Spectrum – they don't make it any new one any more

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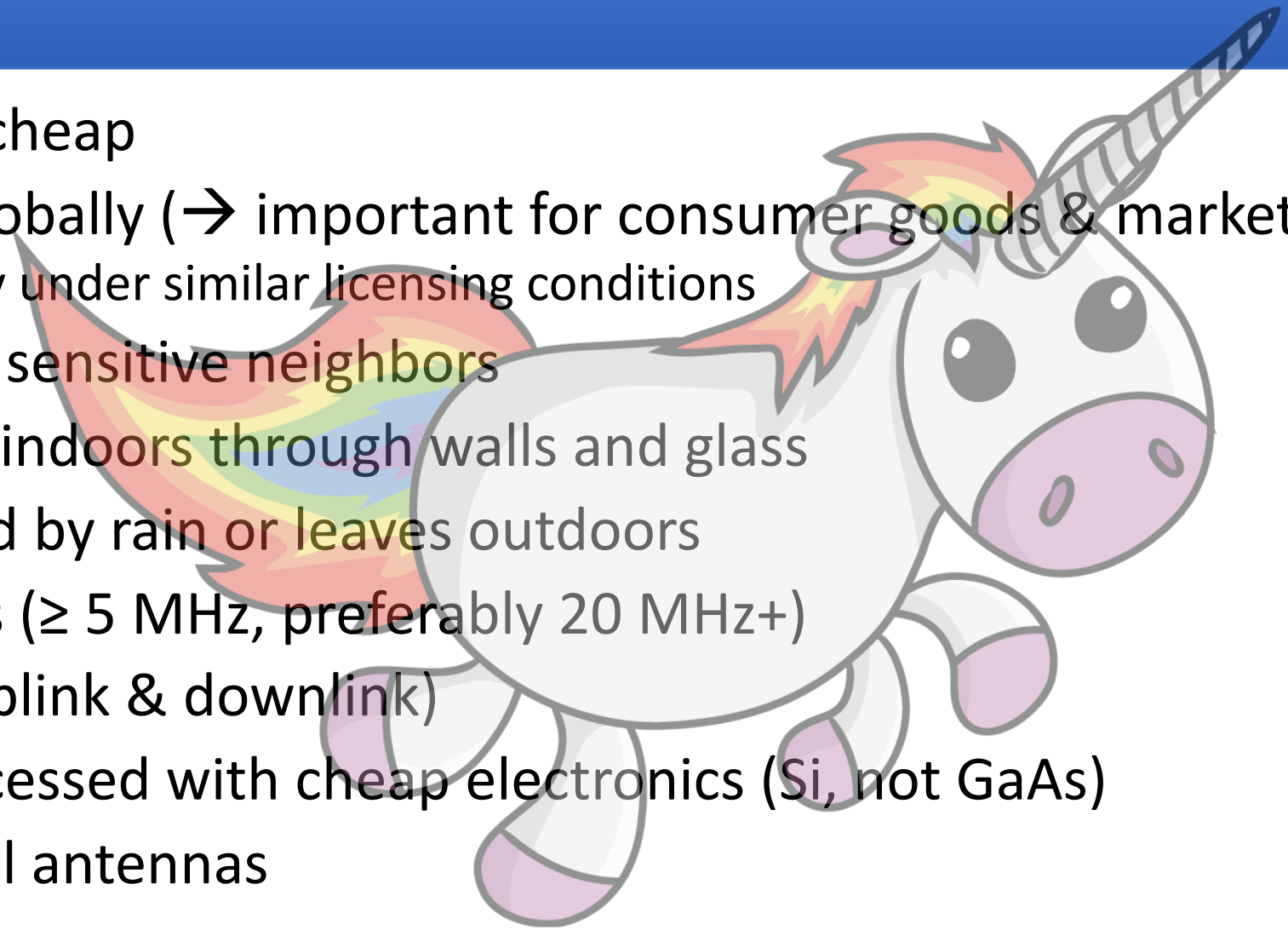
Ideal spectrum

- Unused or cheap
- Available globally (→ important for consumer goods & market size)
  - preferably under similar licensing conditions
- No noisy or sensitive neighbors
- Propagates indoors through walls and glass
- Not affected by rain or leaves outdoors
- Wide bands (≥ 5 MHz, preferably 20 MHz+)
- Is paired (uplink & downlink)
- Can be processed with cheap electronics (Si, not GaAs)
- Allows small antennas



Spectrum management

Until the 2000s

- Single purpose
- Fixed technology (modulation)
- Exclusive use
- Narrow bands (except TV)
- Assume single radio per device
  - one frequency at a time
- Worry mostly about OOB to like
- Spectral efficiency secondary
- Single-country
- mostly outdoor

“Modern”

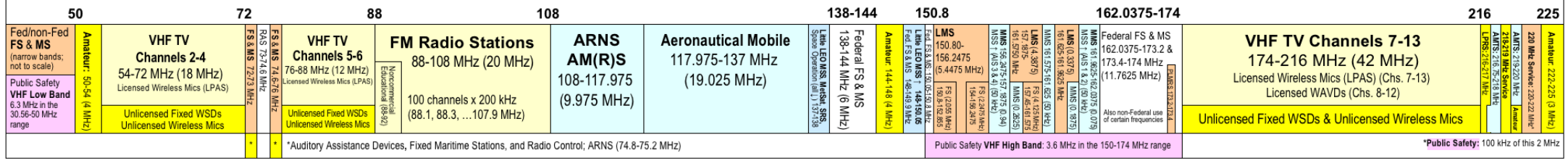
- Flexible use
- Flexible technology
- Shared, over/underlay
- At least 5 MHz, preferably 100
- Multiple (> 4) radios, from 0.6 to 6 GHz
- Receiver requirements?
- Spectral efficiency matters
- International coordination
- mostly indoor (80% of data)

Selected VHF, UHF, and SHF Frequency Bands

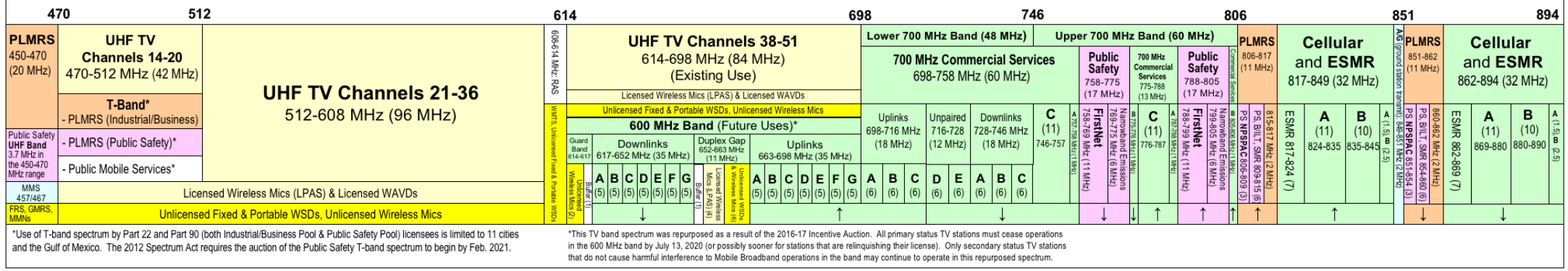
(Reverse side includes key and additional frequency bands)

