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The Critical Role of Spectrum in Wi-Fi and Cellular Networks

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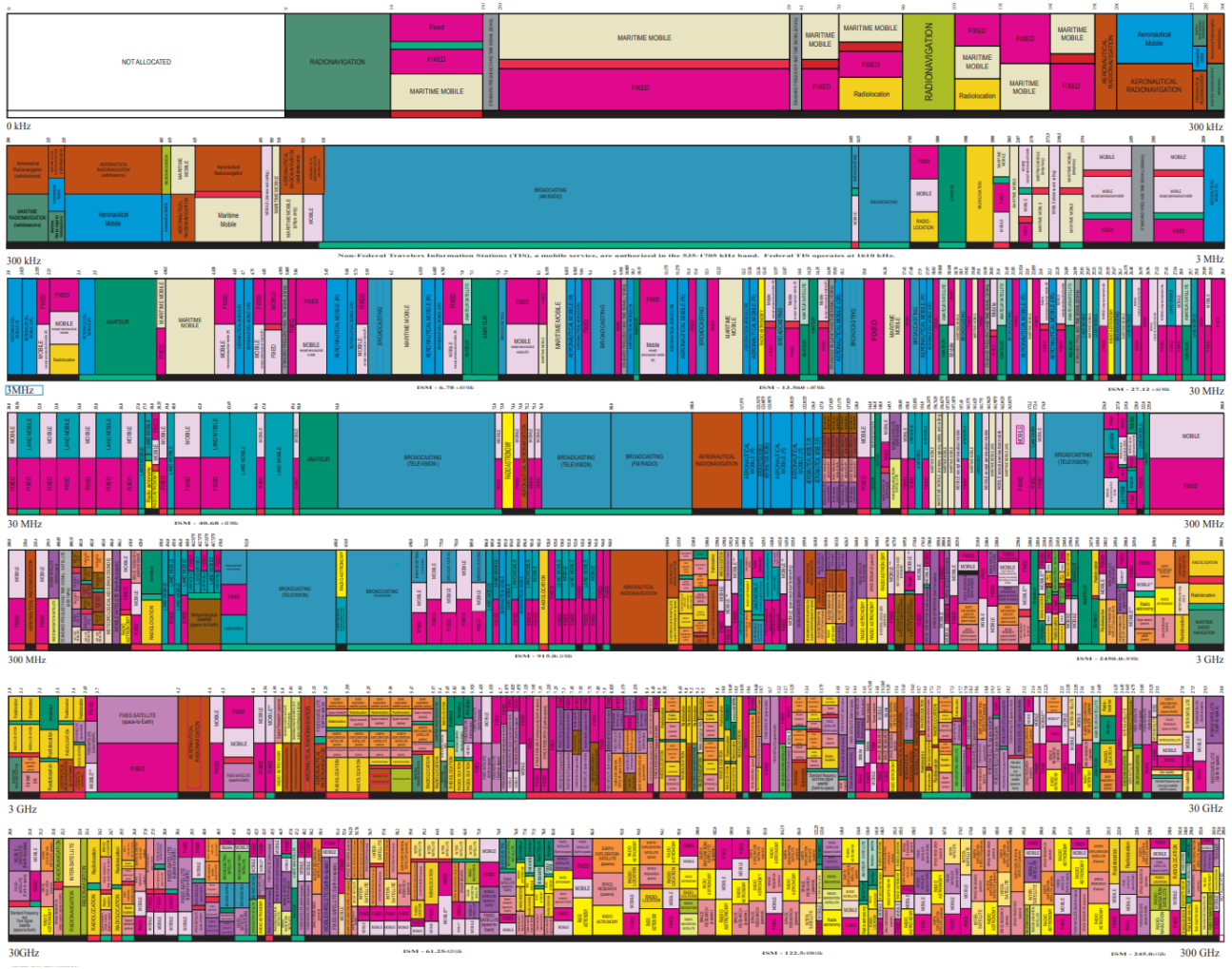
Agenda

- The tradeoffs between different types of spectrum bands
- Spectrum innovations in Wi-Fi and 5G to improve performance and reliability
- Forecasts illustrating the insatiable demand for more spectrum
- Balancing the scales between Wi-Fi and 5G allocations
- Insights from the World Radio Communication Conference (WRC) 23
- Details on the recently announced U.S. National Spectrum Strategy
- United States versus the rest of the world in spectrum assignments and associated risks
- Lessons learned and the future of Citizens Broadband Radio Service (CBRS)
- Pioneering approaches in dynamic spectrum sharing

Spectrum in the United States (3 Hz to 300 GHz)

Too many applications, too many users, too little spectrum.



https://www.ntia.doc.gov/files/ntia/publications/january_2016_spectrum_wall_chart.pdf

United States Licensed Spectrum Inventory

Frequency Band Name	Band	Bandwidth (MHz)	Comments
600 MHz	600 MHz	70	5G coverage layer
700 MHz	700 MHz	70	5G coverage layer
Cellular	850 MHz	64	Original cellular bands
L-Band	1.5/1.6 GHz	40	
AWS-1	1.7/2.1 GHz	90	Advanced Wireless Service
AWS-3	1.7/2.1 GHz	65	
PCS	1.9 GHz	140	Personal Communications Service
AWS-4	2.0/2.2 GHz	40	Previously satellite
WCS	2.3 GHz	20	Wireless Communications Service
BRS/EBS	2.5 GHz	184	Broadband Radio Service, Educational Broadcasting Service
CBRS	3.5 GHz	70	Citizens Broadband Radio Service, 150 MHz toal
C-Band	3.7 GHz	280	Optimal for current 5G networks
3.45 GHz	3.45 GHz	100	
24 GHz	24 GHz	700	
28 GHz	28 GHz	850	
37 GHz	37 GHz	1,000	
39 GHz	39 GHz	1,400	
47 GHz	47 GHz	1,000	
US Total Midband (Including 2.5 GHz)		634	
US Total mmWave		3,400	
			Rysavy Research

United States Unlicensed Spectrum Inventory

Name	Band	Bandwidth (MHz)	Comments
ISM	900 MHz	26	
ISM	2.4 GHz	83	Three non-overlapping bands in United States
CBRS	3.5 GHz	150	General Authorized Access
U-NII-1	5 GHz	100	Unlicensed National Information Infrastructure, low power
U-NII-2A	5 GHz	100	Subject to Dynamic Frequency Selection
U-NII-2B	5 GHz	120	Not available for unlicensed use
U-NII-2C	5 GHz	255	Subject to Dynamic Frequency Selection
U-NII-3	5 GHz	125	
U-NII-4	5 GHz	75	Dedicated Short Range Communications Service (DSRC)
U-NII-5	6 GHz	500	
U-NII-6	6 GHz	100	
U-NII-7	6 GHz	350	
U-NII-8	6 GHz	250	
mmWave	37 GHz	600	Shared coordinated basis
mmWave	60 GHz	14,000	IEEE 802.11ad
Total UNII 5 GHz for unlicensed		505	
Total UNII 6 GHz for unlicensed		1,200	
Total Unlicensed Mid-Band		1,938	
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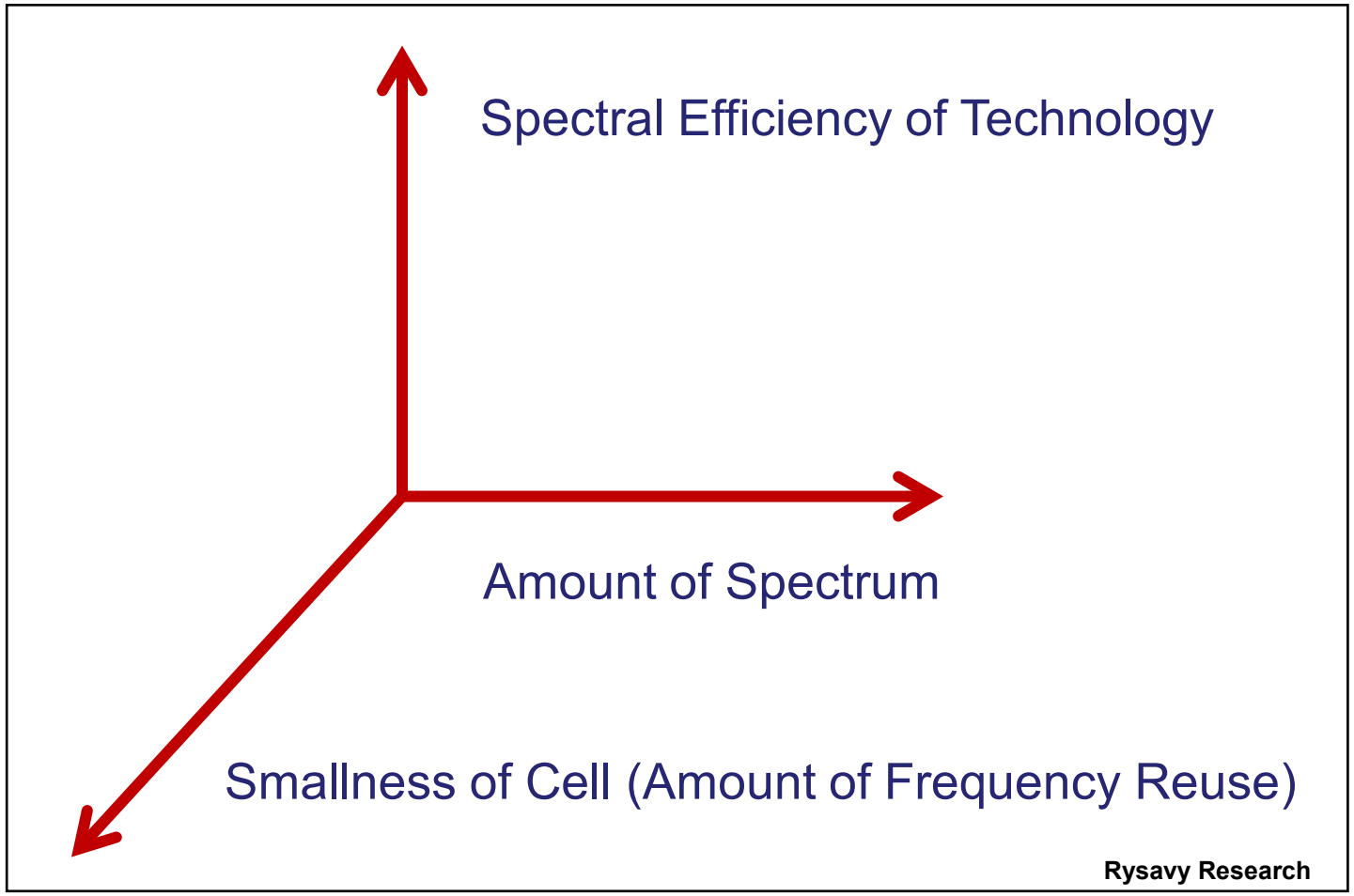
Spectrum on the Global Stage

