The bridge to possible

The 5G System as a Spectrum Management Solution

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BRKSPM-1006

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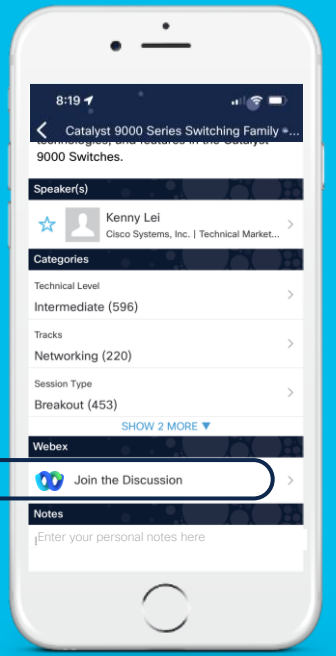


Agenda

- Introduction
- Operator Spectrum Strategies
- Enterprise 5G Spectrum Strategies
- The 5G NR Tools
- Summary

Introduction

5G Requirements are Placed in Buckets …

Enhanced Mobile Broadband (eMBB)

- 10–20 Gbps peak
- 100 Mbps whenever needed
- 10000x more traffic
- Macro and small cells
- Support for high mobility (500 km/h)
- Network energy saving by 100 times

Massive Machine-Type Communications (mMTC)

- High density of devices ($2x10^5$ – 10^6 per km^2)
- Long range
- Low data rate (1 – 100 kbps)
- M2M low cost
- 10 years battery
- Asynchronous access

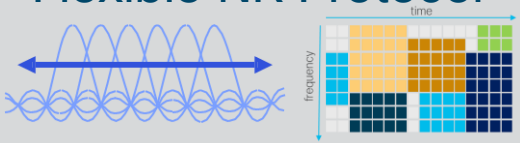
Ultra Reliable Low Latency Communications (URLLC)

- Ultra responsive with latencies (< 1 ms air & < 5 ms E2E)
- Ultra reliable and resilient (> 10^{-5} PLR)
- Low to medium data rates (50 kbps – 10 Mbps)
- High speed mobility

… These buckets do not mean any 5G system will support all these use cases: it depends!

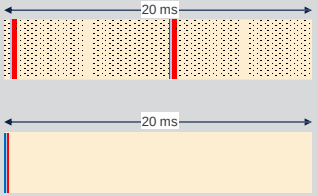
5G New Radio – Improvements

Flexible NR Protocol



- Mixed numerology: Flexible TTI,
- Bandwidth parts – mixed numerology within a carrier (RAN slicing)

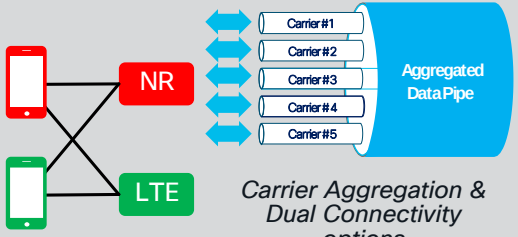
Lean Frame Design



Eliminating LTEs Cell-Specific RS gives capacity & efficient power

Better Frame Structure: about 20% improvement in spectral efficiency

Higher Data rates with Multi-connectivity

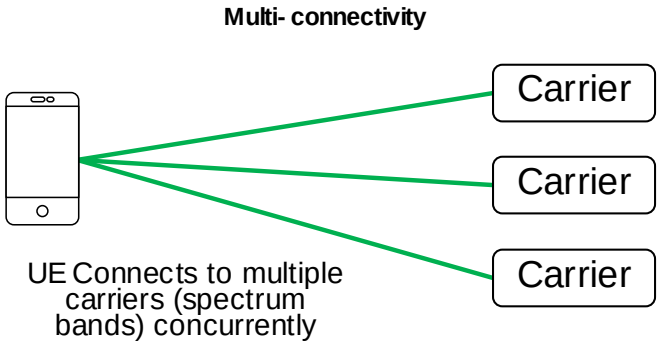


Carrier Aggregation & Dual Connectivity options

Massive MIMO & Beamforming

Better Spectrum Management: Improvements in capacity and reach across multiple bands reduce need for densification

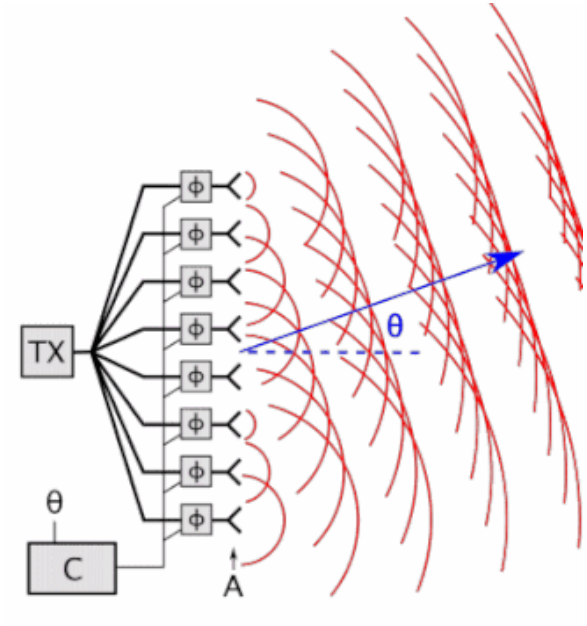
Multi-Connectivity is Essential for 5G



Carrier Aggregation (CA) and Dual Connectivity enable deployments with tightly and loosely coordinated cells

1. EN-DC is dual connectivity across LTE and NR supported by an EPC (Non-Stand-Alone architecture). Leverages LTE investments in first stage of NR deployment
2. Carrier aggregation between C-band and low band or even between mmWave and Sub-6 to provide stability higher throughput, and better coverage
3. Carrier aggregation between licensed and unlicensed spectrum such as a in License Assisted Access when NR-U is deployed
4. Carrier aggregation to use supplementary uplink spectrum (SUL) for better coverage and supplementary downlink for more capacity

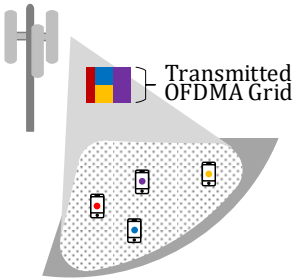
Phased Array Operation



From Wikipedia https://bit.ly/3piHoOT

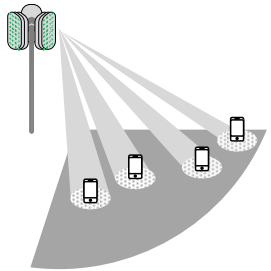
- A phased array steers energy into a desired direction
  - Adjusting phase shifts $\{\phi_i\}$ on copies of a signal replicated into different antennas
  - A digital controller enters values into analog phase shifters
  - Different values of $\{\phi_i\}$ result in different directions
  - TDD is commonly used (means array is used for transmit & receive)

Massive MIMO – Capacity



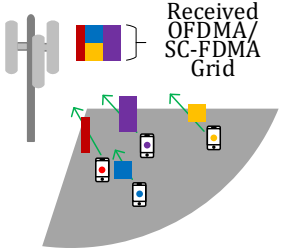
Conventional Downlink

Without MIMO a single beam covers a sector with a DL signal shared by all users. Scheduling of users occurs within the beam using time-frequency resources (OFDMA)



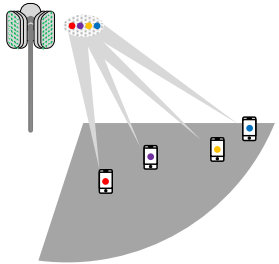
M-MIMO Downlink

Massive MIMO beamforming adds directivity logic in the antenna array based on acquired channel state to focus power beams on each UE to the maximum # of DL beam, called a layer.