Federal Communications Commission
Office of Engineering and Technology
October 16, 2017

30.56-225 MHz (194.44 MHz):



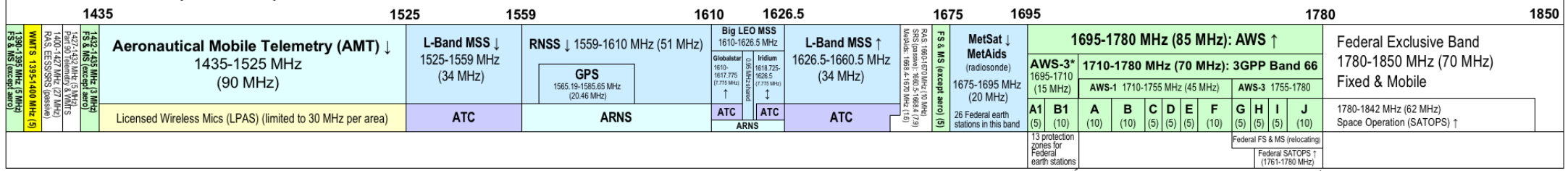
450-894 MHz (444 MHz):



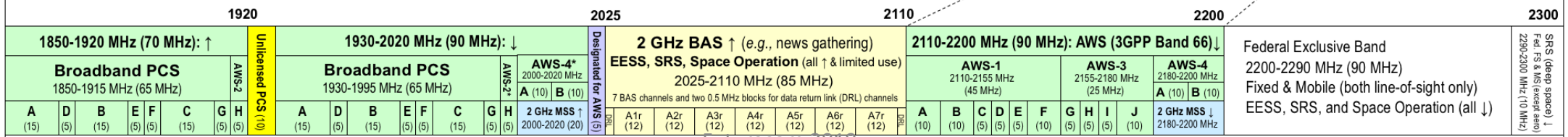
*Use of T-band spectrum by Part 22 and Part 90 (both Industrial/Business Pool & Public Safety Pool) licensees is limited to 11 cities and the Gulf of Mexico. The 2012 Spectrum Act requires the auction of the Public Safety T-band spectrum to begin by Feb. 2021.

*This TV band spectrum was repurposed as a result of the 2016-17 Incentive Auction. All primary status TV stations must cease operations in the 600 MHz band by July 13, 2020 (or possibly sooner for stations that are relinquishing their license). Only secondary status TV stations that do not cause harmful interference to Mobile Broadband operations in the band may continue to operate in this repurposed spectrum.

1390-1850 MHz (460 MHz):

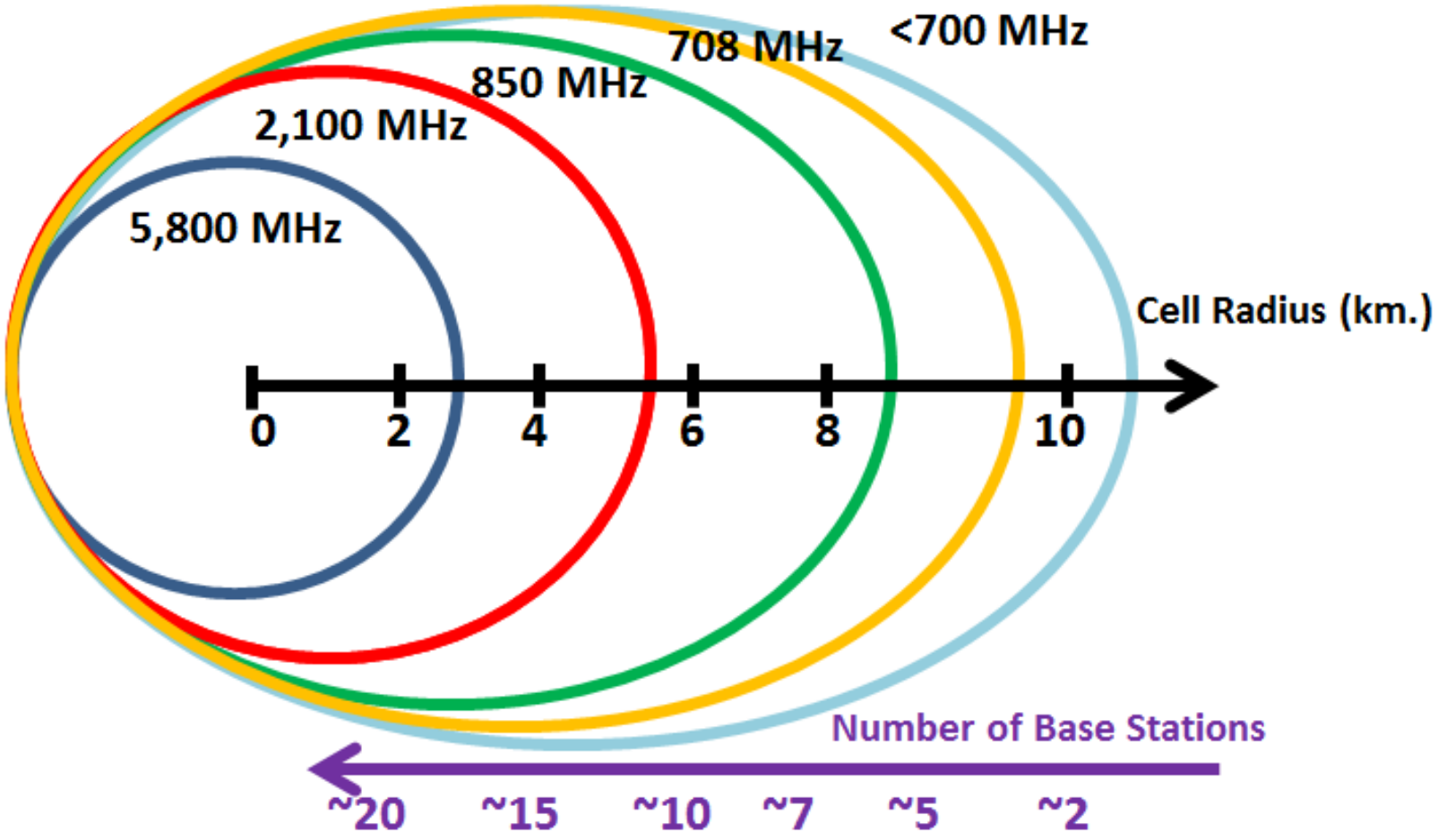


1850-2300 MHz (450 MHz):



* 3GPP Band 70: 1695-1710 MHz uplink (15 MHz); 1995-2020 MHz downlink (25 MHz)

Higher frequency = capacity, but more cells



high-band

- > 6 GHz
- urban & indoor capacity for 5G

mid-band

- 1-6 GHz
- capacity for 4G & 5G

low-band

- 400 MHz - 1 GHz
- rural coverage

Do more with more or less

Action	Advantage	Drawback
Buy more spectrum (auction or private)	scales linearly investment property	scales linearly expensive timing & location unpredictable rely on competitors
Better technology (modulation, power, bidirectional, massive MIMO)	cheap	mostly played out (but 5GNR) requires densification
More cell sites	scales adaptive	costly monthly rent for sites

Challenges for spectrum sharing

Unlicensed ~2000

- indoor home
- indoor enterprise
- campus
- --> natural separation
- only power rules (no listen-before-talk (CS) required)

Unlicensed now

- secondary public SSID
  - e.g., CableWiFi
- re-use HFC/FTTH backhaul
- One band, one channel

Unlicensed emerging

- LTE-U, LAA
- what are the “kindergarten” rules?