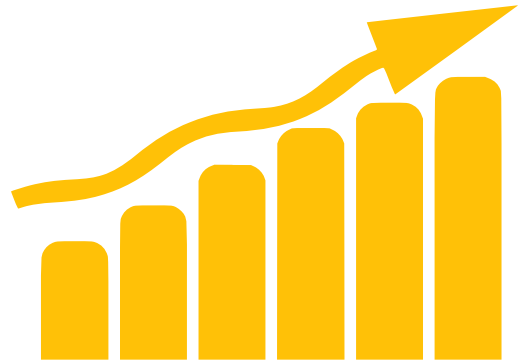
- United States globally has highest ratio of unlicensed to licensed mid-band, 3:1
- Logic dictates similar licensed to unlicensed
- In mmWave, unlicensed has 4:1 ratio over licensed
- Within 5 years
  - China: 1660 MHz licensed mid-band
  - Japan: 1100 MHz licensed mid-band
  - United states: no current path beyond 634 MHz
- United States is only country to allocate entire 6 GHz for unlicensed operation

Wireless Capacity



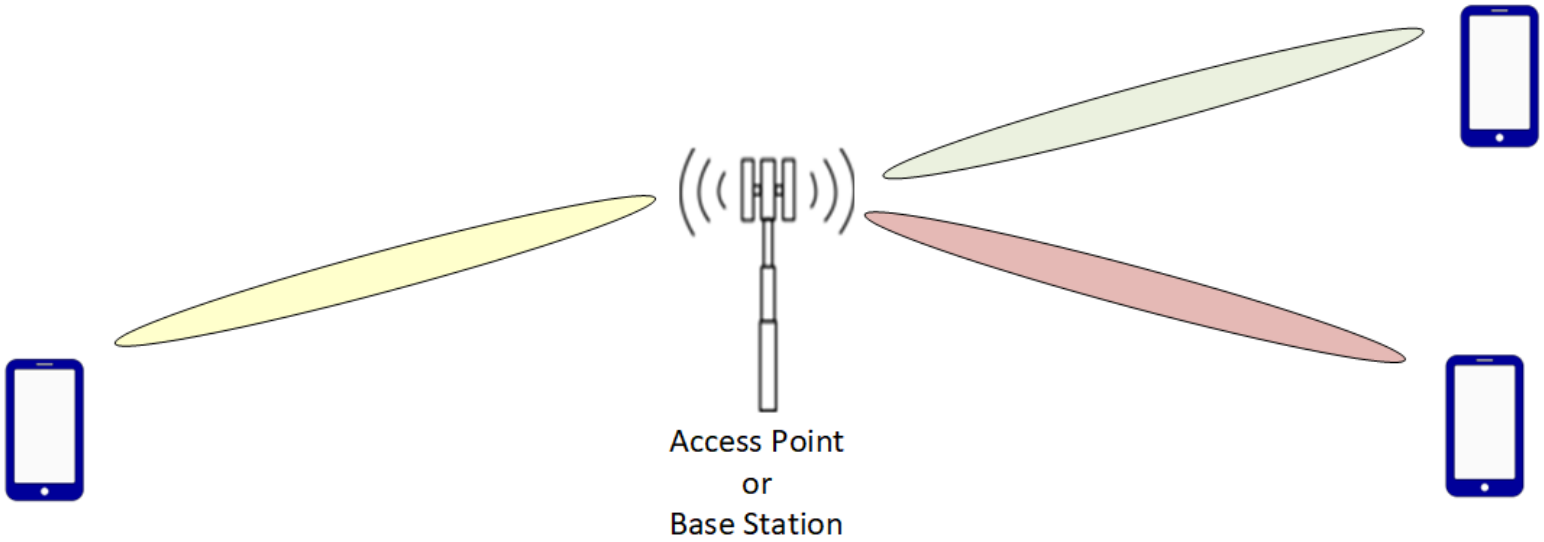
5G Spectrum Demand Forecast

- Ericsson Mobility Report, Nov. 2023, 17% U.S. CAGR data growth 2023-2029
- Limits to deployment of new cell sites
- Limits to increasing spectral efficiency
- The Brattle Group: 400 MHz shortfall by 2027, 1400 MHz by 2032
- Rysavy Research modeling: 440 MHz shortfall by 2028
- Wi-Fi expects increased needs, but huge 6 GHz swath just became available



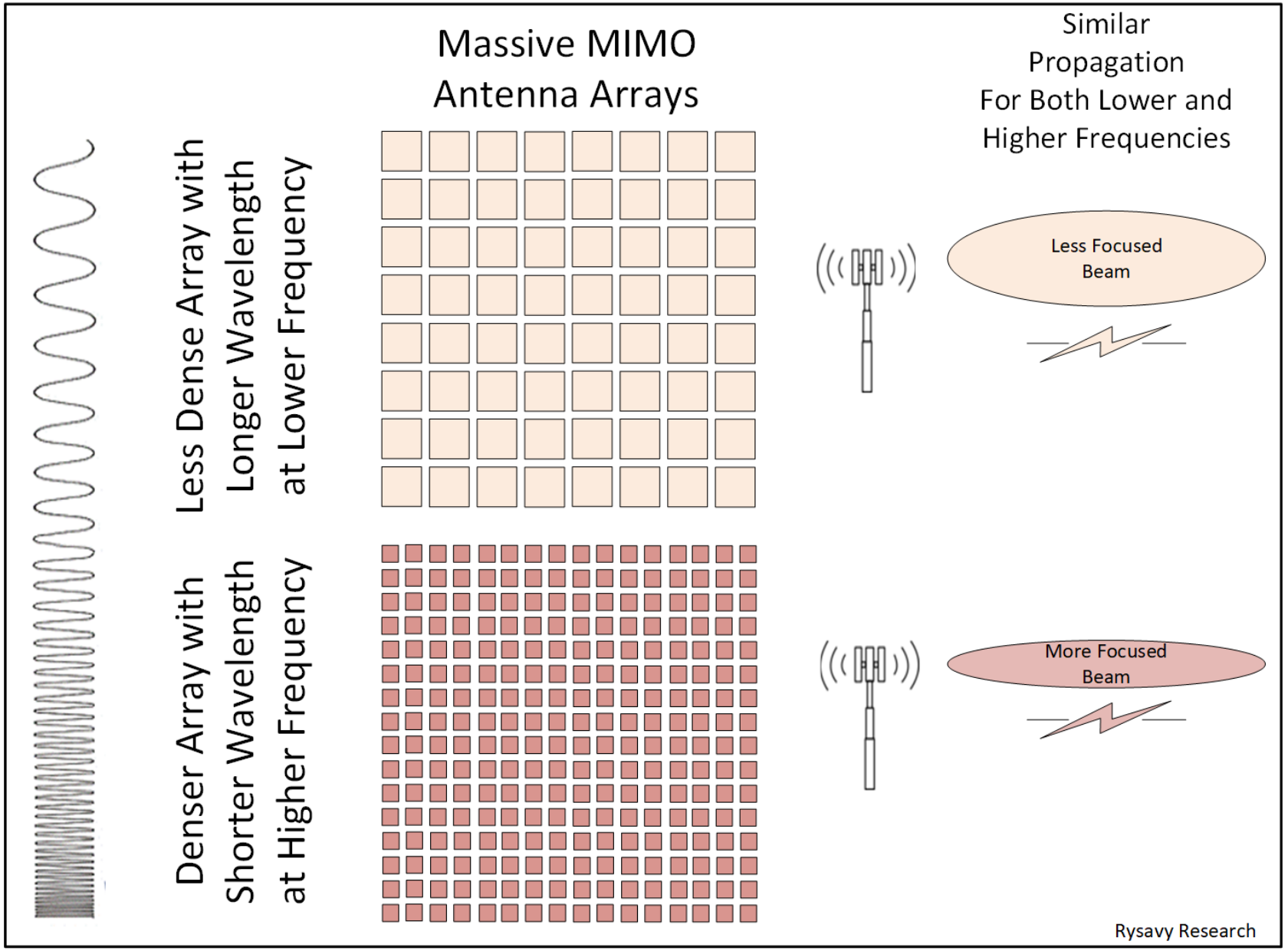
Modulation and Coding

Multiple Input Multiple Output (MIMO)

