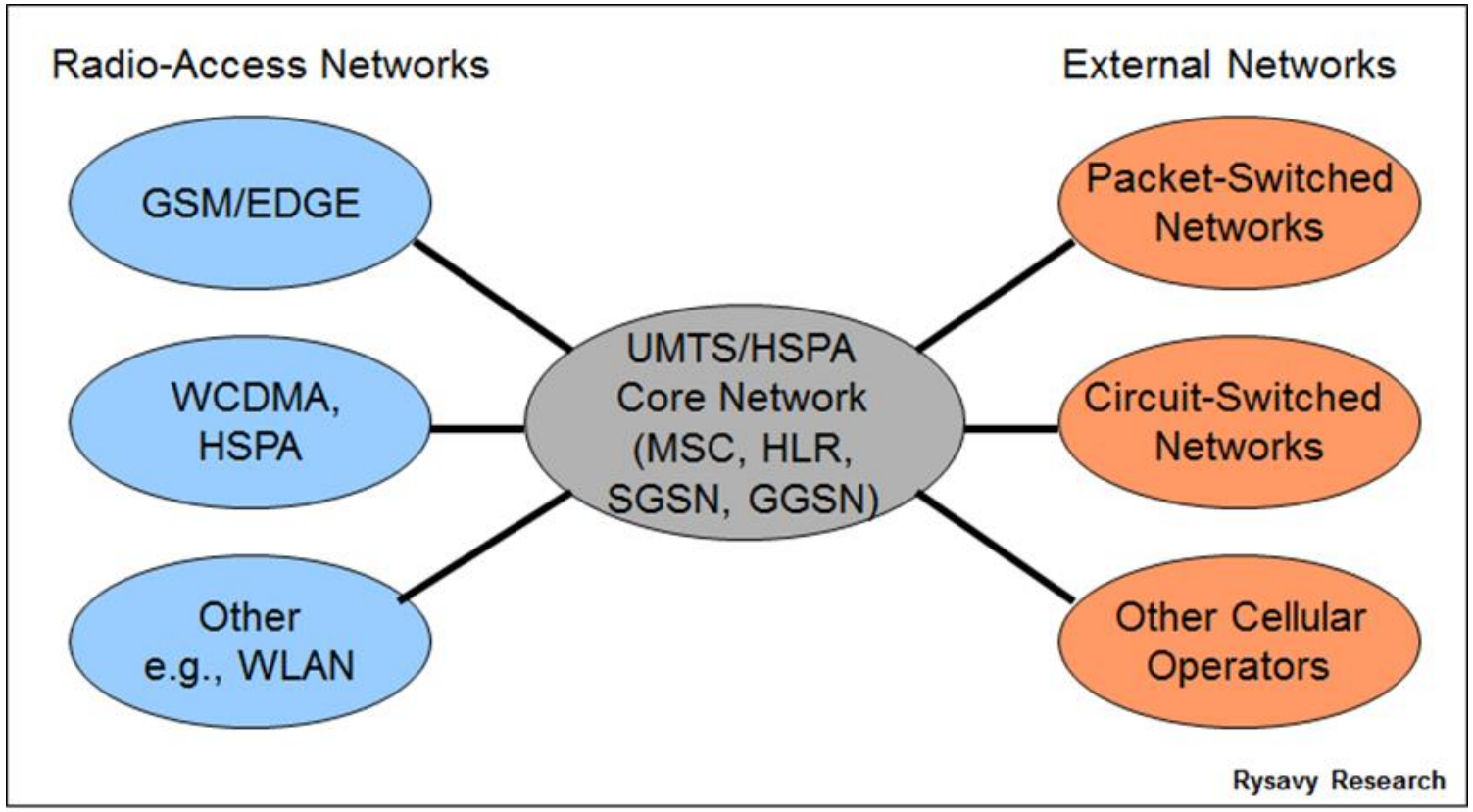


Efficient Broadcasting with OFDM