Spectrum co-existence

"high tower, high power"
(TV, cellular downlink, radar transmitter)

vs.

- cellular downlink receiver
- radar receiver
- GPS receiver

UL TX: 24 dBm
DL TX: 43-48 dBm

TV: 90 dBm (1 MW UHF)

acquisition -138 dBm
tracking: -146 dBm

-105 dBm

how do I quickly identify sources of interference?

Beauty contests and auctions are converging

Beauty contest

- prettiest network of them all

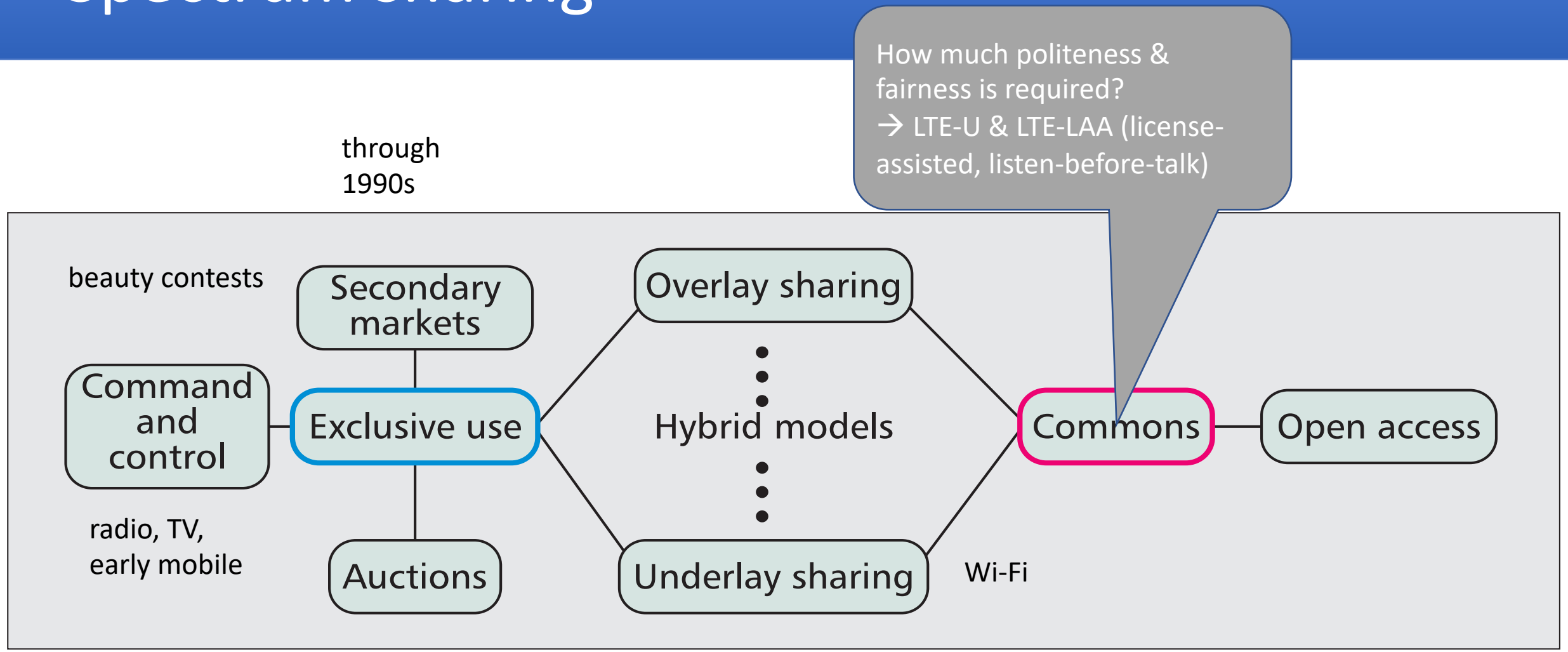
Pure auction

- use-it-or-lose it

Auction with conditions

- coverage build-out
- tower sharing
- bandwidth
- rural bidding credits
- performance credits (US USF)
- paired licenses

Spectrum sharing



US: since 1994

There are many spectrum dials

license model

blocks

geographic area

duration

build-out

“Best and highest value use”

- Metric: $ per MHz and population covered → **$/MHz/POP**
- How do you estimate the value of spectrum, beyond auction price?
  - What about public safety usage?
- No good estimate of value for unlicensed spectrum
- How do you encourage more efficient usage of existing spectrum?
  - b/s/Hz → b/s/Hz/sq mi
- Example: TV spectrum value is largely indirect
  - 10-15% watch over-the-air in the US
  - but TV stations get must-carry right and network exclusivity
- Avoid spectrum hoarding & speculation
  - foreclosure value
  - build-out & service requirements (“use it or lose it”)
  - but can create minimal networks that serve few real customers (e.g., NB-IoT)

