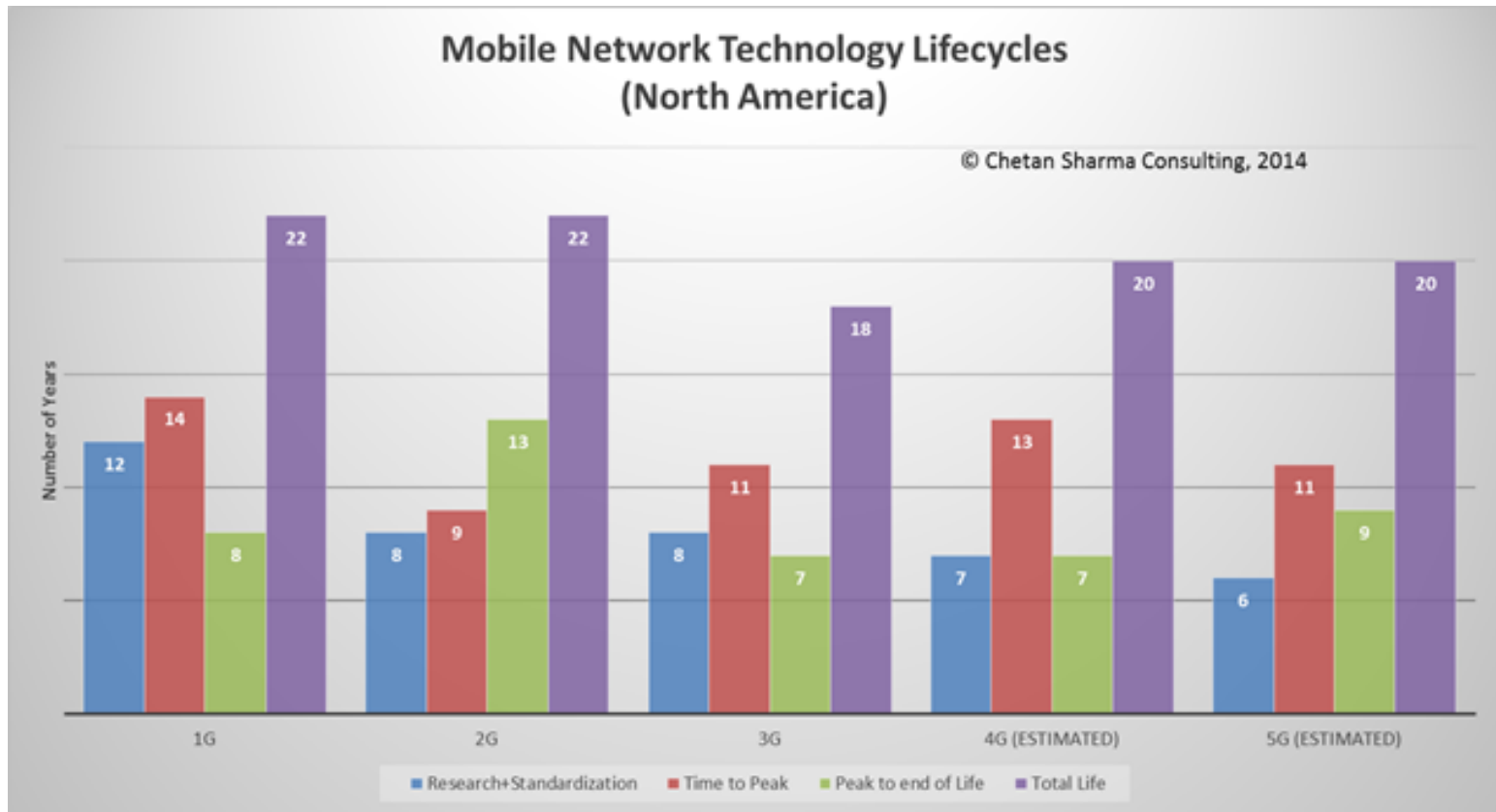


5G: Enabled by technology, with Public Policy Assist

HENNING SCHULZRINNE















The views and opinions expressed in this presentation are those of the author and do not necessarily reflect the official policy or position of any agency of the U.S. government. Any resemblance to actual policies, living or dead, or actual events is purely coincidental.