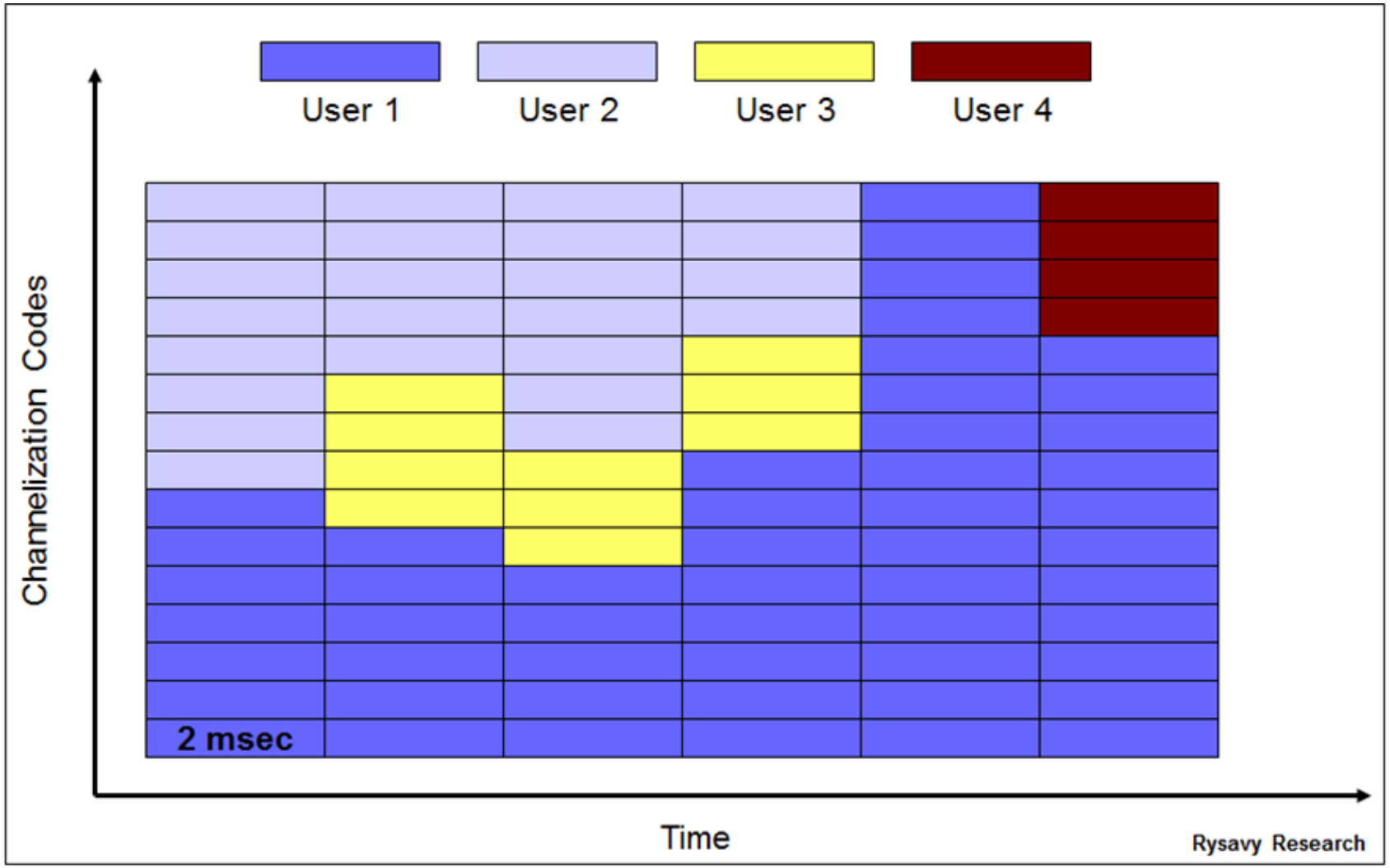
LTE will leverage OFDM-based broadcasting capabilities