Auctions have limitations

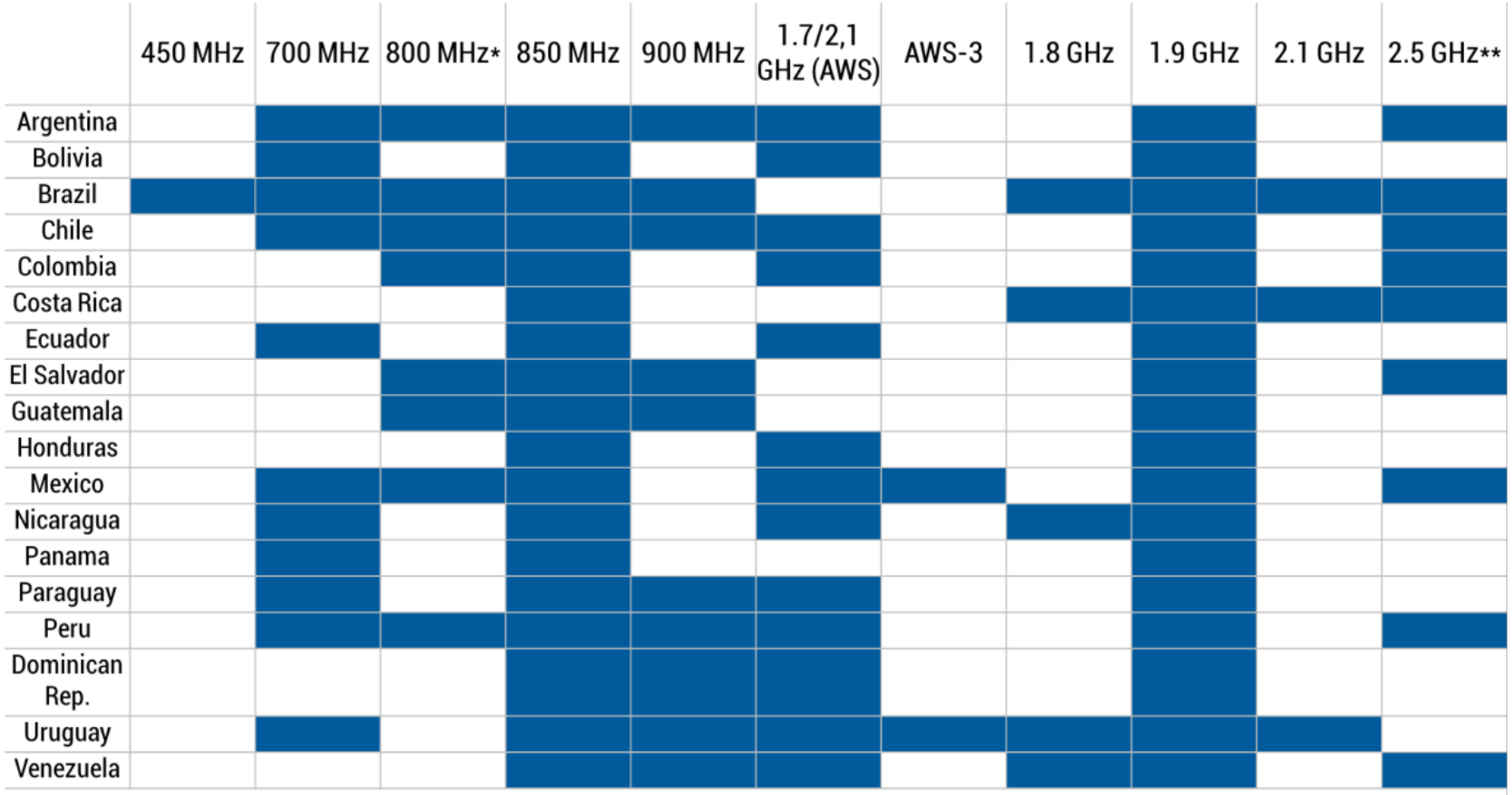
- One-time estimate of value
  - most spectrum is licensed indefinitely (renewable license)
  - technology may change value – up or down
    - e.g., small cells, MIMO
  - new neighbors may change value
- May encourage speculation
  - build-out requirements help (and common), but can be 3-10 years
- Relies on small (3-4) number of carriers
  - only subscription model
  - how do you aggregate the value of 5.8 GHz spectrum?
- Likely necessary where spectrum requires nationwide multi-$B investment

Unlicensed & lightly-licensed bands (US)

- UHF (476-700 MHz) – incentive auctions (licensed) + some unlicensed + TV white spaces
- ISM (902-908 MHz) – BlueTooth
- 1920-1930 MHz – cordless phones (DECT)
- 2.4 GHz (73 MHz) – 802.11b/g
- 3.550 GHz (150 MHz) – shared, database
- 3.6 GHz (100 MHz) – for backhaul & WISPs
- 4.9 GHz (50 MHz) – public safety; under reconsideration
- 5.8 GHz (400 MHz) – 802.11 a/n
- 5.9 GHz (1.2 GHz) – discussed by FCC (used for backhaul today)

Mobile spectrum in Latin America

Mobile Spectrum Allocations in Latin America (September 2018)



	450 MHz	700 MHz	800 MHz*	850 MHz	900 MHz	1.7/2,1 GHz (AWS)	AWS-3	1.8 GHz	1.9 GHz	2.1 GHz	2.5 GHz**
Argentina		■	■	■	■	■			■		■
Bolivia		■		■		■			■		
Brazil	■	■	■	■	■			■	■	■	■
Chile		■	■	■	■	■			■		■
Colombia			■	■		■			■		■
Costa Rica				■				■	■	■	■
Ecuador		■		■		■			■		
El Salvador			■	■	■				■		■
Guatemala			■	■	■				■		
Honduras				■		■			■		
Mexico		■	■	■		■	■		■		■
Nicaragua		■		■		■		■	■		
Panama		■		■					■		
Paraguay		■		■	■	■			■		
Peru		■	■	■	■	■			■		■
Dominican Rep.				■	■	■			■		
Uruguay		■		■	■	■	■	■	■	■	
Venezuela				■	■	■		■	■		■

*Originally used for iDEN deployments in the region, the band is being refarmed in Argentina, Brazil, Chile, Mexico and Peru.
**In Peru, one operator acquired a group of fixed service providers and their 2.5 GHz licenses. Another mobile operator holds regional 2.5 GHz licenses, but the band will be reorganized for an upcoming auction. In Paraguay, a mobile operator agreed to return spectrum from the 2.5 GHz band after acquiring a fixed service provider.

5G Americas

ITU mobile spectrum recommendations

ITU Recommendations: spectrum allocation for the development of IMT and IMT-Advanced technologies

Market environment	Spectrum Requirement for RATG 1 (MHz)			Spectrum Requirement for RATG 2 (MHz)			Total Spectrum Requirement (MHz)		
Year	2010	2015	2020	2010	2015	2020	2010	2015	2020
Higher market environment	840	880	880	0	420	840	840	1300	1720
Lower market environment	760	800	800	0	500	480	760	1300	1280

Source: International Telecommunication Union (ITU-R M.2078 and ITU-R M.2290)

RATG1 = pre-IMT, IMT; RATG2 = IMT-advanced

Spectrum allocation in Latin America

Percentage of Spectrum Allocated according to the ITU Recommendation for 2015 and 2020

Country	Spectrum (MHz)	2015 Goal	2020 Goal (high scenario)	2020 Goal (low scenario)
Argentina	390	30.0%	19.9%	29.1%
Bolivia	284	21.8%	14.5%	21.2%
Brazil	609	46.8%	31.1%	45.4%
Chile	490	37.7%	25.0%	36.6%
Colombia	362.5	27.9%	18.5%	27.1%
Costa Rica	400	30.8%	20.4%	29.9%
Ecuador	290	22.3%	14.8%	21.6%
El Salvador	244	18.8%	12.4%	18.2%
Guatemala	210.6	16.2%	10.7%	15.7%
Honduras	290	22.3%	14.8%	21.6%
Mexico	584.3	44.9%	29.8%	43.6%
Nicaragua	420	32.3%	21.4%	31.3%
Panama	240	18.5%	12.2%	17.9%
Paraguay	350	26.9%	17.9%	26.1%
Peru	394.4	30.3%	20.1%	29.4%
Dominican Republic	270	20.8%	13.8%	20.1%
Uruguay	395	30.4%	20.2%	29.5%
Venezuela	324	24.9%	16.5%	24.2%
Average	**363.8**	**28.0%**	**18.6%**	**27.1%**