Conventional Uplink

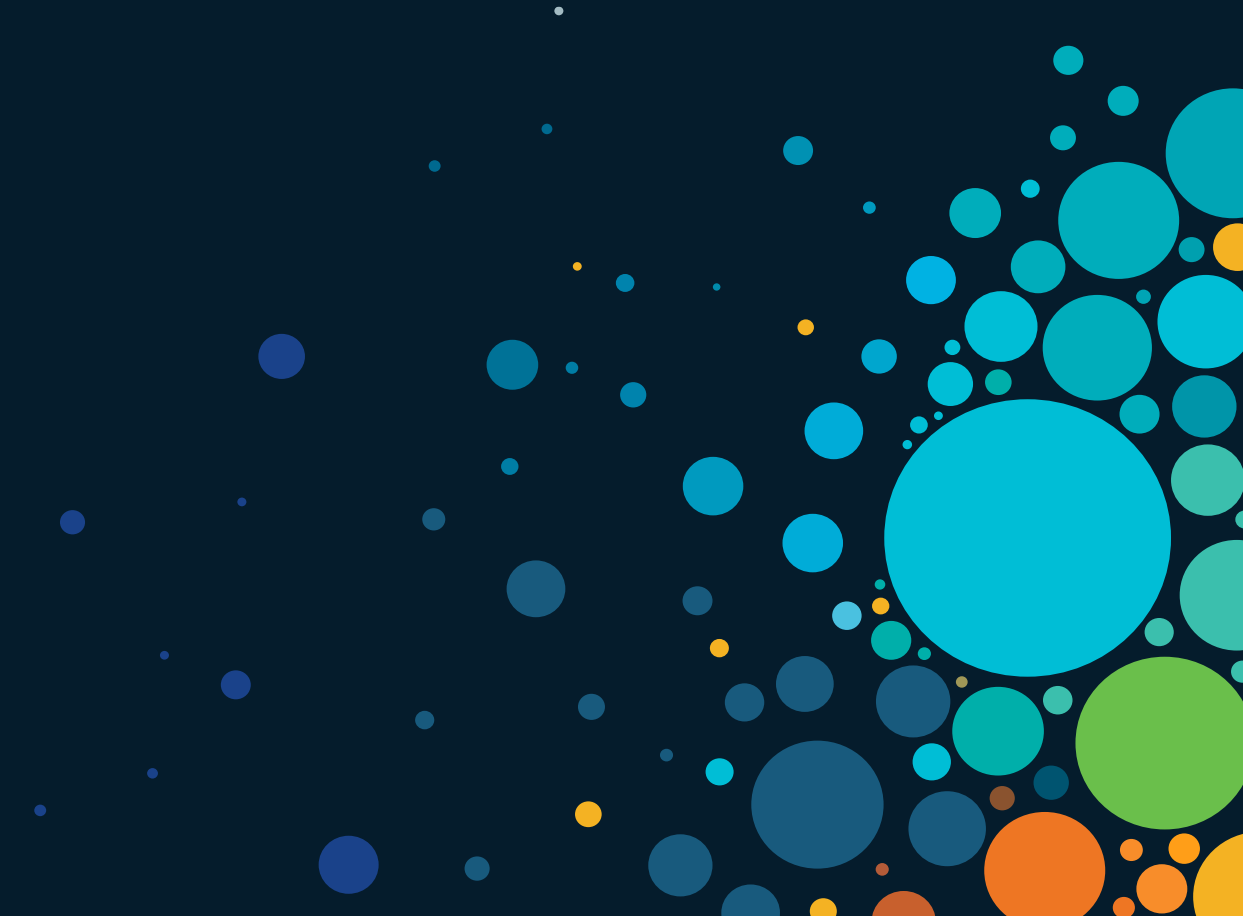
The BS tells the UE which non-overlapping resources in the time-frequency grid can be used for upstream traffic. This is where the BS will listen for traffic from a specific UE.



M-MIMO Uplink

Massive MIMO uplink uses the acquired channel state matrix to resolve power received into power components attributable to each UE through a signature derived from the propagation channel

Operator Spectrum Strategies



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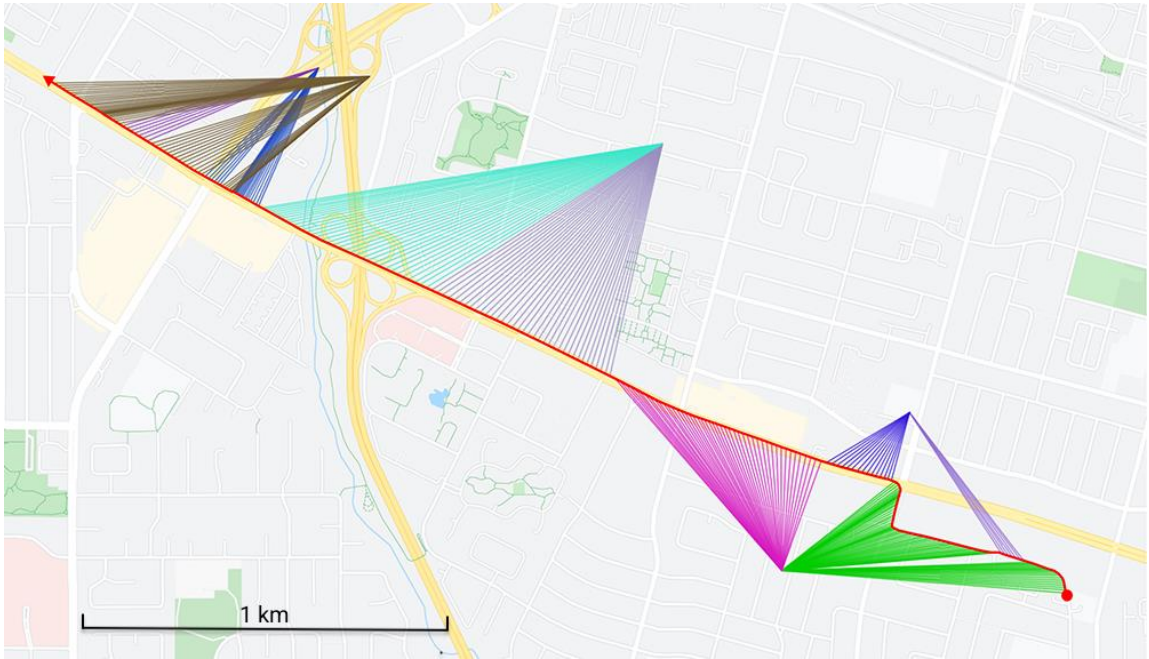
Myth: “Cell Coverage Areas are Tidy Packed Hexagons”

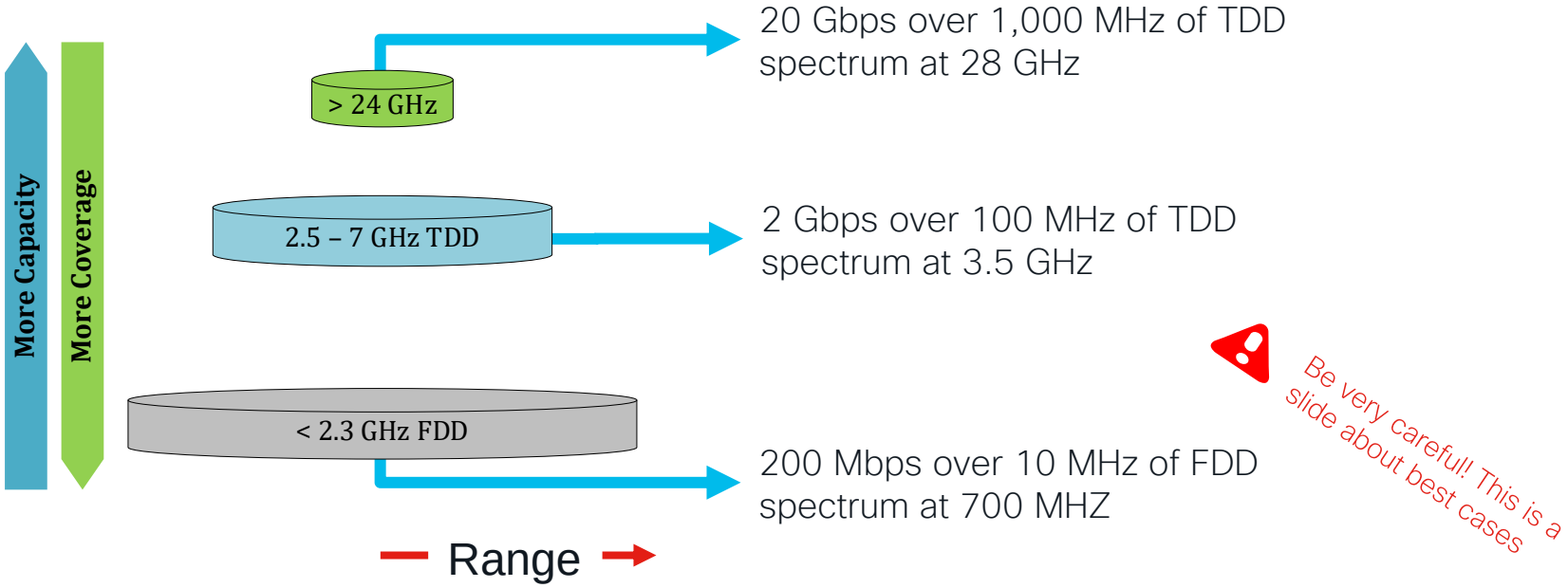
Map shows cells serving a moving user across a 3.7 km drive (5 towers & 9 cells).

Sunnyvale to downtown Mountain View in 7 min.

Source: https://fabiensanglard.net/lte/index.html

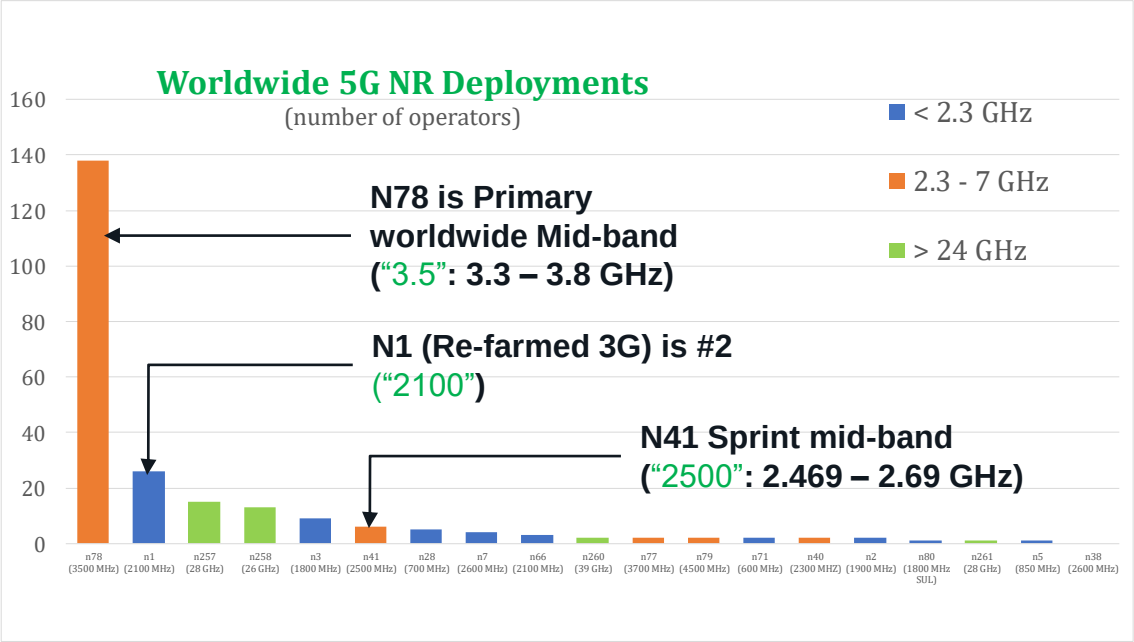


Different spectrum bands have different characteristics and therefore are not “fungible” …