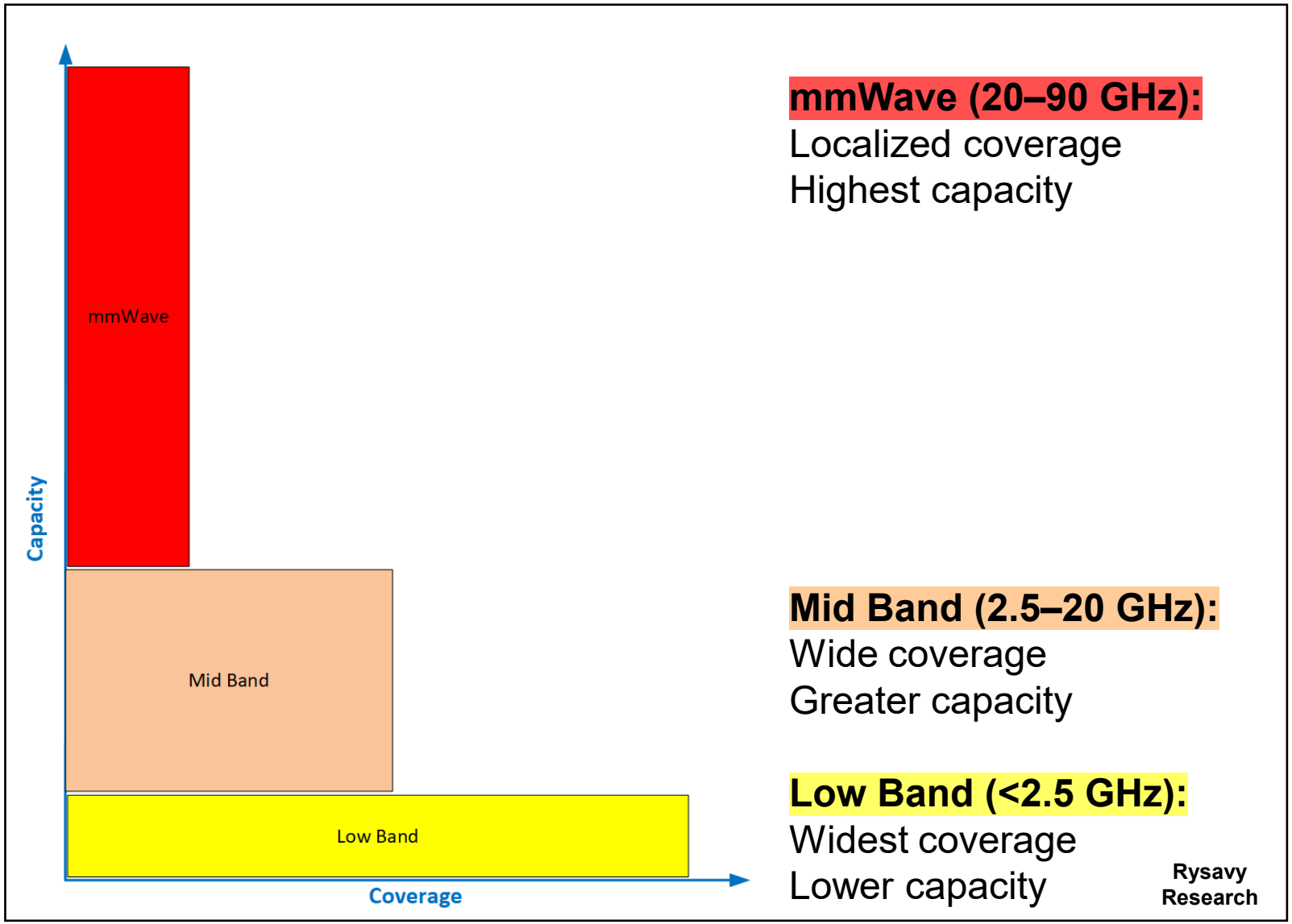


Antenna arrays allow beamforming
Beamforming can extend range
Multi-User MIMO allows simultaneous connections to multiple users
64T 64R common for 5G, will increase in the future
Wi-Fi 7 supports up to 16 antennas

