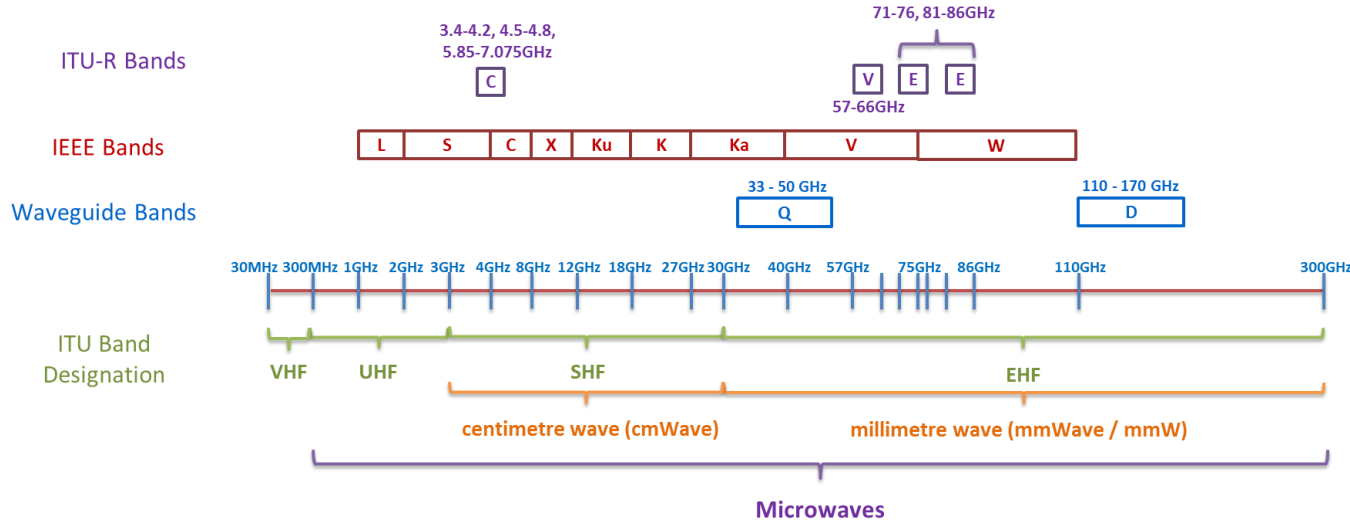
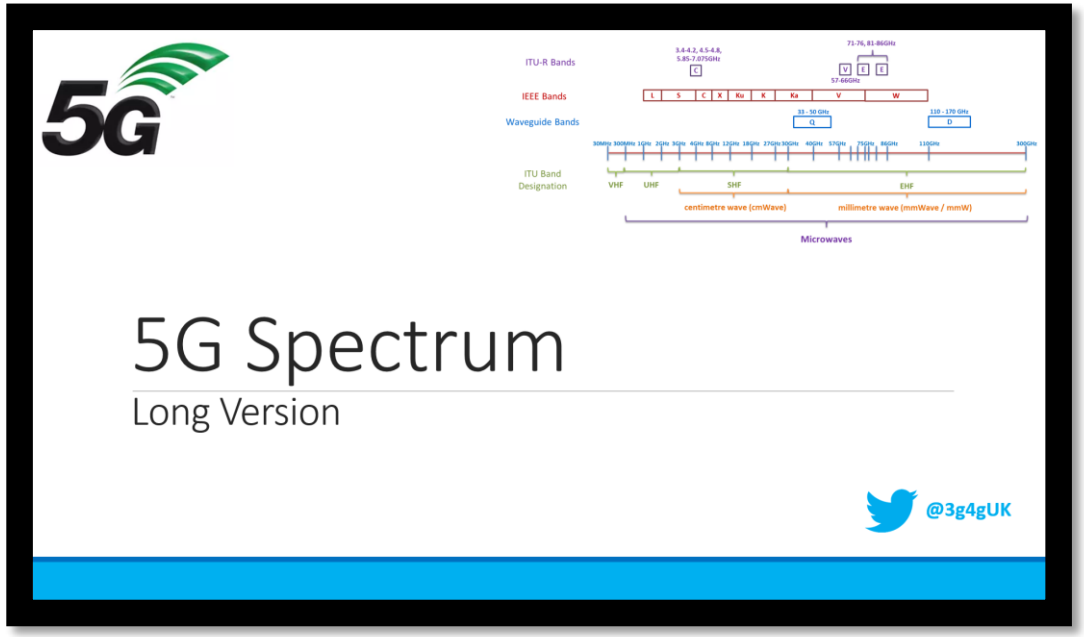
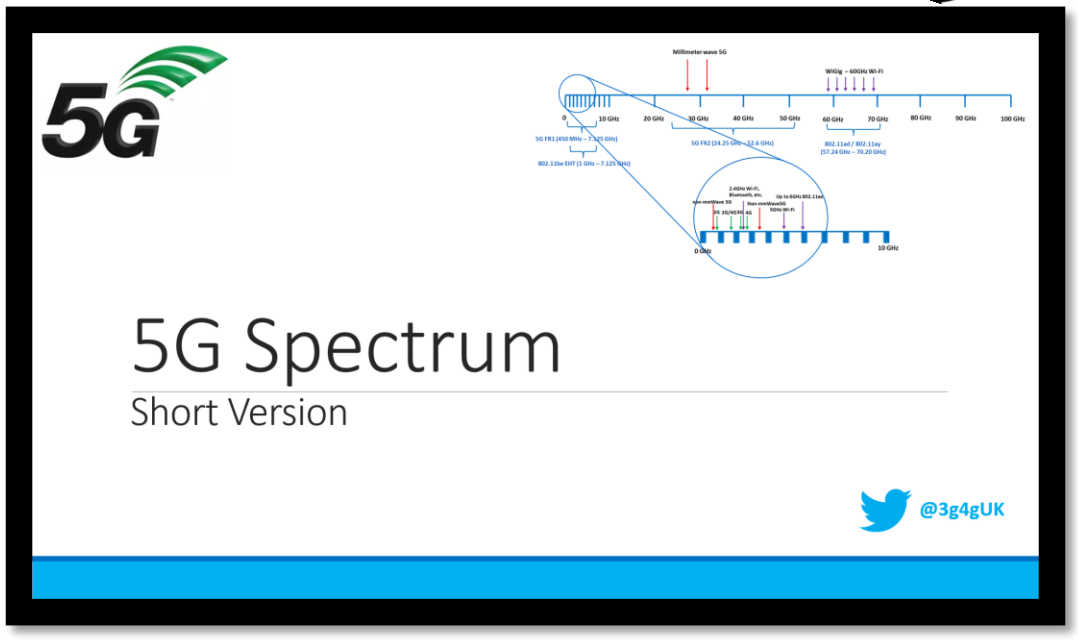


5G Spectrum

Long Version

@3g4gUK





THIS IS LONG VERSION – FOR SHORT VERSION CLICK ON THE LINK ON TOP RIGHT

Chart of the Electromagnetic Spectrum

Size reference


football field


man's height


baseball


paperclip thickness


paper thickness


cells


bacteria


viruses


water molecule


atom


subatomic particles →

wavelength λ (m)

1 ft | 1 cm | 1 mm | 1 mil | 1 µ | 1 nm | 1 Å | 1 pm

10^{3} 10^{2} 10 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12}

wavenumber (cm^{-1})

10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10}

electron volt (eV)

10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}

frequency (Hz)

1 MHz | 1 GHz | 1 THz | 1 PHz | 1 EHz | 1 ZHz

10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} 10^{21}

Bands

Radio Spectrum | Terahertz | Infrared | Ultraviolet | X-ray | Gamma

Broadcast and Wireless | Microwave | Far IR | Mid IR | Near IR | Near UV | Extreme UV | Soft X-ray | Hard X-ray

Visible wavelengths (nm): 700 625 575 540 470 440

electronics ◄ | optics ►

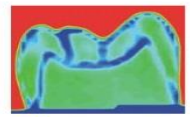
Sources and Uses of Frequency Bands

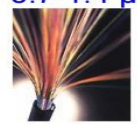

AM radio
600kHz-1.6MHz


FM radio
88-108 MHz


Mobile Phones
900MHz-2.4GHz


Radar
1-100 GHz

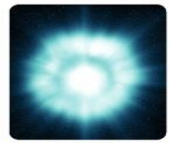

Bio imaging
1-10 THz


Fiber telecom
0.7-1.4 µ


Visible Light
425-750THz
700-400nm


Dental Curing
200-350nm


Medical X-rays
10-0.1 Å

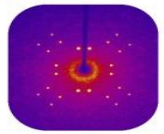

Cosmic ray observations
<<1 Å

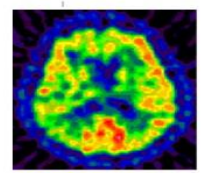

Baggage screen
10-1.0 Å

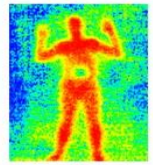

Remotes
850 nm


Night Vision
10-0.7 µ


Suntan
400-290nm


Crystallography
2.2-0.7 Å


PET imaging
0.1-0.01 Å


Screening
0.2-4.0 THz


Ultrasound
1-20 MHz


Sound Waves
← 20Hz-10kHz


TV Broadcast
54-700 MHz


Wireless Data
~ 2.4 GHz

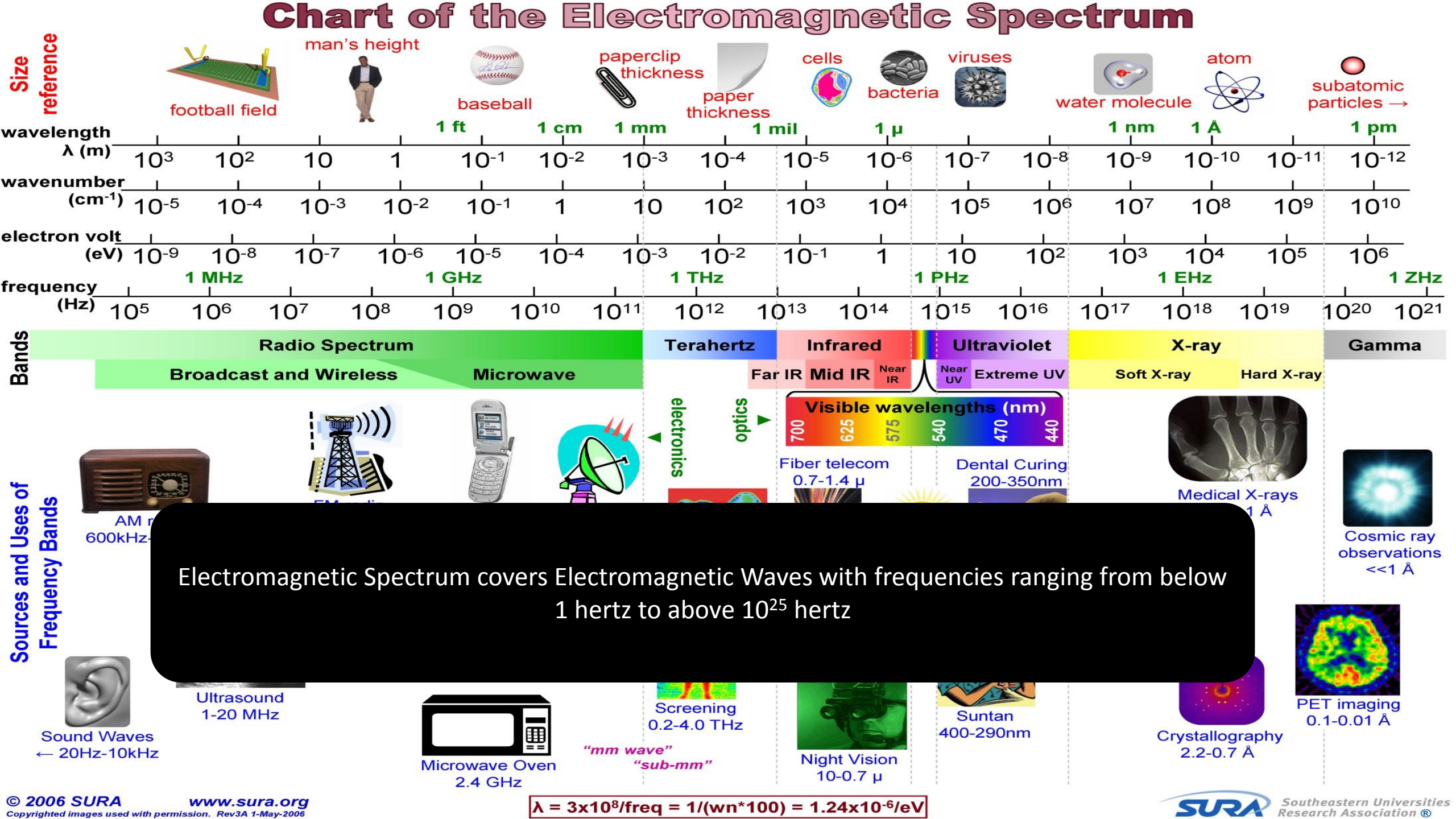

Microwave Oven
2.4 GHz

"mm wave"
"sub-mm"

$\lambda = 3x10^{8}/freq = 1/(wn*100) = 1.24x10^{-6}/eV$

SURA Southeastern Universities Research Association ®

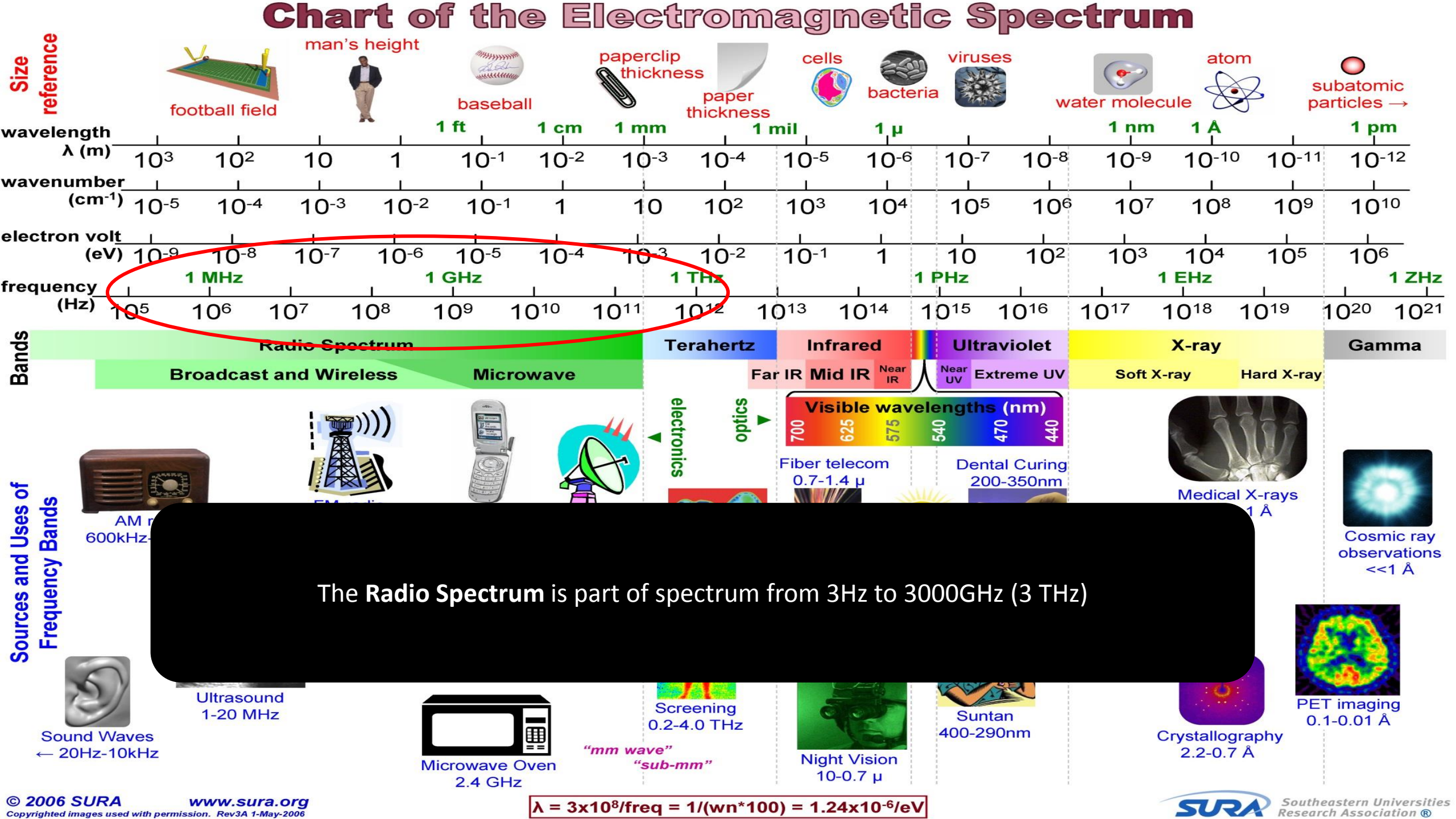
Chart of the Electromagnetic Spectrum



Electromagnetic Spectrum covers Electromagnetic Waves with frequencies ranging from below 1 hertz to above 10^{25} hertz

$\lambda = 3\times10^{8}/\text{freq} = 1/(\text{wn}*100) = 1.24\times10^{-6}/\text{eV}$

Chart of the Electromagnetic Spectrum



The **Radio Spectrum** is part of spectrum from 3Hz to 3000GHz (3 THz)

$\lambda = 3\times10^{8}/\text{freq} = 1/(\text{wn}*100) = 1.24\times10^{-6}/\text{eV}$

5G is only looking at frequencies from 450 MHz to 52.6 GHz

3GPP has divided 5G frequencies in 2 parts:

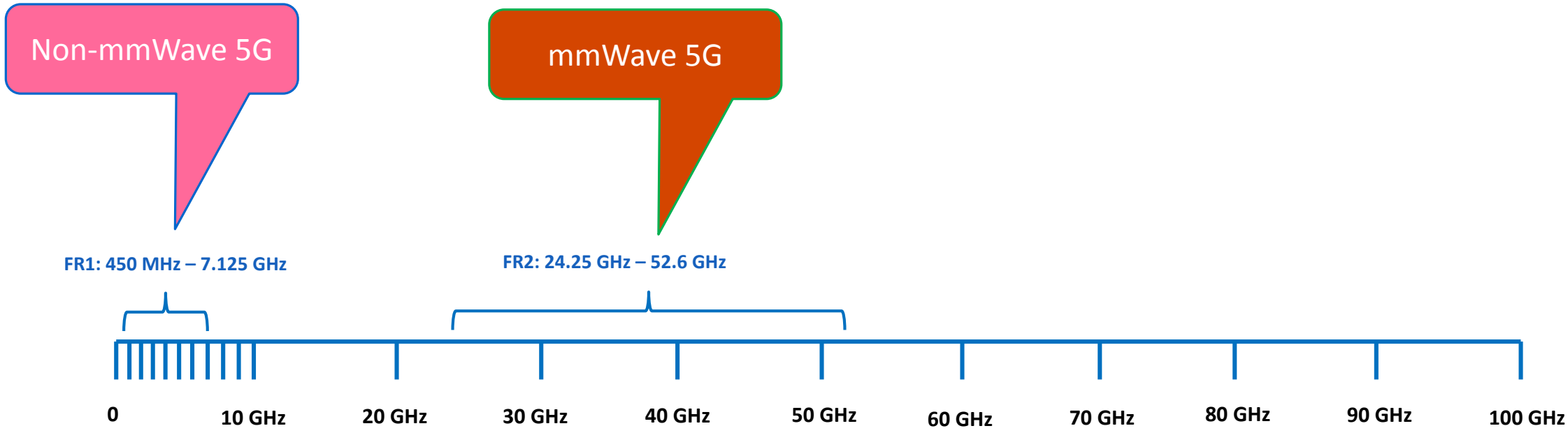
- Frequency Range 1 (FR1): 450 MHz – 7.125 GHz
- Frequency Range 2 (FR2): 24.25 GHz – 52.6 GHz

5G is only looking at frequencies from 450 MHz to 52.6 GHz

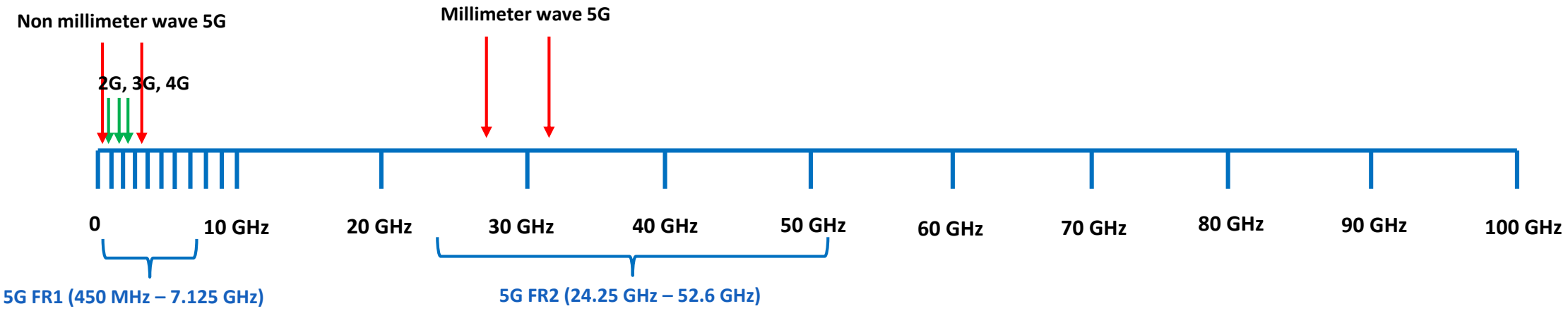
Technically mmWave starts from 30 GHz but people refer to all frequencies in FR2 as mmWave

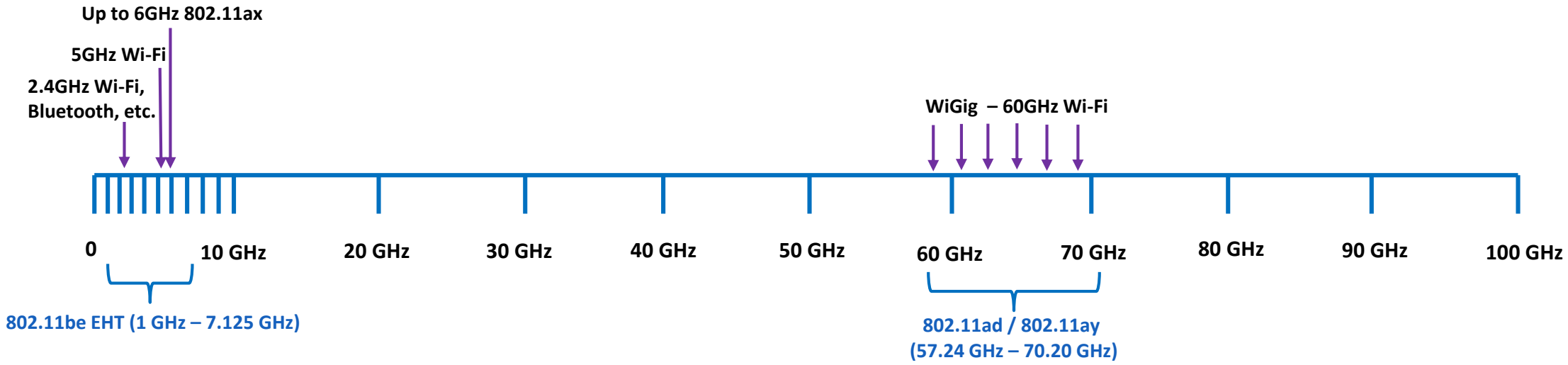
3GPP has divided 5G frequencies into 2 parts:

- Frequency Range 1 (FR1): 450 MHz – 7.125 GHz
- Frequency Range 2 (FR2): 24.25 GHz – 52.6 GHz

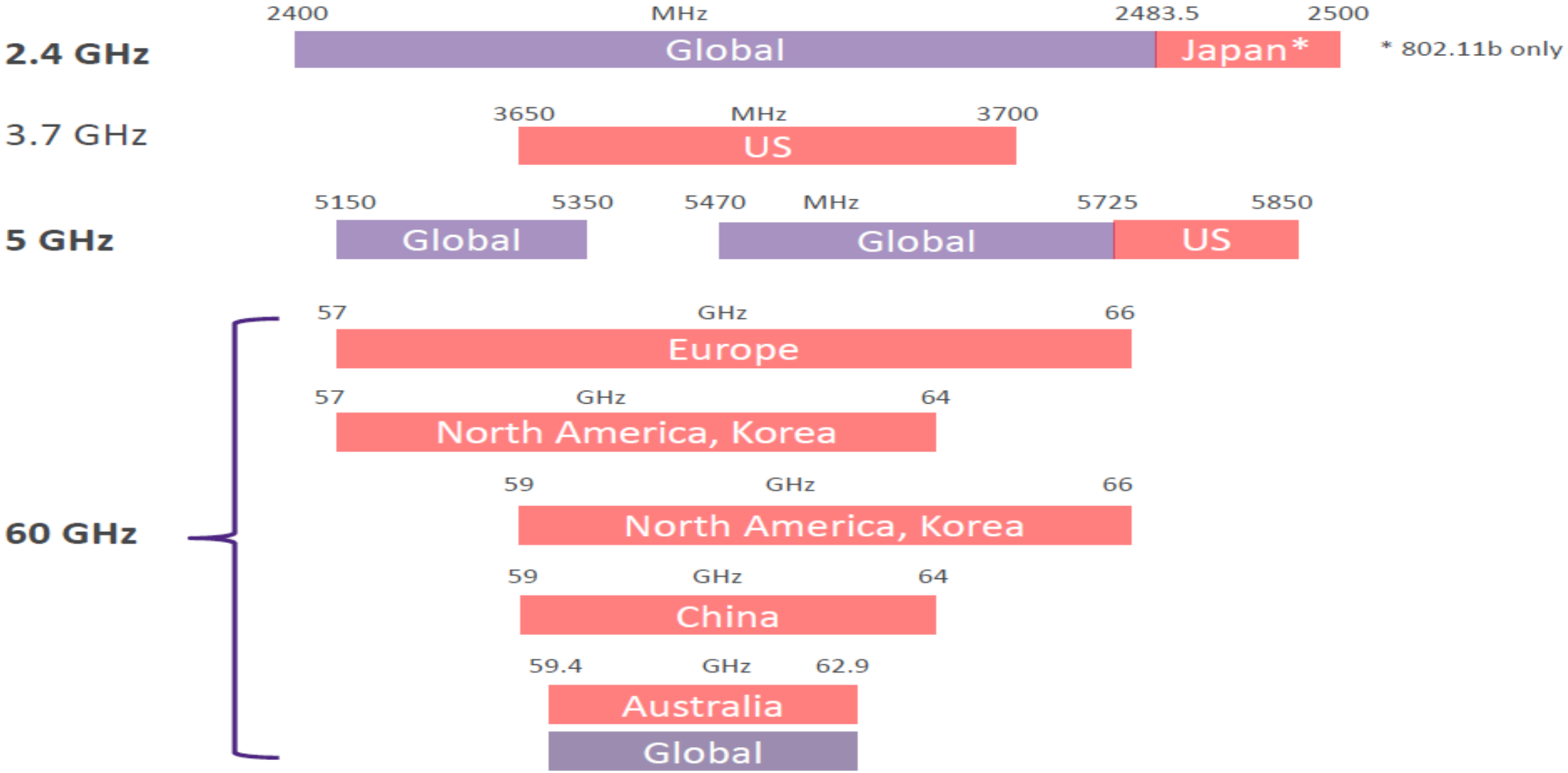

Non-mmWave 5G
mmWave 5G
FR1: 450 MHz – 7.125 GHz
FR2: 24.25 GHz – 52.6 GHz
0
10 GHz
20 GHz
30 GHz
40 GHz
50 GHz
60 GHz
70 GHz
80 GHz
90 GHz
100 GHz