Design for 20 years



Generations are distinct

Talking a different language

| Formative experiences | Maturists (pre-1945) Wartime rationing Rock'n'roll Nuclear families Defined gender roles - particularly for women  | Baby boomers (1945-1960) Cold War 'Swinging Sixties' Moon landings Youth culture Woodstock Family-orientated  | Generation X (1961-1980) Fall of Berlin Wall Reagan/Gorbachev/ Thatcherism Live Aid Early mobile technology Divorce rate rises  | Generation Y (1981-1995) 9/11 terrorists attacks Social media Invasion of Iraq Reality TV Google Earth  | Generation Z (Born after 1995) Economic downturn Global warming Mobile devices Cloud computing Wiki-leaks  |
|--|--|---|---|--|---|
| Percentage in UK workforce | 3% | 33% | 35% | 29% | Employed in either part-time jobs or apprenticeships |
| Attitude toward career | Jobs for life  | Organisational - careers are defined by employees | "Portfolio" careers - loyal to profession, not to employer | Digital entrepreneurs - work "with" organisations | Multitaskers - will move seamlessly between organisations and "pop-up" businesses |
| Signature product | Automobile  | Television  | Personal computer  | Tablet/smartphone  | Google glass, 3-D printing |
| Communication media | Formal letter  | Telephone  | E-mail and text message  | Text or social media  | Hand-held communication devices |
| Preference when making financial decisions | Face-to-face meetings | Face-to-face ideally but increasingly will go online | Online - would prefer face-to-face if time permitting | Face-to-face | Solutions will be digitally crowd-sourced |

land
line

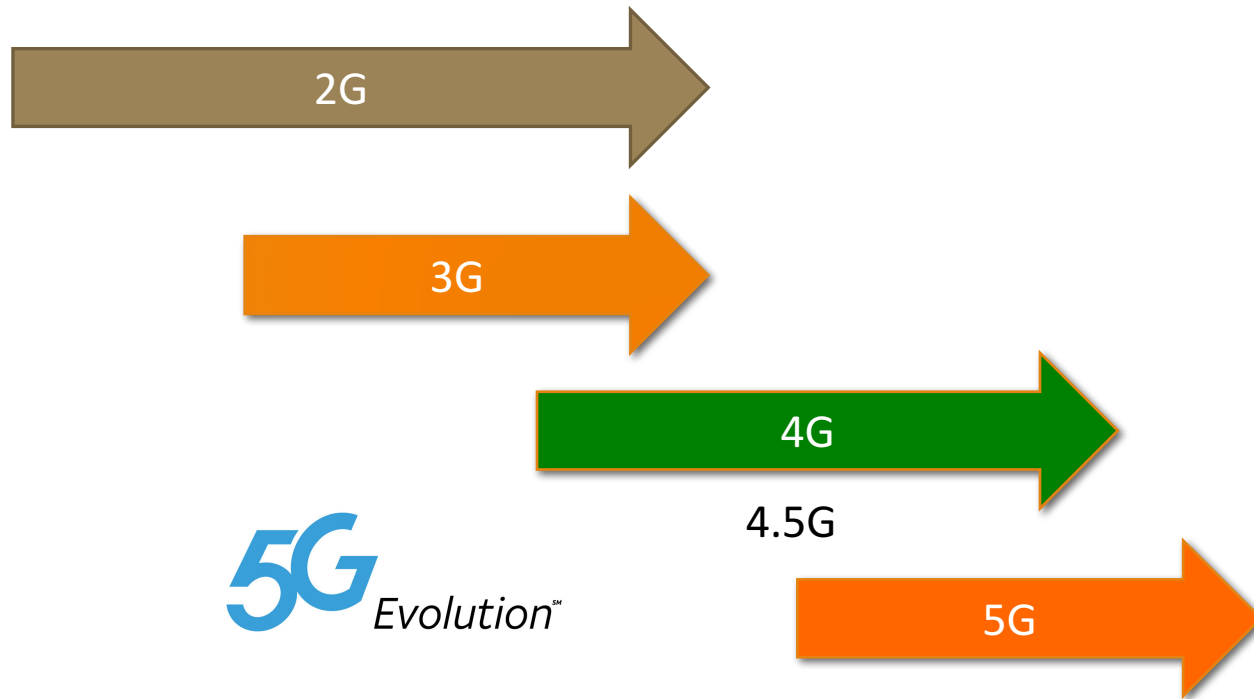
2G

3G

4G

Source: Barclays, University of Liverpool

Generations overlap



Generational surprises

| Generation | Expectation | Surprise |
|------------|-----------------------------------|--|
| 2G | better voice quality (“digital!”) | SMS |
| 3G | WAP | web |
| 4G | IMS | YouTube, WhatsApp, notifications |
| 5G | IoT (low latency) | ? |

underestimated cost and fixed-equivalence as drivers

Lessons, in brief

| Experience | Lessons |
|-----------------------------|--|
| VoLTE, IMS | avoid complexity avoid entanglement plan intercarrier interfaces |
| Wi-Fi | don't trust the RAN/AP |
| disaggregation of functions | clear & simple interfaces don't assume trust between elements |
| app stores | keep it application-neutral |
| FTTH, backhaul cost | re-use backhaul where you can find it |

2G → 3G → 4G → 5G → increasing number of technology components

5G is a systems standard

| Technology component | Proposed application | Less exciting, but likely |
|----------------------|---|---|
| mmWave | 10 Gb/s user rates | capacity in stadiums fixed wireless? |
| edge computing | IoT | video caching |
| M2M | billions & billions of devices! autonomous vehicles! | electric meters |
| 1 ms latency | autonomous vehicles! | keep it application-neutral |
| slicing | QoS | test networks, VPNs |