Massive MIMO



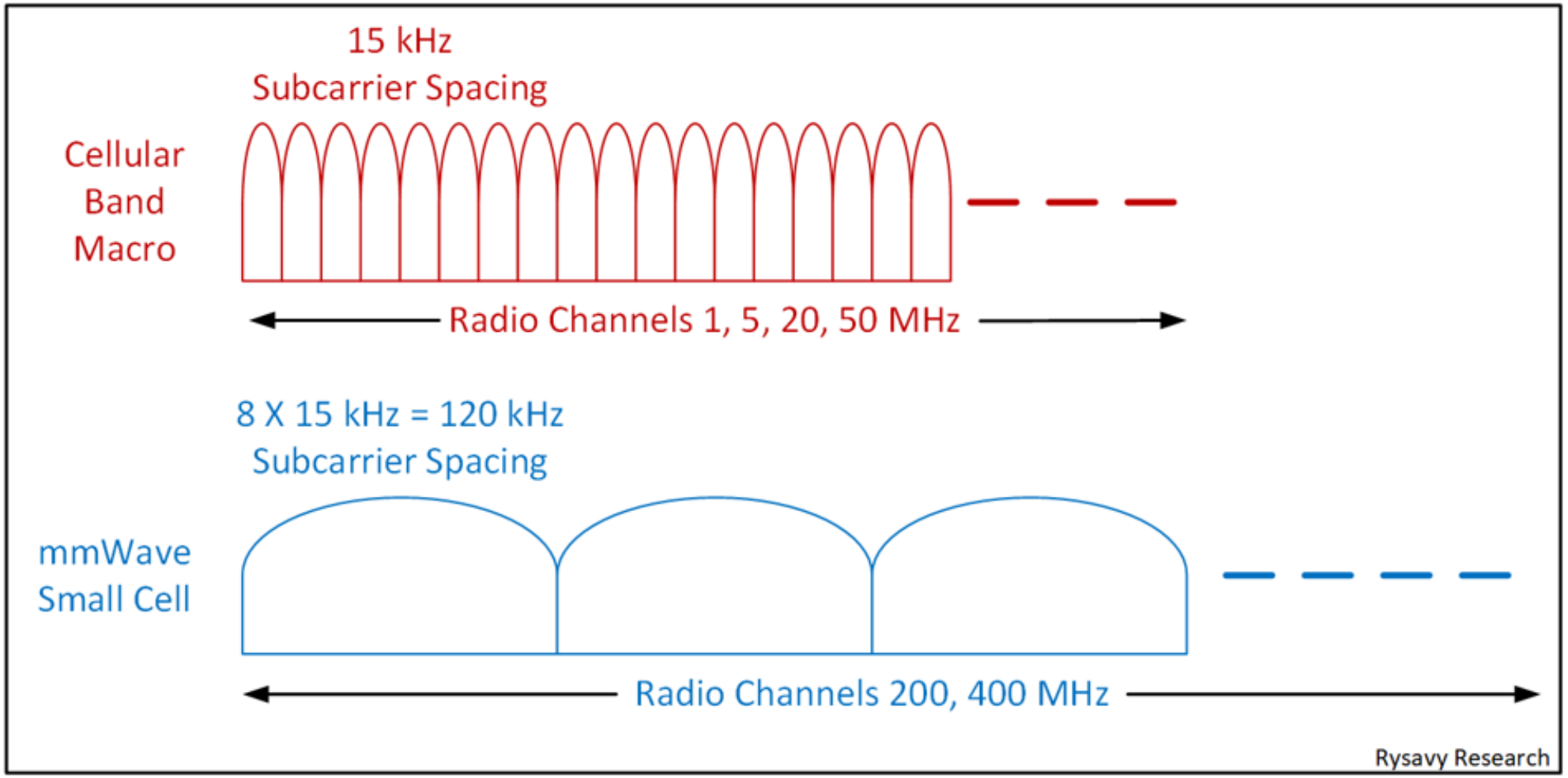
Spectrum Tradeoffs



Sub-THz:
6G
90–300 GHz

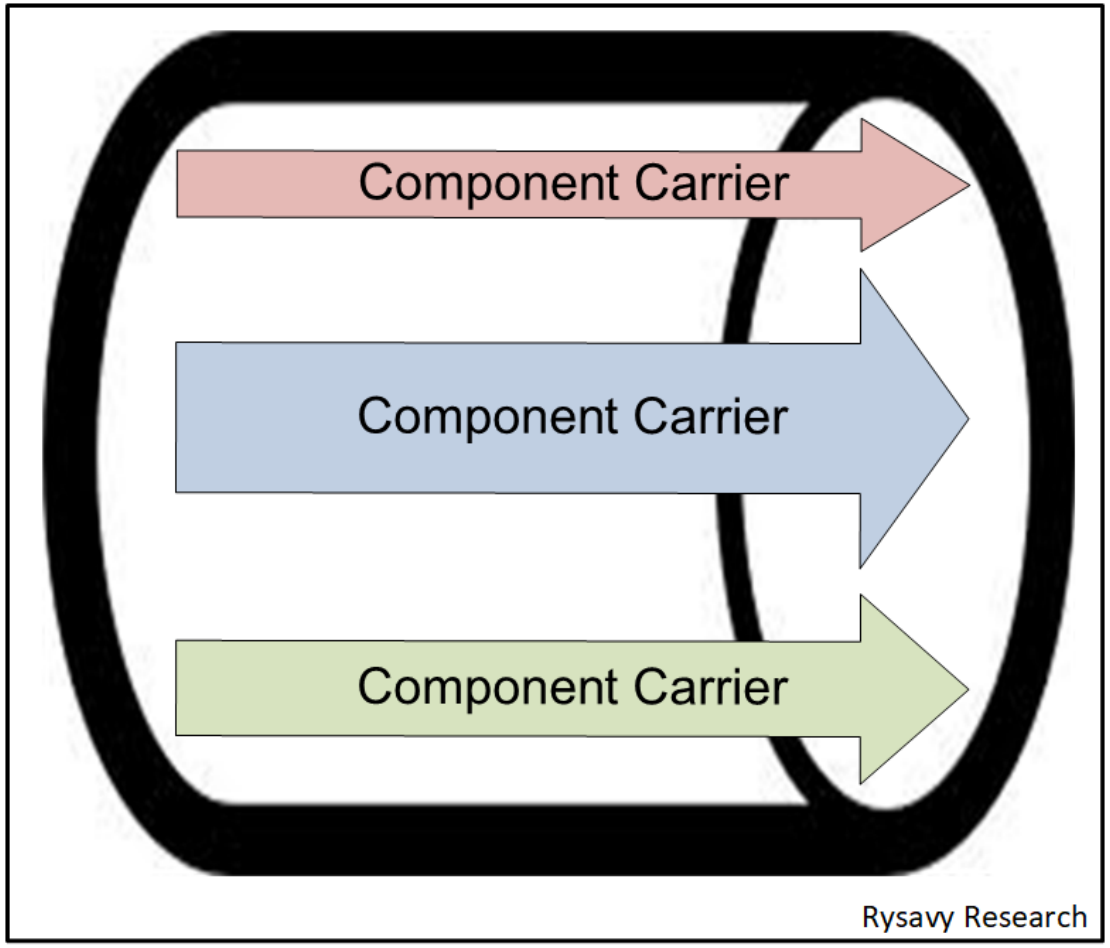
15 GHz practical limit for wide-area coverage

5G Radio Channels

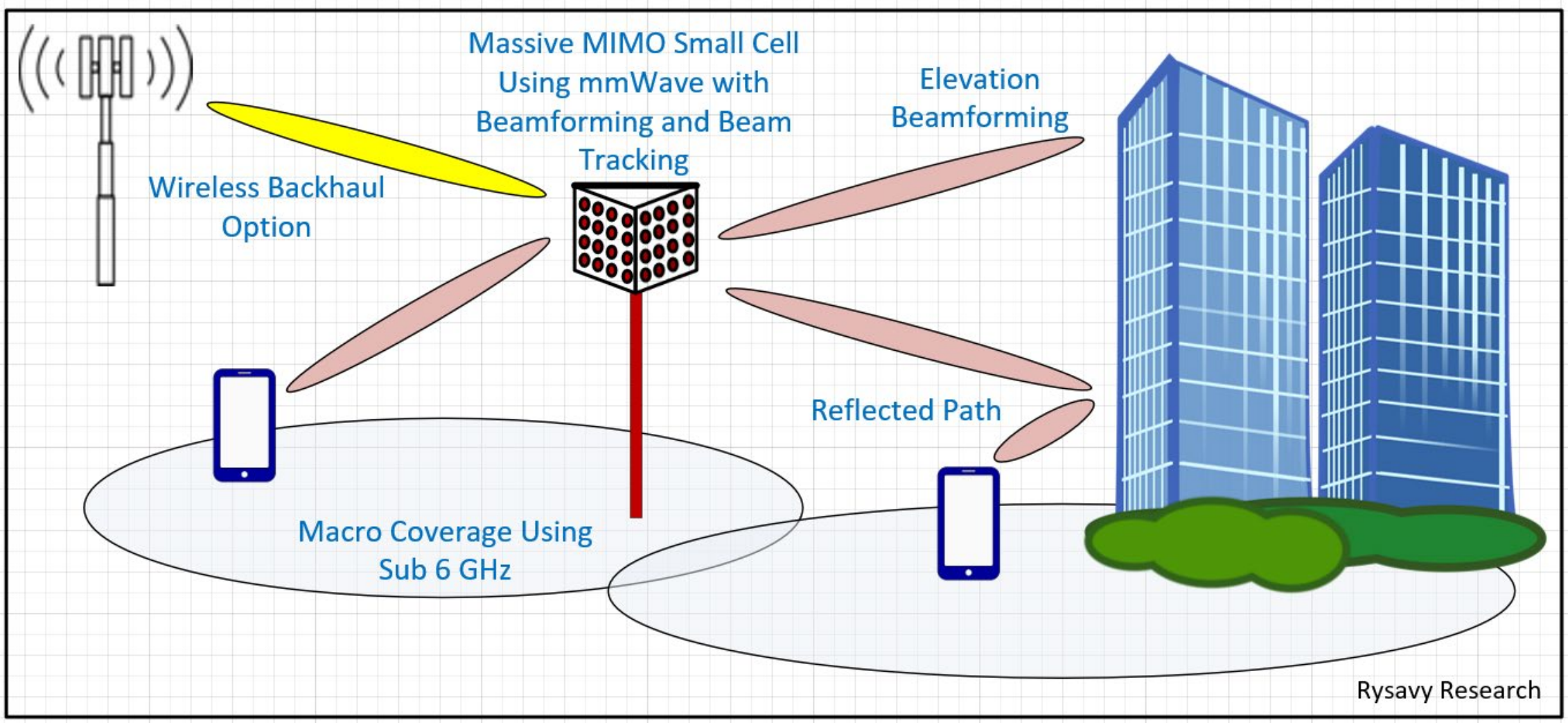


5G Carrier Aggregation

- Improves throughput and reliability
- Same band or across bands
- 5G up to 16 component carriers
- CC up to 100 MHz wide sub 6 GHz
- CC up to 400 MHz wide above 6 GHz
- Separate CA downlink and uplink