5G outcomes will depend on spectrum

N78 (in Mid-band) is by Far, the Most Widely Deployed 5G NR Band

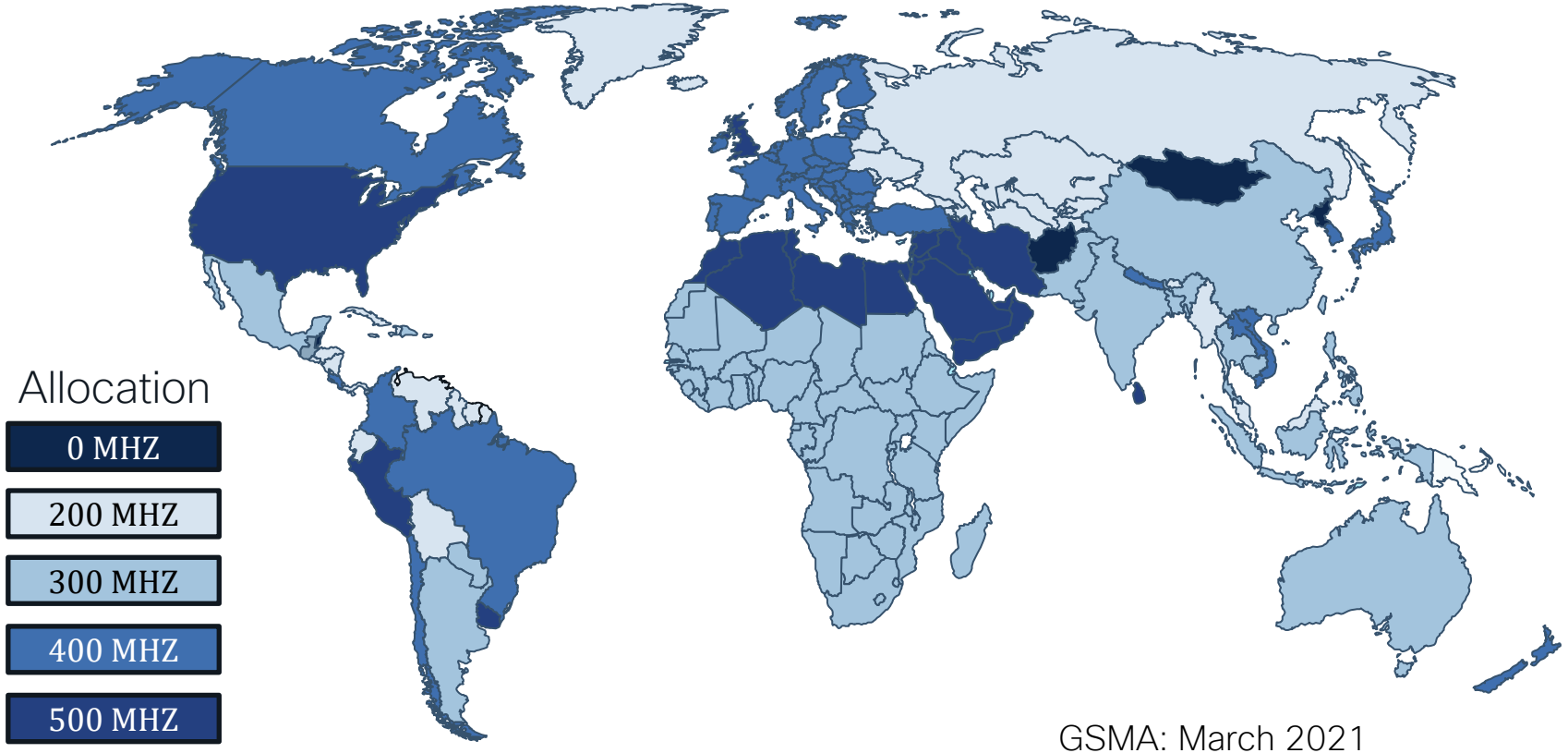


We can anticipate mid-band TDD spectrum to have the most developed ecosystem in 5G for the next few years (2.3 – 6 GHz)

Provides a good balance between capacity and coverage

Source is crowd-sourced data in https://en.wikipedia.org/wiki/List_of_5G_NR_networks (3/25/21)
The list includes market trials

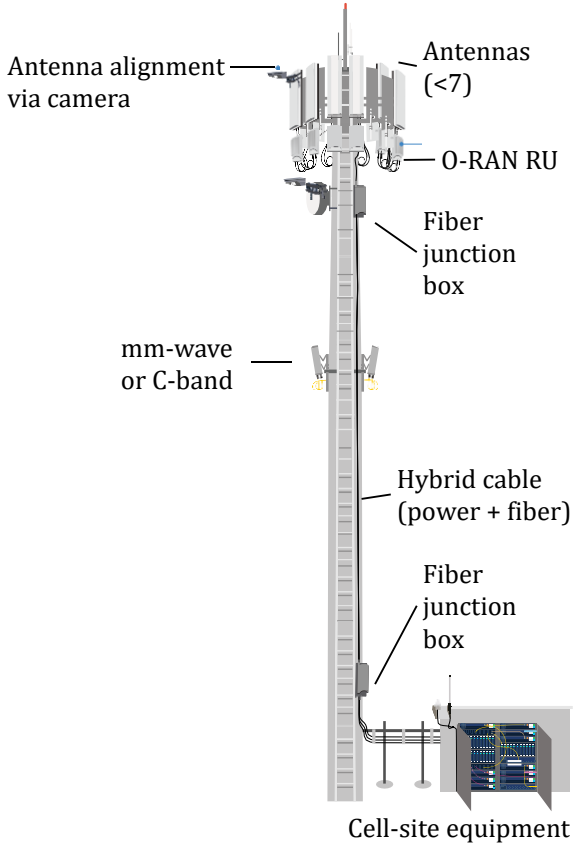
3-4 GHz Spectrum Allocation Worldwide



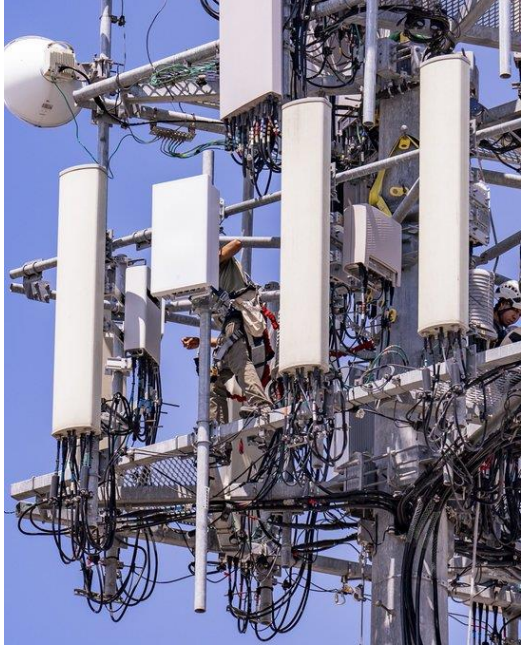
GSMA: March 2021

Review: Anatomy of a Mast

- Radio Units (RU)
  - One per cell-sector
  - Convert between digital baseband and analog RF
- Low band often at top of mast whereas C-band is added lower (historical reasons)
- Cabling
  - Fiber interfaces into RUs are much preferred (lighter and lossless)
  - New cabling is hybrid and includes fiber optics, and power “all-in one” (hybriflex cable)
  - Legacy coax cables may also be present for older 2G & 3G with ground mounted radios
- Antennas use Remote Electrical Tilt (RET) to optimize their coverage footprints
- Equipment
  - In US and many parts of the world, equipment is in an environmentally controlled shed
  - If no shed is available, hardened equipment is needed
  - Power: can be very high (> 6 kW with mid-band massive MIMO accounting for up to 3 kW)

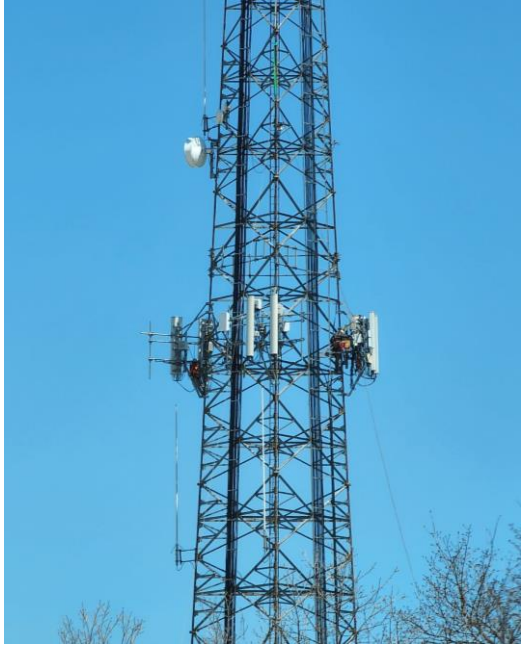


Picture source is Viavi: https://telecoms.com/wp-content/blogs.dir/1/files/2020/05/5G-Cell-site-installation-poster.pdf