Changing spectrum environment

Except at highest frequencies, all new spectrum likely to be shared

- e.g., 3.5 GHz
- in time & space

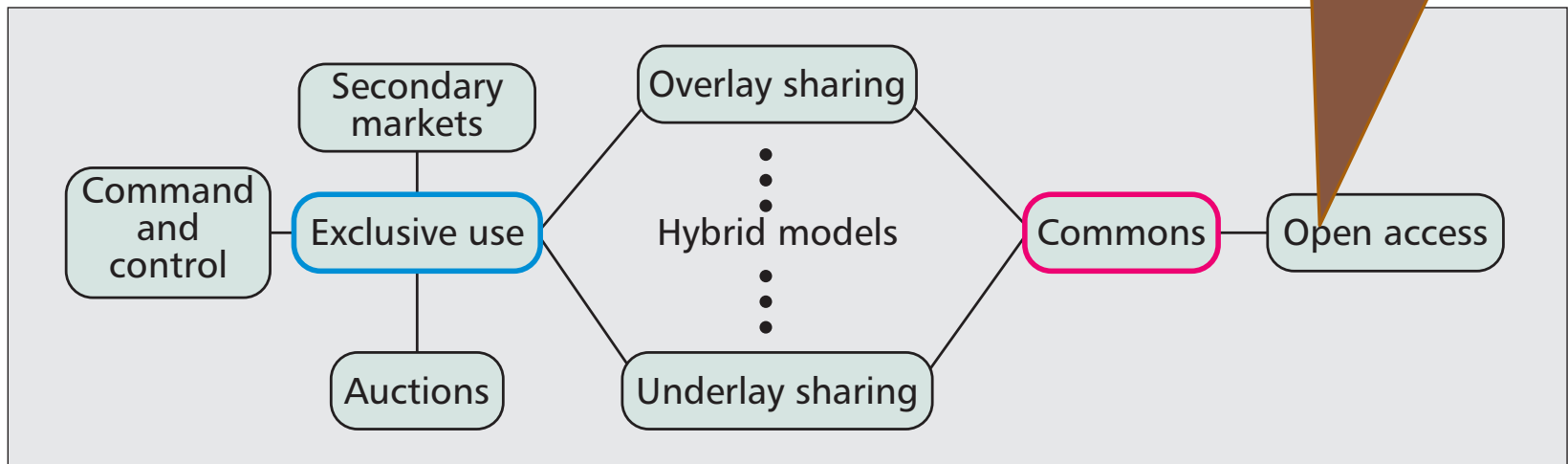
→ need frequency-agile systems that can shift capacity to different bands, quickly

→ few common bands for consulting spectrum database

- **now**: scan, pray & wait
- **5G**: shared band → database

Spectrum sharing

How much politeness & fairness is required?
→ LTE-U & LTE-LAA (license-assisted, listen-before-talk)



Ideal spectrum

Unused or cheap

Available globally (important for consumer electronics (size))