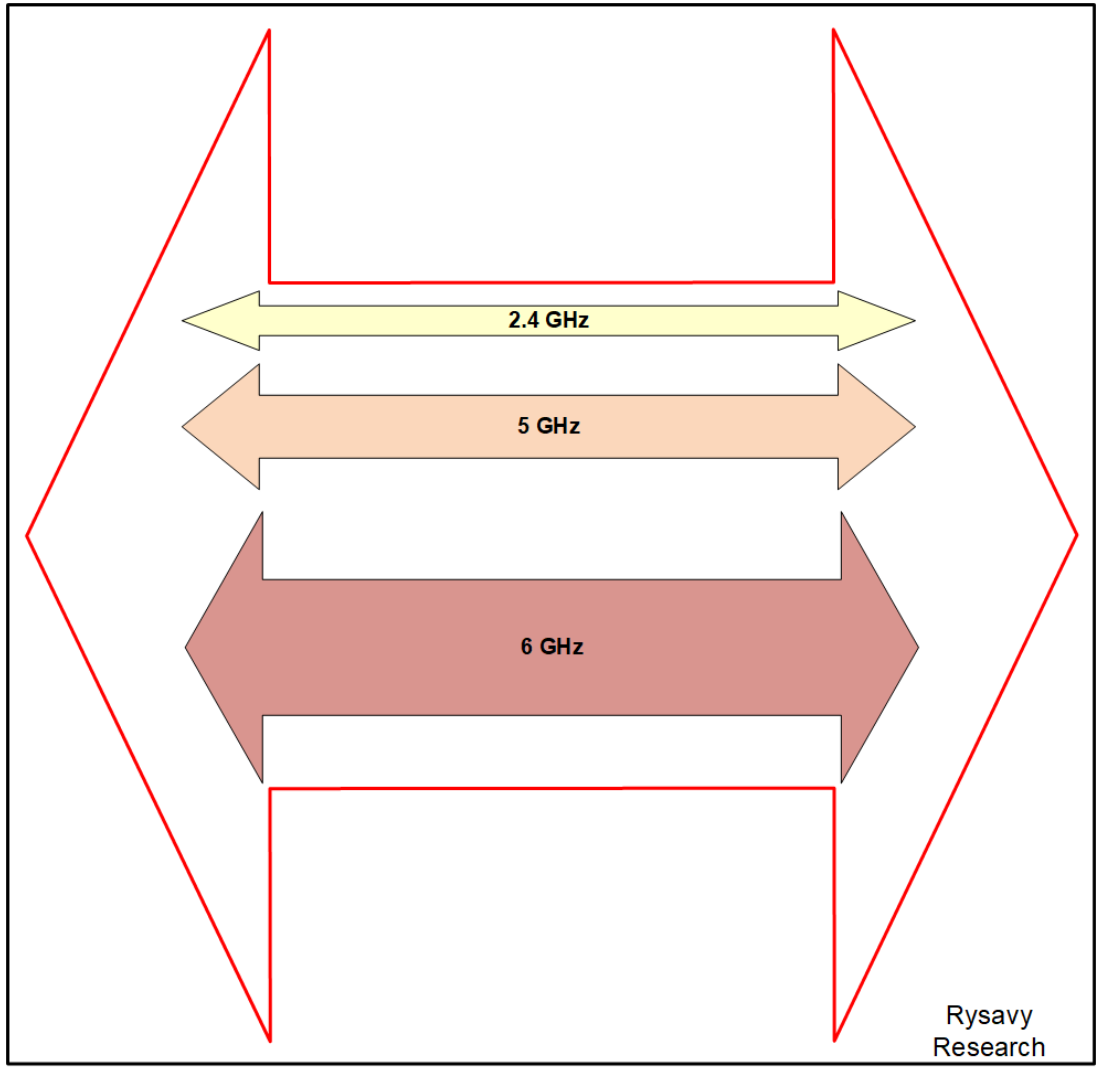


Combining Bands in 5G

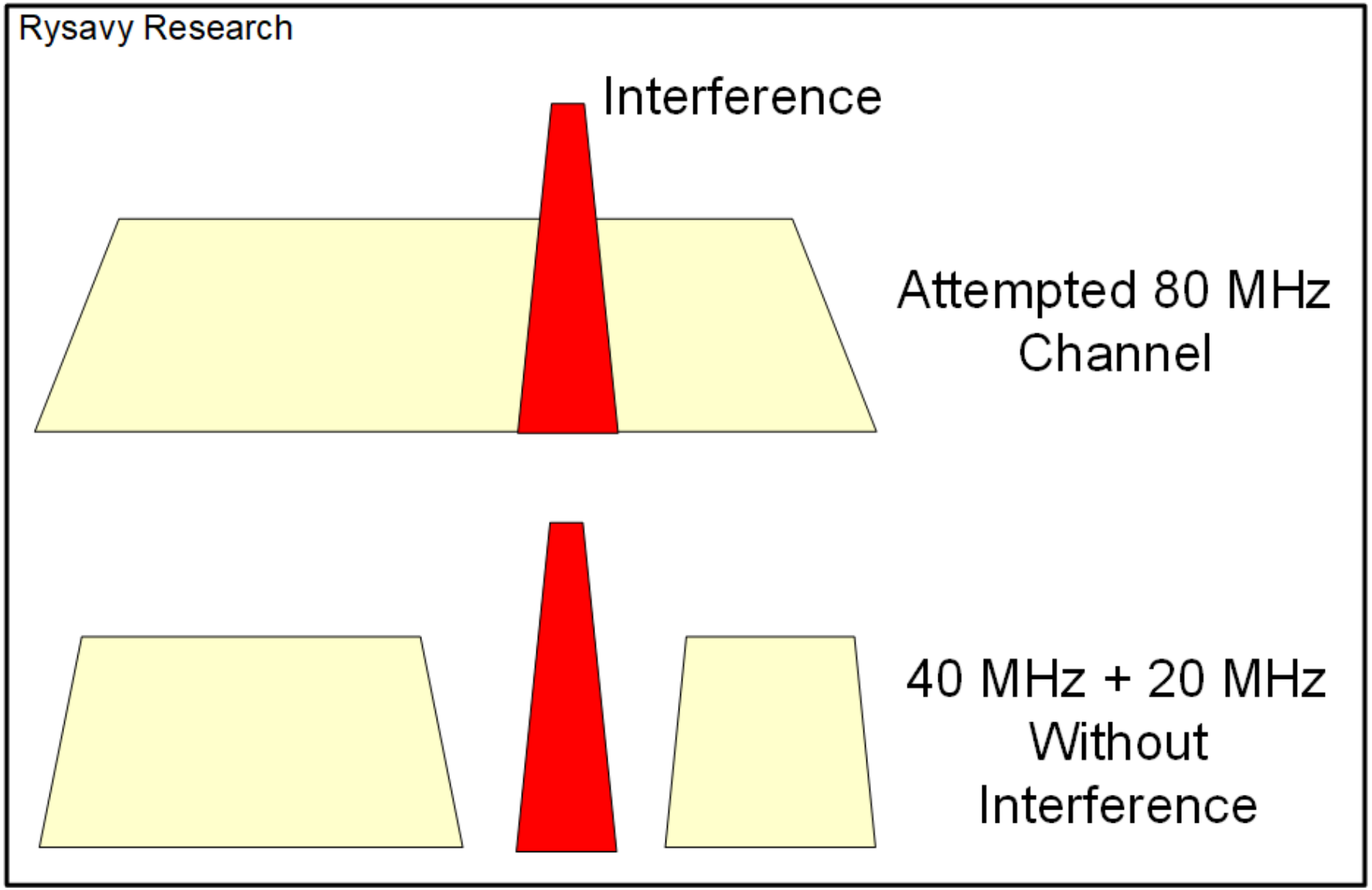


Wi-Fi 7 Multilink Operation

- Improves throughput and reliability
- Can combine channels from 2.4 GHz, 5 GHz, and 6 GHz bands
- No aggregation from same band (different from 5G)
- 5 GHz channels up to 80 MHz wide
- 6 GHz channels up to 320 MHz wide



Wi-Fi 7 Puncturing



National Spectrum Strategy

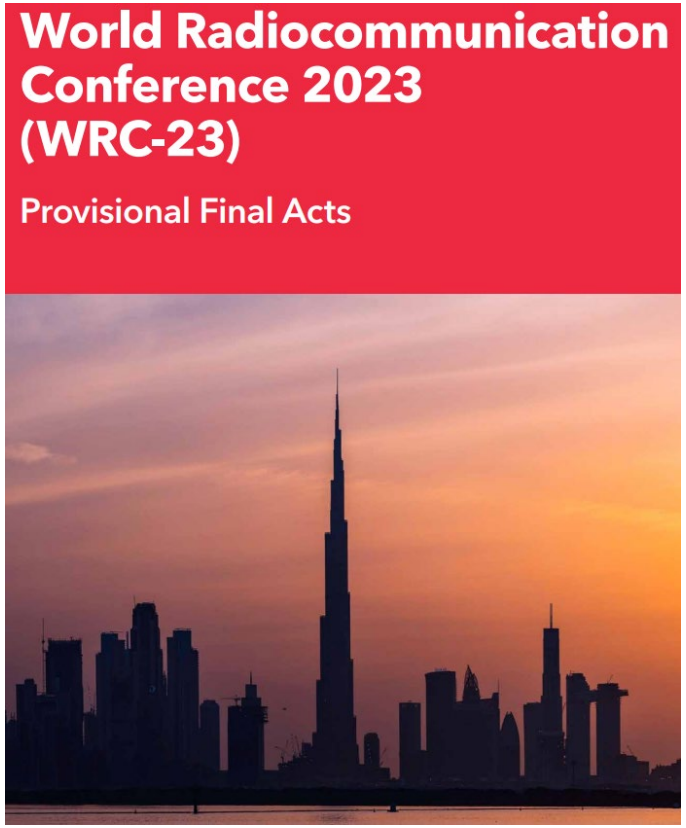
- Published by National Telecommunications and Information Administration (NTIA), Nov. 13, 2023
- Strategic objectives:
  - Develop spectrum pipeline
  - Conduct collaborative long-term planning
  - Innovate through technology development
  - Expand spectrum expertise and elevate national awareness
- Key bands to study (2.7 GHz total, 1.6 GHz mid-band)
  - 3.1–3.45 GHz (desired for 5G, used by DOD)
  - 7.125–8.40 GHz (lower 125 desirable for Wi-Fi, key for 6G)
  - 18.1–18.6 GHz (satellite)
  - 37.0–37.6 GHz (shared use framework)
- Emphasizes spectrum sharing
- Two-year timeframe expected

Plan: https://www.ntia.gov/sites/default/files/publications/national_spectrum_strategy_final.pdf

Comments: https://www.ntia.gov/issues/national-spectrum-strategy/stakeholder-engagement/received-comments/implementation-comments

World Radiocommunication Conference 2023 (WRC-23)

- Global harmonization effort, meets every four years, under auspices of the International Telecommunication Union (ITU)
- Harmonized 3.3–3.8 GHz for mobile
  (United States currently down to 3.45 GHz only)
- Designated 6.425–7.125 GHz for mobile
  (United Sates has assigned entire 6 GHz to Wi-Fi)
- Study on 4.4–4.8 GHz
- Study on 7.125–8.5 GHz
- Study on 14.8–15.35 GHz

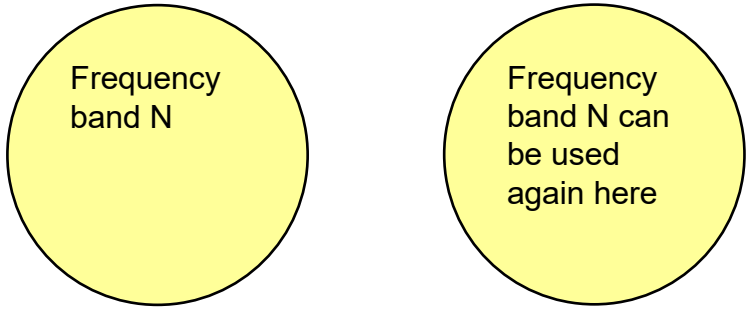


https://www.5gamericas.org/the-evolution-of-5g-spectrum/

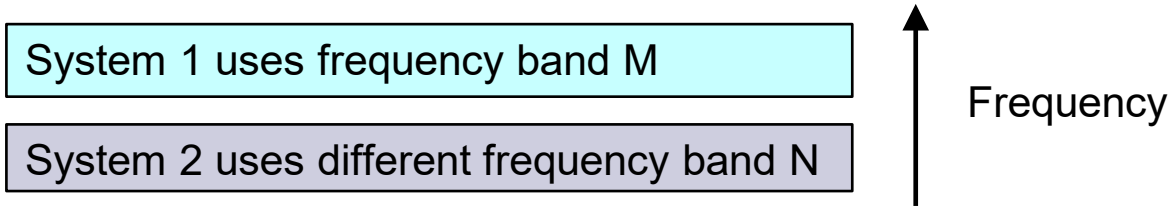
https://www.itu.int/dms_pub/itu-r/opb/act/R-ACT-WRC.15-2023-PDF-E.pdf