AT&T cell-site in S. Florida upgraded to C-band

Drillisch 1&1



Verizon cell-site being upgraded

Midband and 5G Macro Evolution

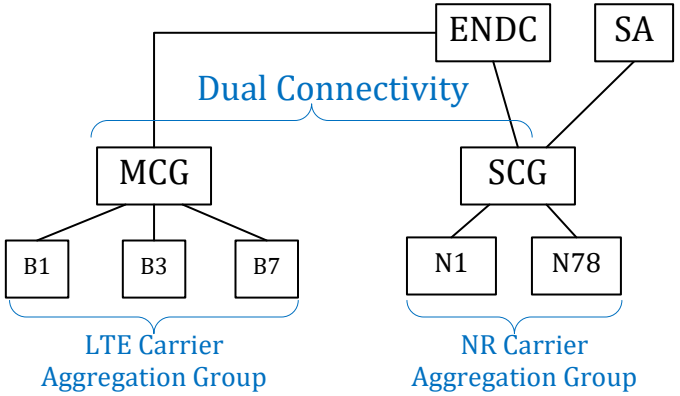
Sources:

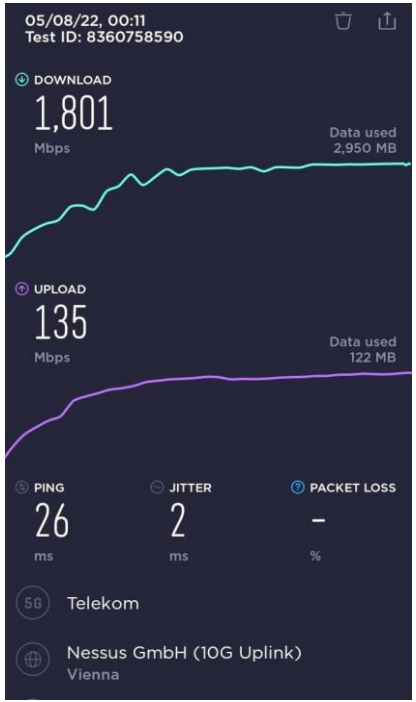
https://twitter.com/acethelikes/status/1516760776966492160
https://twitter.com/Gabeuk/status/1533808727538723057
https://twitter.com/EMTech_/status/1521904041537724417

Multi-connectivity Example: C-Band with Carrier Aggregation and Dual Connectivity (Deutsche Telekom)

Bands:

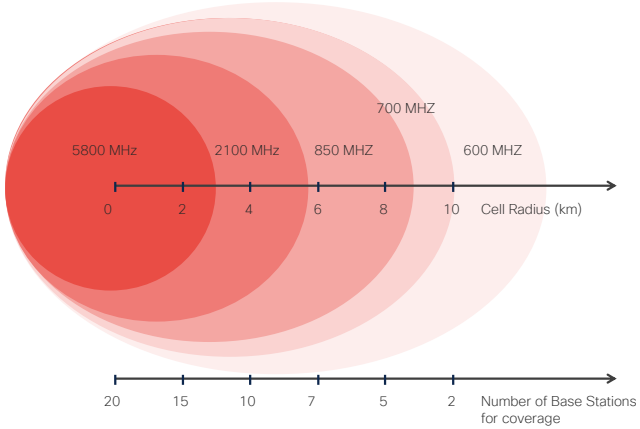
- B1 (2100 MHz, 2x2, 20MHz)
- B3 (1800 MHz, 4x4, 30MHz)
- B7 (2600 MHz, 2x2, 20MHz)
- N1 (2100 MHz, 2x2, 20MHz)
- N78 (3.5 GHz, 64x64, 90Mhz)



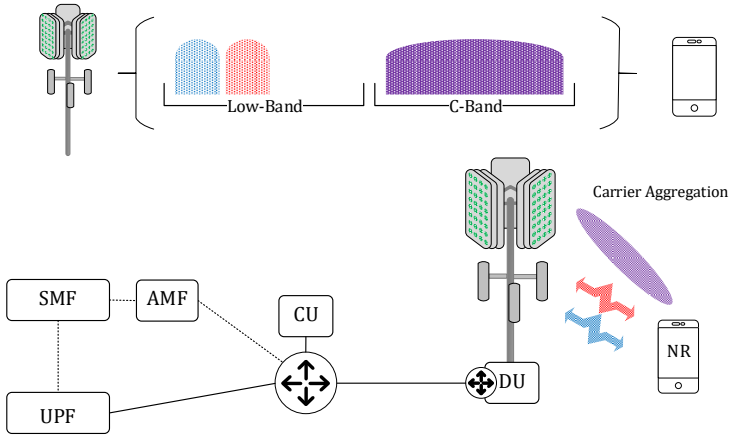


Source: https://twitter.com/RxyzrCSGO/status/1523083780252368897

5G NR Provides Tools for Expanding Coverage



Old reality: path loss on power-limited UL increases with frequency requiring more base stations at higher bands for equivalent coverage at lower bands



5G reality: Combine a low band and a mid-band using m-MIMO into a carrier aggregate and use the low band to schedule downlink/uplink service on same grid as low band

The 5G Spectrum management system enables higher range operation at mid-band with little or no investment in densification

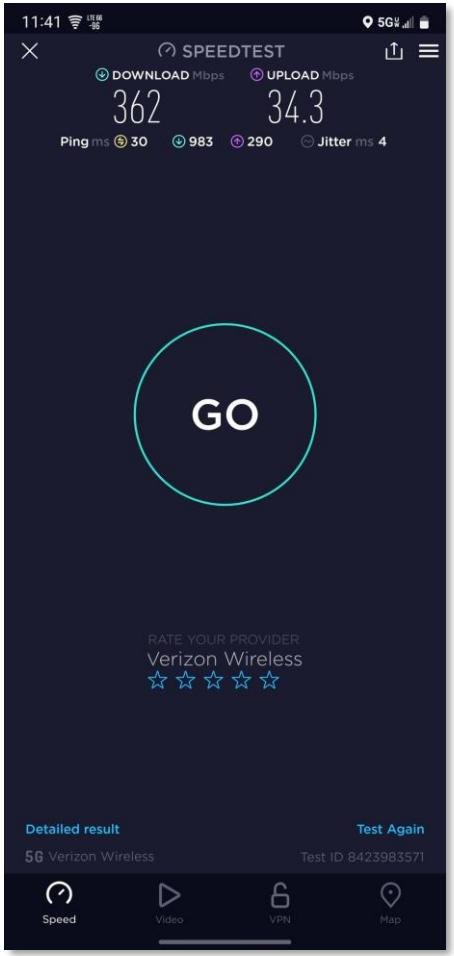
Range Extension

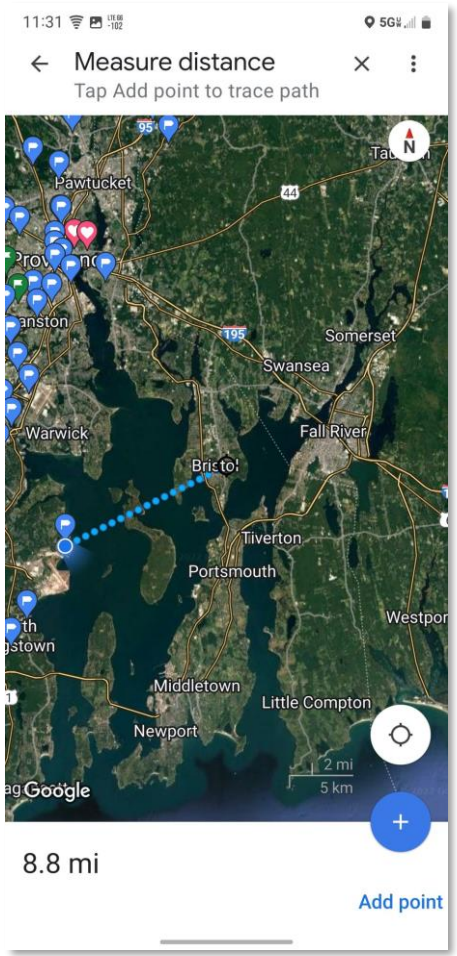
Almost 9 miles of range on VZW C-band with cross-carrier scheduling (IDEAL CONDITIONS)

Note:

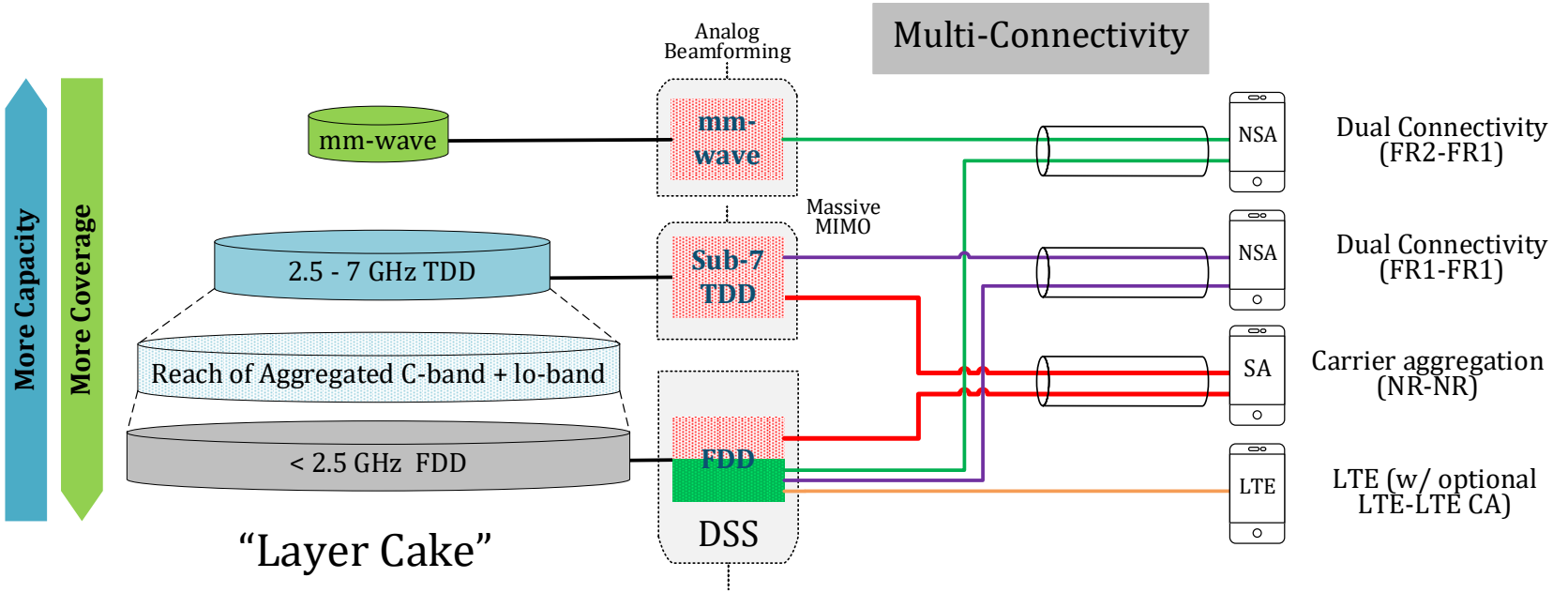
- Always outdoors
- In this case, very favorable LOS propagation

https://twitter.com/jakepimental99/status/1532392110925791233





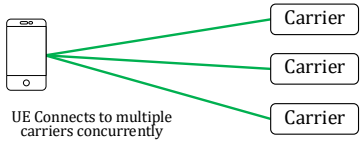
… 5G is a Powerful Spectrum Management Solution that brings the spectrum together



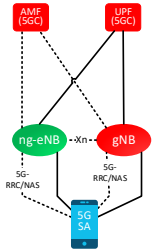
The "layer cake" approach to multi-connectivity has the virtue of extending C-band range to the point cell-site grid densification is not necessary

5G Macro Evolution: the Basic Toolchain

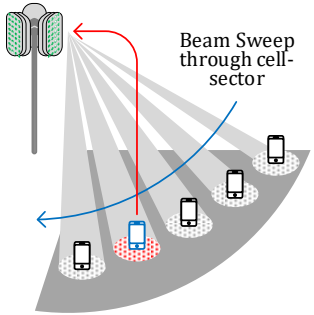
1 Multi-Connectivity



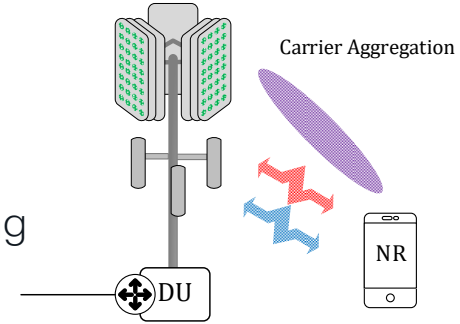
3 SA Architecture



2 Beam-based air interface & m-MIMO



4 Cross-Carrier Scheduling

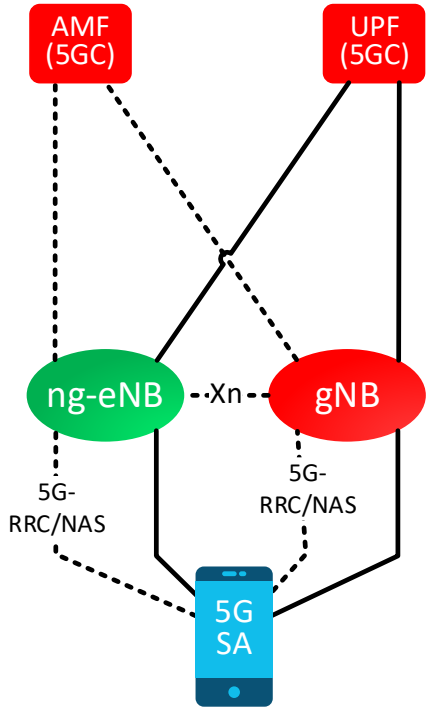


5G has a Powerful Toolchain for High Performance Mid-Band

The SA Architecture and why it Matters for Mid-Band TDD

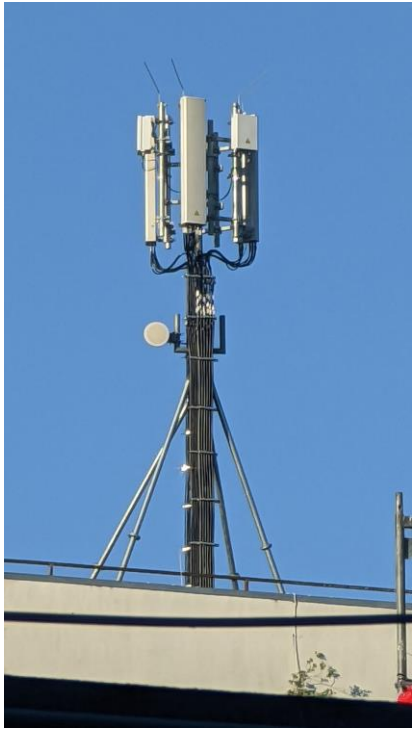
- Yes, NSA is very powerful and capable of many features particularly if you enhance LTE signaling
- SA unlocks the value of the 5G system architecture
  - Unlike NSA, device signaling is based on NR protocols which support the full NR feature set
  - UL 256-QAM and UL 2×2 MIMO are unlocked in SA
  - The greenfield 5G band (e.g., C-band) can be completely unlocked for 5G operation
  - NR Carrier Aggregation can be used extensively and so can cross-carrier scheduling
- Note both NR & SA are supported in most recent device modem chipsets

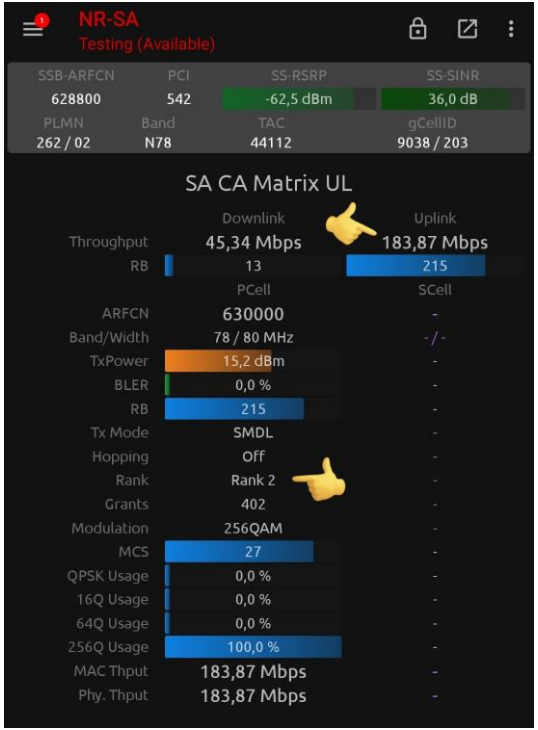
Operators deploying C-band should also upgrade to SA



UL 2×2 MIMO and 256 QAM and Carrier Aggregation

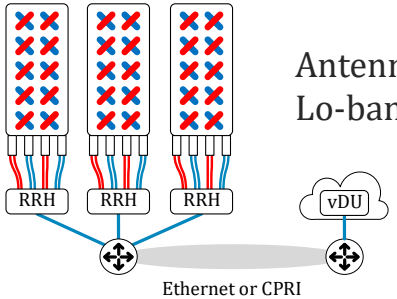
- UL 2×2 MIMO Modes
  - Spatial diversity
  - Spatial multiplexing
- Transmitted power
  - Power transmitted by UE in Power Class 2: 26 dBm (400 mW) allowed in High Performance (“HPUE”) in:
    - TD 2300 (N40: 2.3 – 2.4 GHz), TD 2500 (N41: 2.496 – 2.690 GHz)
    - C-Band (N77: 3.3 – 4.2 GHz, N78: 3.3 – 3.8 GHz, N79: 4.4 – 5 GHz,)
  - Usage: One antenna at 26 dBm or two antennas at 23 dBm each (UL 2×2 MIMO)





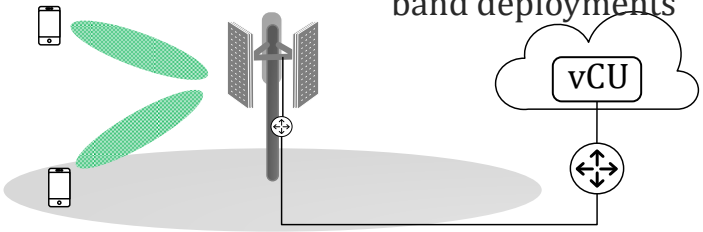
Source: https://twitter.com/High3eam/status/1582608765232160768