Lots of radios

iPhone X
$999+

Model A1865*	FDD-LTE (Bands 1, 2, 3, 4, 5, 7, 8, 12, 13, 17, 18, 19, 20, 25, 26, 28, 29, 30, 66) TD-LTE (Bands 34, 38, 39, 40, 41) TD-SCDMA 1900 (F), 2000 (A) CDMA EV-DO Rev. A (800, 1900, 2100 MHz) UMTS/HSPA+/DC-HSDPA (850, 900, 1700/2100, 1900, 2100 MHz) GSM/EDGE (850, 900, 1800, 1900 MHz)
Model A1901* Model A1901 does not support CDMA networks, such as those used by Verizon and Sprint.	FDD-LTE (Bands 1, 2, 3, 4, 5, 7, 8, 12, 13, 17, 18, 19, 20, 25, 26, 28, 29, 30, 66) TD-LTE (Bands 34, 38, 39, 40, 41) UMTS/HSPA+/DC-HSDPA (850, 900, 1700/2100, 1900, 2100 MHz) GSM/EDGE (850, 900, 1800, 1900 MHz)
All models	802.11ac Wi-Fi with MIMO Bluetooth 5.0 wireless technology NFC with reader mode

Moto G5 Plus
$220

Technology	GSM / CDMA / HSPA / EVDO / LTE COLLAPSE ▲
2G bands	GSM 850 / 900 / 1800 / 1900 - SIM 1 & SIM 2 (dual-SIM model only)
	CDMA 800 / 1900 - XT1687 (USA)
3G bands	HSDPA 850 / 900 / 1700(AWS) / 1900 / 2100 - XT1687 (USA)
	CDMA2000 1xEV-DO - XT1687 (USA)
	HSDPA 850 / 900 / 1900 / 2100 - XT1684, XT1685
4G bands	LTE band 1(2100), 2(1900), 3(1800), 4(1700/2100), 5(850), 7(2600), 8(900), 12(700), 13(700), 17(700), 25(1900), 26(850), 38(2600), 41(2500), 66(1700/2100) - XT1687 (USA)
	LTE band 1(2100), 3(1800), 5(850), 7(2600), 8(900), 19(800), 20(800), 28(700), 38(2600), 40(2300), 41(2500) - XT1684, XT1685
Speed	HSPA 42.2/5.76 Mbps, LTE-A (2CA) Cat6 300/50 Mbps, EV-DO Rev.A 3.1 Mbps
GPRS	Yes
EDGE	Yes

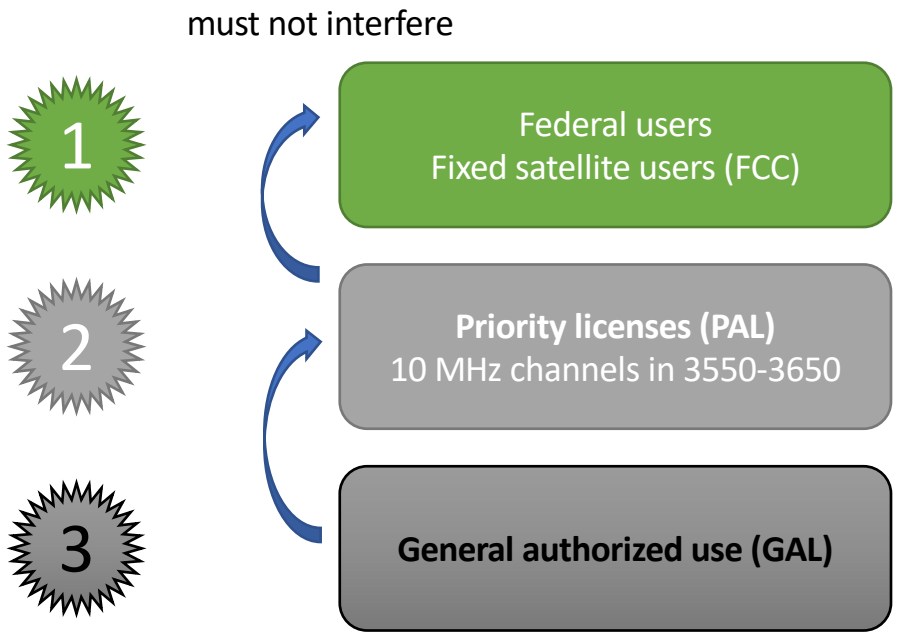
Bands differ across regions

Band	Duplex Mode[B 1]	*f* (MHz)	Common Name	North America[B 2]	Latin America[B 2]	Caribbean[B 2]	Europe[B 3]	Africa[B 3]	Asia[B 4]	Oceania[B 4]
01	**FDD**	**2100**	**IMT**	No	Brazil, Costa Rica	No	Yes	South Africa (Cell C, MTN, Vodacom)	Yes	Australia (Vodafone)
02	FDD	1900	PCS[B 5]	Yes	Yes	Partial	No	No	No	No
03	**FDD**	**1800**	**DCS**	No	Brazil, Costa Rica, French Guiana, Suriname, Venezuela	Partial	Yes	Yes	Yes	Yes
04	FDD	1700	AWS[B 5]	Yes	Yes	Partial	No	No	No	No
05	FDD	850	CLR	Yes	El Salvador, Guatemala	Barbados, Bermuda, Dominican Republic (Altice)	No	Malawi (Access Communications)	Cambodia (SEATEL), India (Jio), Indonesia (Smartfren), Malaysia (Telekom Malaysia), Pakistan (Telenor),	Australia (Vodafone)

FCC 4G & 5G auctions and spectrum actions

Band	Units	Geography	When?	Bids	Licensees
698-806 MHz	62 MHz (6-22)	EA, CMA, US	2008	$19B	101
614-698 MHz	7x2x6 MHz	PEA	2017 - July 2020	$19.8B	
28 GHz	2x425 MHz	county	Jan. 2019	$700M	33
24 GHz	7x100 MHz	PEA	May 2019	$2.2B	29
37-40 GHz	24x100 MHz	PEA	Dec. 2019		
47 GHz	10x100 MHz	PEA	Dec. 2019		
3.5 GHz	7x10 + 8x10 MHz	county	June 2020		
3.7-4.2 GHz	2x20 MHz each	?	?		
5.9-7.1 GHz	1.2 GHz	local	?	unlicensed	