Popular Frequency bands for different Technologies

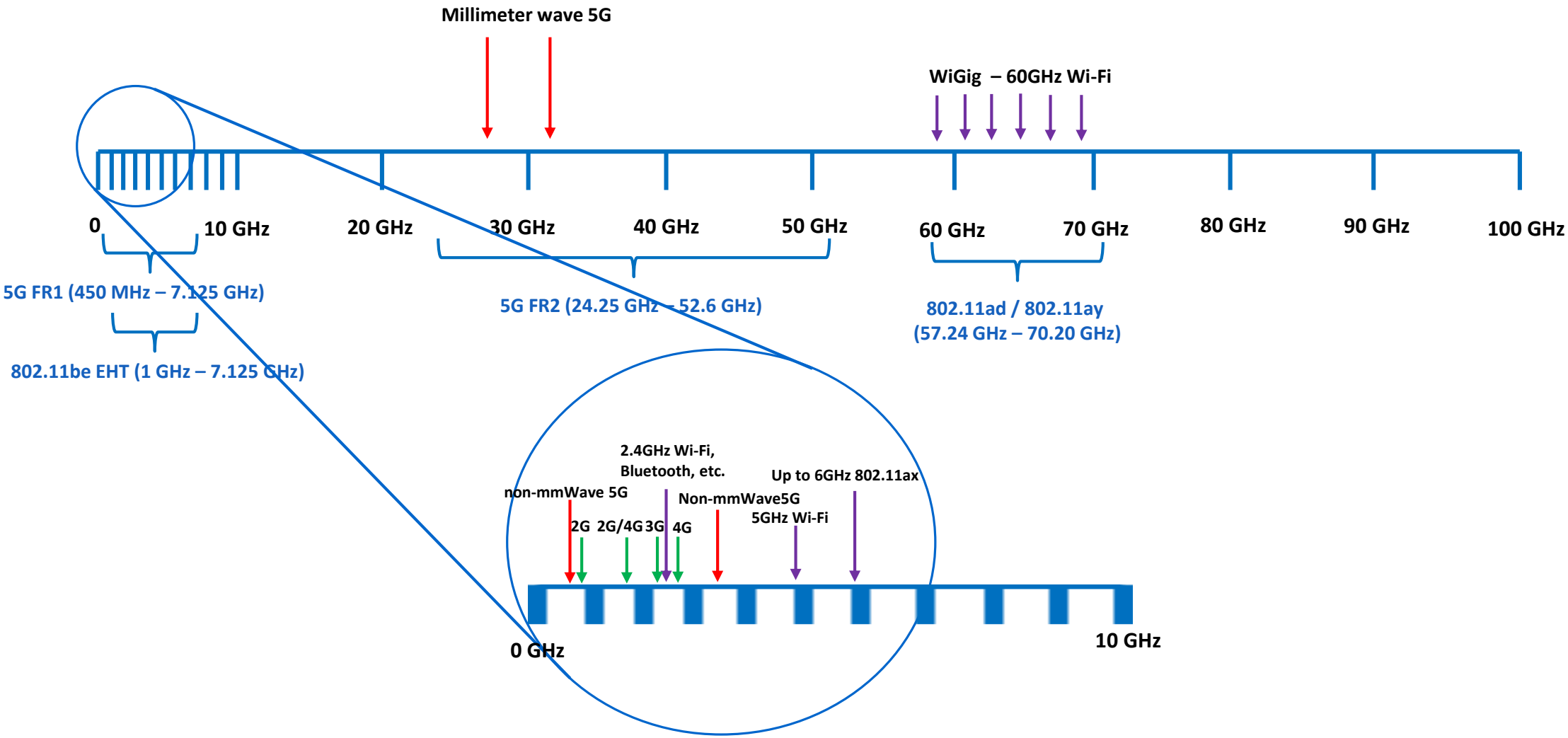




Wi-Fi Spectrum around the world

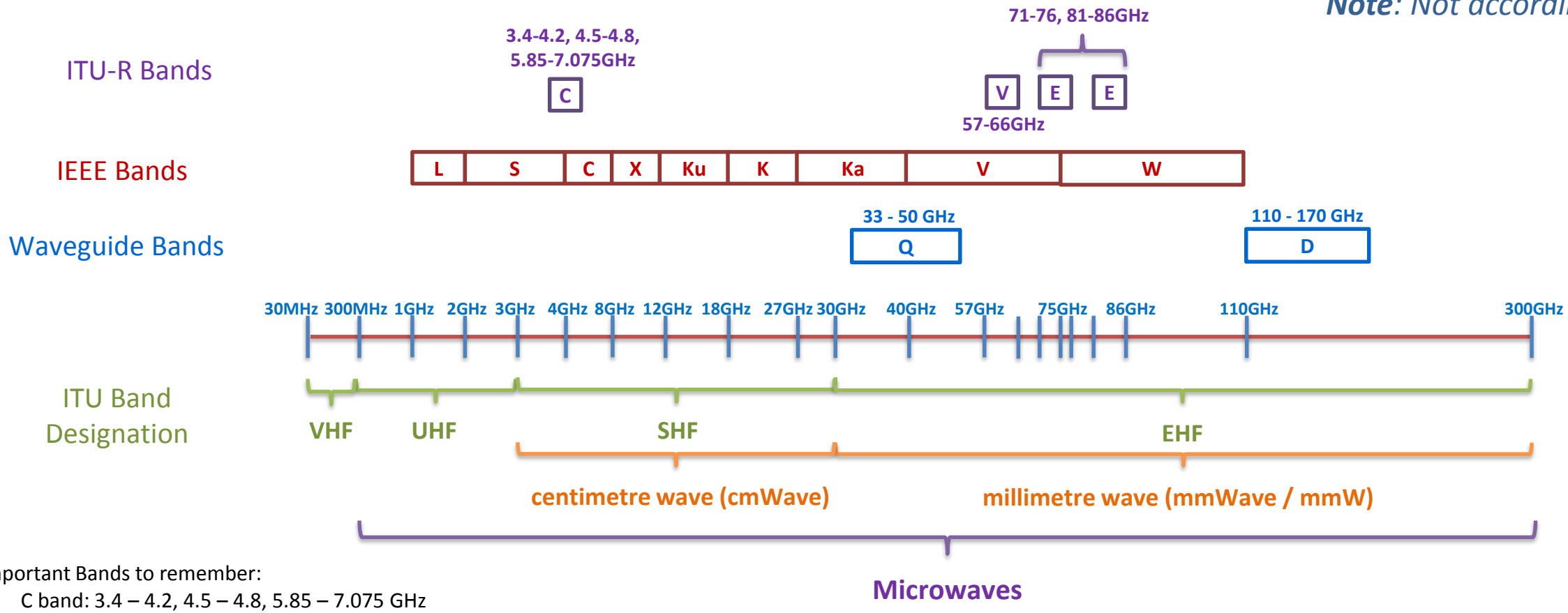


Summary: Popular Frequency bands for different Technologies



Summary of Spectrum Band Names

***Note**: Not according to scale*

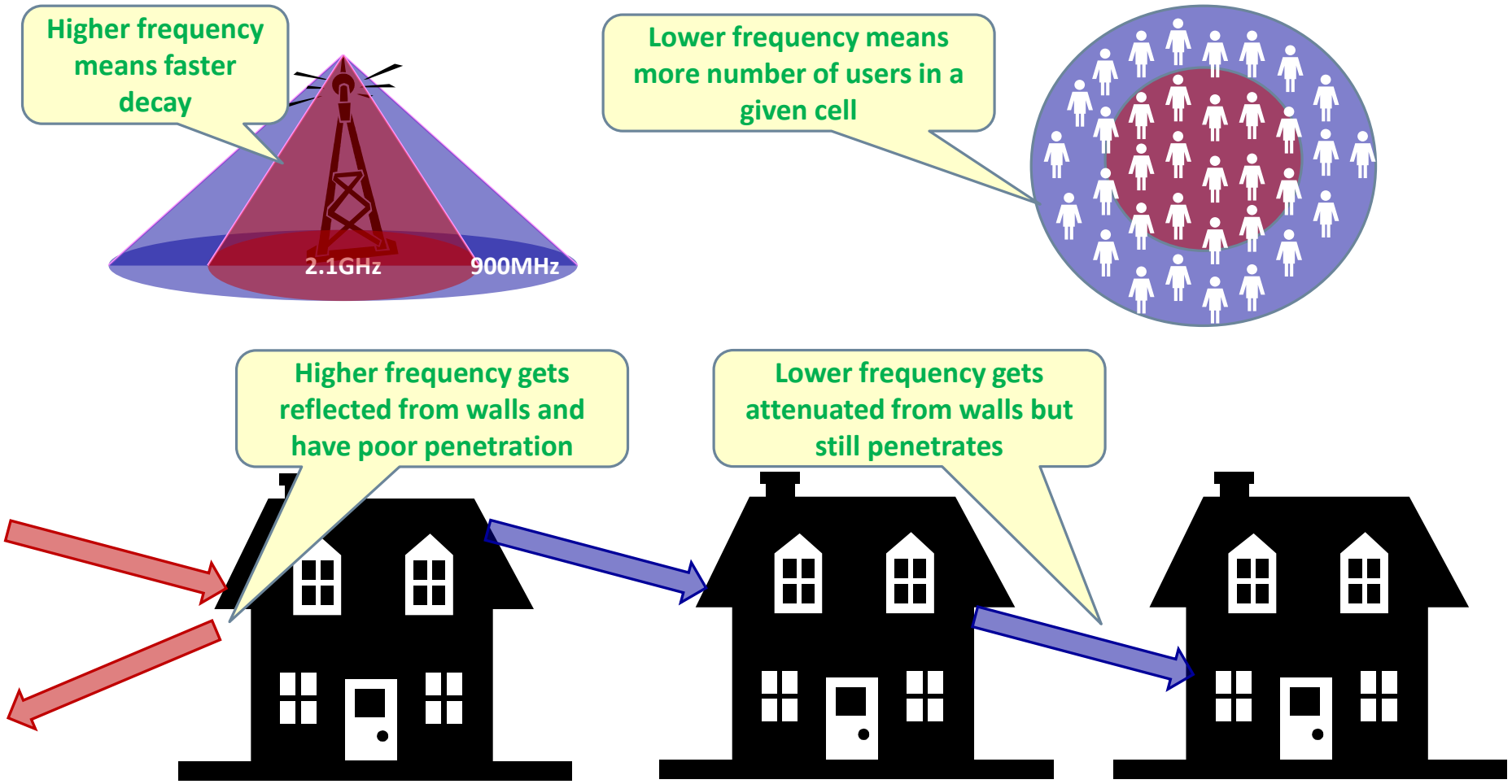


Important Bands to remember:

- C band: 3.4 – 4.2, 4.5 – 4.8, 5.85 – 7.075 GHz
- Ku band: 12 – 18 GHz
- K band: 18 – 26.5 GHz
- Ka band: 26.5 – 40 GHz
- mmWave start from 30 GHz

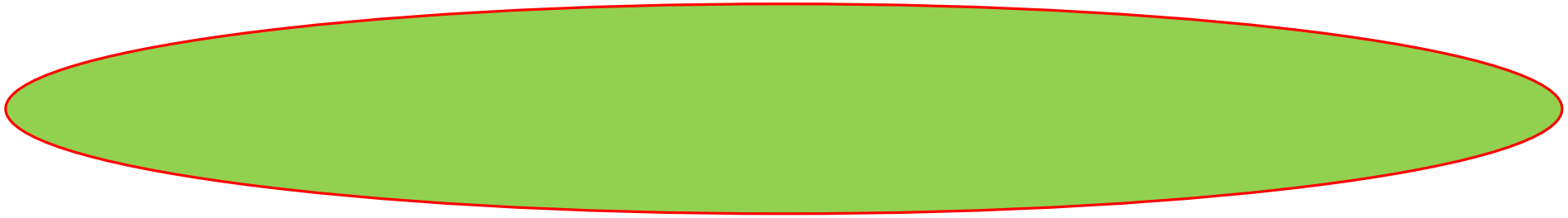
For more details, see: Rec. ITU-R V.431-7

Importance of Frequency selection

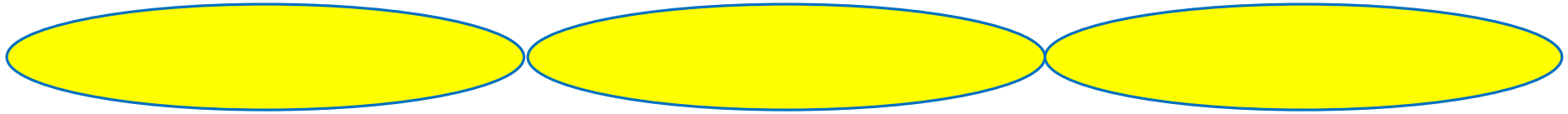


5G: Multiple Layers for multiple needs

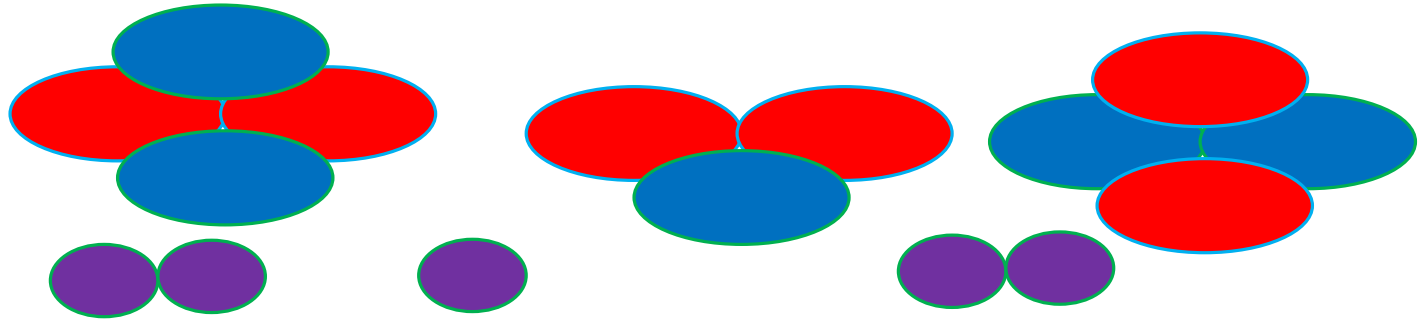
Coverage Layer
Sub-1GHz



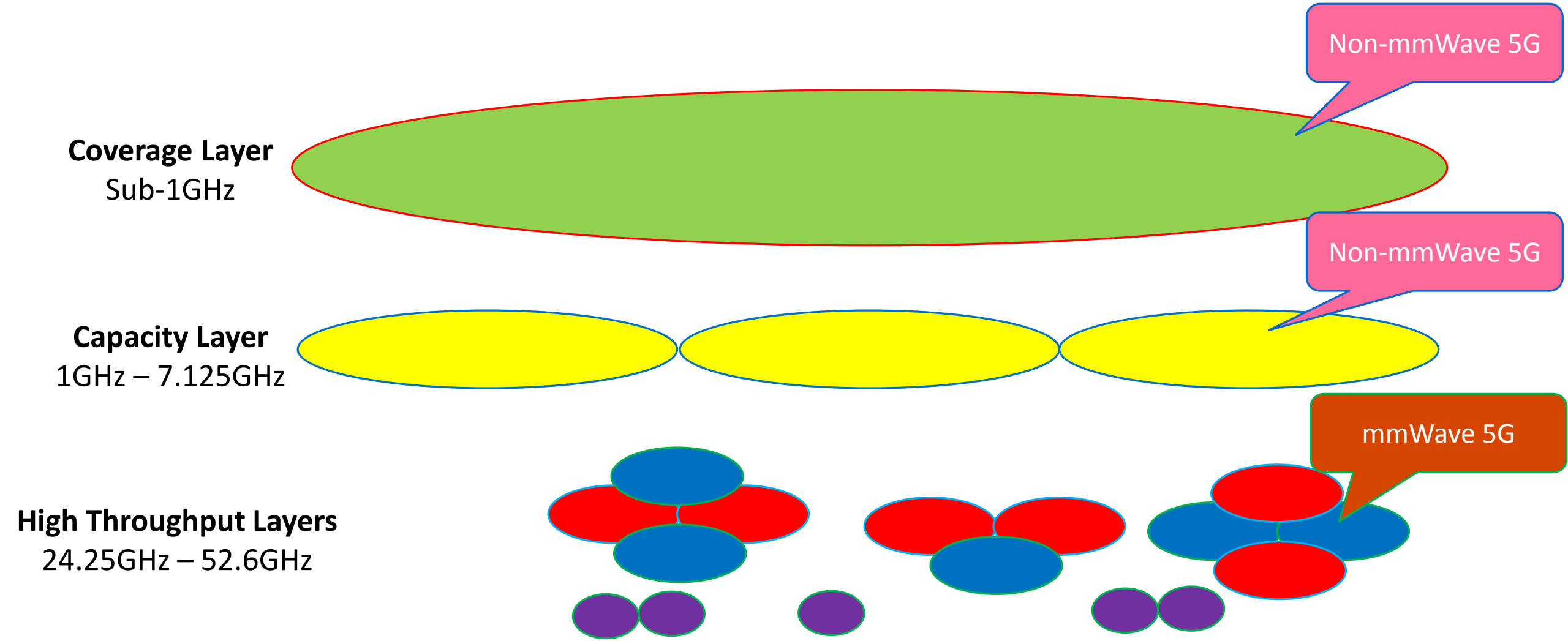
Capacity Layer
1GHz – 7.125GHz



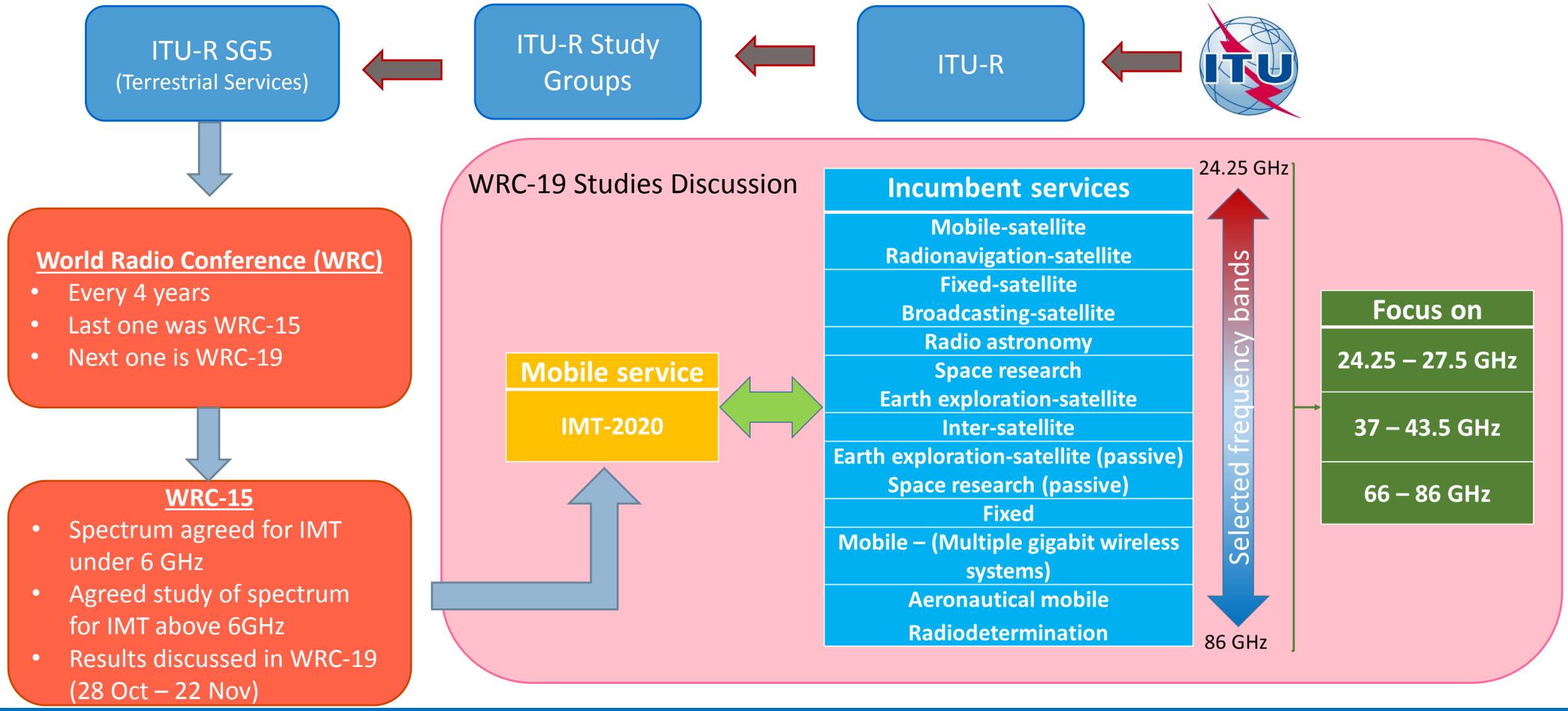
High Throughput Layers
24.25GHz – 52.6GHz