- preferably unlicensed

No license

Propagation

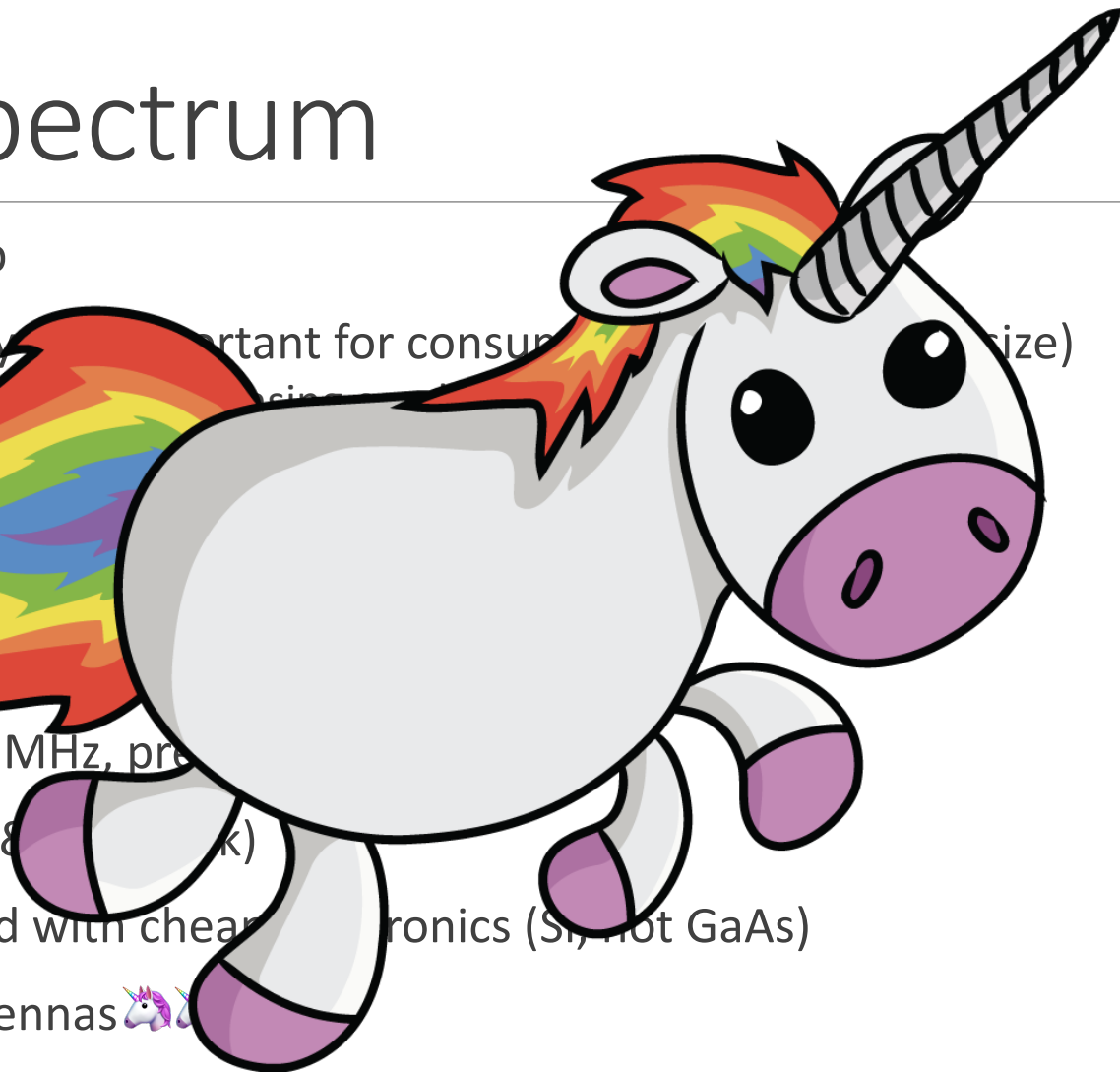
Not affected

Wide bands (≥ 5 MHz, preferably)

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
Worry mostly about OOB to like
Spectral efficiency secondary
Single-country

“MODERN”

Flexible use
Flexible technology
Shared, over/underlay
At least 5 MHz, preferably 100
Multiple (> 4) XTR/RCV
Receiver requirements?
Spectral efficiency matters
International coordination

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 uplink
- radar receiver
- GPS receiver

Spectrum roles



base-level coverage
(particularly rural)