Dimensions of Spectrum Sharing

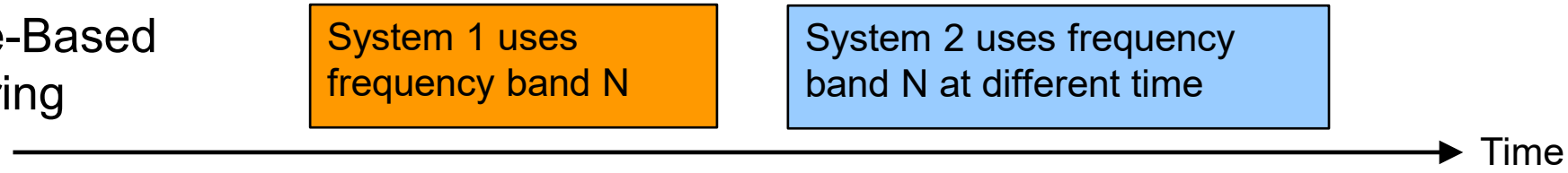
Geography-Based Sharing



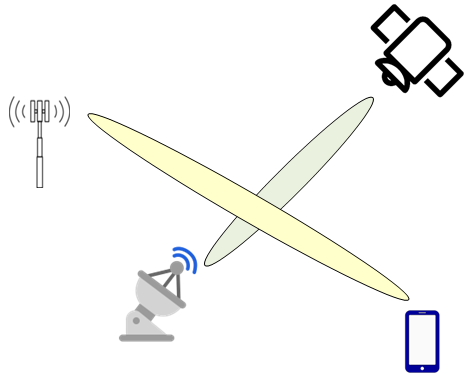
Frequency-Based Sharing



Time-Based Sharing



Spatial Sharing



Beamforming

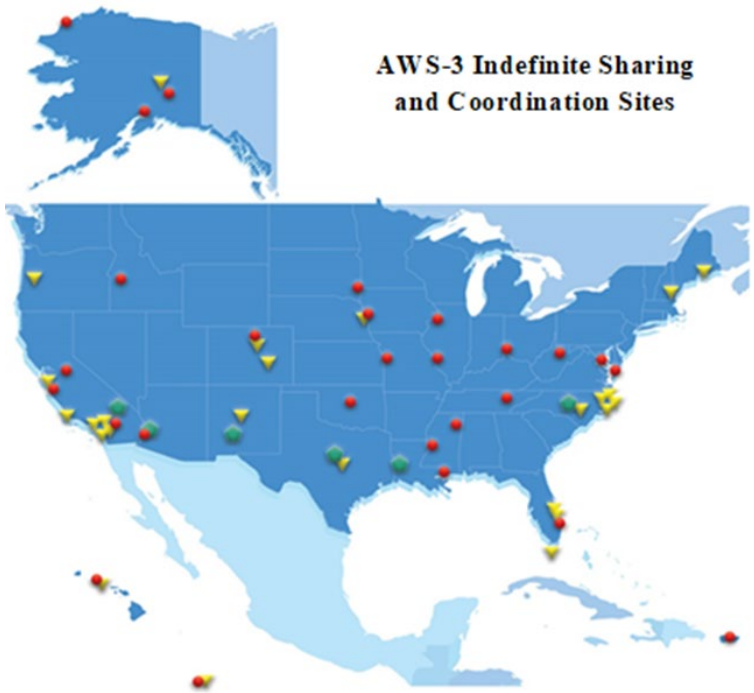
Some Existing Spectrum Sharing Solutions (United States)

Sharing Technology	What is Shared	Bands	Approach	Complexity
Advanced Wireless Service-3 Coordination Procedures	Federal systems and cellular networks	1.7 GHz	Geographic	Low
5G Dynamic Spectrum Sharing (DSS)	LTE and 5G	Current cellular bands	Dynamic coordination	High
LTE Licensed Assisted Access (LAA)	LTE and Wi-Fi	5 GHz unlicensed	Sensing	High
5G NR-Unlicensed (NR-U)	5G and Wi-Fi	5 GHz, 6 GHz unlicensed	Sensing	High
Citizens Band Radio Service (CBRS)	Government incumbents, licensed LTE/5G, "unlicensed" LTE/5G	3.5 GHz	Sensing and semi-dynamic coordination	High
White Space Networks	Computing devices and television	600 MHz	Static coordination	Medium
Industrial Scientific and Medical (ISM) FCC rules	Wi-Fi and Bluetooth	2.4 GHz unlicensed	Sensing	Medium
Wi-Fi Dynamic Frequency Selection	Radar and Wi-Fi	5 GHz	Sensing	Medium
Wi-Fi Automated Frequency Coordination (AFC)	Fixed microwave and Wi-Fi	6 GHz	Dynamic coordination	High

- Sensing means a system measures radio environment to detect activity of other systems
- Coordination means central system with database assigns access to systems needing spectrum
- Static coordination means assignments do not change regularly and dynamic means they do
- Each of these sharing solutions took years to develop and deploy
- Each addresses a specific scenario for specific systems with specific parameters

Simple Sharing: AWS-3

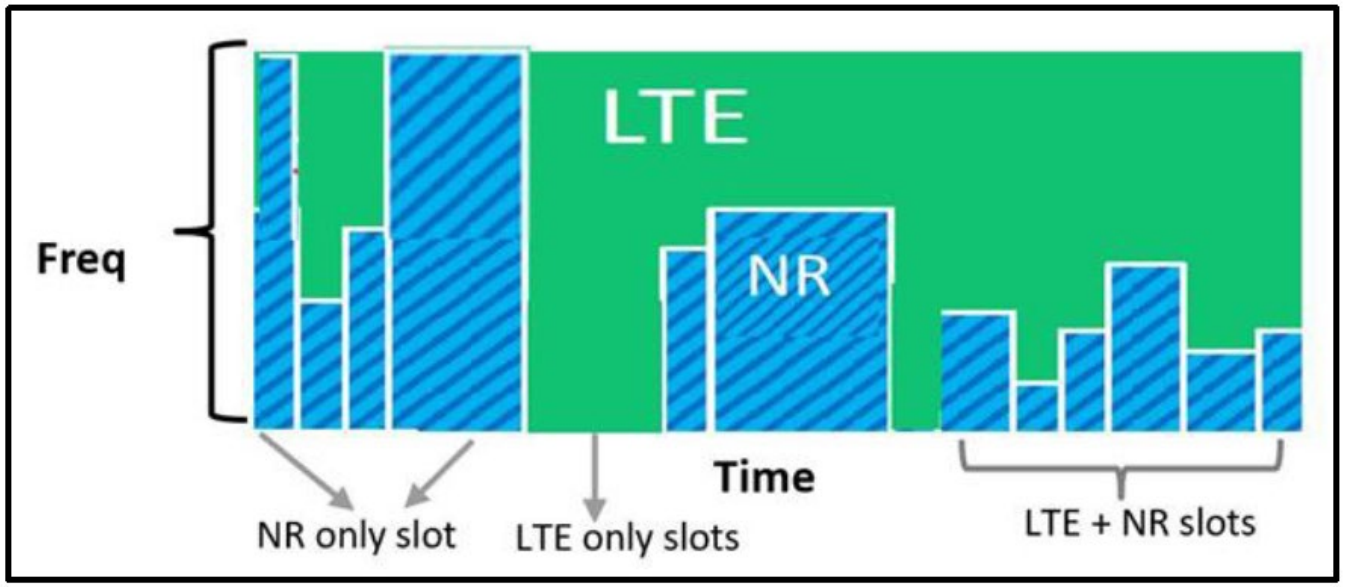
- 1.7/2.1 GHz Advanced Wireless Service 3 (AWS-3) band coordinated with federal use on permanent basis by geography
- Protection of federal satellite uplink stations
- Details: FCC Coordination Procedures in the 1695-1710 MHz and 1755-1780 MHz Bands, https://www.fcc.gov/wireless/bureau-divisions/broadband-division/advanced-wireless-services-aws



NTIA, *Spectrum Sharing: An Emerging Success*, Aug. 2019.
https://www.ntia.gov/blog/2020/spectrum-sharing-emerging-success