5G Needs Different Frequency Bands



5G Frequency Study / Agreement Process



5G Spectrum

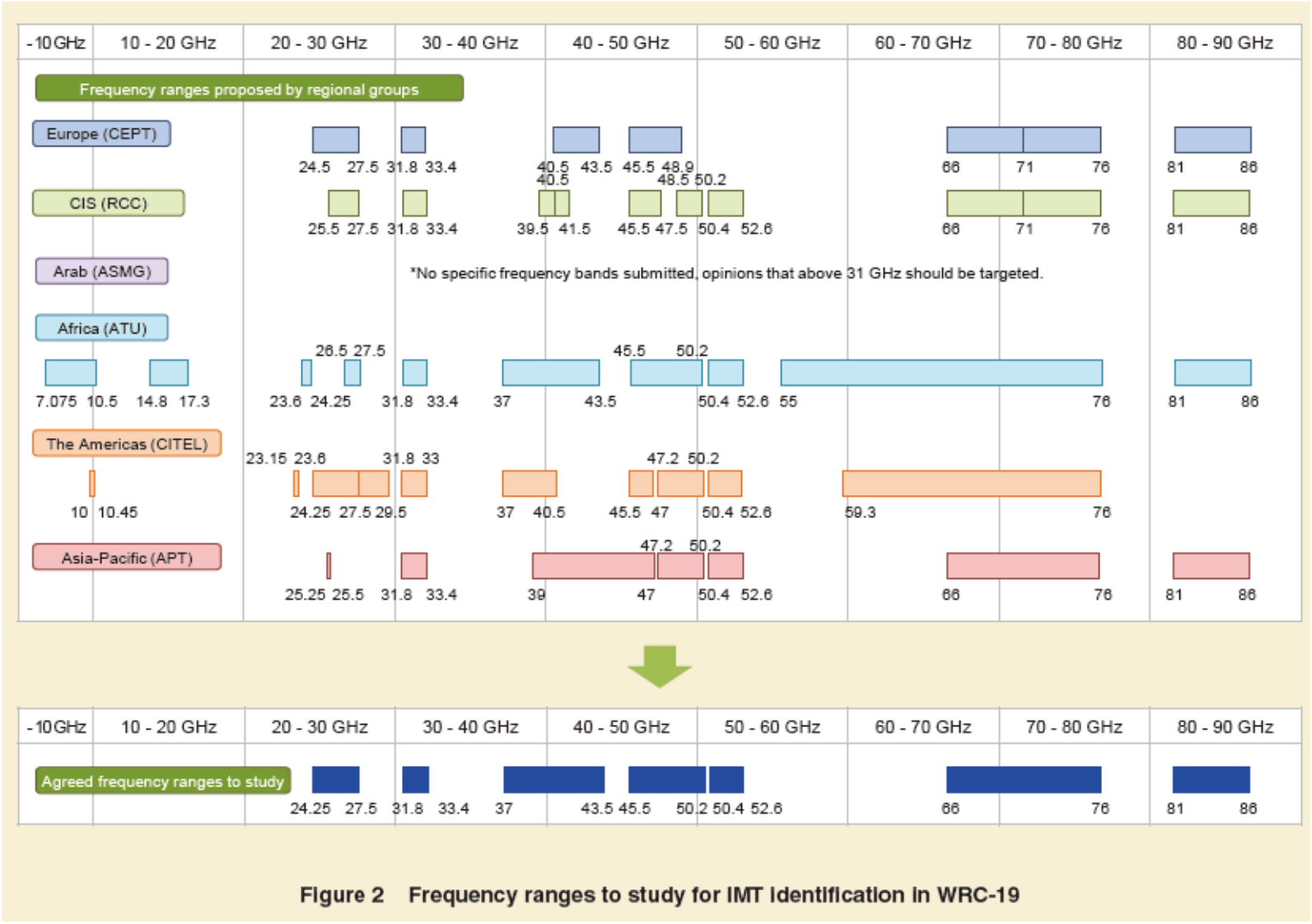


Figure 2 Frequency ranges to study for IMT identification in WRC-19

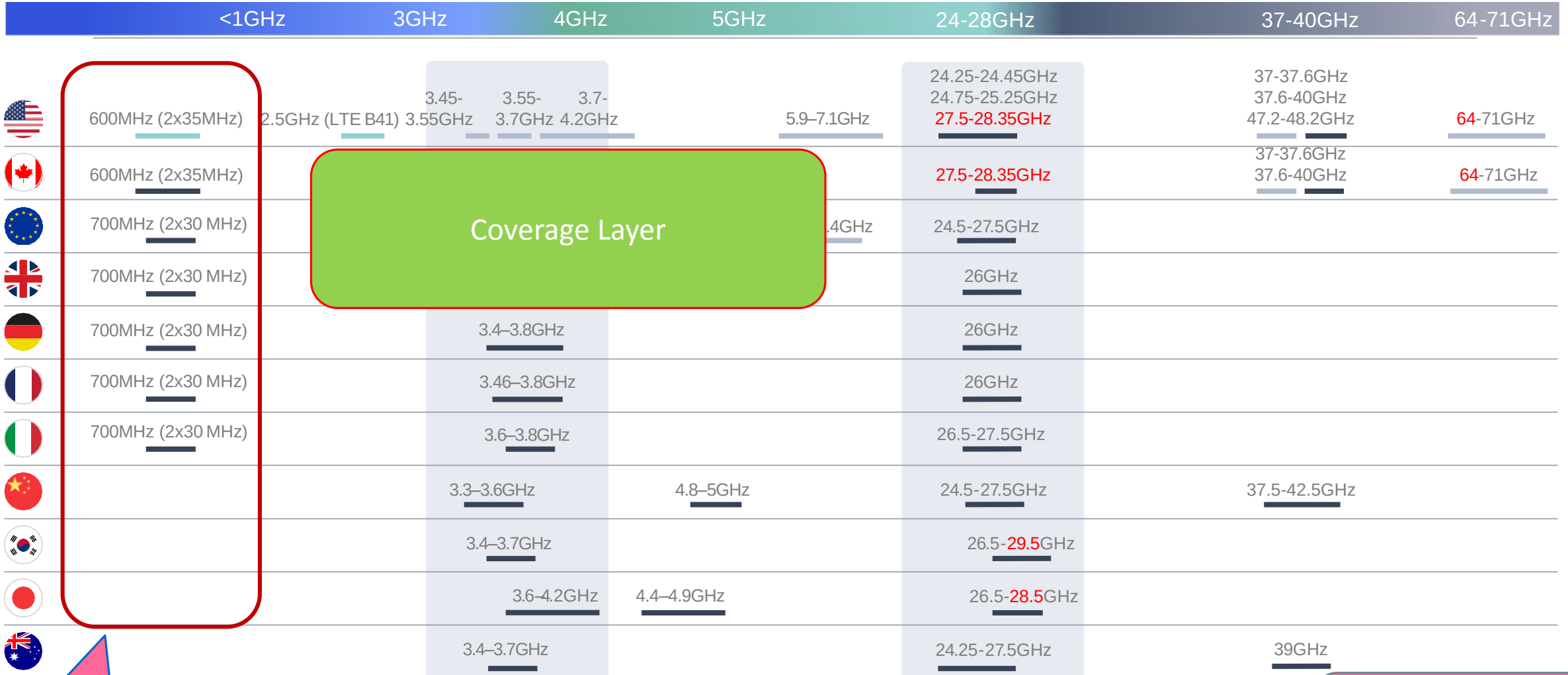
ITU WRC-15 Report from NTT Docomo Technical Journal

Most Popular 5G Frequency Bands

Source: Qualcomm

Red highlights frequencies not approved for ITU study

Most Popular 5G Frequency Bands



So

Red highlights frequencies not approved for ITU study

Most Popular 5G Frequency Bands

So

Red highlights frequencies not approved for ITU study

Most Popular 5G Frequency Bands

Source: Qualcomm

Red highlights frequencies not approved for ITU study

Summary: Most Popular 5G Frequency Bands

26/28 GHz – most popular band

3.5 GHz – most popular band

700 MHz – most popular band

Picture Source: Deutsche Telekom / T-Mobile USA

5G Bands Defined by 3GPP

Release 15

3GPP TS 38.101-1 V15.3.0 (2018-09)

Table 5.2-1: NR operating bands in FR1

NR operating band	Uplink (UL) *operating band* BS receive / UE transmit F_{UL_low} – F_{UL_high}	Downlink (DL) *operating band* BS transmit / UE receive F_{DL_low} – F_{DL_high}	Duplex Mode
n1	1920 MHz – 1980 MHz	2110 MHz – 2170 MHz	FDD
n2	1850 MHz – 1910 MHz	1930 MHz – 1990 MHz	FDD
n3	1710 MHz – 1785 MHz	1805 MHz – 1880 MHz	FDD
n5	824 MHz – 849 MHz	869 MHz – 894 MHz	FDD
n7	2500 MHz – 2570 MHz	2620 MHz – 2690 MHz	FDD
n8	880 MHz – 915 MHz	925 MHz – 960 MHz	FDD
n12	699 MHz – 716 MHz	729 MHz – 746 MHz	FDD
n20	832 MHz – 862 MHz	791 MHz – 821 MHz	FDD
n25	1850 MHz – 1915 MHz	1930 MHz – 1995 MHz	FDD
n28	703 MHz – 748 MHz	758 MHz – 803 MHz	FDD
n34	2010 MHz – 2025 MHz	2010 MHz – 2025 MHz	TDD
n38	2570 MHz – 2620 MHz	2570 MHz – 2620 MHz	TDD
n39	1880 MHz – 1920 MHz	1880 MHz – 1920 MHz	TDD
n40	2300 MHz – 2400 MHz	2300 MHz – 2400 MHz	TDD
n41	2496 MHz – 2690 MHz	2496 MHz – 2690 MHz	TDD
n50	1432 MHz – 1517 MHz	1432 MHz – 1517 MHz	TDD[1]
n51	1427 MHz – 1432 MHz	1427 MHz – 1432 MHz	TDD
n66	1710 MHz – 1780 MHz	2110 MHz – 2200 MHz	FDD
n70	1695 MHz – 1710 MHz	1995 MHz – 2020 MHz	FDD
n71	663 MHz – 698 MHz	617 MHz – 652 MHz	FDD
n74	1427 MHz – 1470 MHz	1475 MHz – 1518 MHz	FDD
n75	N/A	1432 MHz – 1517 MHz	SDL
n76	N/A	1427 MHz – 1432 MHz	SDL
n77	3300 MHz – 4200 MHz	3300 MHz – 4200 MHz	TDD
n78	3300 MHz – 3800 MHz	3300 MHz – 3800 MHz	TDD
n79	4400 MHz – 5000 MHz	4400 MHz – 5000 MHz	TDD
n80	1710 MHz – 1785 MHz	N/A	SUL
n81	880 MHz – 915 MHz	N/A	SUL
n82	832 MHz – 862 MHz	N/A	SUL
n83	703 MHz – 748 MHz	N/A	SUL
n84	1920 MHz – 1980 MHz	N/A	SUL
n86	1710 MHz – 1780MHz	N/A	SUL

NOTE 1: UE that complies with the NR Band n50 minimum requirements in this specification shall also comply with the NR Band n51 minimum requirements.

New Bands in 5G, not in LTE

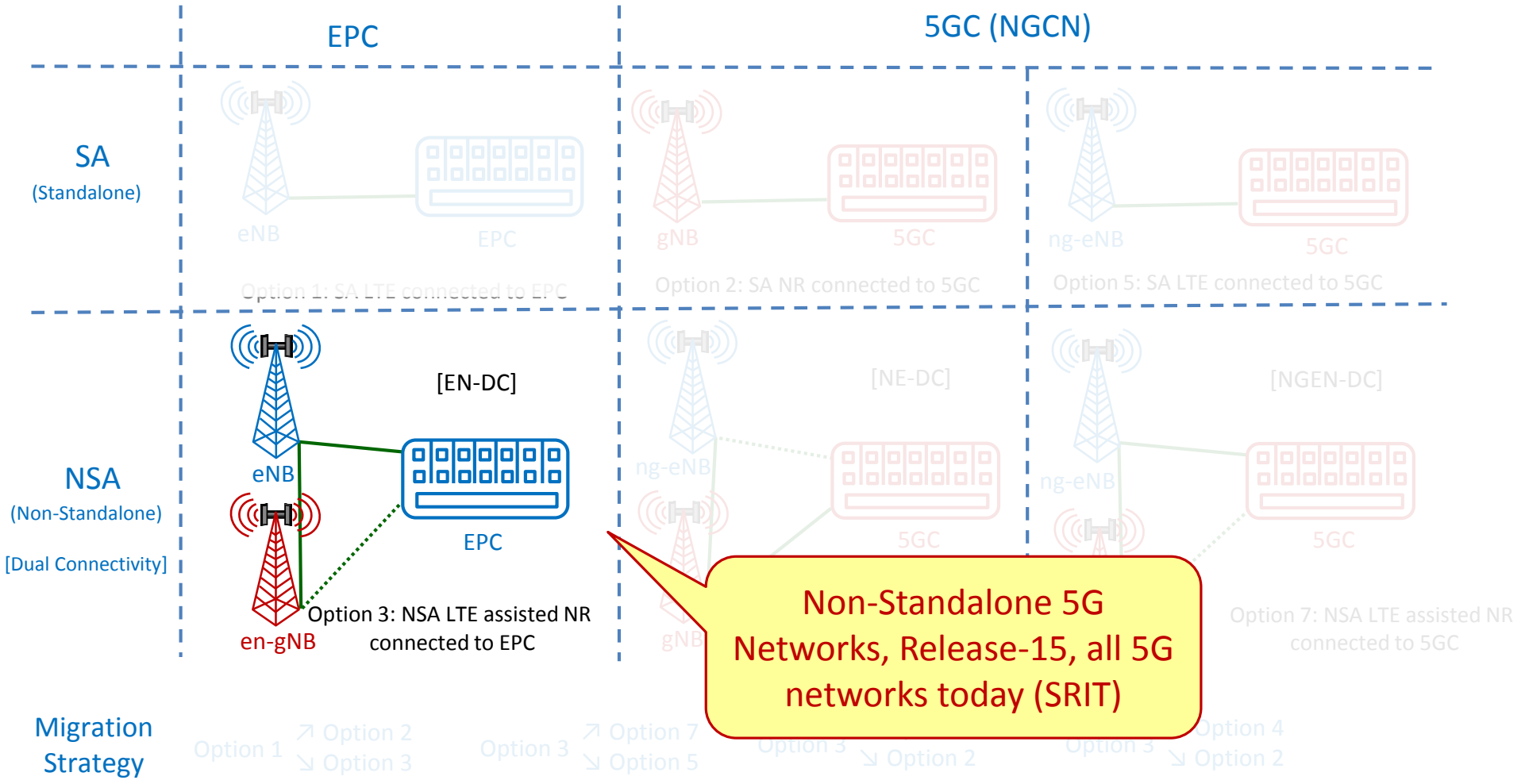
5G needs large amounts of bandwidth?

	NR band / SCS / UE Channel bandwidth												
NR Band	SCS kHz	5 MHz	10[1,2] MHz	15[2] MHz	20[2] MHz	25[2] MHz	30 MHz	40 MHz	50 MHz	60 MHz	80 MHz	90 MHz	100 MHz
n1	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60		Yes	Yes	Yes								
n2	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60		Yes	Yes	Yes								
n3	15	Yes	Yes	Yes	Yes	Yes	Yes						
	30		Yes	Yes	Yes	Yes	Yes						
	60		Yes	Yes	Yes	Yes	Yes						
n5	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60												
n7	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60		Yes	Yes	Yes								
n8	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60												
n12	15	Yes	Yes	Yes									
	30		Yes	Yes									
	60												
n20	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60												
n25	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60		Yes	Yes	Yes								
n28	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60												
n34	15	Yes	Yes	Yes									
	30		Yes	Yes									
	60		Yes	Yes									
n38	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60		Yes	Yes	Yes								
n39	15	Yes	Yes	Yes	Yes	Yes	Yes	Yes					
	30		Yes	Yes	Yes	Yes	Yes	Yes					
	60		Yes	Yes	Yes	Yes	Yes	Yes					

	NR band / SCS / UE Channel bandwidth												
NR Band	SCS kHz	5 MHz	10[1,2] MHz	15[2] MHz	20[2] MHz	25[2] MHz	30 MHz	40 MHz	50 MHz	60 MHz	80 MHz	90 MHz	100 MHz
n71	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60												
n74	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60		Yes	Yes	Yes								
n75	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60		Yes	Yes	Yes								
n76	15	Yes											
	30												
	60												
n77	15		Yes	Yes	Yes			Yes	Yes				
	30		Yes	Yes	Yes			Yes	Yes	Yes	Yes	Yes	Yes
	60		Yes	Yes	Yes			Yes	Yes	Yes	Yes	Yes	Yes
n78	15		Yes	Yes	Yes			Yes	Yes				
	30		Yes	Yes	Yes			Yes	Yes	Yes	Yes	Yes	Yes
	60		Yes	Yes	Yes			Yes	Yes	Yes	Yes	Yes	Yes
n79	15							Yes	Yes				
	30							Yes	Yes	Yes	Yes		Yes
	60							Yes	Yes	Yes	Yes		Yes
n80	15	Yes	Yes	Yes	Yes	Yes	Yes						
	30		Yes	Yes	Yes	Yes	Yes						
	60		Yes	Yes	Yes	Yes	Yes						
n81	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60												
n82	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60												
n83	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60												
n84	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60		Yes	Yes	Yes								
n86	15	Yes	Yes	Yes	Yes			Yes					
	30		Yes	Yes	Yes			Yes					
	60		Yes	Yes	Yes			Yes					

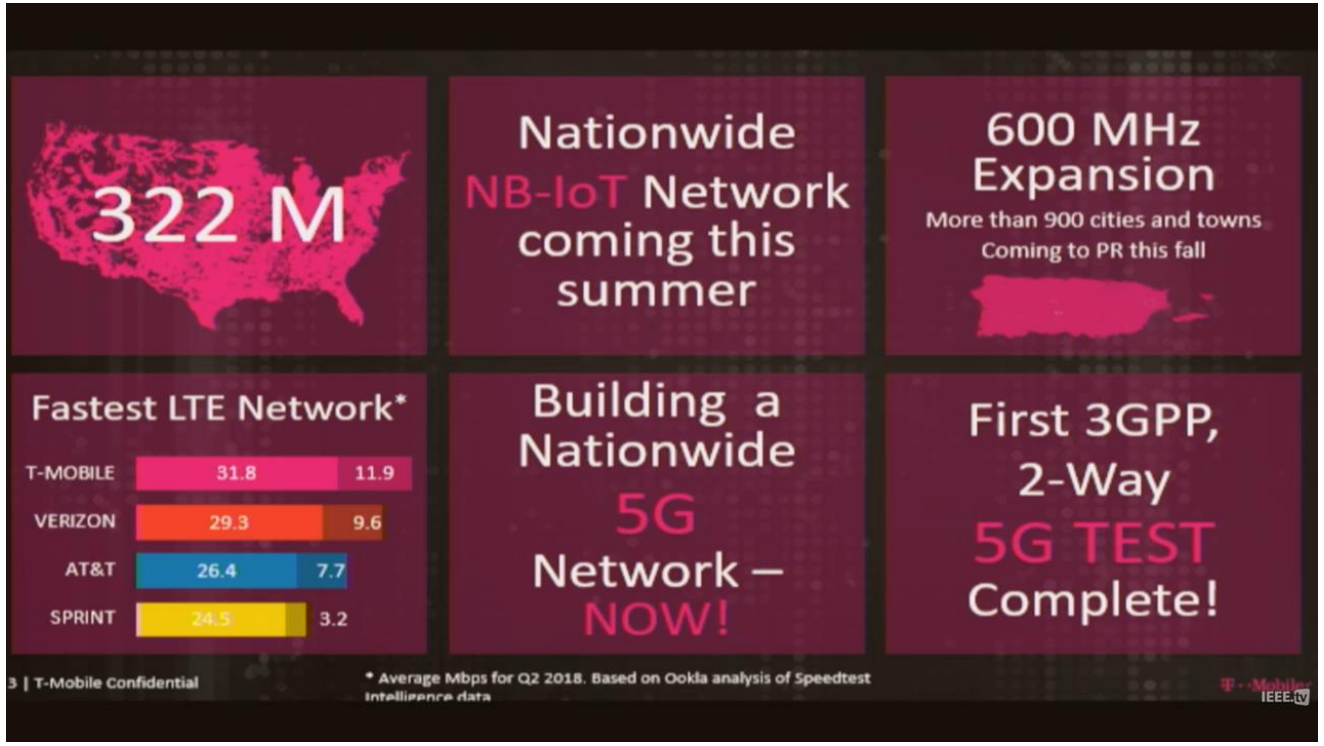
NOTE 1: 90% spectrum utilization may not be achieved for 30kHz SCS.
NOTE 2: 90% spectrum utilization may not be achieved for 60kHz SCS.
NOTE 3: This UE channel bandwidth is applicable only to downlink.