urban capacity

indoor & capacity

directional
capacity

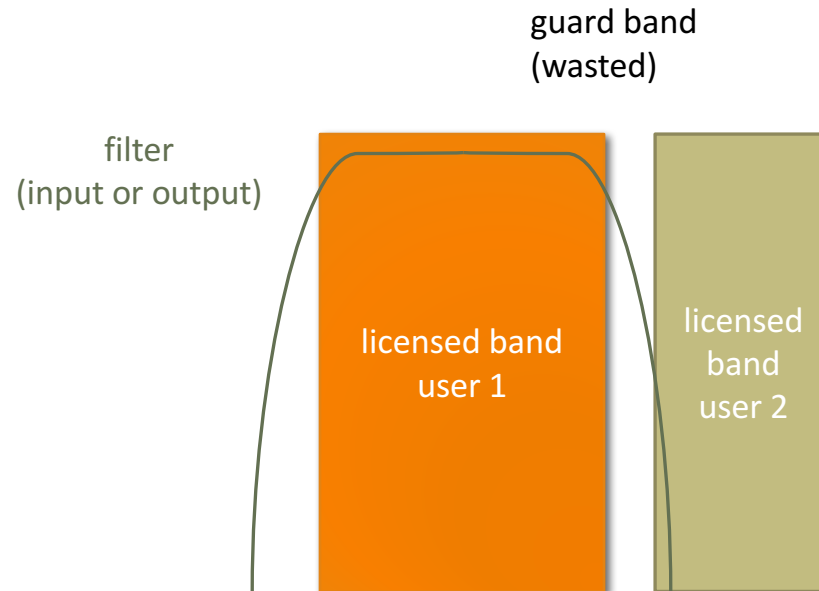
Digital dividend
TV incentive auction

AWS-3

3.5 GHz

mmWave R&O

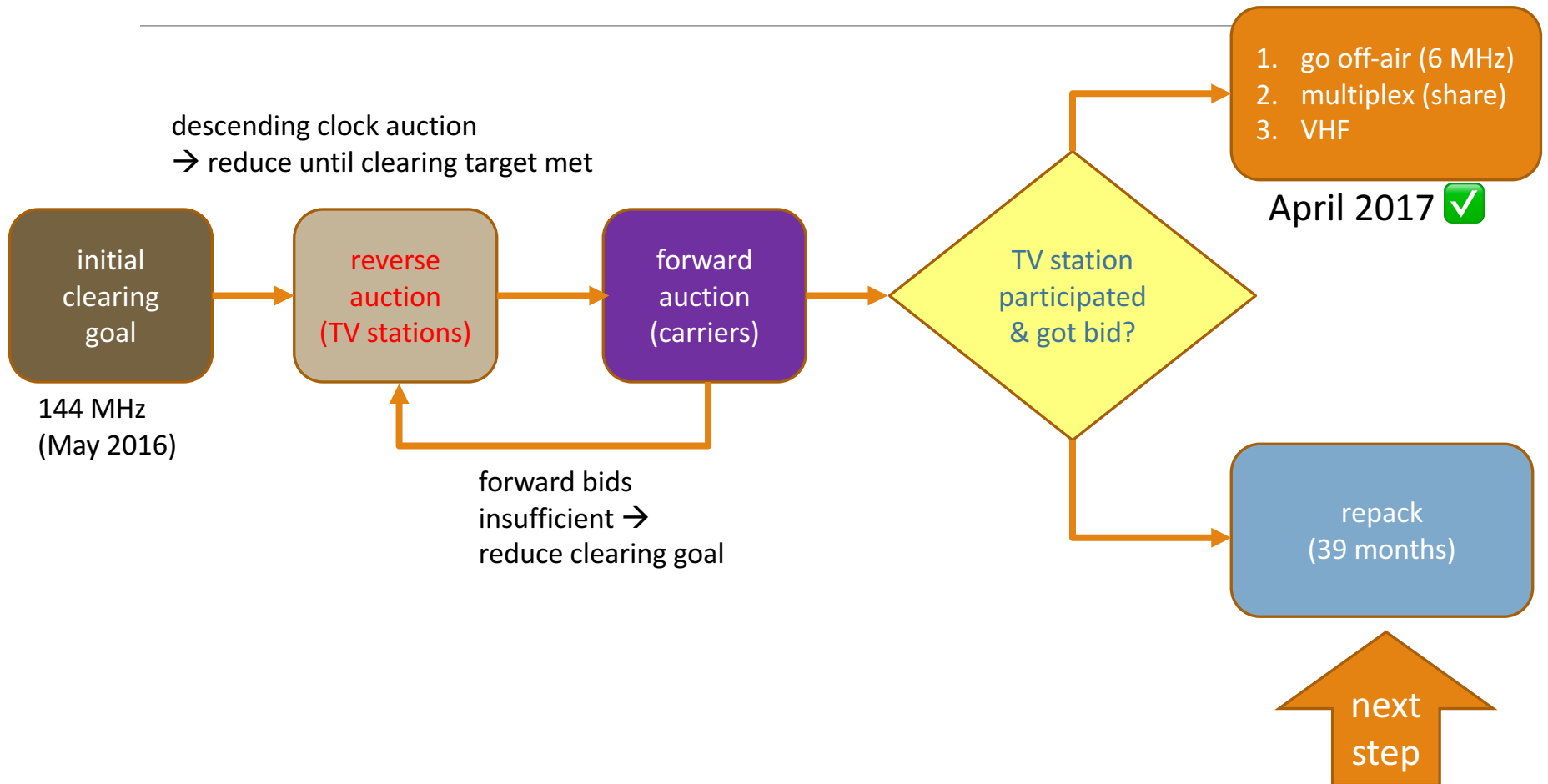
The filter problem



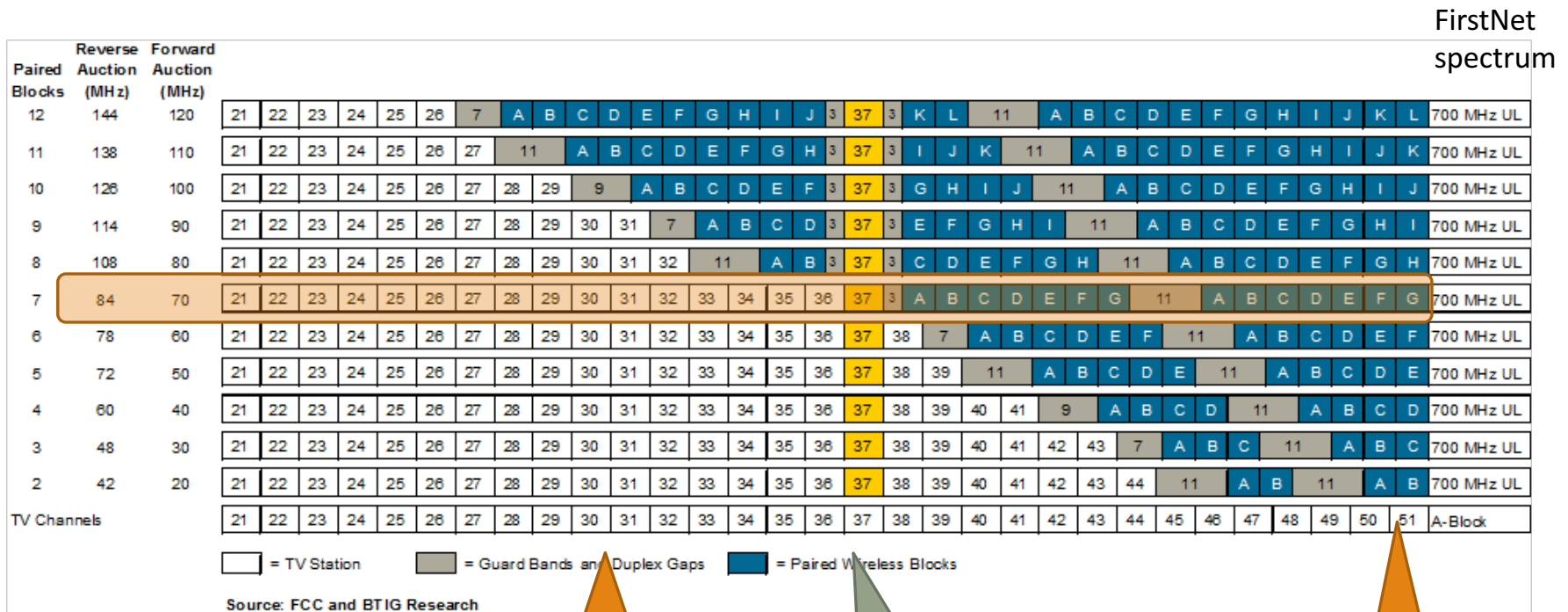
Power imbalance:

- cell downlink: 100 W ERP
- cell uplink: 0.05 – 2 W

TV incentive auction



600 MHz incentive auction



5 MHz downlink blocks

radio astronomy, medical monitoring

5 MHz uplink blocks

Incentive auction facts

Forward Auction

\$19.8 billion

Gross revenues (2nd largest in FCC auction history)

\$19.3 billion

Revenues net of requested bidding credits

\$7.3 billion

Auction proceeds for federal deficit reduction

70 MHz

Largest amount of licensed low-band spectrum ever made available at auction

14 MHz

Spectrum available for wireless mics and unlicensed use

2,776

License blocks sold (out of total of 2,912 offered)

\$1.31

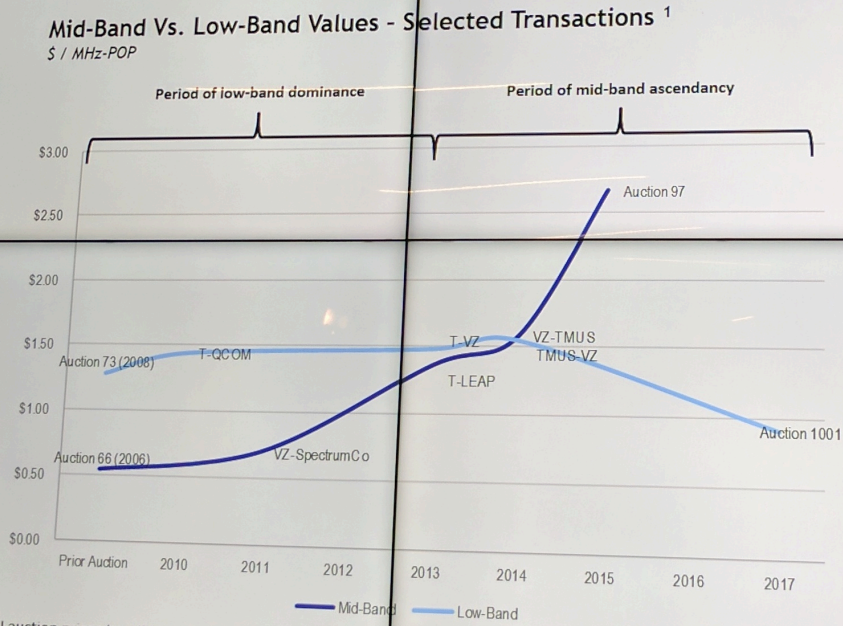
Average price/MHz-pop *sold* in Top 40 PEAs