UMTS Multi-Radio Network

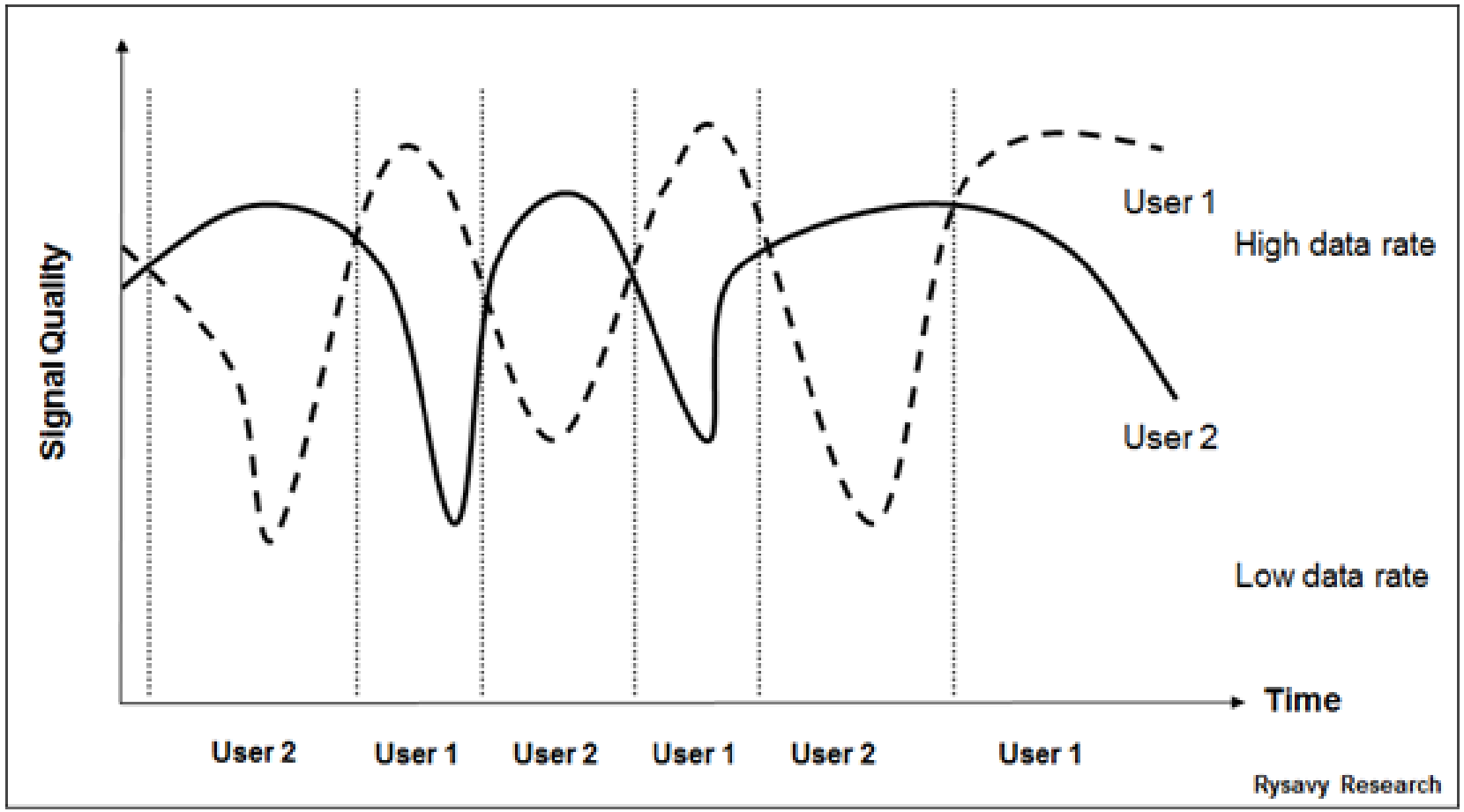


Common core network can support multiple radio access networks

HSPA Channel Assignment - Example