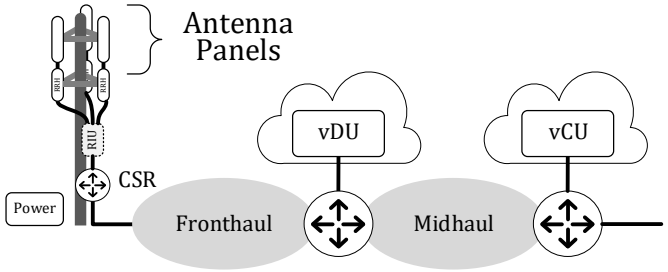
Open vRAN Architectural Elements (Macro)



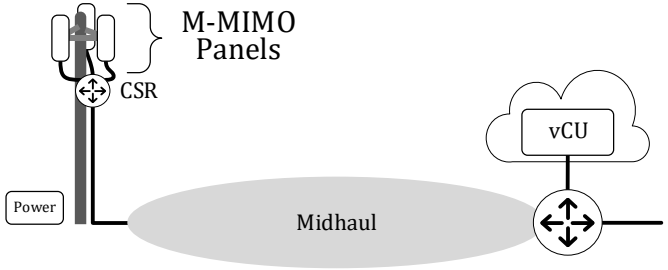
Antenna Configuration for Lo-band deployments

Massive MIMO configuration for mid-band deployments

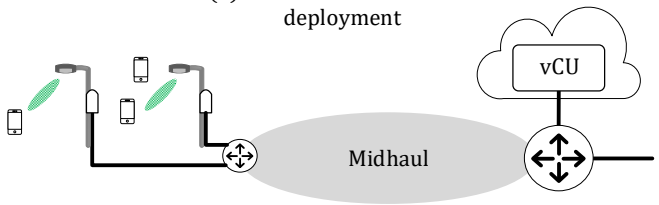




(a) Low band FDD deployment



(b) Intermediate band TDD deployment



(c) mm-wave band TDD deployment for beamforming

Enterprise 5G Spectrum Strategies

Enterprise 5G



“A 5G-based system supporting the special requirements for coverage, service, and overall performance for wireless access of an enterprise”

Two main delivery mechanisms

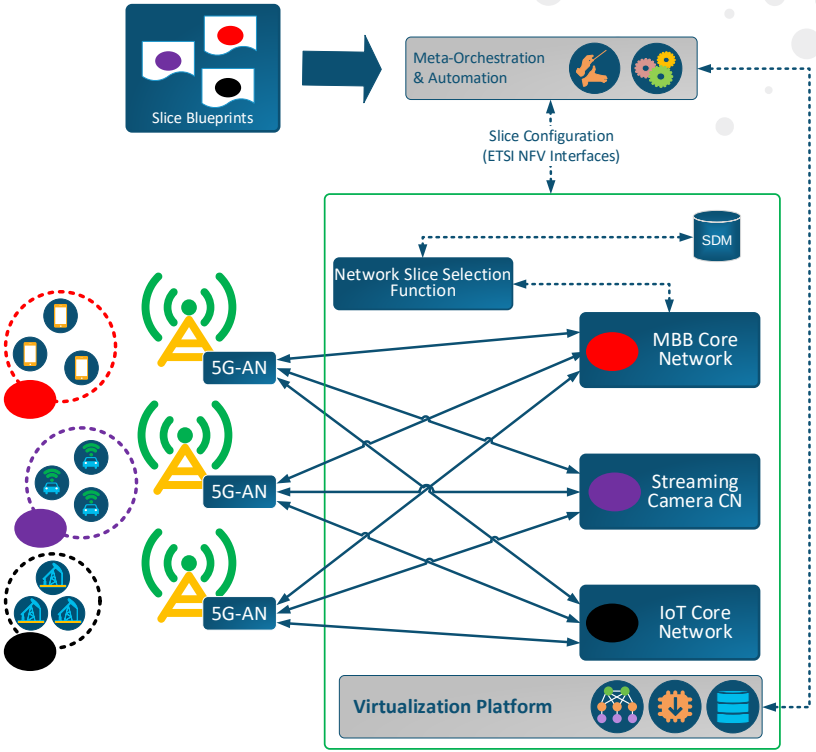
- Private 5G – delivered independent of public networks (NPN)
- Network Slicing – delivered from public network (example of PNI-NPN)

Begin with Network Slicing

Definition:

- Network Slicing is an end-to-end partitioning of the network resources and network functions so that selected applications/services/connections may run in isolation from each other for a specific business purpose
- Proposed as a component of the “enterprise 5G” tool-chain to tackle the 5G vision of supporting diversity of use cases (eMBB, URLLC, mMTC)

- Allows consumption of wide-area network resources to support enterprise verticals
- The critical element of the definition: Isolation interpreted as “no shared-fate” across slice instances
- Network slicing has emerged as a major talking point for operators and their plans for E5G



Localized E5G Examples

Robotic Control

Advanced Inventory Management

Power plant operation

Just-in-time logistics

AR for jet engine maintenance

Industrial IoT
Factories require wirelessly connected robots for easy reconfiguration

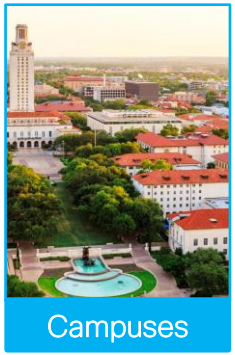
Warehouse Control
Mobile inventory management & tracking within the warehouse

Manufacturing and Maintenance
Control loops for monitoring resources and other mission critical functions

NR-U

- NR-U is a flavor of NR designed to work in unlicensed spectrum
  - Indoors: respects the Listen-Before-Talk discipline and uses mini-slots (begin transmission immediately)
  - Supports mini-slots for fast transmission on detection of an open window
- Two main deployment cases
  - Anchored operation where it supplements a licensed carrier
  - Stand-alone operation where it is used by itself, and
- NR-U should start showing up in UE chips in 2023


Hotspots


Campuses


Malls

Anchored NR-U


Ports


Mines


Warehouses

Standalone NR-U

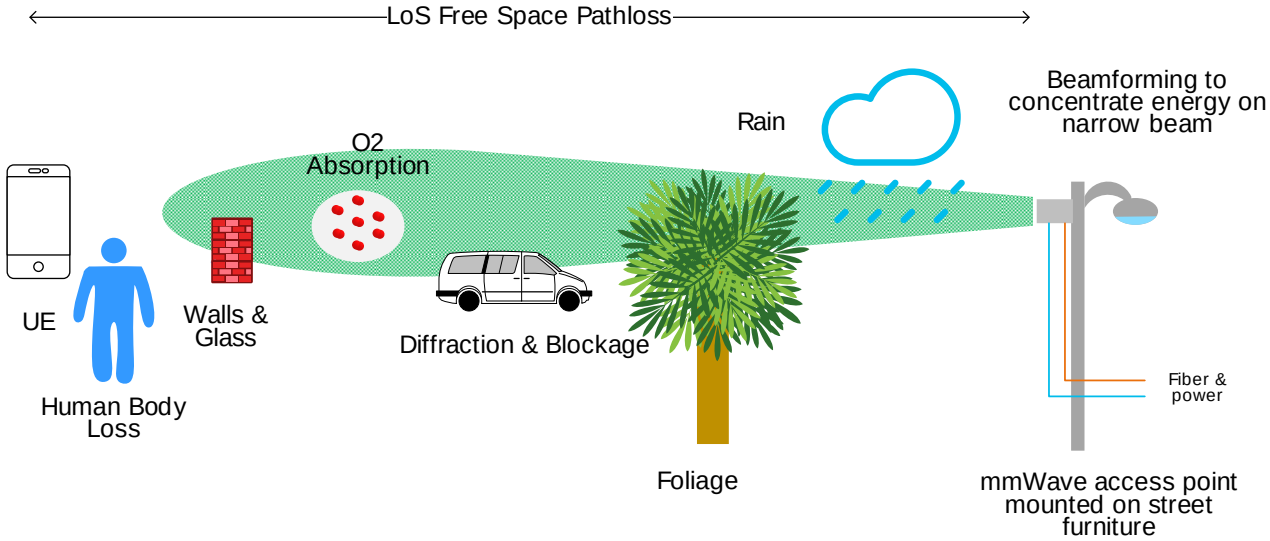
(*) Slide adapted from Qualcomm

Potential Enterprise 5G Spectrum (partial list)

Sub-7 (lightly licensed or locally licensed)		
Country	Spectrum	Band
US (CBRS)	3.55 – 3.7 GHz	N48
Germany	3.7 – 3.8 GHz	N78/N77
France	2.57 – 2.62 GHz	N38
UK	3.8 – 4.2 GHz	N77
Japan, China	4.4 – 5.0 GHz	N79
Spain	2.3 – 2.4 GHz	N30
Norway	3.8 – 4.2 GHz	N77

Unlicensed (n96)		
Country	Spectrum	Band
US	5.9 – 7.1 GHz	N96
EU	5.9 – 6.4 GHz	N96
S. Korea	5.9 – 7.1 GHz	N96

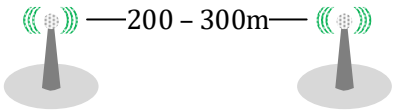
Path Loss at mmWave



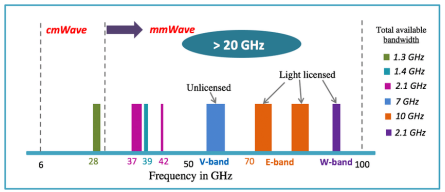
At current emission levels (EIRP) allowed by most regulators and current receiver sensitivities, mmWave appears to be a good fit for delivering high throughput at short distances (< 0.5 km) in a contained environment