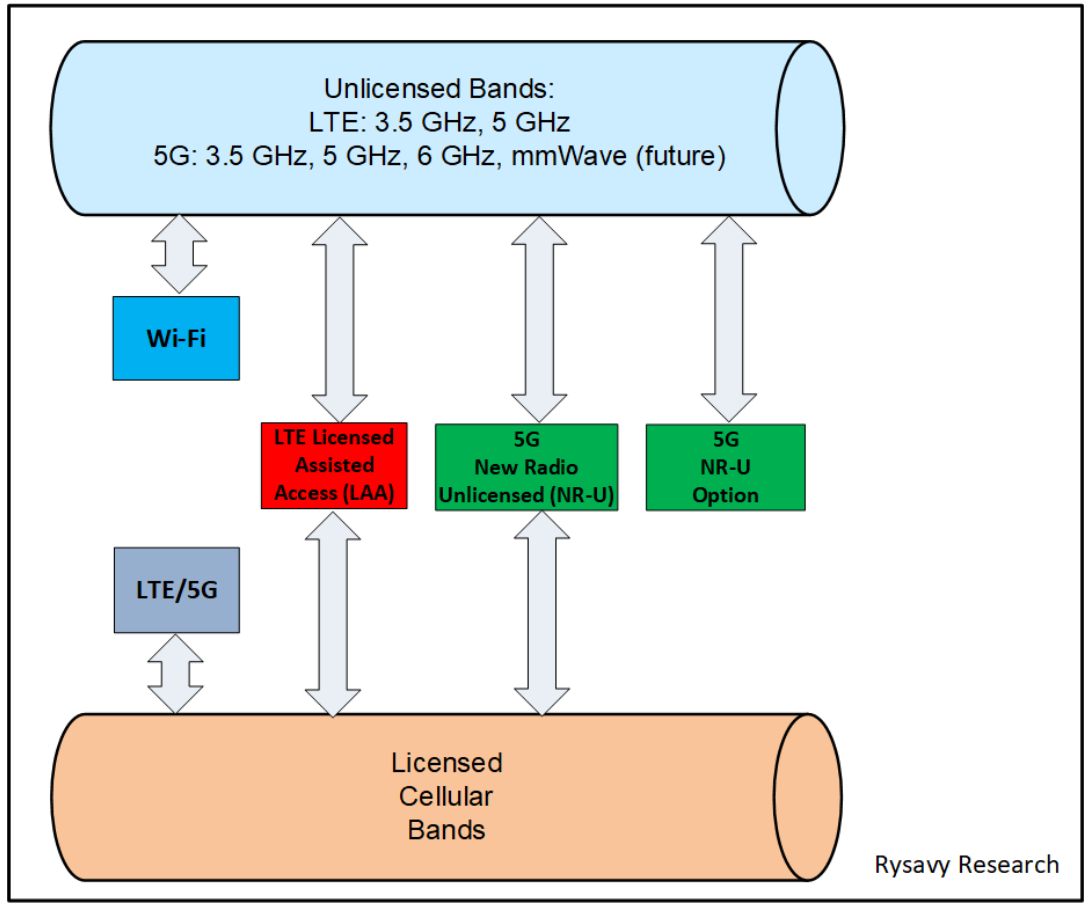
Complex Sharing: 5G Dynamic Spectrum Sharing

- LTE and 5G New Radio (NR) can share same radio channel
- Resources shared in time and frequency blocks
- Dynamically coordinated by base station scheduler
- Facilitates rollout of 5G by not needing clear spectrum
- Not extensible to sharing 5G with non-cellular systems



Rysavy Research, *Global 5G: Rise of a Transformational Technology*, Sep. 2020, p. 41, also pp. 177-180.
https://rysavyresearch.files.wordpress.com/2020/09/2020-09-global-5g-rise-of-a-transformational-technology.pdf

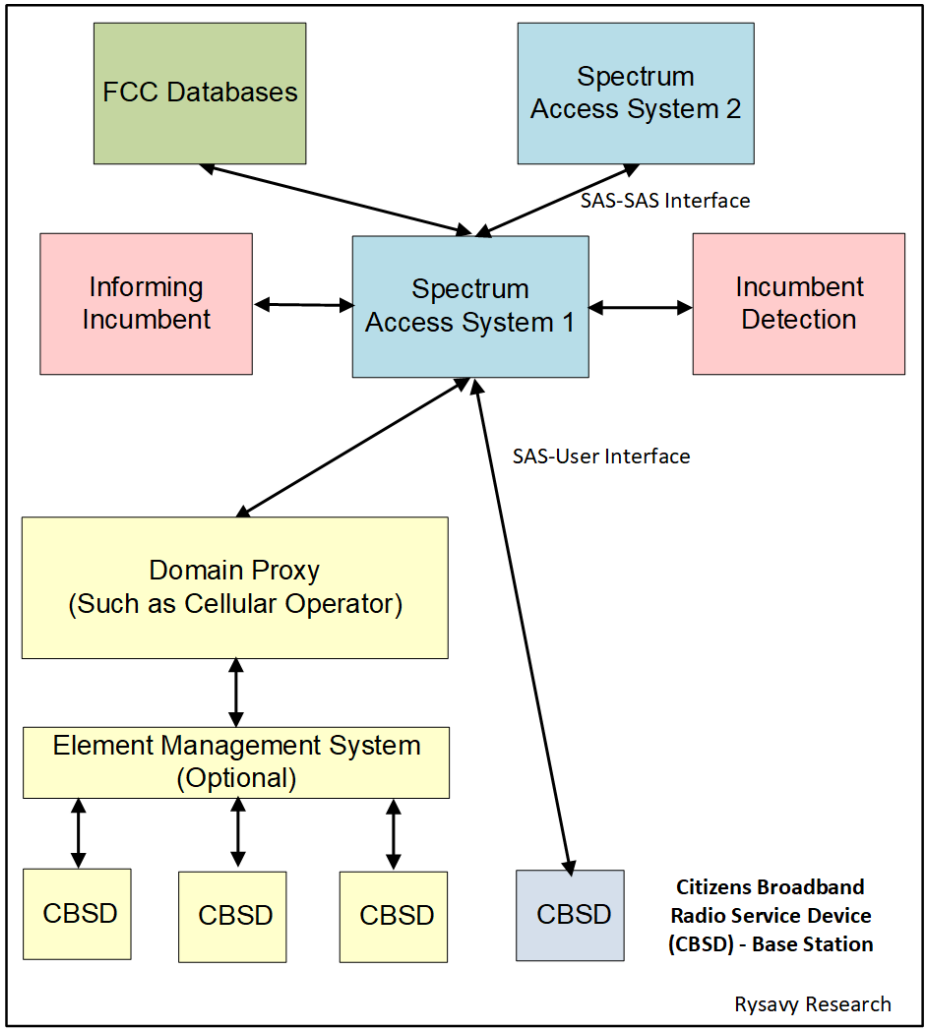
Sharing Between 4G/5G and Wi-Fi on Unlicensed Bands



- LTE Licensed Assisted Access (LAA) and 5G New Radio Unlicensed (NR-U) can share unlicensed spectrum with Wi-Fi
- LTE and 5G operate as good Wi-Fi neighbors taking only "fair" amount of capacity
- 5G/LTE senses Wi-Fi operation and Wi-Fi senses 5G/LTE

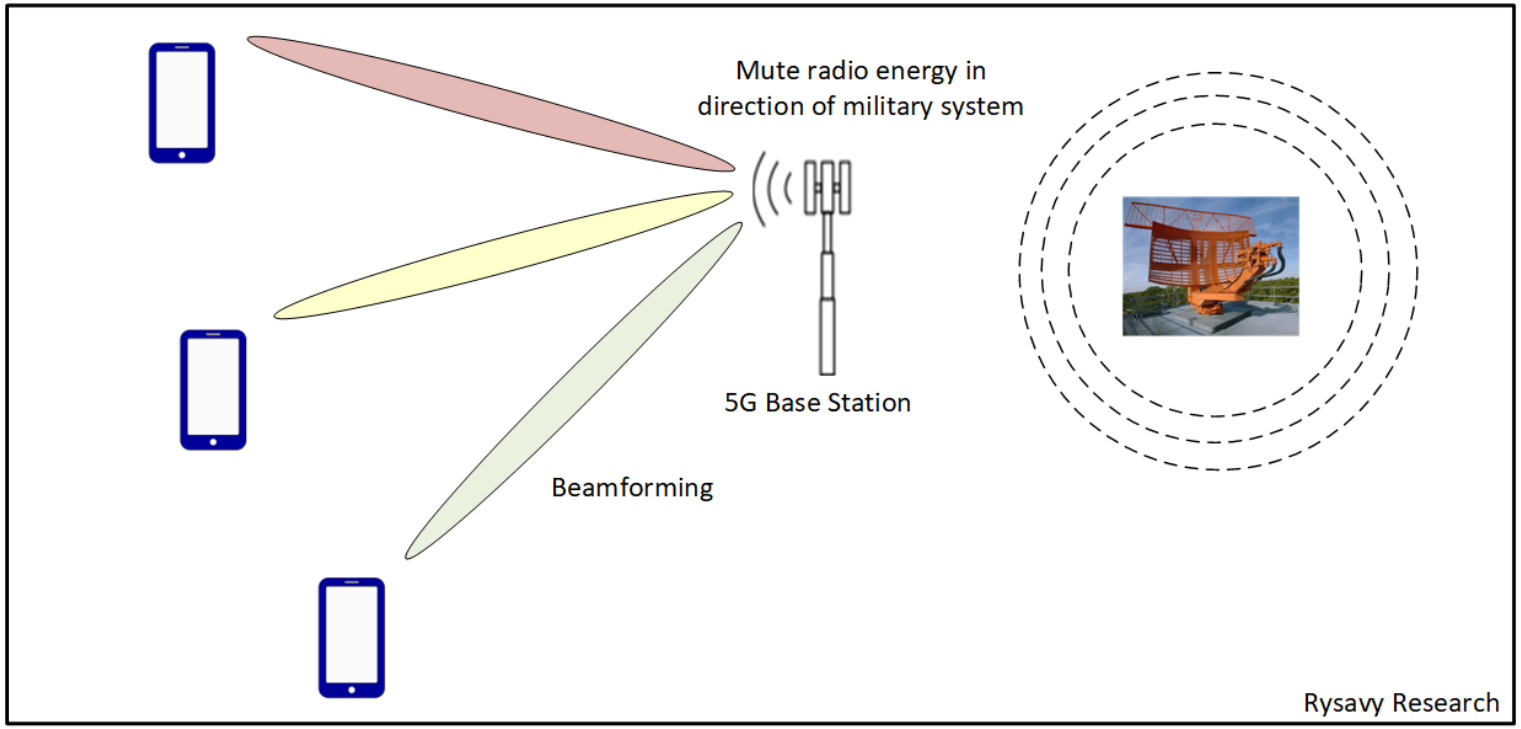
CBRS for Future Spectrum Sharing

- Citizens Broadband Radio Service
- Three tiers: Incumbents (mostly Navy radar), Priority Access Licenses (LTE and 5G), General Authorized Access (LTE and 5G)
- Spectrum Access System (SAS) dynamically coordinates access, subject to incumbent (government) use
- Environmental Sensing Capability (ESC) along coastlines senses Navy radar
- Not a good solution for wide-area cellular coverage due to small license areas and low power
- Future Incumbent Informing Capability (IIC) could "fix" ESC but an entirely new approach that will take years to develop, test, and deploy
- Other possible enhancements, such as more real-time capability, will also take years to develop, test, and deploy
- Based on older technology and does not leverage current RAN capabilities