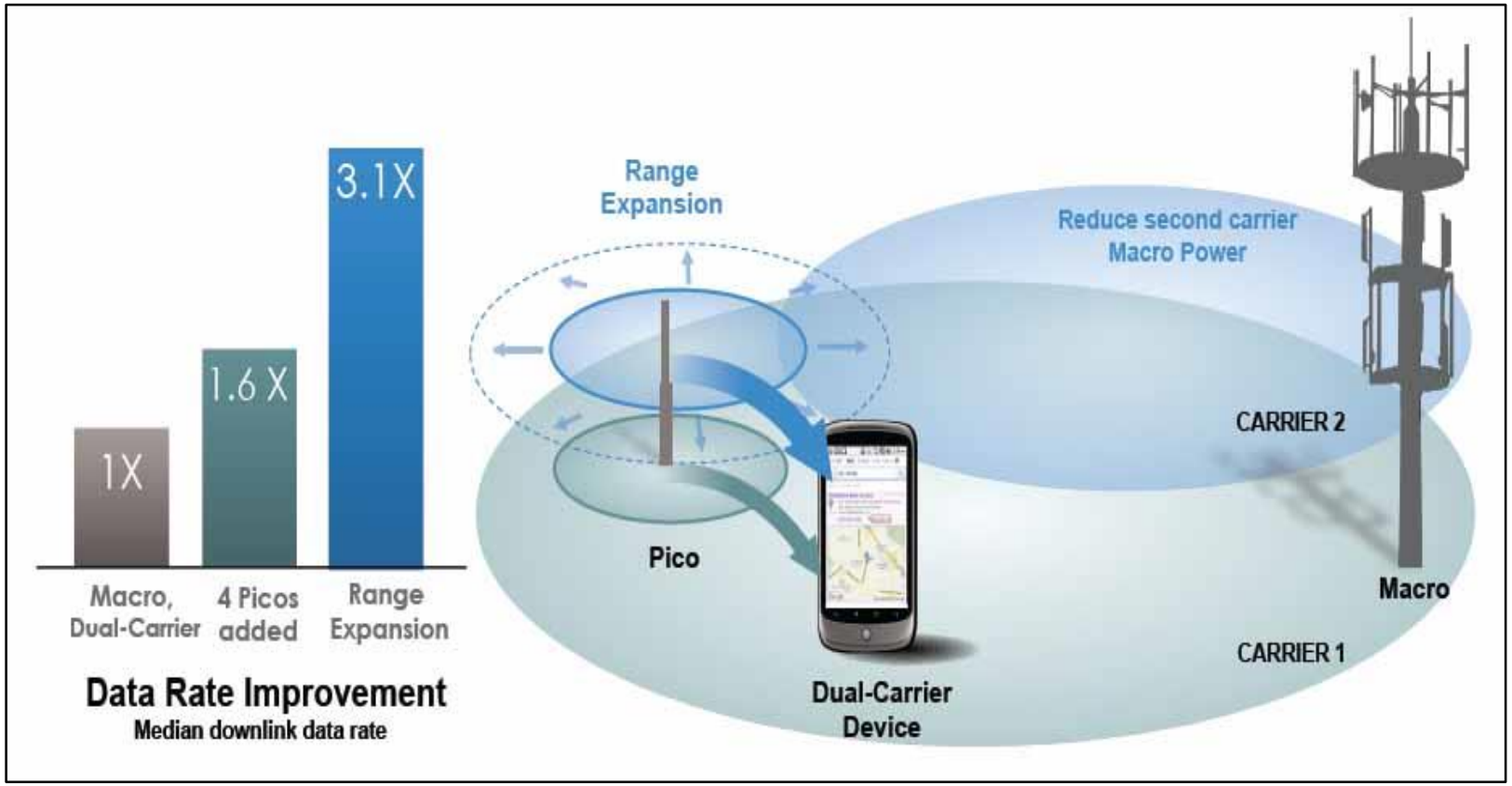


HSPA Multi-User Diversity



Efficient scheduler favors transmissions to users with best radio conditions