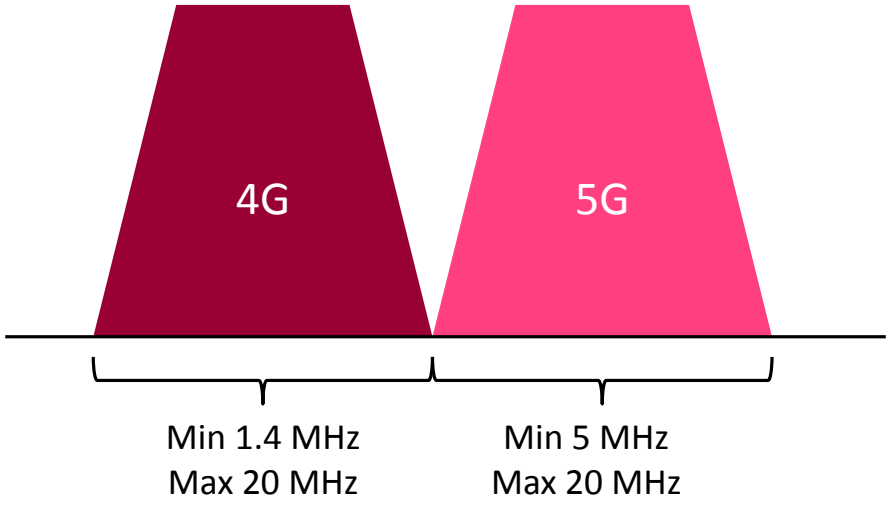
5G Deployment Options and Migration Strategy



Refarming the existing frequency bands

- T-Mobile USA launching 5G in 600 MHz
  - 600 MHz used for 4G at present





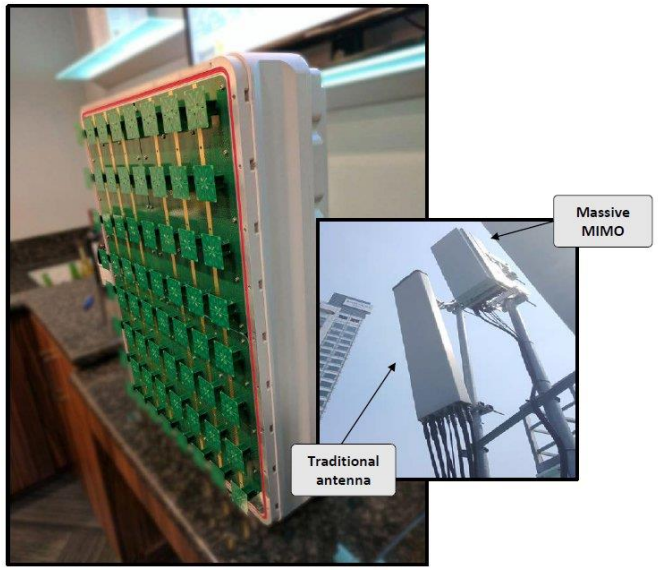
	NR band / SCS / UE Channel bandwidth								
NR Band	SCS kHz	5 MHz	$10^{1,2}$ MHz	15^{2} MHz	20^{2} MHz	25^{2} MHz	30 MHz	40 MHz	50 M
n71	15	Yes	Yes	Yes	Yes				
	30		Yes	Yes	Yes				
	60								

Refarming the existing frequency bands

- Sprint USA launching 5G in 2.5 GHz
  - 2.5 GHz used for 4G at present

TDD-LTE Massive MIMO for 5G

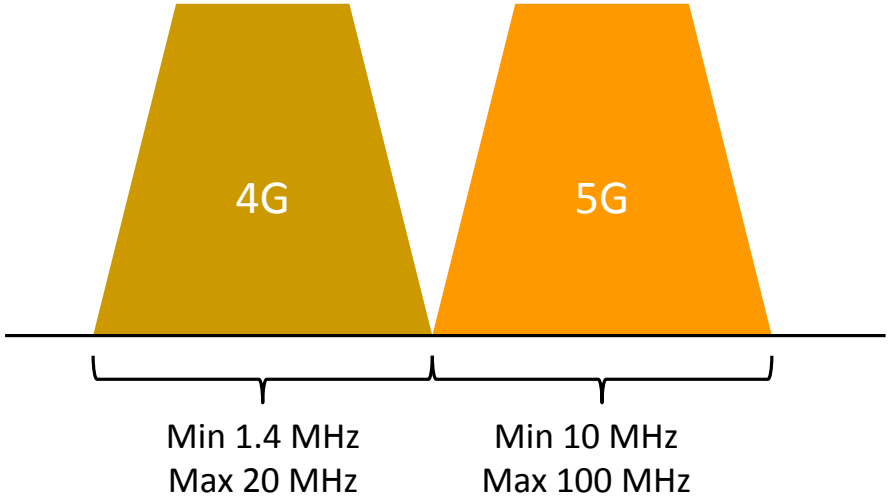
Sprint



Massive MIMO leverages a massive number of antennas and advanced antenna beamforming to improve performance

- Sprint will deploy 64T64R Massive MIMO (128 Antenna Elements) at 2.5 GHz
- Upgrade thousands of 2.5 GHz sites with Massive MIMO to support LTE and 5G simultaneously at existing sites

5



	NR band / SCS / UE Channel bandwi								
NR Band	SCS kHz	5 MHz	10[1,2] MHz	15[2] MHz	20[2] MHz	25[2] MHz	30 MHz	40 MHz	50 MH
n41	15		Yes	Yes	Yes			Yes	Ye
	30		Yes	Yes	Yes			Yes	Ye
	60		Yes	Yes	Yes			Yes	Ye

5G needs large amounts of bandwidth?

- 3GPP defines new NR (New Radio) bands in FR1 and FR2 in 3GPP Rel.15 NR
- FR1: 450 MHz – 6 GHz
  - Upper range is changing to 7.125 GHz
- FR2: 24.25 GHz – 52.6 GHz

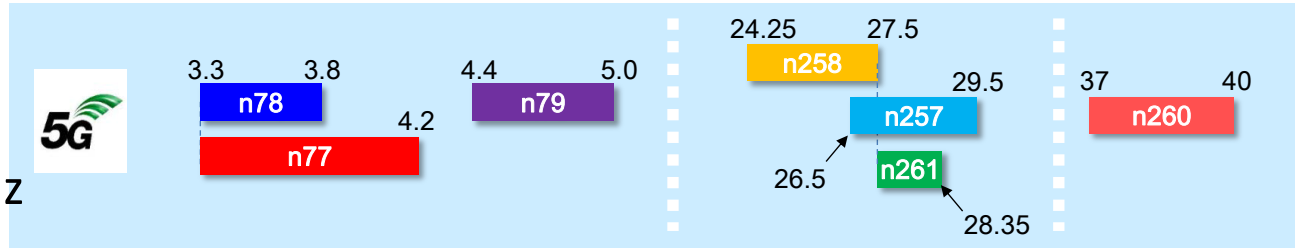


Table 2 NR bands specified in this WI

NR operating band	Uplink (UL) operating band	Downlink (DL) operating band	Duplex Mode	Bandwidth
n77	3300 MHz – 4200 MHz	3300 MHz – 4200 MHz	TDD	900 MHz
n78	3300 MHz – 3800 MHz	3300 MHz – 3800 MHz	TDD	500 MHz
n79	4400 MHz – 5000 MHz	4400 MHz – 5000 MHz	TDD	600 MHz
n257	26500 MHz – 29500 MHz	26500 MHz – 29500 MHz	TDD	3000 MHz (3 GHz)
n258	24250 MHz – 27500 MHz	24250 MHz – 27500 MHz	TDD	3250 MHz (3.25 GHz)
n260	37000 MHz – 40000 MHz	37000 MHz – 40000 MHz	TDD	3000 MHz (3 GHz)
n261	27500 MHz – 28350 MHz	27500 MHz – 28350 MHz	TDD	850 MHz

5G needs large amounts of bandwidth?

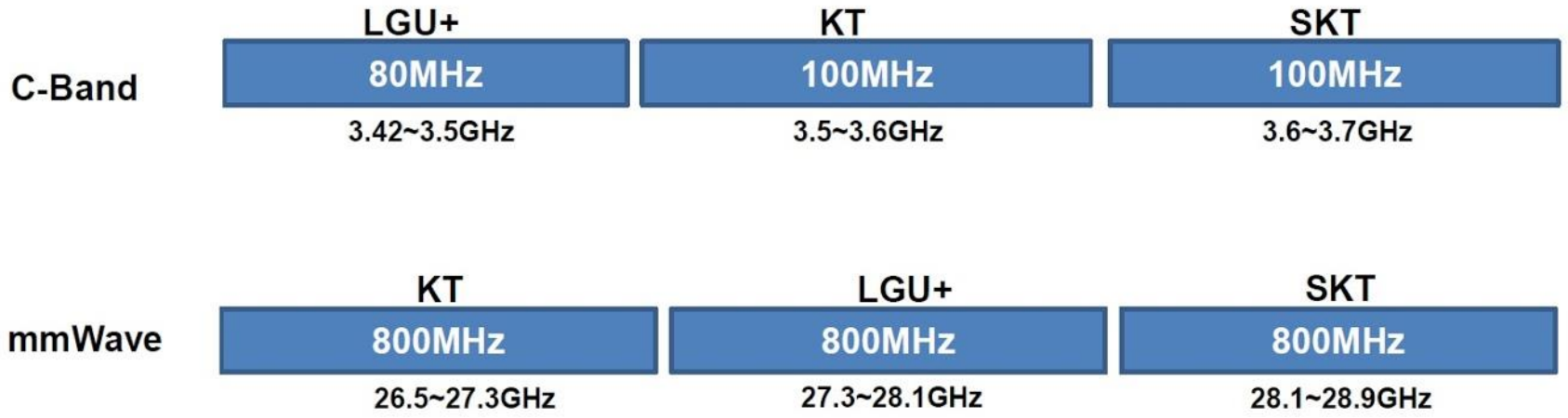
Table 5.3.5-1: Channel bandwidths for each NR band

Operating band / SCS / UE channel bandwidth					
Operating band	**SCS kHz**	**50 MHz**	**100 MHz**	**200 MHz**	**400 MHz**
n257	60	Yes	Yes	Yes	
	120	Yes	Yes	Yes	Yes
n258	60	Yes	Yes	Yes	
	120	Yes	Yes	Yes	Yes
n260	60	Yes	Yes	Yes	
	120	Yes	Yes	Yes	Yes
n261	60	Yes	Yes	Yes	
	120	Yes	Yes	Yes	Yes

5G Spectrum Plans / Allocation – South Korea

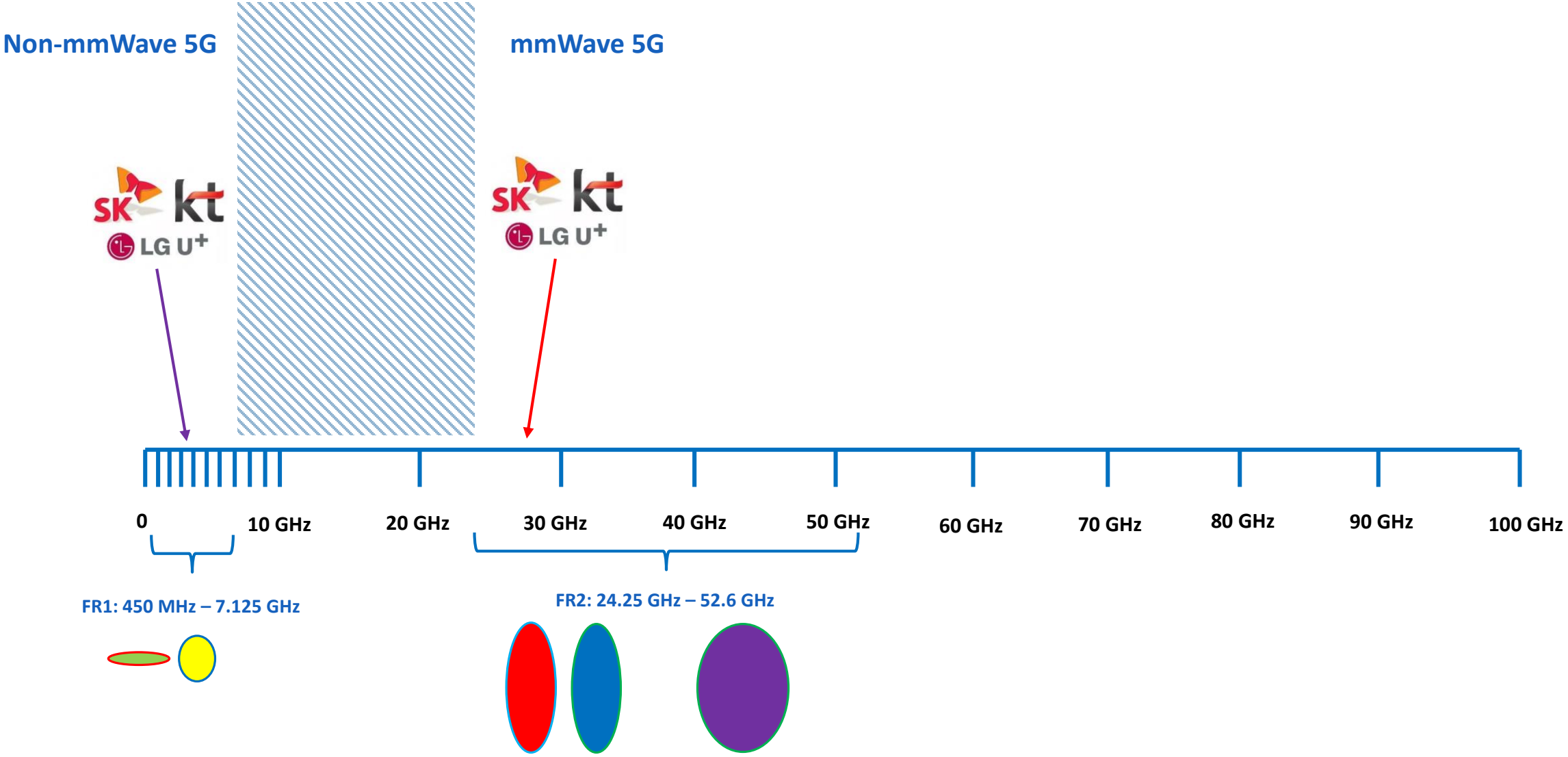
Korea: finish C Bands and mmWave Auction

Band plan according to the auction in June, 2018

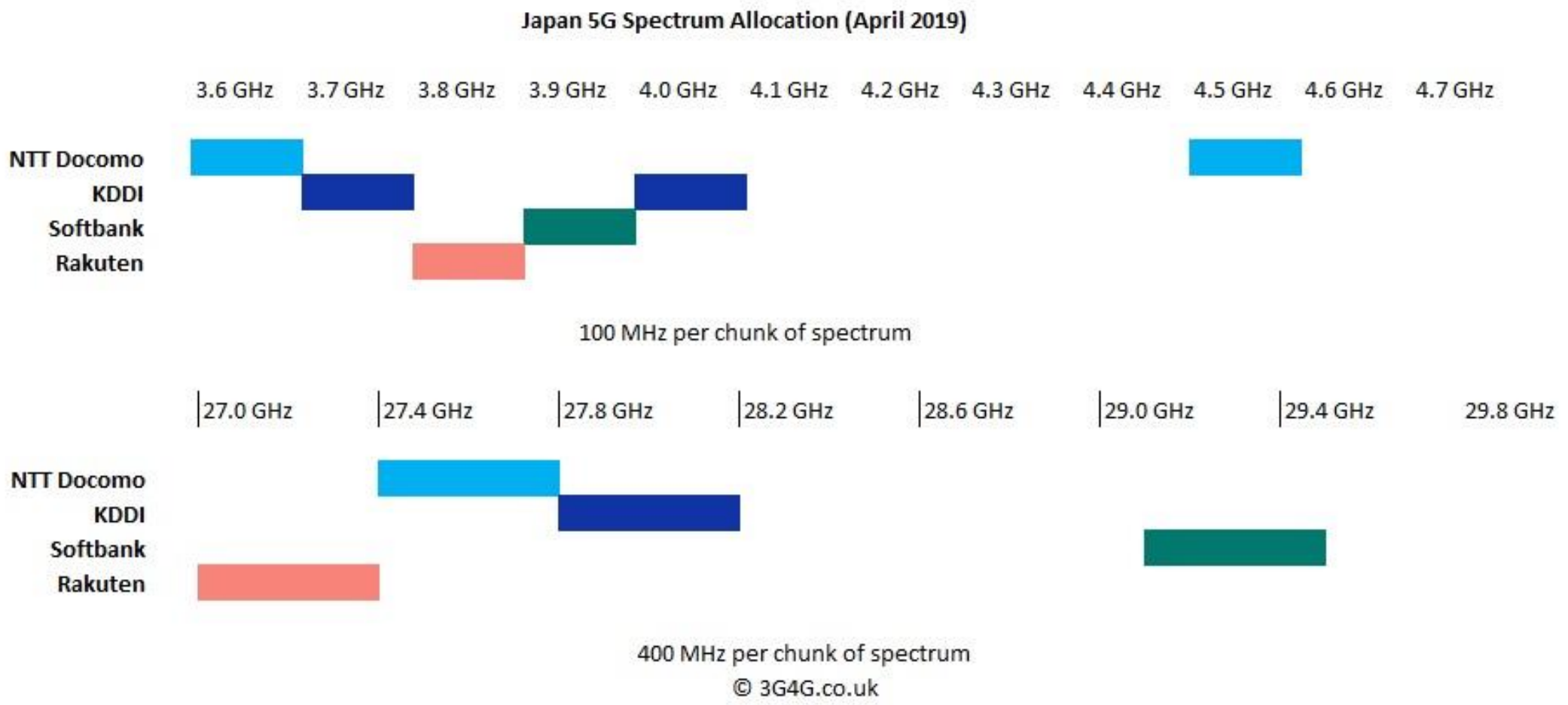


Further Reading: [Operator Watch Blog]