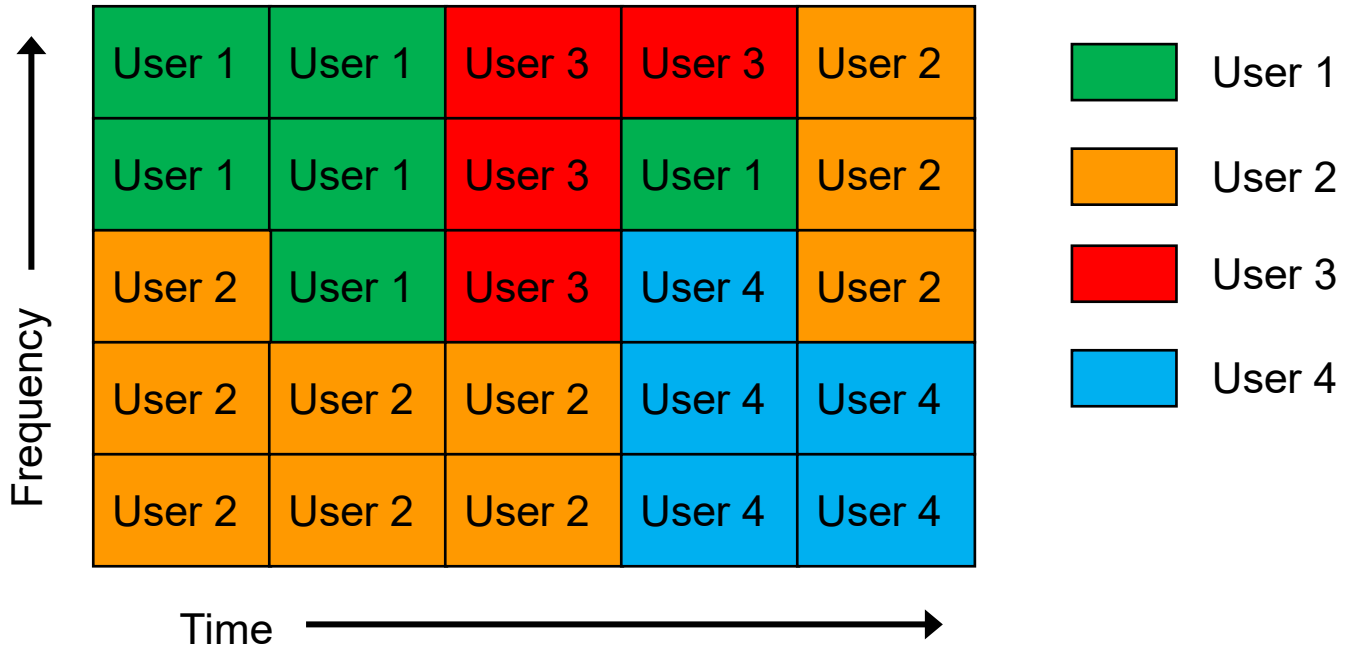


Pioneering Methods for Spectrum Sharing

- Leverage intelligent, active RAN
- Network operates at full power
- Possible database on incumbent operation
- Possible sensing receivers for incumbents
- AI for analysis
- Beam muting
- Null steering
- Physical resource block blanking



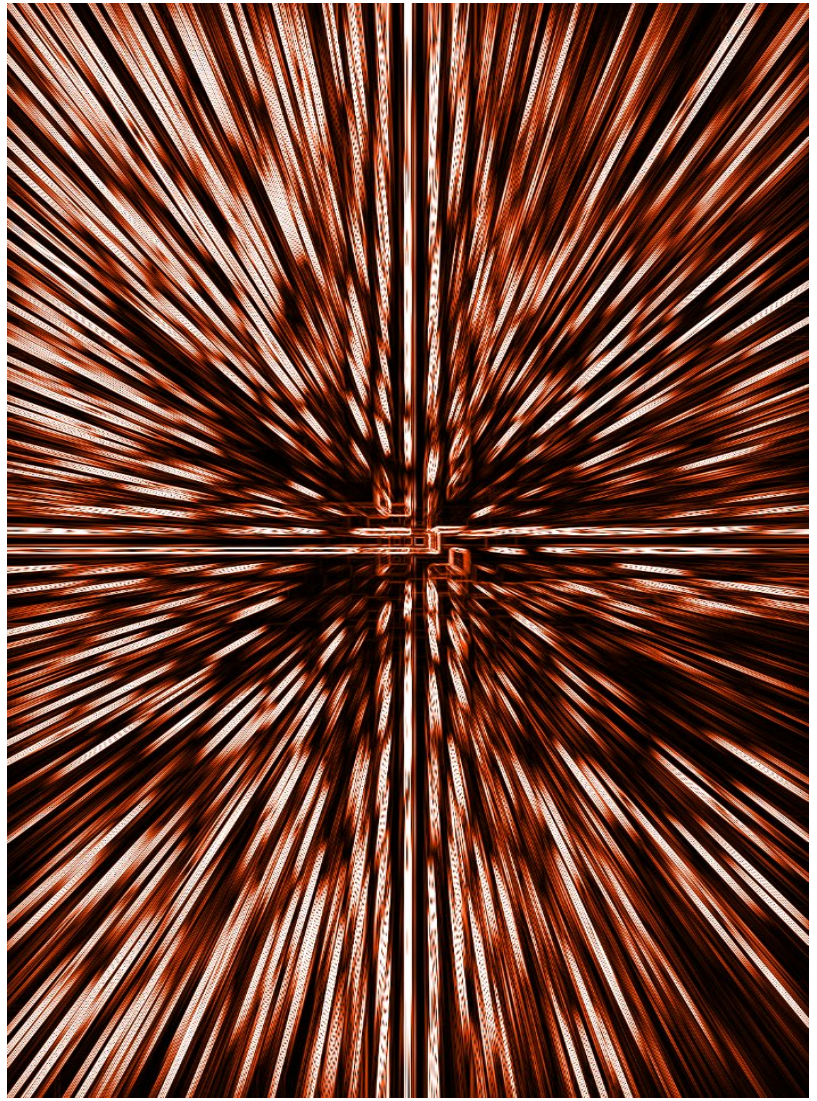
Physical Resource Block Blanking



- 4G and 5G system dynamically assign resources in small increments of time and frequency
- Can mute frequencies or time slots if in use by incumbent

Conclusion

- Spectrum roadmap critical for success of modern wireless systems
- Roadmap currently absent and National Spectrum Strategy years from completion
- Wi-Fi and cellular play an equally important role
- Wi-Fi in United States has outsize spectrum relative to rest of world
- Policy makers leaning heavily on spectrum sharing
- No generalized spectrum sharing solution exists
- Any spectrum sharing should leverage most powerful approaches



Rysavy Research on Spectrum

- *Annotated Spectrum Sharing PowerPoint Presentation*
  - *https://rysavyresearch.files.wordpress.com/2023/02/2023-02-rysavy-spectrum-sharing.pdf*
- *Lessons Learned from the CBRS Spectrum Experiment*
  - https://rysavyresearch.files.wordpress.com/2022/05/2022-04-cbrs-lessons-learned.pdf
- *No Magic Spectrum Sharing Solutions*
  - https://rysavyresearch.files.wordpress.com/2021/04/2021-04-no-magic-spectrum-sharing.pdf
- *5G Mid-Band Spectrum Deployment*
  - https://rysavyresearch.files.wordpress.com/2021/02/2021-02-5g-mid-band-spectrum-deployment.pdf
- *Global 5G: Rise of a Transformational Technology*
  - *https://rysavyresearch.files.wordpress.com/2020/09/2020-09-global-5g-rise-of-a-transformational-technology.pdf*
- *DoD's Proposed 5G Spectrum Sharing Fraught with Problems*
  - https://www.fiercewireless.com/wireless/industry-voices-rysavy-dod-s-proposed-5g-spectrum-sharing-fraught-problems
- *Bad Idea of Nationalized 5G Network Put to Rest*
  - https://www.fiercewireless.com/wireless/industry-voices-rysavy-bad-idea-a-nationalized-5g-network-put-to-rest