HSPA+ Het-net Using Multipoint Transmission



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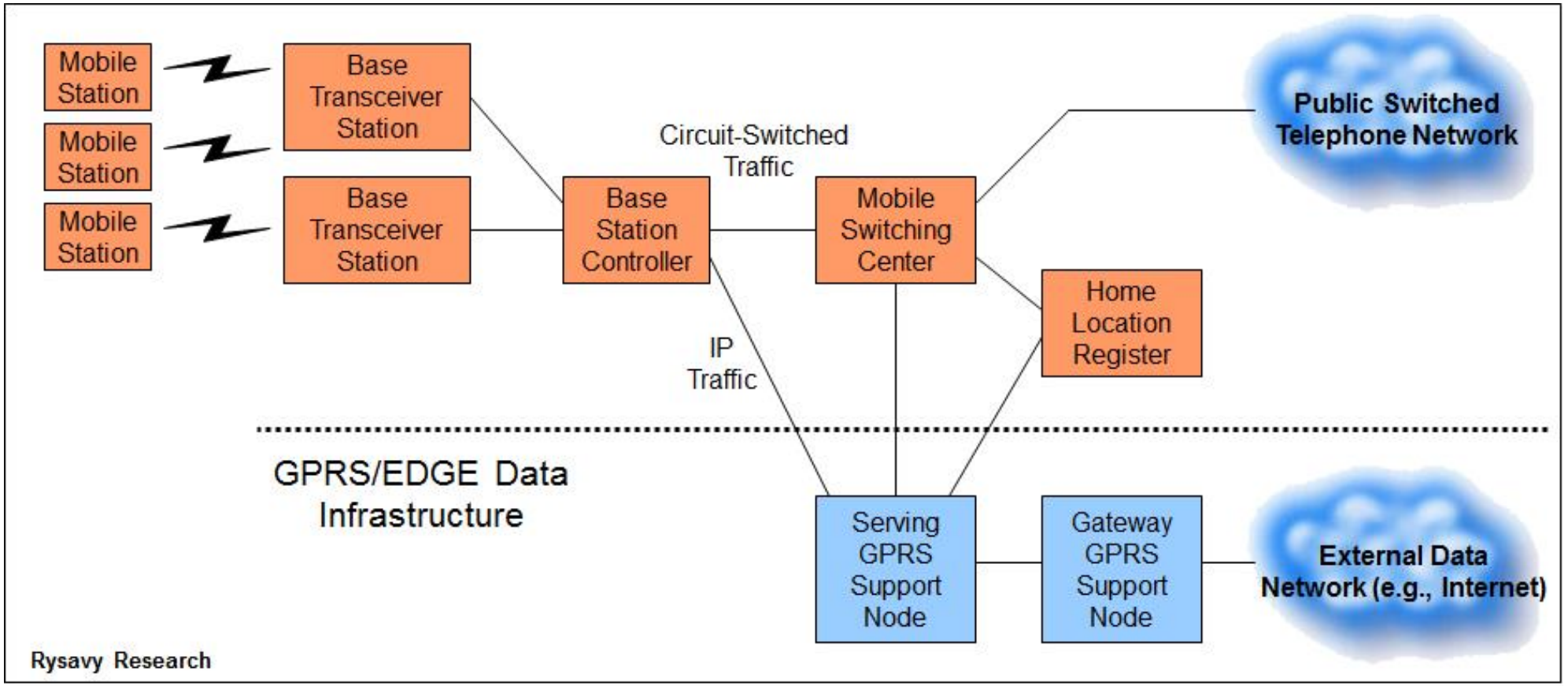
HSPA Throughput Evolution