South Korea: Both non-mmWave & mmWave 5G

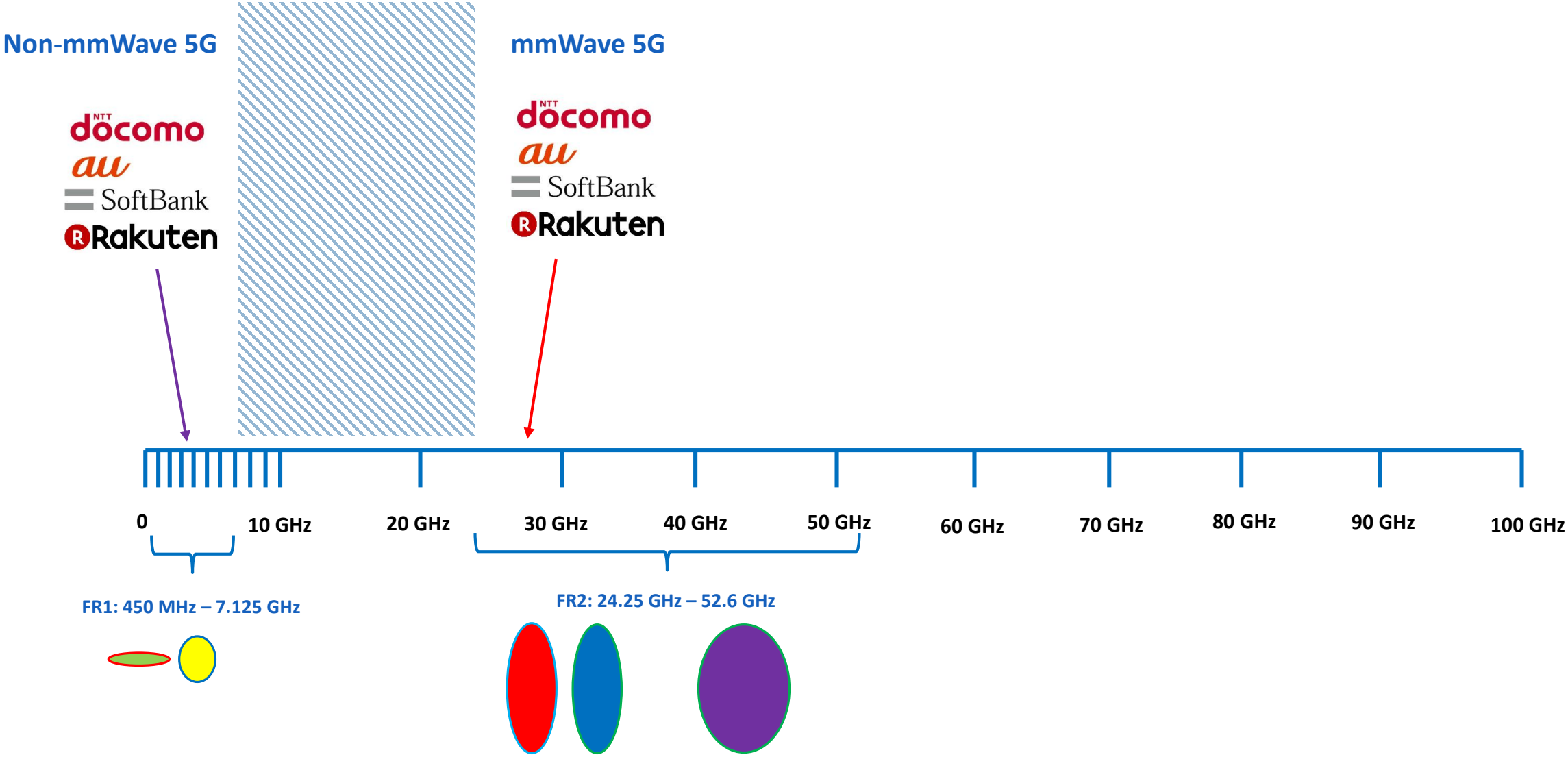


5G Spectrum Plans / Allocation – Japan



Further Reading: [Operator Watch Blog]

Japan: Both non-mmWave & mmWave 5G



5G Spectrum Plans / Allocation – Italy

Final award prices

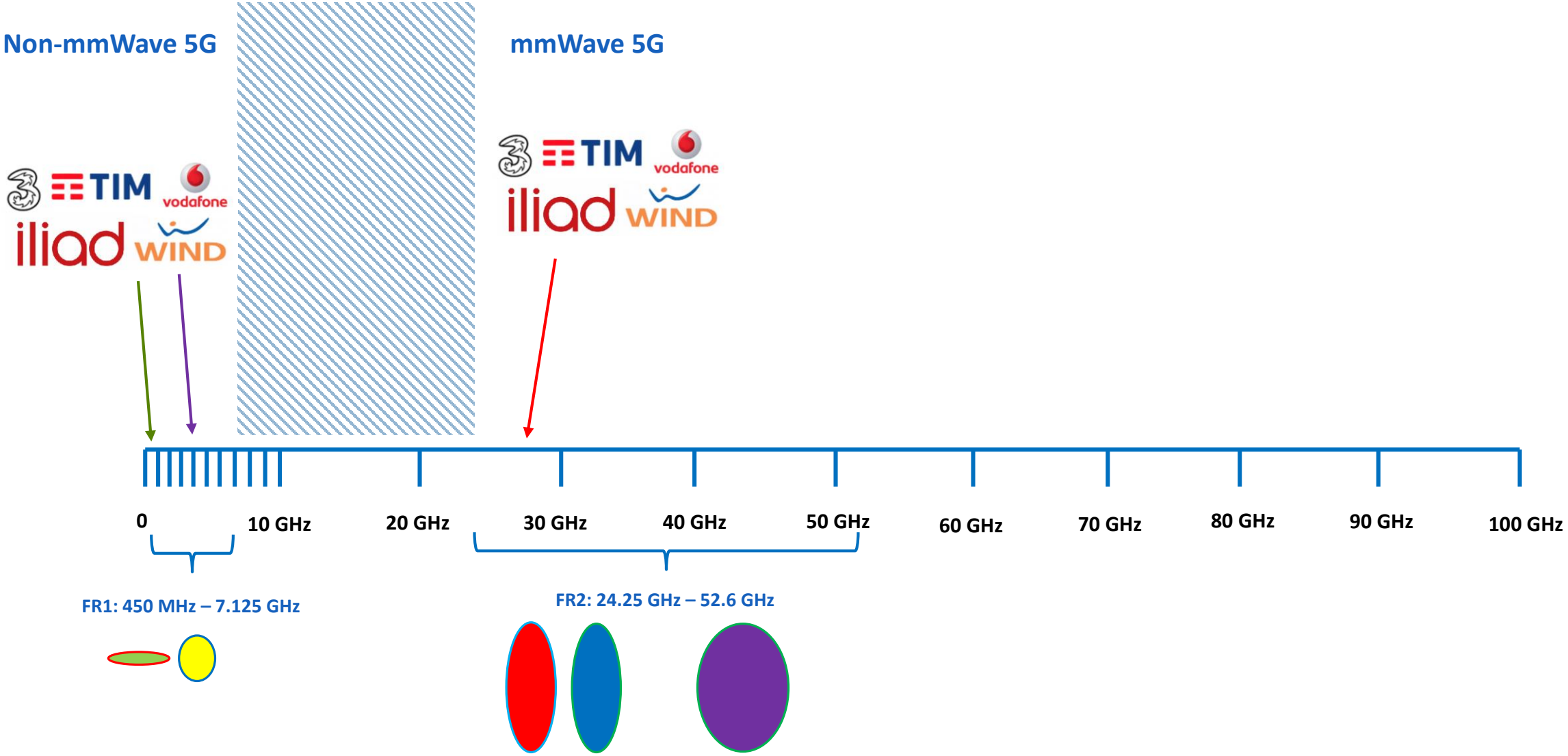
Band	Lot	Spectrum [MHz]	Winner	Price [€]	+% *vs* reserve price
700 MHz FDD	700_R	2x10	Iliad	676.472.792	0%
	700_FDD	2x5	Vodafone	345.000.000	2%
	700_FDD	2x5	Vodafone	338.236.396	0%
	700_FDD	2x5	TIM	340.100.000	0,6%
	700_FDD	2x5	TIM	340.100.000	0,6%
		2x30		***2.039.909.188***	***0,52%***
3.7 GHz	3700_C1	80	TIM	1.694.000.000	970%
	3700_C2	80	Vodafone	1.685.000.000	962%
	3700_C3	20	Wind Tre	483.920.000	1120%
	3700_C4	20	Iliad	483.900.000	1120%
		200		***4.346.820.000***	***997%***
26 GHz	26G	200	TIM	33.020.000	1,3%
	26G	200	Iliad	32.900.000	1,0%
	26G	200	Fastweb	32.600.000	0,04%
	26G	200	Wind Tre	32.586.535	0%
	26G	200	Vodafone	32.586.535	0%
		1000		**163.693.070**	**0,5%**
ALL		***1260***		**6.550.422.258**	**162,0%**

Mauro Martino

AGCOM

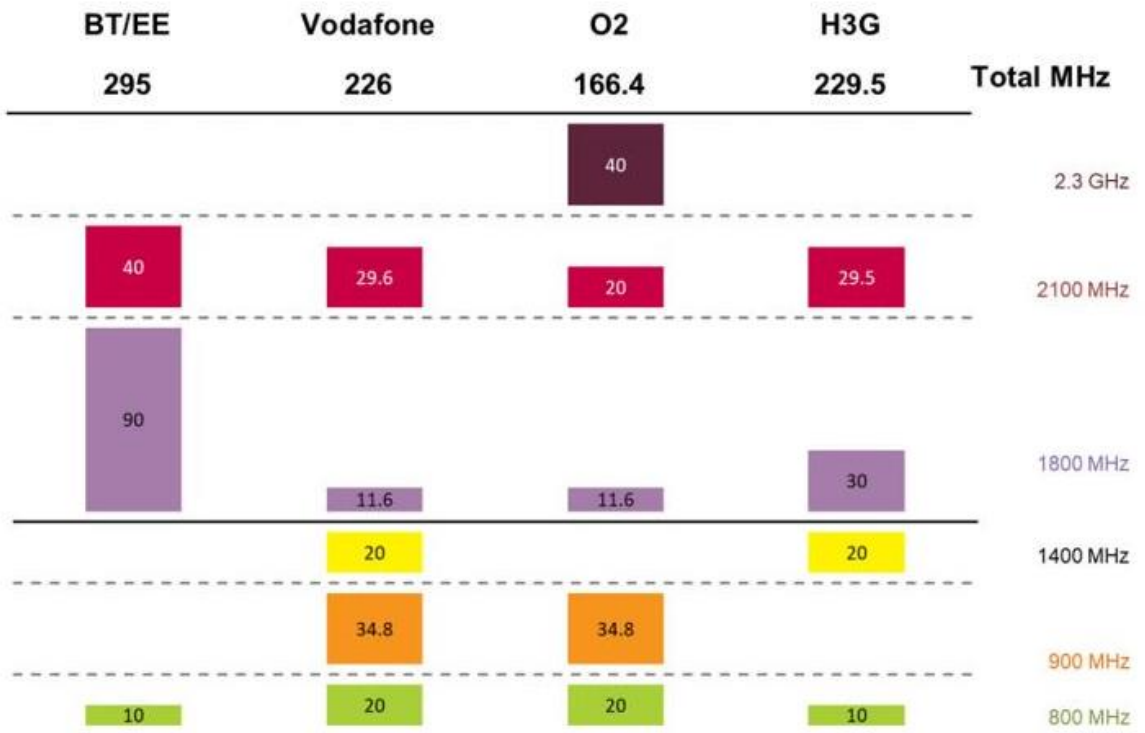
Source

Italy: Both non-mmWave & mmWave 5G



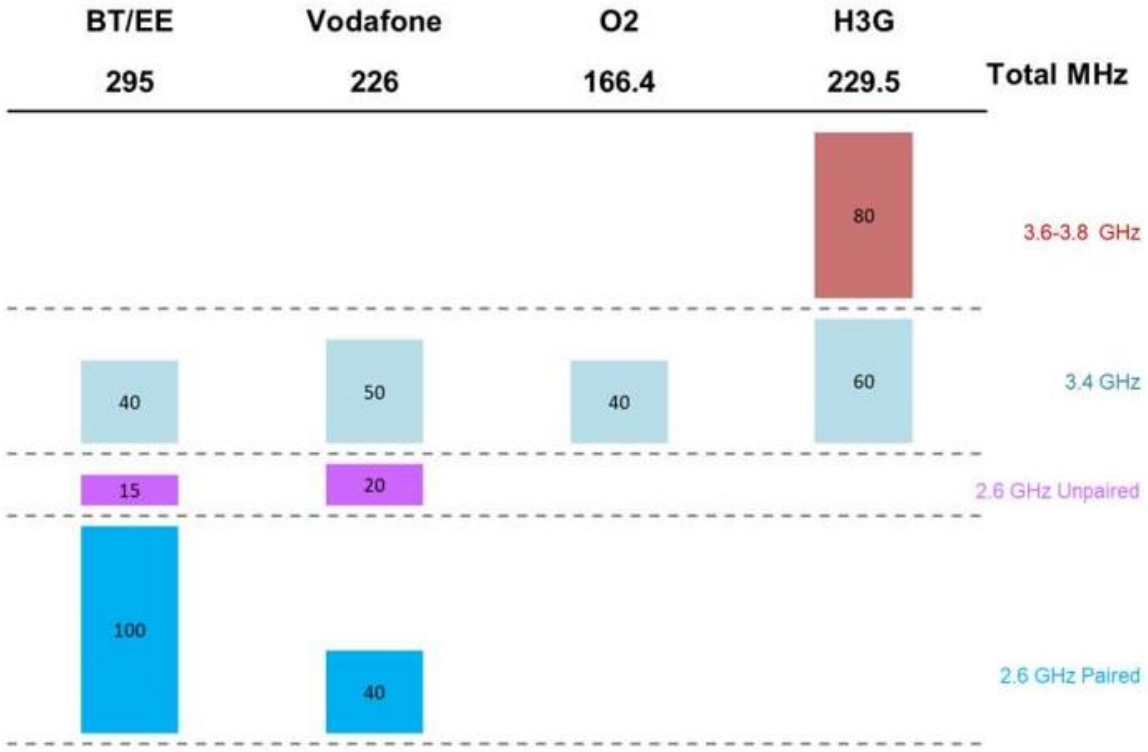
UK mobile spectrum holdings (present)

Figure 5.2: UK mobile spectrum holdings[82]



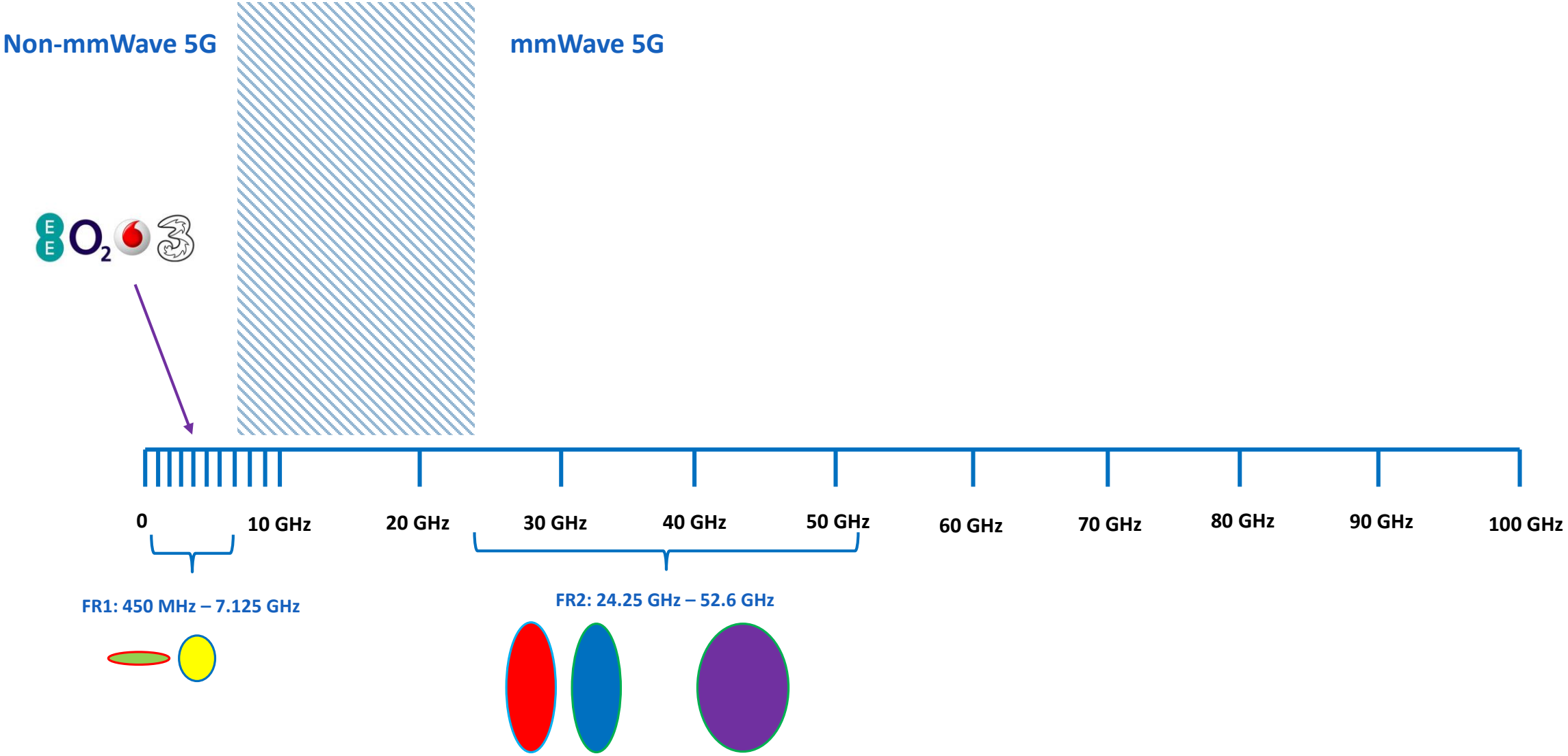
Total amount of spectrum with MNOs = **919.9 MHz**