\$.93

Average price/MHz-pop *sold* nationwide

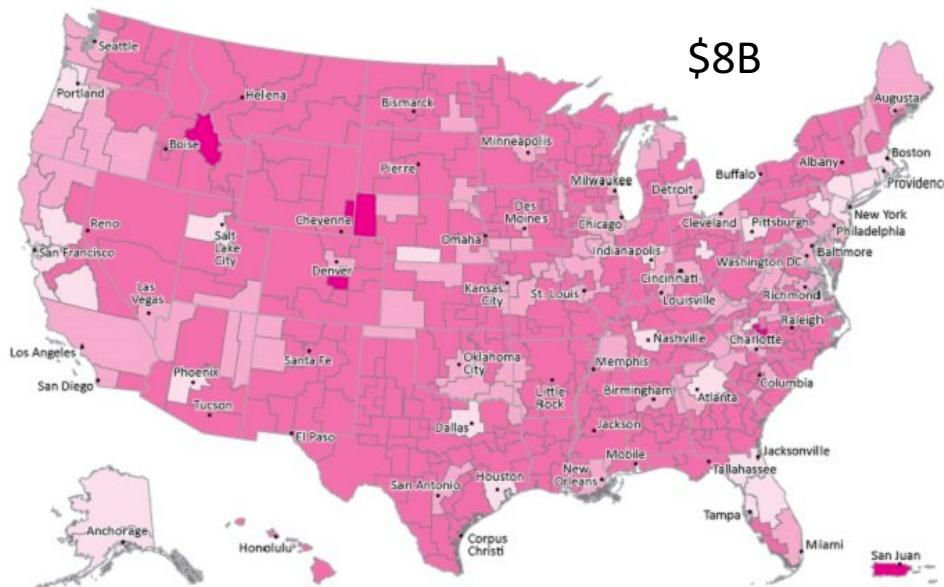
Spectrum Needs And Values Are Changing

Prior to 2013, low-band routinely fetched 2x the amount of mid-band. The perceived value of mid-band vs low-band started to shift after VZ deployed LTE on 700MHz. By the AWS-3 auction in 2015, mid-band sold for more than 2x the last significant low-band transaction. The incentive auction was conceived in an era when low-band was the most valuable spectrum, and executed in an era when focus had shifted to higher bands.



1) Indexes reported values to national auction prices for all transactions, save VZ-SpectrumCo and auctions themselves.
 Source: Company data, FCC, New Street Research estimates

Forward auction: T-Mobile & others



T-Mobile

600 MHz Incentive Auction Results: Aggregate MHz Won



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\$6.2B
486 licenses



\$1.7B
145M POPS



at&t

\$1B
18 PEAs
(has 700 MHz spectrum)
FirstNet spectrum

TV white spaces (US)

First large-scale spectrum database

But limited use in the US

- number of channels
- power levels
- equipment
- available mostly in rural areas, not urban
- change after incentive auction

| Channel Number | Frequency Range (MHz) | Allowable Antenna Height (meters AGL) |
|----------------|-----------------------|---------------------------------------|
| 2 | 54-60 | 30 |
| 7 | 174-180 | 30 |
| 8 | 180-186 | 30 |
| 9 | 186-192 | 30 |
| 13 | 210-216 | 30 |
| 18 | 494-500 | 30 |
| 24 | 530-536 | 30 |
| 25 | 536-542 | 30 |
| 26 | 542-548 | 30 |

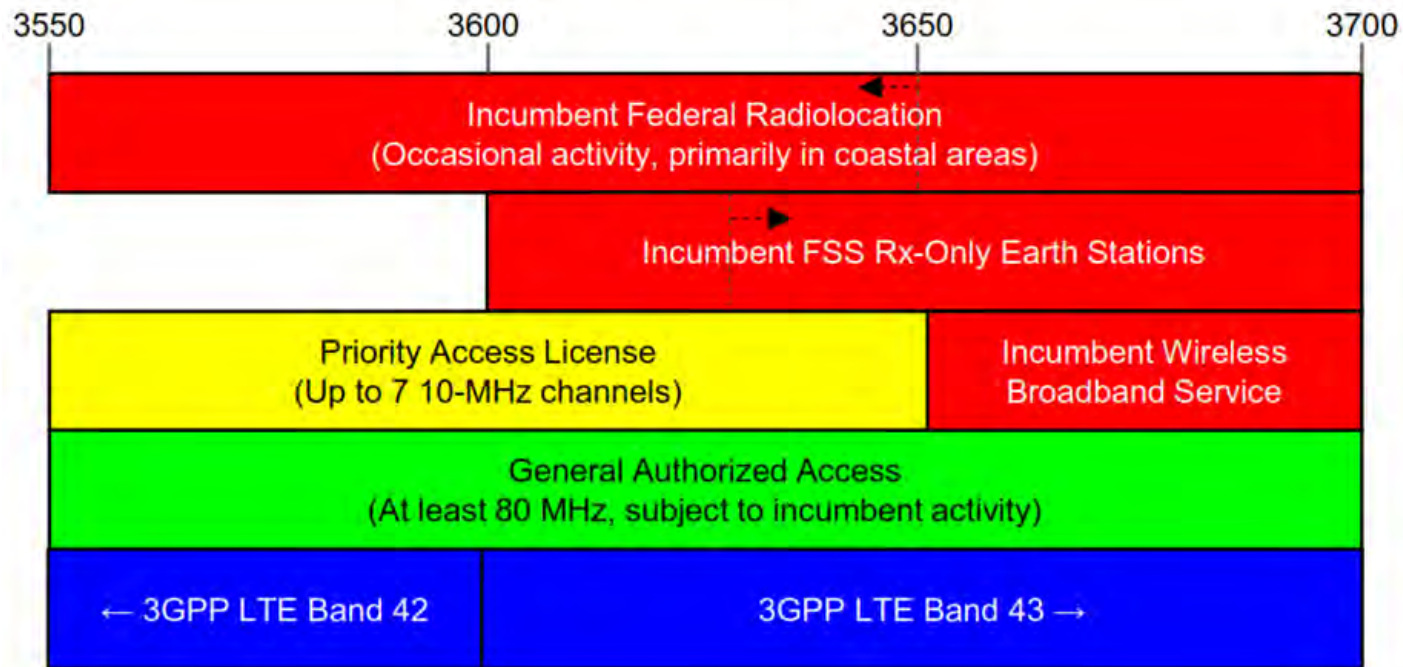
Leonia, NJ

| Channel Number | Frequency Range (MHz) | Allowable TX Power (mW) |
|----------------|-----------------------|-------------------------|
| 42 | 638-644 | 40 |