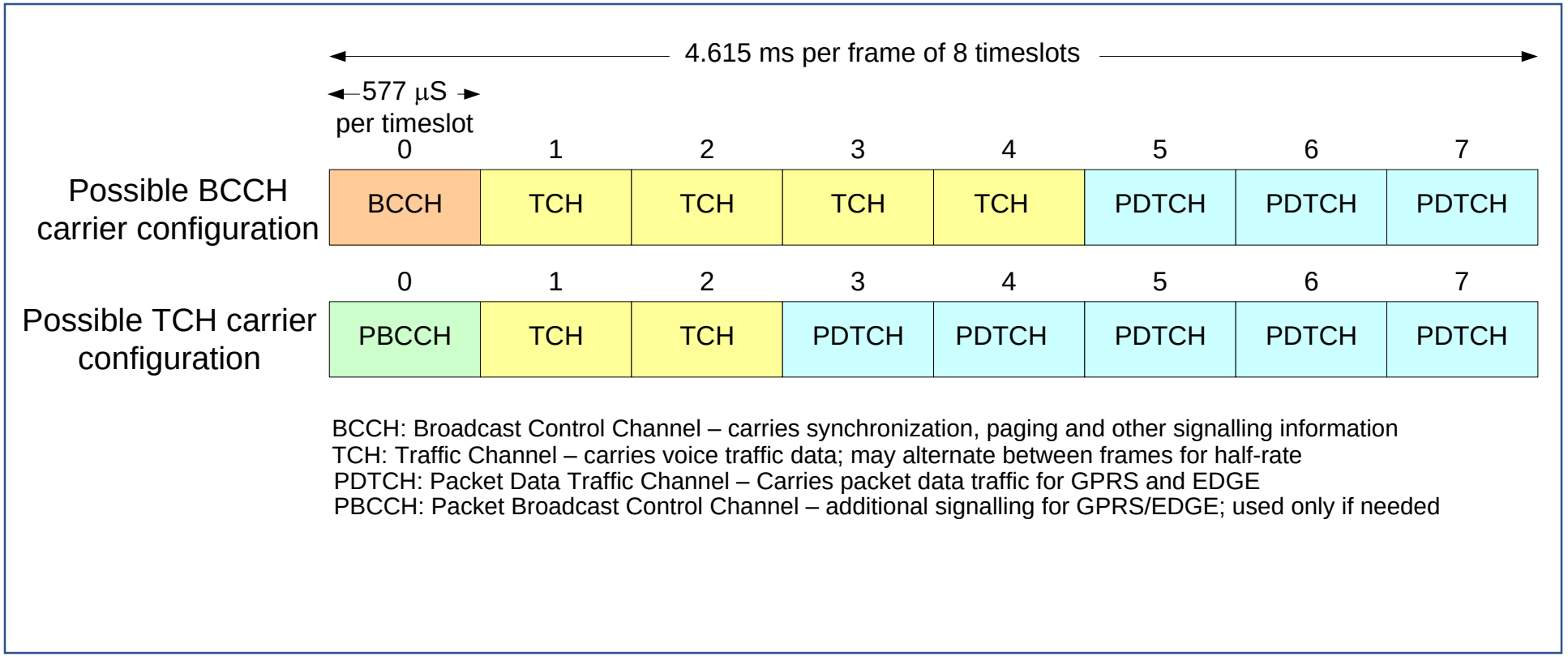
Technology	Downlink (Mbps) Peak Data Rate	Uplink (Mbps) Peak Data Rate
HSPA as defined in Release 6	14.4	5.76
Release 7 HSPA+ DL 64 QAM, UL 16 QAM, 5+5 MHz	21.1	11.5
Release 7 HSPA+ 2X2 MIMO, DL 16 QAM, UL 16 QAM, 5+5 MHz	28.0	11.5
Release 8 HSPA+ 2X2 MIMO DL 64 QAM, UL 16 QAM, 5+5 MHz	42.2	11.5
Release 8 HSPA+ (no MIMO) Dual Carrier, 10+5 MHz	.2	11.5
Release 9 HSPA+ 2X2 MIMO, Dual Carrier DL and UL, 10+10 MHz	84.0	23.0
Release 10 HSPA+ 2X2 MIMO, Quad Carrier DL, Dual Carrier UL, 20+10 MHz	168.0	23.0
Release 11 HSPA+ 2X2 MIMO DL and UL, 8 Carrier, Dual Carrier UL, 40+10 MHz	336.0	69.0

No operators have announced plans to deploy HSPA in a quad (or greater) carrier configuration. Three carrier configurations, however, have been deployed.

GPRS/EDGE Architecture



Example of GSM/GPRS/EDGE Timeslot Structure



BCCH: Broadcast Control Channel – carries synchronization, paging and other signalling information
TCH: Traffic Channel – carries voice traffic data; may alternate between frames for half-rate
PDTCH: Packet Data Traffic Channel – Carries packet data traffic for GPRS and EDGE
PBCCH: Packet Broadcast Control Channel – additional signalling for GPRS/EDGE; used only if needed

5G Americas Member contribution

Conclusion

- Mobile broadband remains at the forefront of innovation and development in computing, networking, and application development.
- LTE has become the global 4G standard.
- Release-15 5G networks rolling out globally, emphasizing enhanced mobile broadband.
- Release 16 standards by 2020 (IAB, unlicensed spectrum, C-V2X, URLLC, …).
- 5G will be able to access more than 10 times as much spectrum as previous generations.
- LTE-Advanced Pro innovations will continue.
- Small cells will play an ever-more important role.
- More spectrum remains a priority. 28 GHz and 24 GHz auctions completed.
- Future of wireless technology is bright, with no end in sight for continued growth.