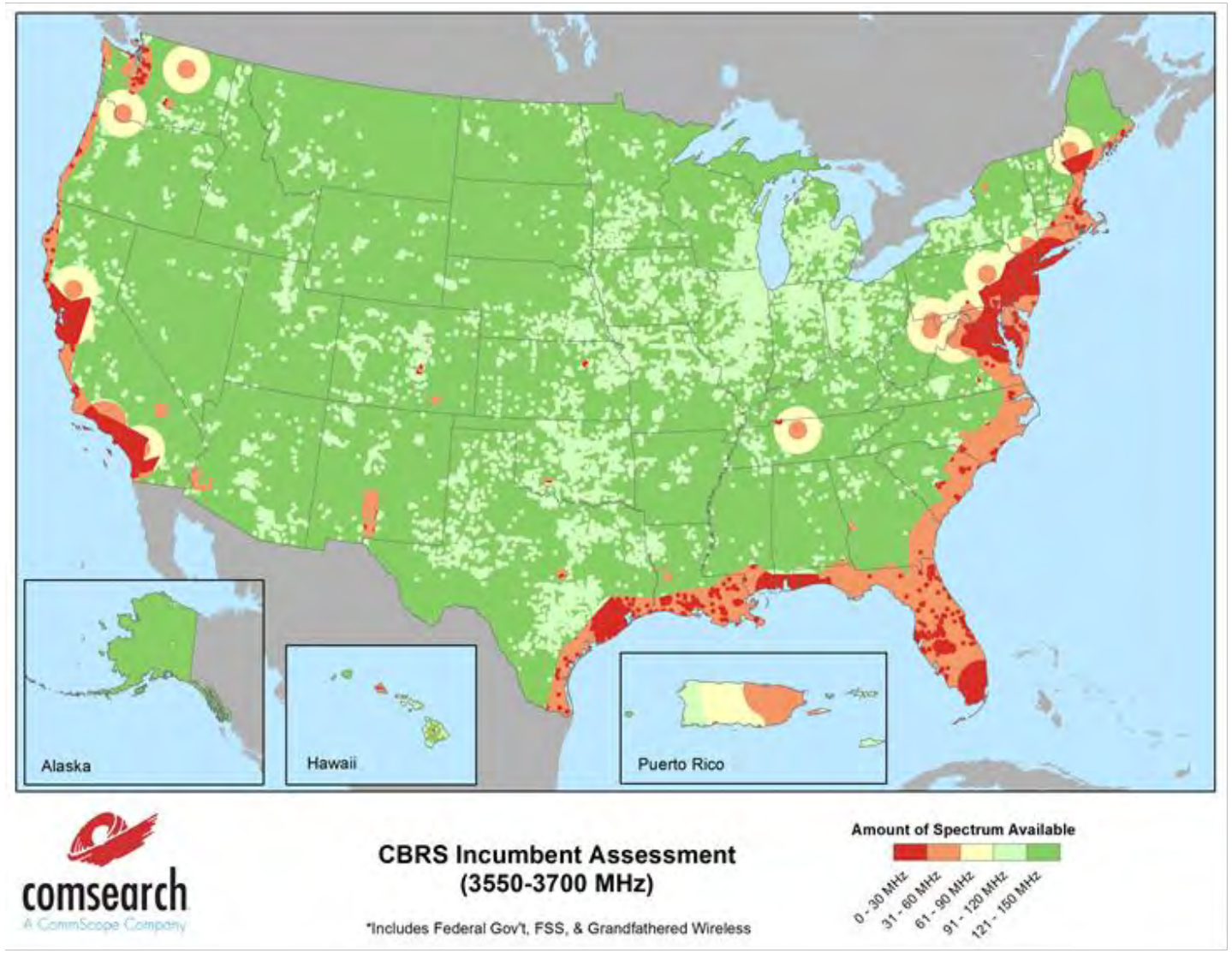
3.5 GHz user classes



census tract
≤ 70 MHz
3-year licenses
assigned via SAS

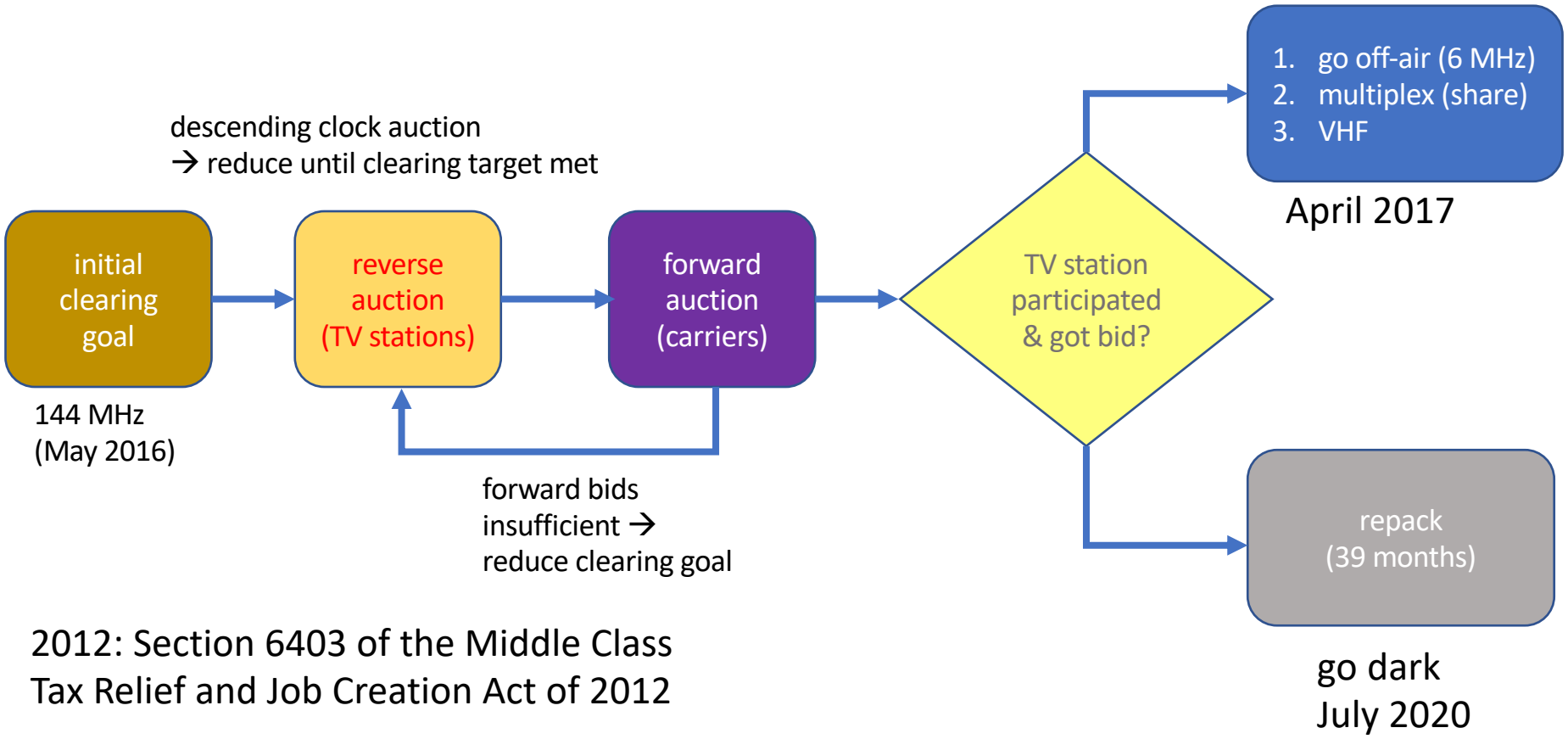
ESC (environmental sensing capability) allows commercial use in coastal and Great Lakes region