Factors to Consider in mmWave

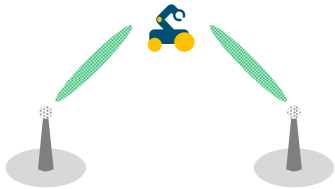
Inter-Site Distance (ISD)



Lots of Spectrum

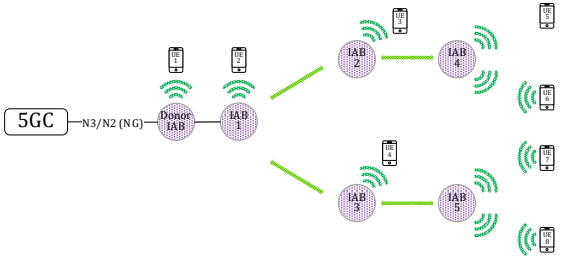


Multiple Transmission Points

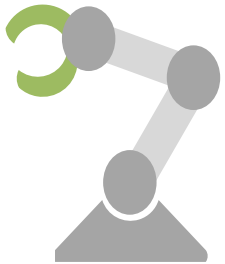


Line-of-Sight (LOS)

Relays & IABs



Low Latency



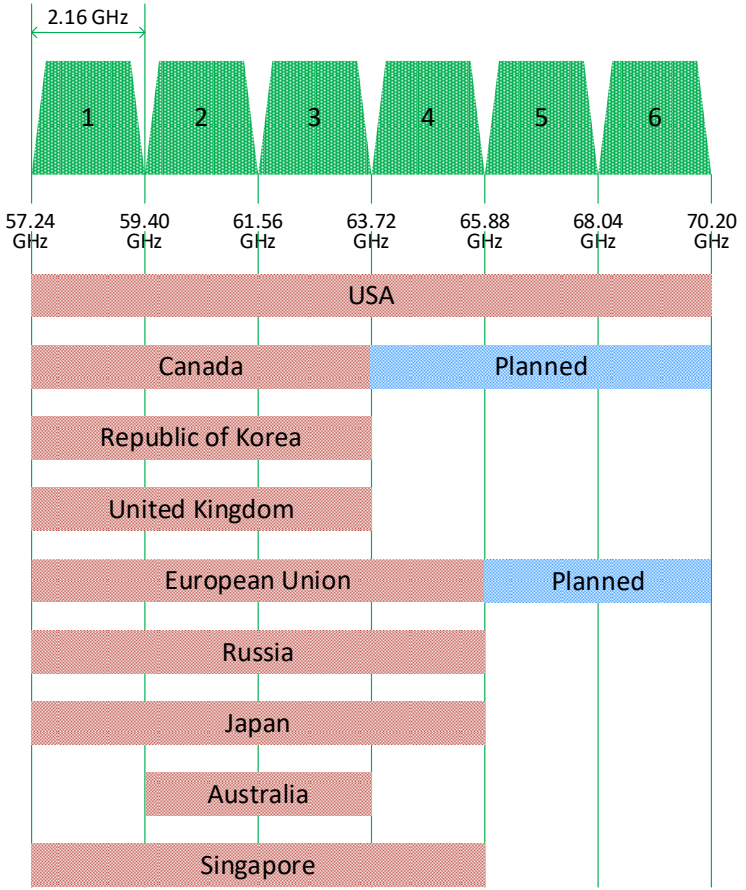
60 GHz by Region

Canada and the EU are expected to expand to six channels for licenses-exempt use soon.

In some countries, most notably India, there is no license exempt spectrum in V-band

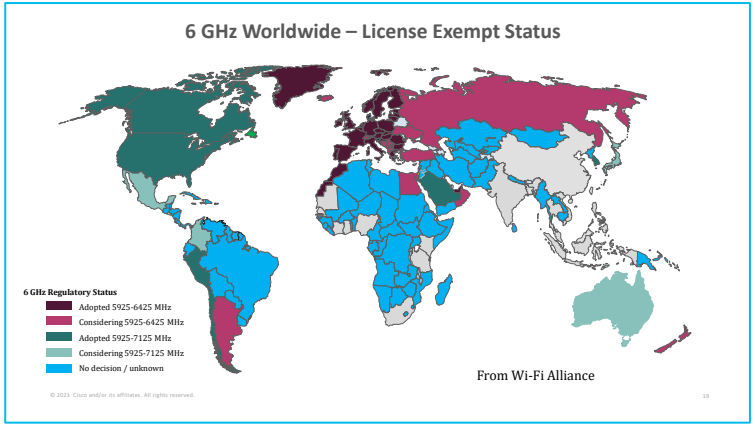
3GPP has standardized N263 for V-band with the following CA options

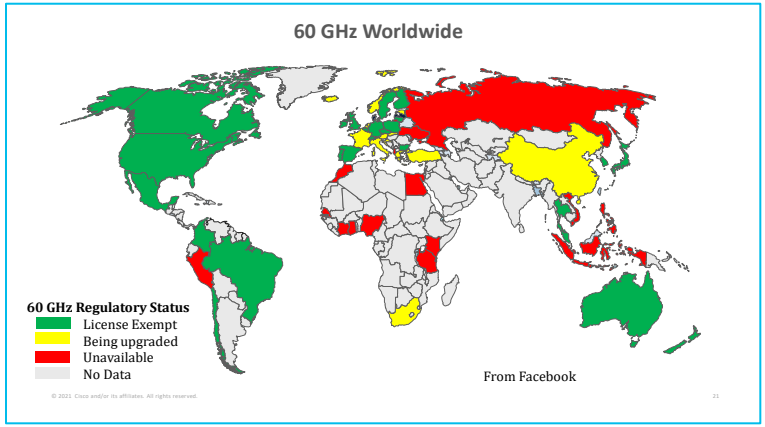
NR CA Band	NR Band
CA_n41-n263	n41, n263
CA_n77-n263	n77, n263
CA_n79-n263	n79, n263



Spectrum Availability is Subject to National Regulator

Cisco has been part of a broad alliance of industry interest groups who promote opening 6 GHz to unlicensed operation

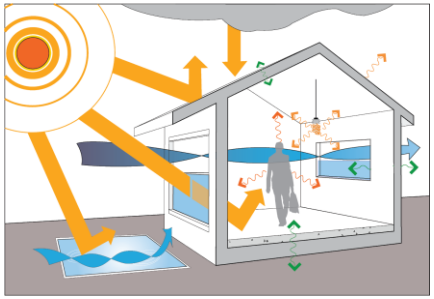


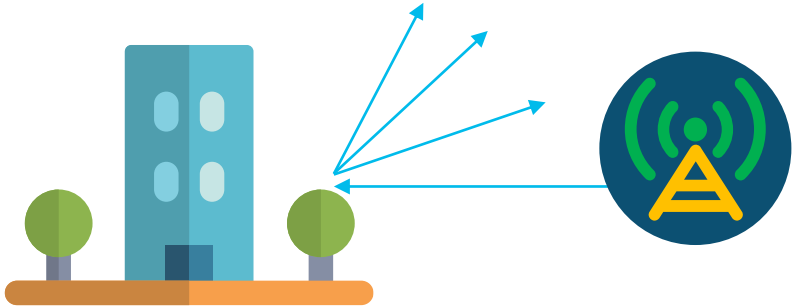


In places where 60 GHz is license-exempt, there is 3x more spectrum at 60 GHz than the aggregate of all licensed spectrum

The Layer Cake, Green Buildings, and Indoor Coverage

Good carbon neutral design practices consider incident/radiated sunlight into a building [1]





Outdoor-indoor 5G coverage will need to reconcile with green design

Walls attenuate RF at between 5 – 50 dB [2]

Green buildings don't know how to distinguish RF from sunlight

- Are designed with windows that reflect RF
- Insulate the inside from the outside using metallic foil

Consequently, outdoor 5G coverage does not easily extend indoors

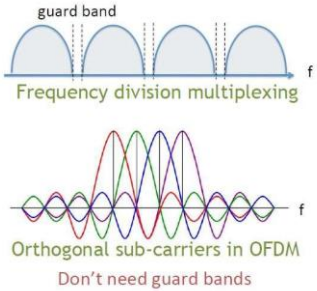
- Answer: Indoor small cell densification via 5G (small cells or DAS) or Wi-Fi 6

References:
[1] La Roche, P. (2017). Carbon-neutral architectural design. Boca Raton, CRC Press, Taylor & Francis Group
[2] https://doi.org/10.6028/NIST.IR.6055

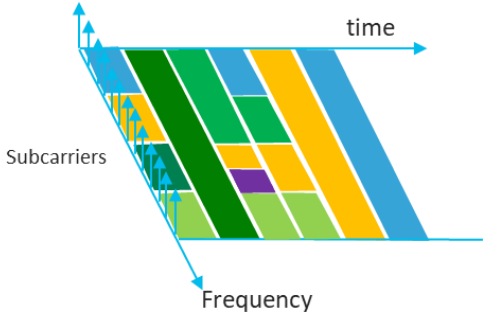
The 5G NR Toolchain

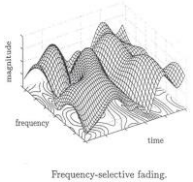
OFDMA Addresses Radio Propagation Issues