Figure 5.2: UK mobile spectrum holdings[82]

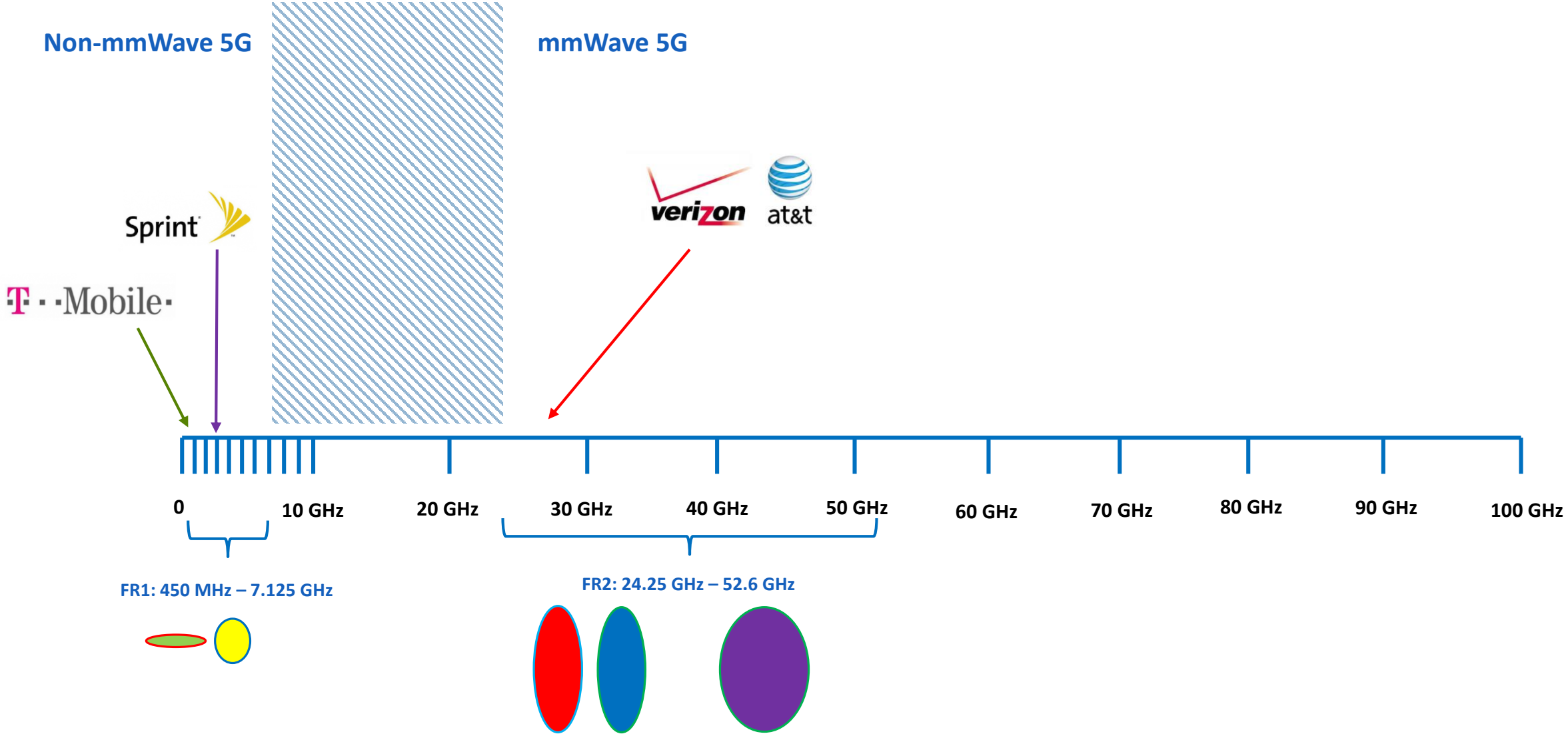


Source: Ofcom

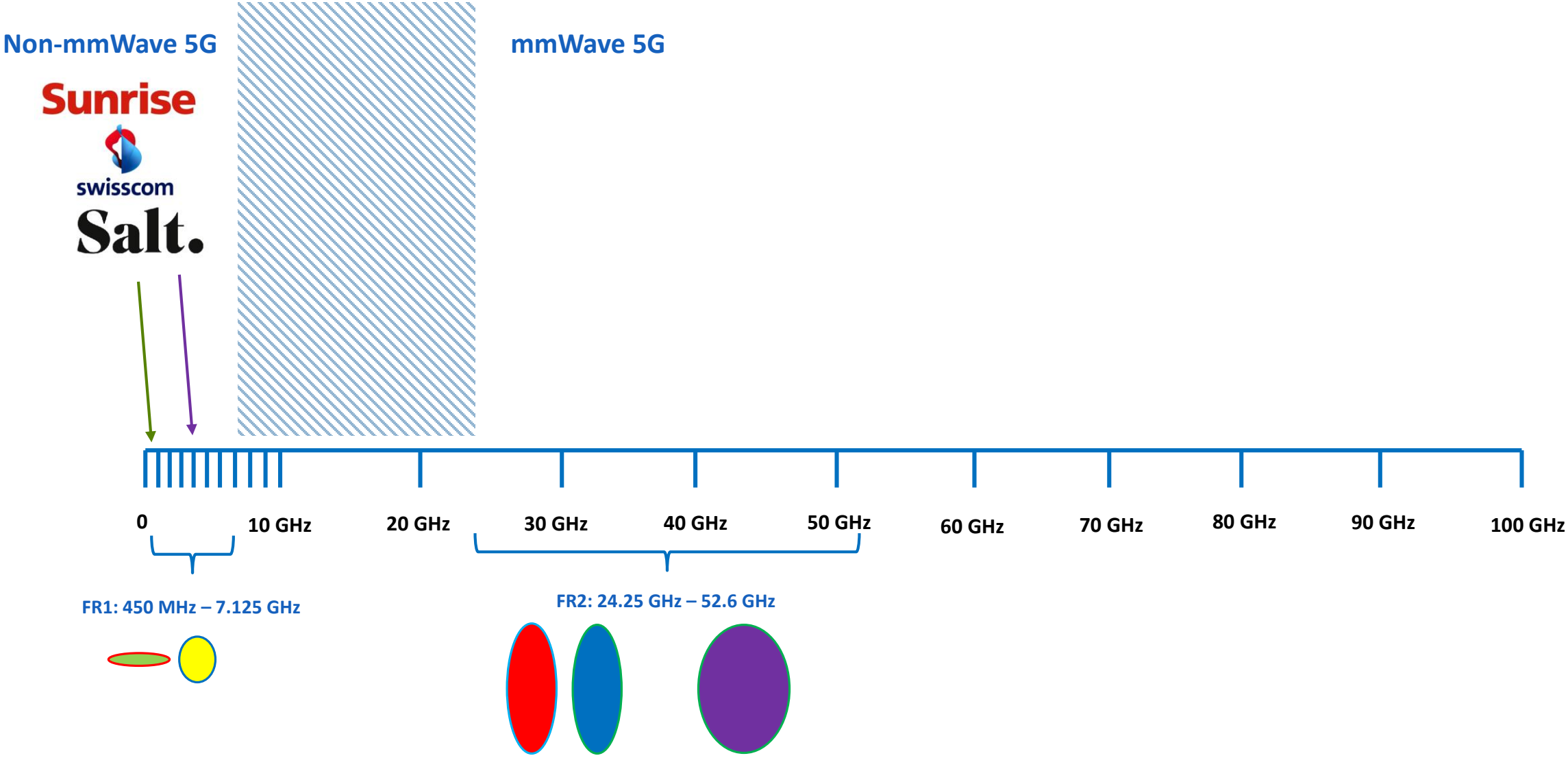
UK: Only non-mmWave 5G right now



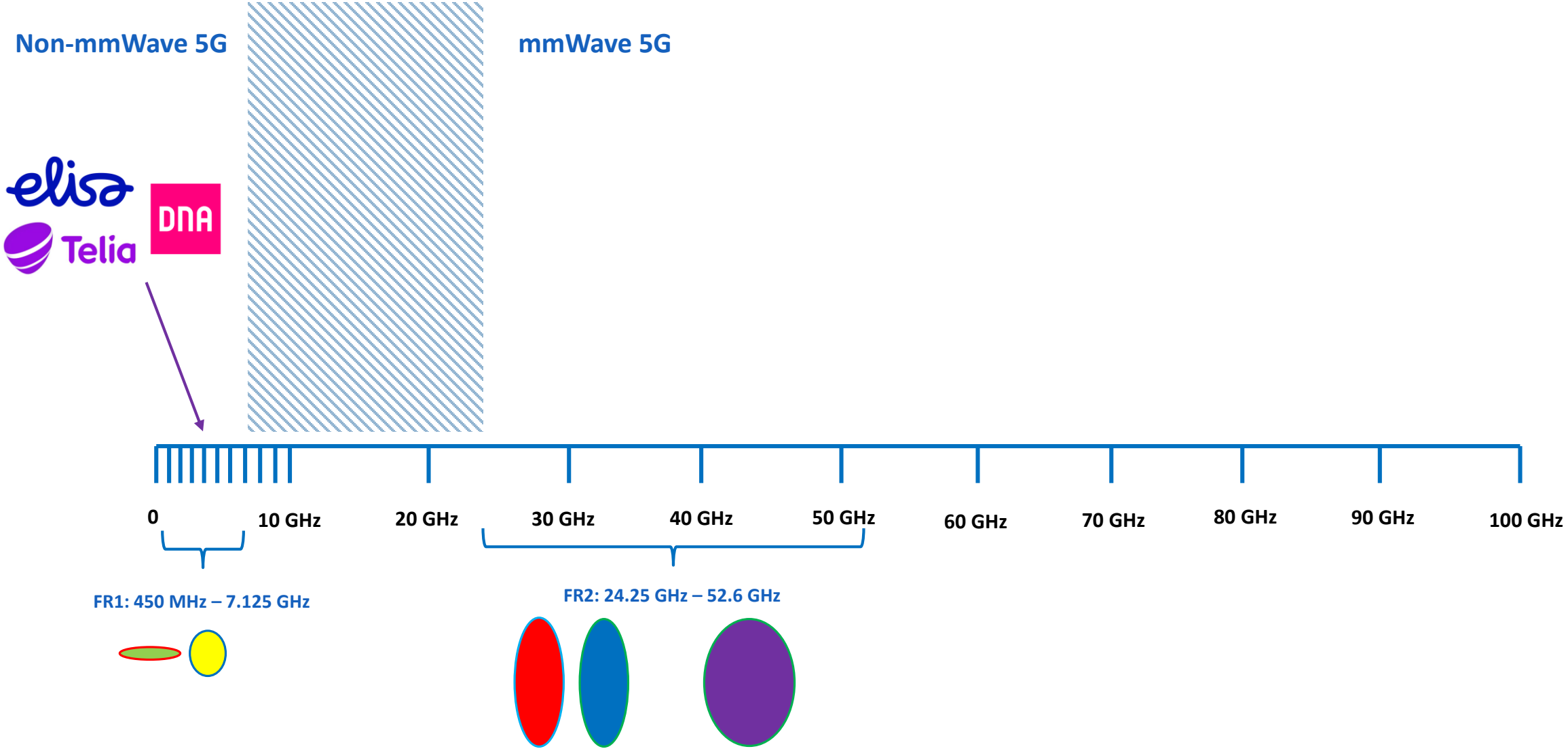
USA: Mix of mmWave & non-mmWave



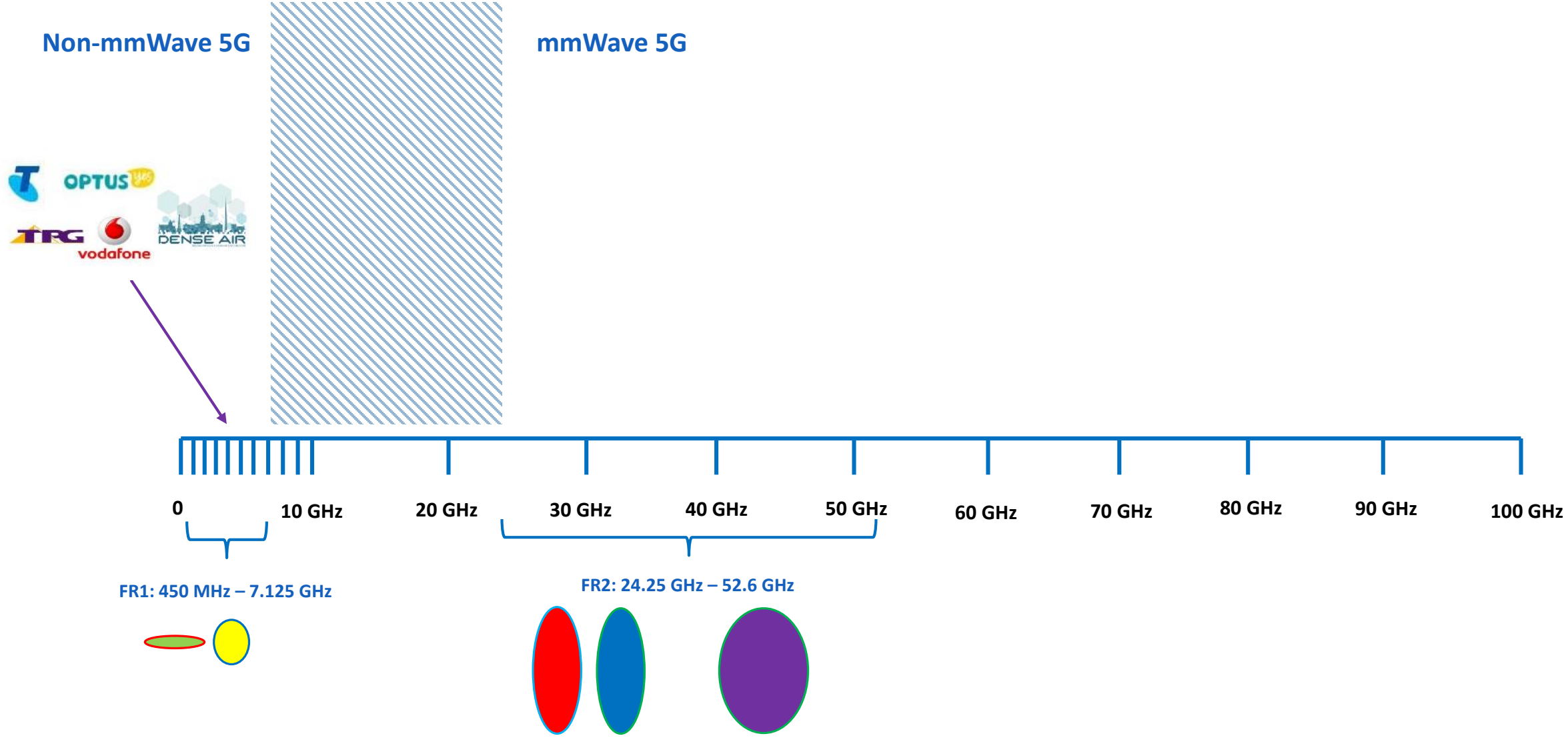
Switzerland: Only non-mmWave 5G right now



Finland: Only non-mmWave 5G right now



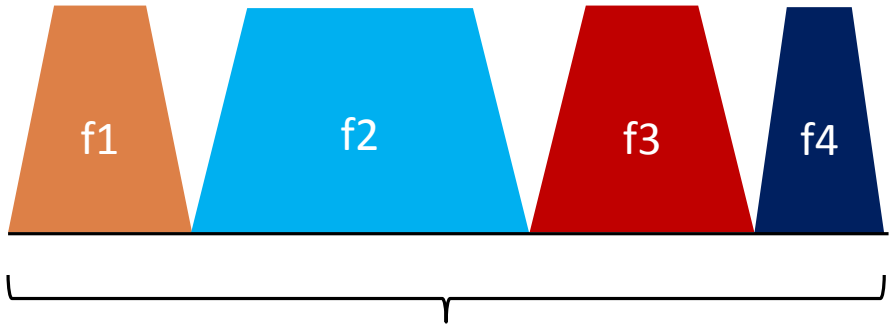
Australia: Only non-mmWave 5G right now



5G Spectrum Challenge

- In theory

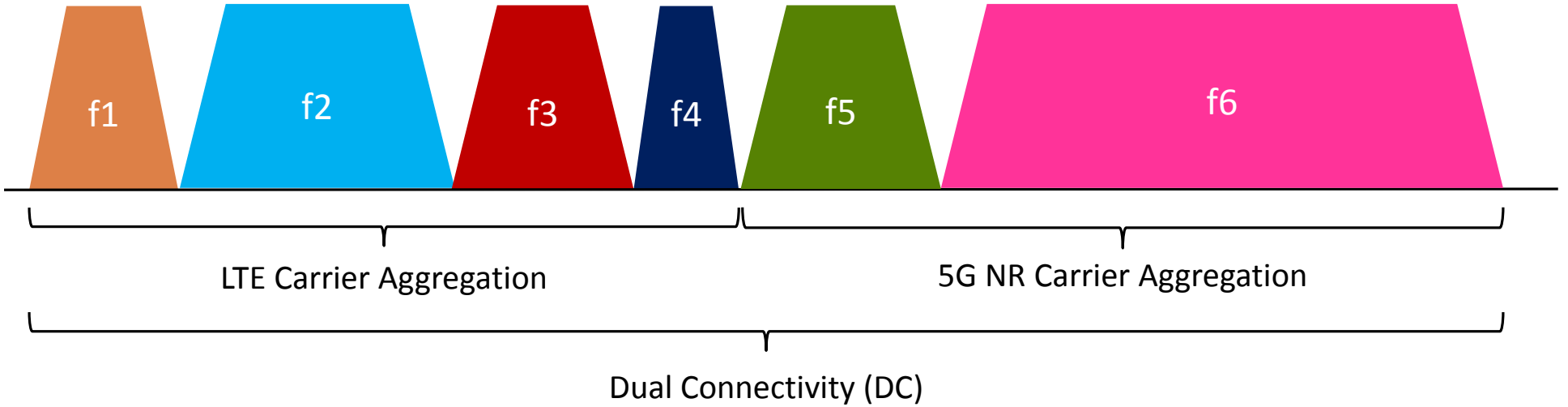
4G / LTE



While LTE-A supported up to 5 Component Carriers (CC), each with a max of 20 MHz for Carrier Aggregation, LTE-A Pro supports 32 CCs