CBRS availability



Source: CommScope

TV incentive auction



2012: Section 6403 of the Middle Class Tax Relief and Job Creation Act of 2012

mmWave bands

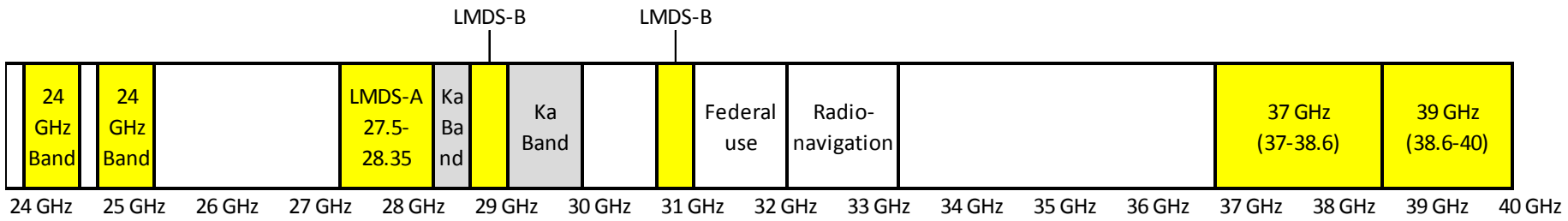
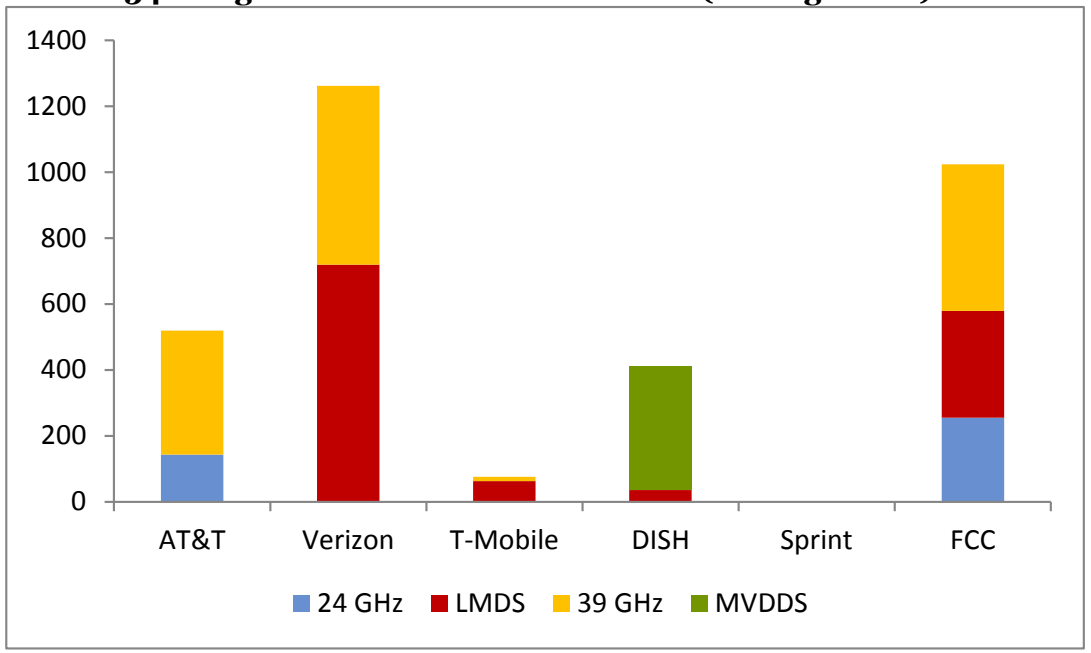


Exhibit 34: Largest mmWave Licenseholders (Average MHz)



Note: Allocates FiberTower licenses to AT&T and Straight Path and XO (Nextlink) licenses to Verizon.
Source: FCC, company reports, AllNet and Wells Fargo Securities.

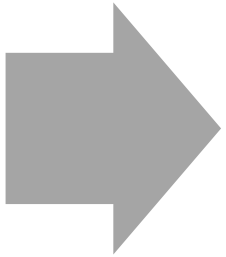
Unlicensed:
64-71 GHz
70-80 GHz (new uses)

Satellite:
24.75-25.25 GHz (FSS earth)
40—42 GHz
48.2—50.2 GHz

The (near) future: spectrum databases

Old model

- frequency range
- width of band
- OOB parameters



New model

- sensing?
- database query?

Conclusion

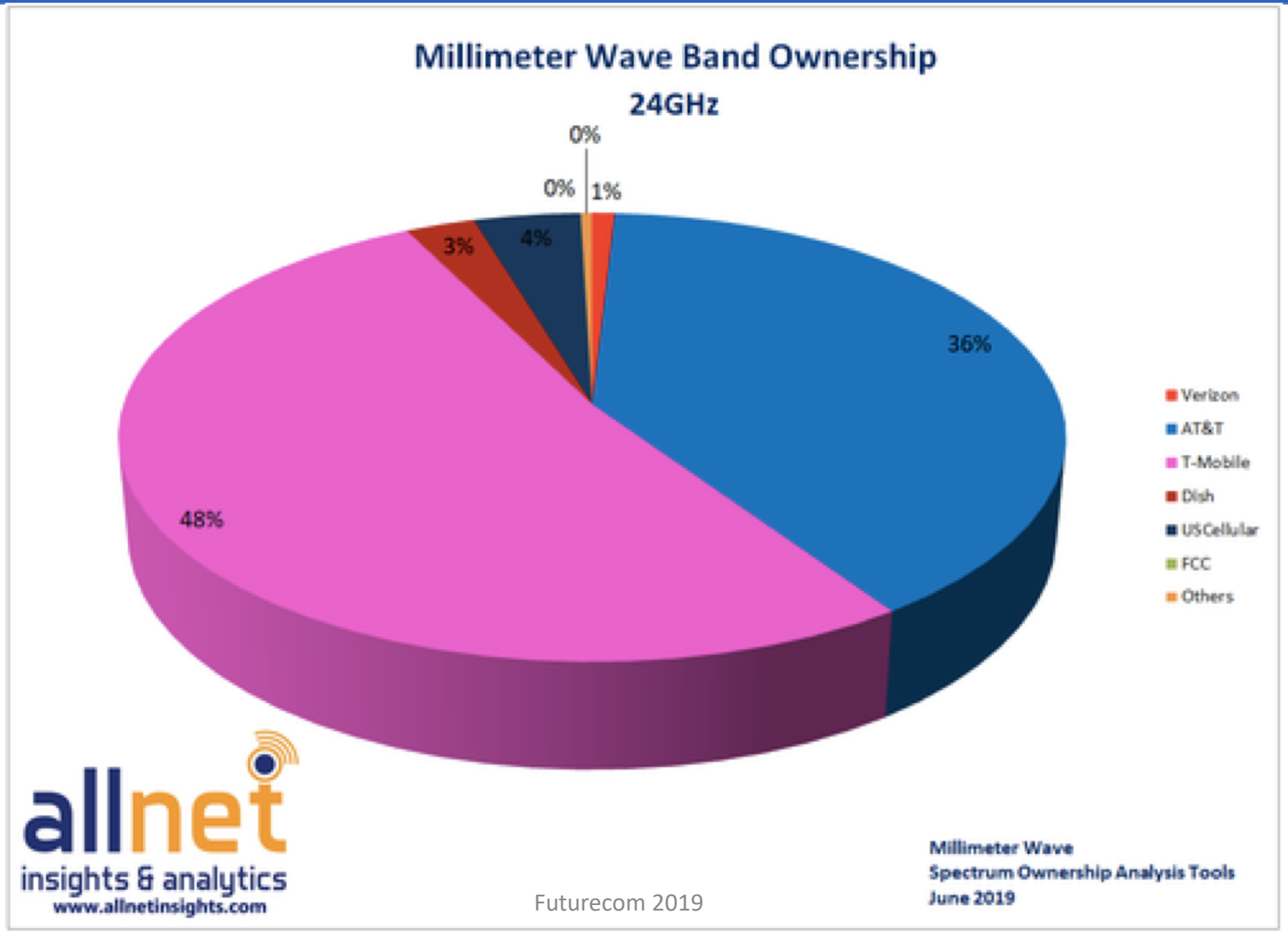
- Spectrum used to be pretty simple: move up in frequency
- Now, complex interaction of coordination & displacability
- Auctions used to be the obvious choice
- Network usage dominated by indoor → consider unlicensed as alternative