OFDM compared to FDM



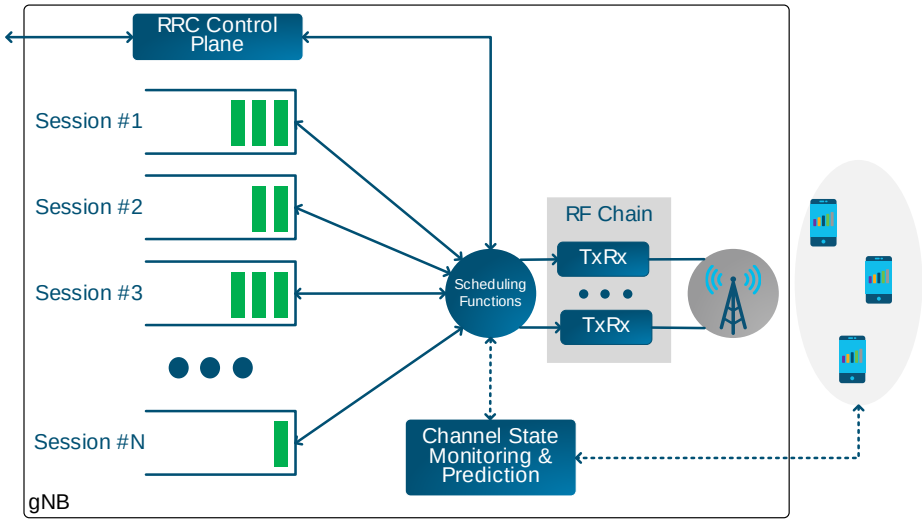
OFDMA allocates users in time-frequency grid



Problem	Description	Solution
Small Scale Frequency Selective Fading	 Frequency-selective fading. Multi-path and Doppler result in a radio channel where attenuation is dependent on frequency and time	Divide spectrum into frequency bins (tones or subcarriers) each with a modulation (QAM constellation) that depends on radio channel
Inter-Symbol Interference (ISI)	Time dispersion (delay spread) means a symbol can overlap with the adjacent symbol	Add a cyclic prefix (CP) to extend the symbol into a guard band
Inter-Carrier Interference (ICI)	Doppler shifts received frequencies on moving objects, so subcarriers overlap	In bands susceptible to Doppler, make frequency bins larger!

OFDMA Scheduling in NR (2)

- Scheduling is a MAC layer function
  - Control loop relies on near-instantaneous state of the radio channel as conveyed by CSI (DL) and SRS (UL)
  - gNB scheduler controls both UL & DL resources
- Scheduler
  - Uses QoS indication (5QI) conveyed by 5G Core as input
  - Maps data bits to “blocks” packing more bits in the higher order QAM blocks
  - Populates a PDCCH (Physical Downlink Control Channel) with all the information needed for the receiver to receive bits and with information on where to put the UL bits
  - Maps digital traffic to each antenna in multi-antenna (MIMO) configurations

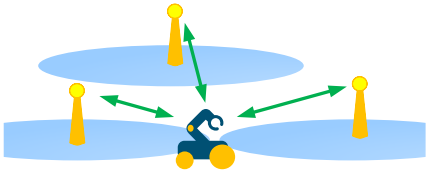


3GPP Definition of the URLLC:

A 32-byte message is successfully transmitted over the radio interface within 1 ms with 99.999% probability.

URLLC is about delivering wireless services that are equivalent to what can be accomplished with the most stringent wired applications

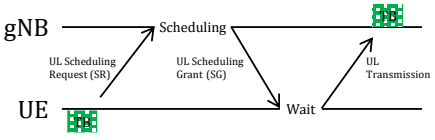
URLLC will Require a Special Toolchain



Resilient connectivity through CoMP/JT

μ	$\Delta f_\mu = 2^\mu \times 15$ kHz	$T^\mu_{slot} = 2^{-\mu} \times 1$ms	Cyclic Prefix
0	15	1 ms	Normal
1	30	0.5 ms	Normal
2	60	0.25 ms	Normal, Extended
3	120	0.125 ms	Normal
4	240	0.0625 ms	Normal

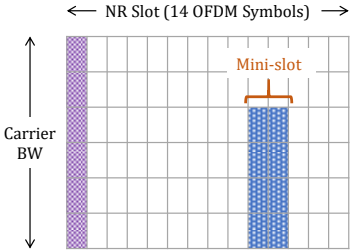
5G Numerologies

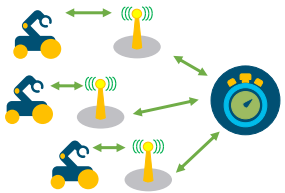


Dynamic UL Scheduling

Grant-Free UL Scheduling

Mini-slot transmissions





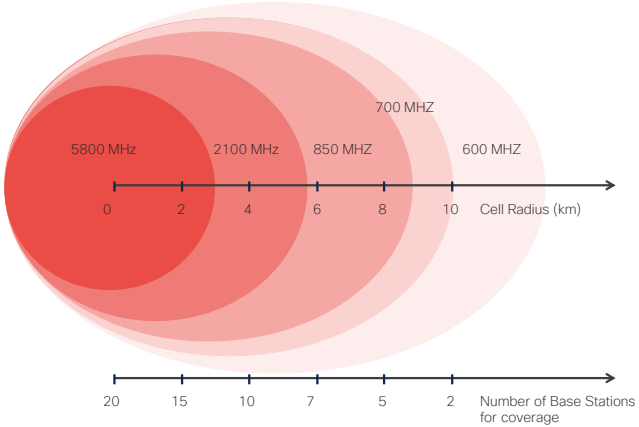
Network-timing OTA

- Wired IEEE TSN is one of many communications links used today in the IIoT scenario
- What appears to be requested is TSN functionality OTA
- Automation industry envisions TSN as the (single) wired communication technology that allows critical real-time communication on a common communication platform
  - IEEE 802.1 ➔ TSN standardization
  - IEC/IEEE project 60802 ➔TSN automation profile
- How do we build TSN into a 5G RAN interface? That is the technical challenge!

Summary

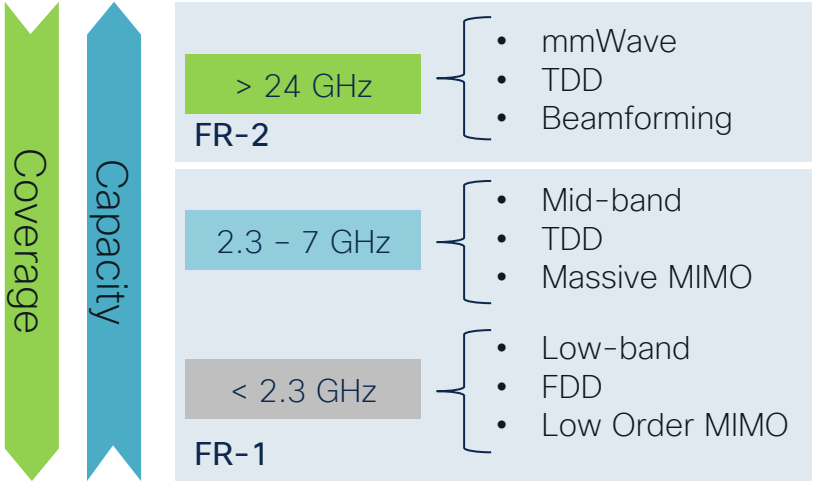
New 5G Technology Changes the Way to Characterize Spectrum

Pre-5G Spectrum Characterization is based on path loss



The higher the frequency, the worse the Coverage: low-band was 400 MHz to 1 GHz and mid-band is 1 – 3 GHz

Post-5G Spectrum Characterization is defined by enabling technology



Coverage and capacity can be optimized simultaneously through the technology introduced in 5G

Learnings

- Not all 5G systems and not all spectrum applies to the same objectives: eMBB (consumer), m-MTC (IOT), and URLLC (industrial) all have very different features
  - The essence of using 5G successfully is to select the adequate spectrum and system for the use case
  - For eMBB high-capacity performance demand multiple bands
- Since 5G is (mostly) licensed technology, this gives operators an advantage but … private 5G spectrum is becoming available
- Special features (e.g., URLLC) will not be free and will certainly not be available everywhere (they will be localized)
- Why is 5G interesting? It is a superior system for spectrum management!

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The bridge to possible

Thank you

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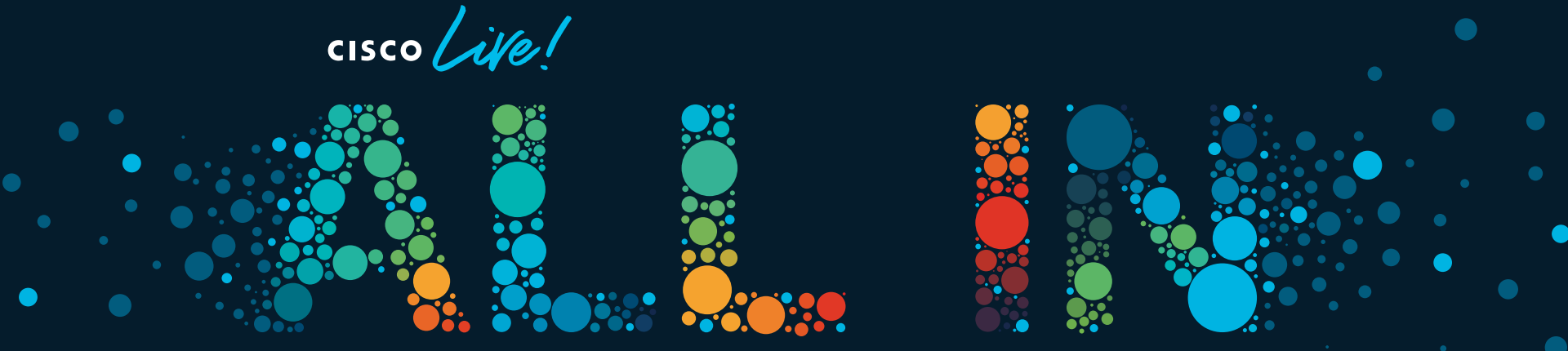
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