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

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Ideal spectrum

- Unused or cheap
- Available globally (\rightarrow 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):

	•		,									
50		72	8	8 10	8		138-144	150.8	162.0375-174		216	225
Fed/non-Fed FS & MS (narrow bands; not to scale) Public Safety VHF Low Band 6.3 MHz in the 3.56-50 MHz range	VHF TV Channels 2-4 54-72 MHz (18 MHz) Licensed Wireless Mics (LPAS) Unlicensed Fixed WSDs Unlicensed Wireless Mics	F3 6 m3 7 14:040 MHZ RAS 73-74.6 MHz FS & MS 72-73 MHz	VHF TV Channels 5-6 76-88 MHz (12 MHz) Licensed Wrekess Mics (LPAS) Unlicensed Fixed WSDs Unlicensed Wrekess Mics	FM Radio Stations 88-108 MHz (20 MHz) 100 channels x 200 kHz (88.1, 88.3,107.9 MHz)	ARNS AM(R)S 108-117.975 (9.975 MHz)	Aeronautical Mobile 117.975-137 MHz (19.025 MHz)	Federal FS & MS 138-144 MHz (6 MHz) Little LEO MSS, MetSat, SRS, Space Operation (all j) 137-138	LMS 1506.024751 Ford FS AIS 150.05492 Little LEO MS5 1 48-150.05 Ford FS AIS 150.05492 AM2 Ford FS AIS 148-149.9 MHz Amateur, 144-148 (4 MHz)	Lines Sectors All 1 <	VHF TV Channels 7-13 174-216 MHz (42 MHz) Licensed Wireless Mics (LPAS) (Chs. 7-13) Licensed WAVDs (Chs. 8-12) Unlicensed Fixed WSDs & Unlicensed Wireless Mics	AMTS: 219-220 MHz Amateur 218-219 MHz Service AMTS: 216.75-218 MHz LPRS: 216-217 MHz	Amateur: 222-225 (3 MHz) 220 MHz Service: 220-222 MHz*
		•	* *Auditory Assistance E	Devices, Fixed Maritime Stations, and Radio	Control; ARNS (74.8-	75.2 MHz)		Public Sa	afety VHF High Band: 3.6 MHz in the 150-174 MHz range	*Public Saf	fety: 100 kHz of t	this 2 MHz

450-894 MHz (444 MHz):

4	70 51	2	614	65	98	746		806		851	894
PLMRS 450-470 (20 MHz)	UHF TV Channels 14-20 470-512 MHz (42 MHz)		608-614 MHz:	UHF TV Channels 38-51 614-698 MHz (84 MHz) (Existing Use)	Lower 700 700 M	MHz Band (48 MHz) Upp IHz Commercial Services 28-758 MHz (60 MHz)	Public 700 MHz Band (60 MHz Public 700 MHz Ommercial Safety Safety) PLMRS 806-817 (11 MHz)	Cellular and ESMR	AG (ground stati	Cellular and ESMR
	T-Band* - PLMRS (Industrial/Business)	UHF TV Channels 21-36 512-608 MHz (96 MHz)	RAS WMTS.	Licensed Wireless Mics (LPAS) & Licensed WAVDs Unicensed Fixed & Portable WSDs, Unicensed Wireless Mics 600 MHz Bapd (Future Lices)*	Uplinks	Unpaired Downlinks	758-775 (17 MHz) 13 MHz)	815- Senices B 805 Hz) Namo 799-5	817-849 (32 MHZ)	860-5 PS, B PS N A (1	B A B A Image: B A B A B A
Public Safety UHF Band 3.7 MHz in the 450-470	- PLMRS (Public Safety)*		Unlicensed Fix	ard and e17 Downlinks Duplex Gap 652-653 MHz (11 MHz) Uplinks 663-698 MHz (35 MHz)	698-716 MHz (18 MHz)	716-728 728-746 MHz (11) (12 MHz) (18 MHz) 746-757	(11) (11)	817 MHz (2 3/ILT, SMR 8 3/ILT,	 ⇒ (11) (10) 3 ⊗ 824-835 835-845 ⊗ 824-835 835-845 	362 MHz (2 VILT, SMR 8 PSPAC 85: 19-851 MHz (3	示 (11) (10) 5 869-880 880-890 8 869-880 880-890 8 25
MHz range MMS 457/467	- Public Mobile Services	nsed Wireless Mics (LPAS) & Licensed WAVDs	Wireless Mics	A B C D E F G B (5)<	A B C (6) (6) (6)	D E A B C (6) (6) (6) (6) (6)	1 MHz) () () () () () () () () () (MHz) 09-815 (6) 6-809 (3) (2) (2) (3) (4) (4) (5) (6) (6) (7) (6) (7) (6) (7) (7) (7) (7) (7) (7) (7) (7	24 (7)	MHz) 54-860 (6) 1-854 (3) 2 MHz)	39 (7)
*Use of T-b	Image: Note of the parties of the parties of the parties determine the parties										

and the Gulf of Mexico. The 2012 Spectrum Act requires the auction of the Public Safety T-band spectrum to begin by Feb. 2021.

he 600 MHz band by July 13, 2020 (or pos 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):