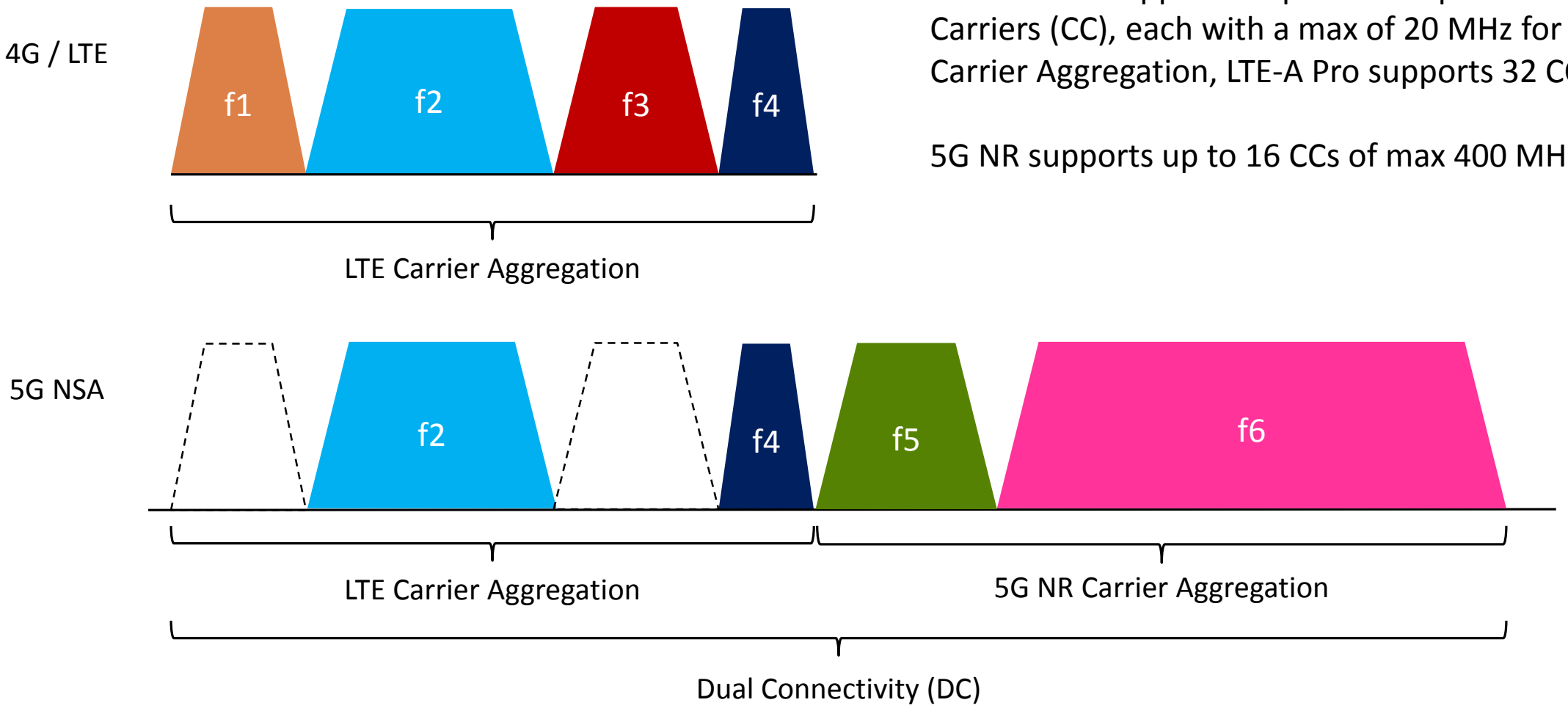
5G NR supports up to 16 CCs of max 400 MHz

5G NSA



5G Spectrum Challenge

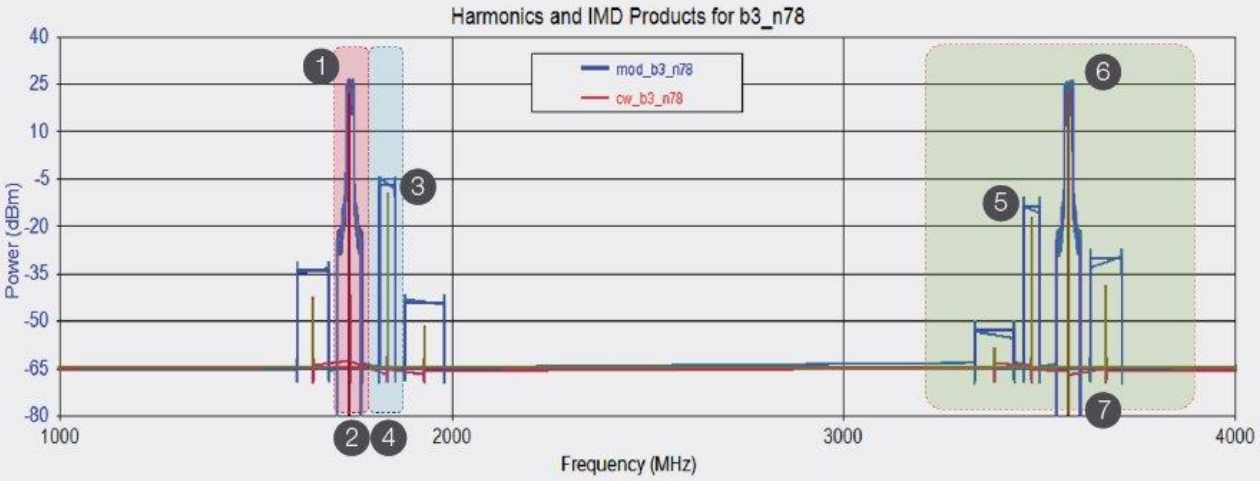
- In practice



While LTE-A supported up to 5 Component Carriers (CC), each with a max of 20 MHz for Carrier Aggregation, LTE-A Pro supports 32 CCs

5G NR supports up to 16 CCs of max 400 MHz

5G Spectrum Challenge – Interference

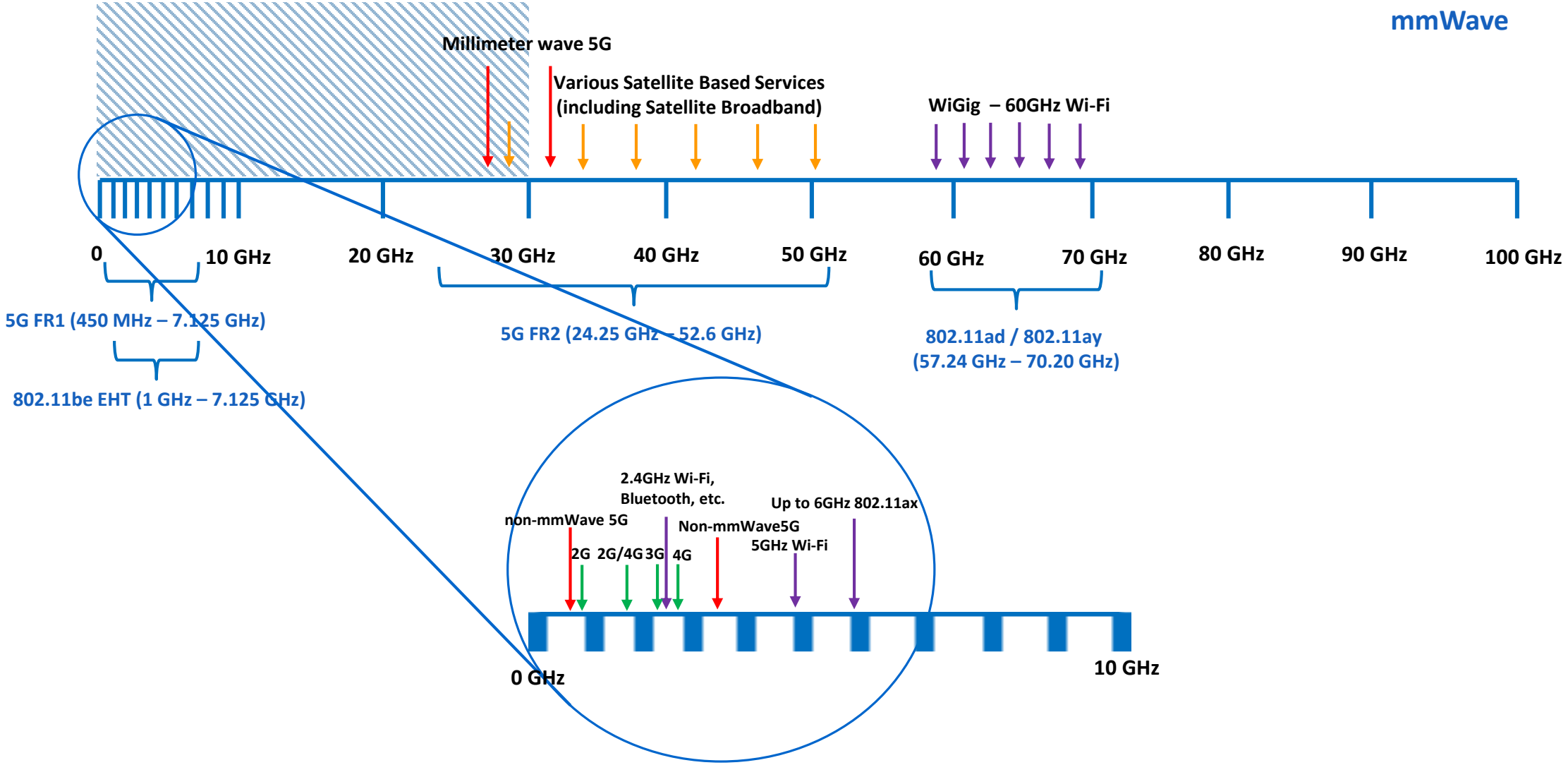


1. b3 uplink signal 1740 MHz
2. b3 uplink band 1710 MHz ~ 1785 MHz
3. IMD's landing on b3 receive frequency 1835 MHz
4. b3 downlink band 1805 MHz ~ 1880 MHz
5. IMD product at 3480 MHz, self-interference for the TDD band?
6. n78 TDD band 3300 MHz ~ 3800 MHz
7. n78 uplink signal 3575 MHz

Figure 3a: Intermodulation and harmonic analysis with two modulated signals at 1740 MHz and 3575 MHz.

- With so many different bands in use, there is a small possibility of interference between them
- A recent whitepaper from Keysight points out that the 5G Uplink transmission in 3.5 GHz band might significantly interfere with 4G in the 1.8 GHz band in downlink direction. Maybe bad news, especially in Europe, where these are heavily used

Popular mmWave Frequency bands for different Technologies



Satellite Services using frequencies above 10 GHz

- Satellite TV is deployed into Ku-band between 8 GHz and 12 GHz (predominantly between 11.7 and 12.7 GHz, which is what most of us watch at home), and in Ka-band at 18.3–18.8 GHz and 19.7–20.2 GHz.
  - The Ka-band allocation (18.3–18.8 GHz + 19.7–20.2 GHz) is used for superhigh-definition and ultra-high definition TV.
- V-band and W-band are used heavily for Military, Commercial, and Automotive Radar
- Satellite Operator Avanti uses Ka band extensively (up to 31 GHz) for providing connectivity to Defence aircrafts, Enterprises, Consumer Broadband and Cellular Backhaul
- Many of the new LEO satellite constellations like OneWeb, O3b, etc. have proposed to use mmWave spectrum as all other spectrum bands are congested and large chunks of contiguous spectrum are not otherwise available

Further Reading on this topic: *'5G and Satellite Spectrum, Standards, and Scale' by Geoff Varrall*

mmWave use for Mobile Backhaul

- Mobile backhaul makes extensive use of frequencies above 10 GHz
- V-Band and E-Band are used extensively today, with D-Band and W-Band primed for future use.

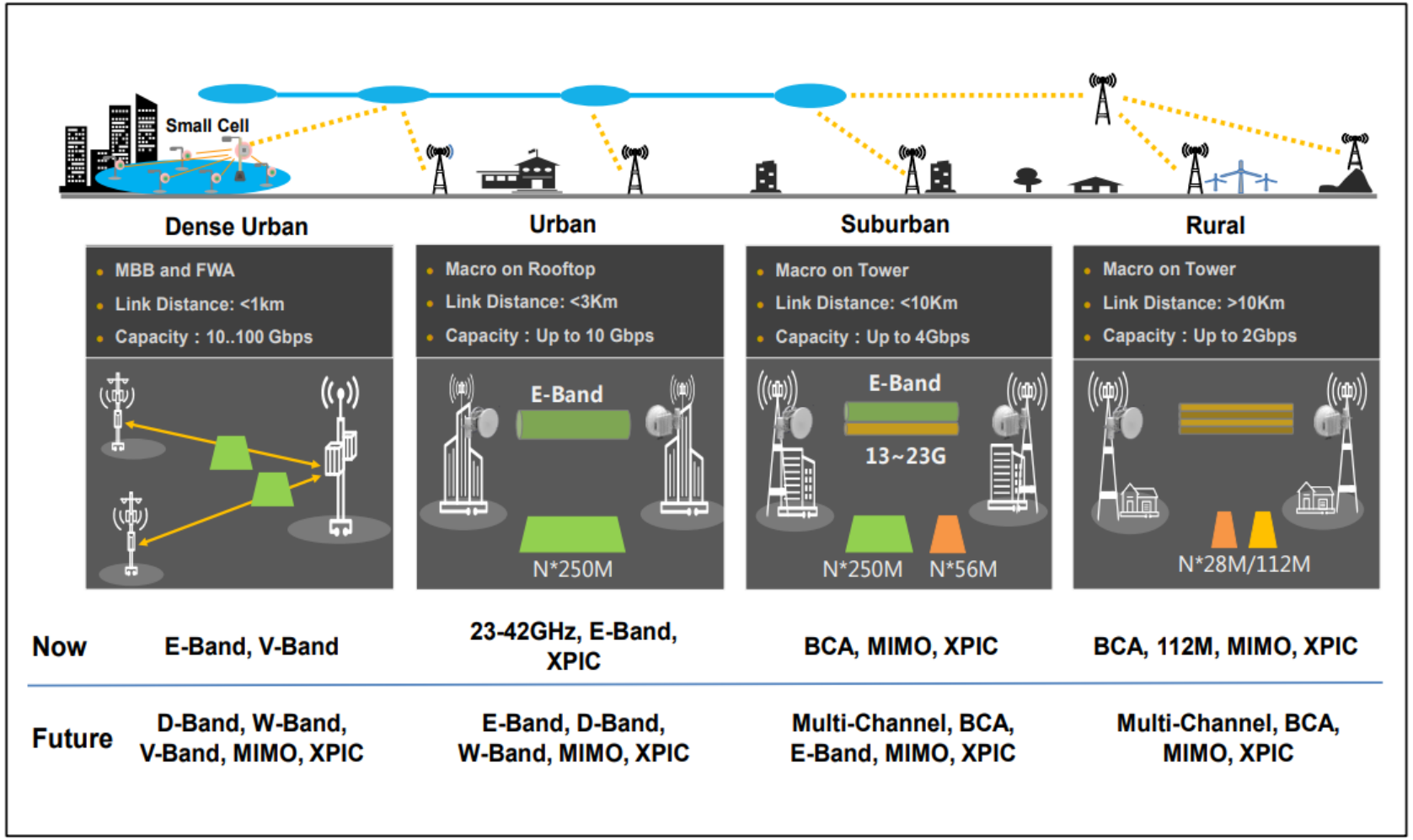


Figure 6 – Microwave technology per network segment

Further Reading:

- ETSI White Paper No. 25: Microwave and Millimetre wave for 5G Transport
- GSMA Mobile backhaul options: Spectrum analysis and recommendations

Summary

- There are three types of 5G bands; Coverage Layer, Capacity Layer and High Throughput Layer that is needed for an ideal 5G rollout
- In terms of frequency, there is non-mmWave 5G and mmWave 5G.
  - Most of the initial rollouts is mainly non-mmWave 5G
  - mmWave 5G will only be available in Urban and Dense-urban areas, not everywhere
- 5G could be rolled out in existing frequency bands by re-farming the spectrum
- While in theory 5G needs large amounts of bandwidth, there is no reason why 5G can’t be rolled out with small bandwidths
- mmWave spectrum is already in use today and it will be complemented by 5G rollouts in that spectrum as well soon.

Thank You

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