Digital dividend

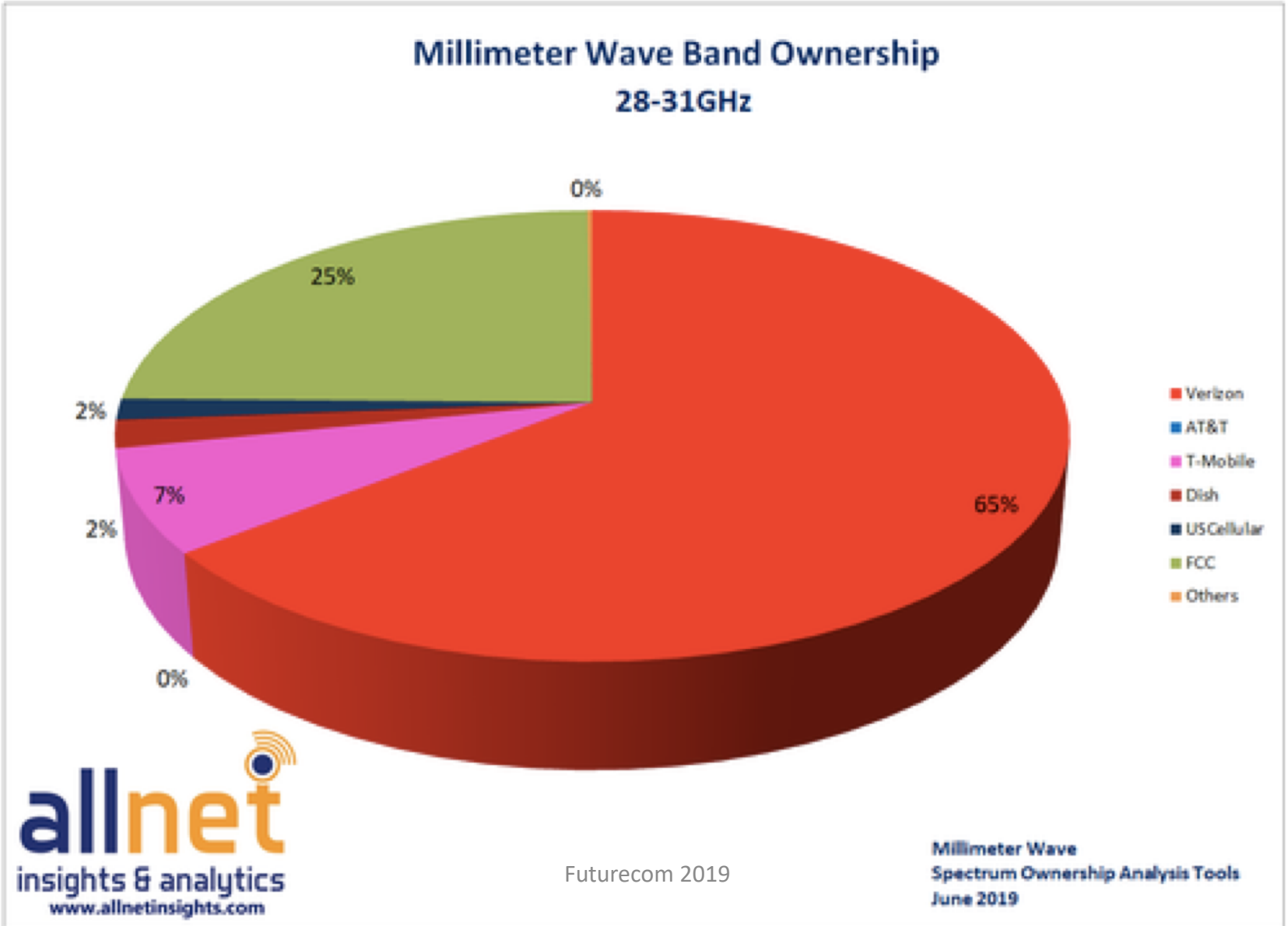
Table 1: Analog Blackout Dates in Latin America – Selected Countries[3]

Mercado	Estándar	Apagón analógico	Observaciones	Mercado	Estándar	Apagón analógico	Observaciones
Argentina	ISDB-T	2019		Nicaragua	ISDB-T	A definir	Fecha tentativa 2019
Bolivia	ISDB-T	2020	Puede extenderse hasta 2022	México	ATSC	2015	
Brasil	ISDB-T	2023	Proceso iniciado por ciudades en 2016	Panamá	ISDB-T	2020	
Chile	ISDB-T	2020		Paraguay	ISDB-T	2024	
Colombia	DVB-T	2019		Perú	ISDB-T	2025	
Costa Rica	ISDB-T	2017		Puerto Rico	ATSC	2015	
Ecuador	ISDB-T	2018		Rep. Domir	ISDB-T	2015	
El Salvador	ISDB-T	A definir	Fecha tentativa 2018	Uruguay	ISDB-T	A definir	
Guatemala	ISDB-T	2021		Venezuela	ISDB-T	2020	
Honduras	ISDB-T	2018					

24 GHz (Auction 102)



28 GHz (Auction 101)



Segmentation of 700 MHz band

Figure 3: Segmentation of the 700 MHz5 Band