143	5 15	25 1	559 161	0 162	6.5	1675	5 16	695	1780) 1850
1432-1 FS & 1 Part 90 1400-1 RAS, E RAS, E NMTS 1390-1 FS & 1	Aeronautical Mobile Telemetry (AMT) ↓	L-Band MSS ↓	RNSS ↓ 1559-1610 MHz (51 MHz)	Big LEO MSS 1610-1626.5 MHz	L-Band MSS ↑	FS & I RAS: 10 SRS (pa MetAids	MetSat ↓ MetAide	1	695-1780 MHz (85 MHz): AWS ↑	Federal Exclusive Band
435 MHz 432 (excep Telemetry 427 MHz E SZ/SRS E SZ/SRS 395 MHz 395 MHz 395 MHz	1435-1525 MHz (90 MHz)	1525-1559 MHz (34 MHz)	GPS	Globalstar 1610- 1617.775 (7.375 MHz) 1618.725- 1626.5 (7.375 MHz)	1626.5-1660.5 MHz (34 MHz)	WS (exce 60-1670 MH ssive): 1668 1668.4-16	(radiosonde)	AWS-3* 1695-1710	1710-1780 MHz (70 MHz): 3GPP Band 66	1780-1850 MHz (70 MHz) Fixed & Mobile
(3 MHz) 5 MHz) 6 WMT 6 (27 MH 6 (27 MH 7 (27 MH))))))))))))))))))))))))))))))))))))	(00 111 12)		(20.46 MHz)			pt aen z (10 Mi .5-1668	(20 MHz)	(15 MHz)	AWS-1 1/10-1/55 MHZ (45 MHZ) AWS-3 1/55-1/80	
1 (1) (5) (5) (5) (5)	Licensed Wireless Mics (LPAS) (limited to 30 MHz per area)	ATC	ARNS	ATC ARNS	ATC	(1.6) 4 (7.9) 26 sta	Federal earth ations in this band	(5) (10)	(10) (10) (5) (5) (5) (10) (5) (5) (5) (10)	Space Operation (SATOPS) ↑
								13 protection zones for Federal	Federal FS & MS (relocating) Federal SATOPS ↑	

1850-2300 MHz (450 MHz):									
1920	:	2025 2110		2200 2300					
1850-1920 MHz (70 MHz): ↑ Image: Constant of the second sec	1930-2020 MHz (90 MHz): ↓ Broadband PCS ▲ AWS-4* 1930-1995 MHz (65 MHz) ↓ ▲ (10) В (10)	2 GHz BAS ↑ (e.g., news gathering) EESS, SRS, Space Operation (all ↑ & limited use) 2025-2110 MHz (85 MHz) 7 BAS channels and two 0.5 MHz blocks for data return link (DRL) channels	AWS-1 AWS-3 AWS-3 2110-2155 MHz 2155-2180 MHz 2155-2180 MHz (45 MHz) (25 MHz) (21 MHz)	66)↓ Federal Exclusive Band 2200-2290 MHz (90 MHz) 3 (10) Fixed & Mobile (both line-of-sight only) MHz					
A D B E F C G H ½ (15) (5) (15) (5) (5) (15) (5	A D B E F C G H 2 GHz MSS † (15) (5) (15) (5) (5) (15) (5) (5) (200-2020 (20)) 3 * 3GPP Band 70: 16	8 2 A1r A2r A3r A4r A5r A6r A7r 8 695-1710 MHz (12)	A B C D E F G H I J 2 2 GHz N (10) (10) (5) (5) (10) (5) (5) (5) (10) 2180-220	$\underset{\substack{SS \ MHz}}{EESS}, SRS, and Space Operation(all \downarrow) \qquad $					

Higher frequency = capacity, but more cells



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)



- cellular downlink receiver
- radar receiver
- GPS receiver



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



TV: 90 dBm (1 MW UHF)

how do I quickly identify sources of interference?



acquisition -138 dBm tracking: -146 dBm



-105 dBm

vs.

Beauty contests and auctions are converging

Beauty contest

 prettiest network of them all

Pure auction

• use-it-or-lose it

Auction with conditions

 coverage buildout



- bandwidth
- rural bidding credits
- performance credits (US USF)
- paired licenses

Spectrum sharing



US: since 1994

There are many spectrum dials



"Best and highest value use"

- Metric: \$ per MHz and population covered \rightarrow \$/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 \rightarrow 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 III Paraguay and their acquiring a fixed service provider.

ITU mobile spectrum recommendations

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

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

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

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 C	OLLAPSE 🛦
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(90) 12(700), 13(700), 17(700), 25(1900), 26(850), 38(2600), 41(2500), 66(170) - XT1687 (USA)	0),)0/2100)
	LTE band 1(2100), 3(1800), 5(850), 7(2600), 8(900), 19(800), 20(800), 28 38(2600), 40(2300), 41(2500) - XT1684, XT1685	(700),
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] ◆	∫ (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	ІМТ	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
						Barbados			Cambodia (SEATEL), India (Jio), Indonesia (Smartfren), Malaysia (Telekom	
05	FDD	850	CLR	Yes	El Salvador, Guatemala	Bermuda, Dominican Republic (Altice)	No	Malawi (Access Communications)	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

must not interfere



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



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.



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 modelsensing?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 \rightarrow consider unlicensed as alternative

Digital dividend

Table 1: Analog Blackout Dates in Latin America – Selected Countries³

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		Futu	recom 2019		

24 GHz (Auction 102)



28 GHz (Auction 101)



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Segmentation of 700 MHz band

Figure 3: Segmentation of the 700 MHz5 Band