Amherst, MA

| Channel Number | Frequency Range (MHz) | Allowable TX Power (mW) |
|----------------|-----------------------|-------------------------|
| 23 | 524-530 | 40 |
| 24 | 530-536 | 100 |
| 25 | 536-542 | 100 |
| 26 | 542-548 | 100 |
| 27 | 548-554 | 40 |
| 41 | 632-638 | 40 |
| 42 | 638-644 | 40 |
| 44 | 650-656 | 40 |
| 47 | 668-674 | 40 |
| 48 | 674-680 | 40 |
| 50 | 686-692 | 40 |

3.5 GHz band



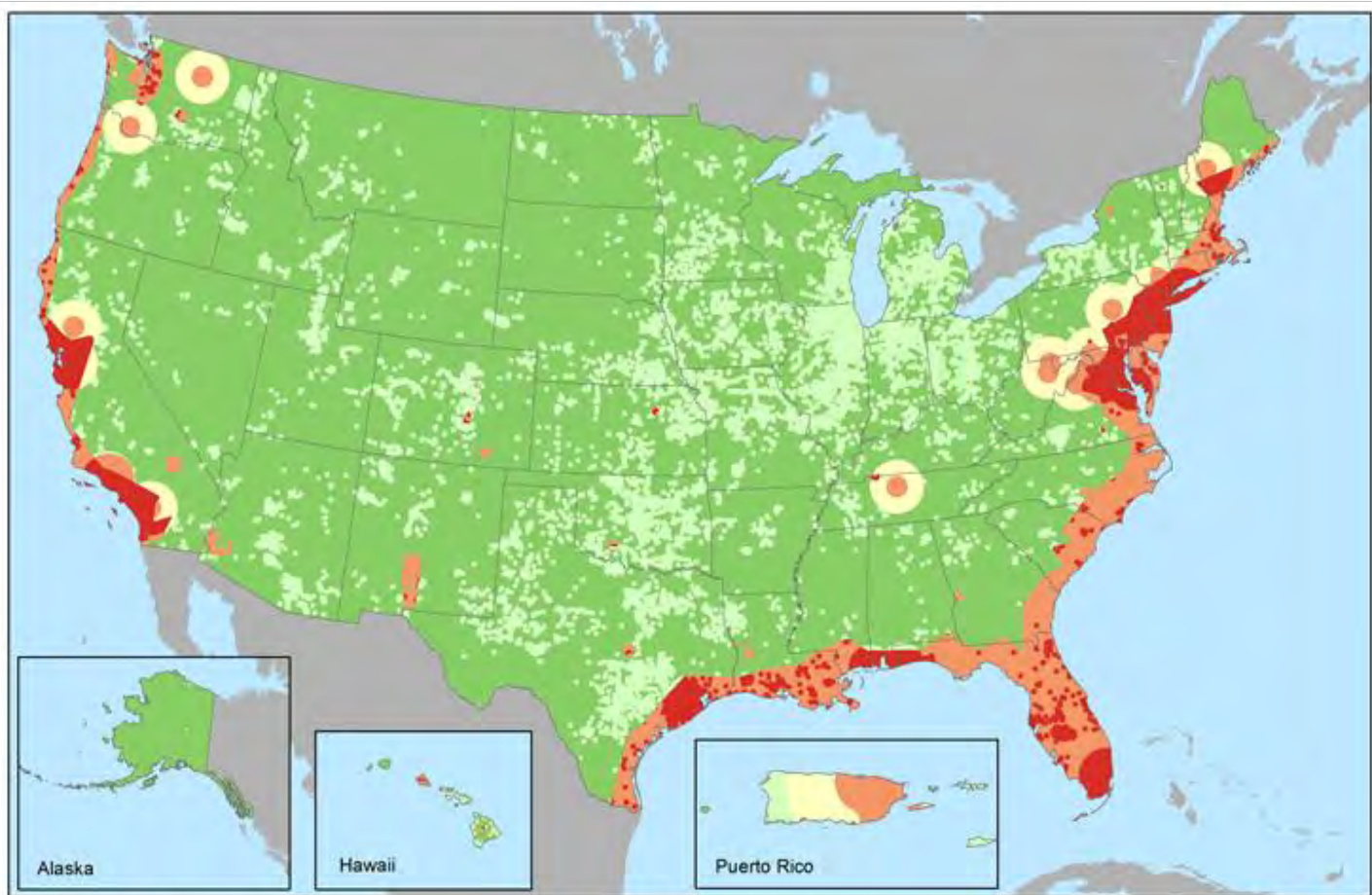
Band 42: TDD, 3.4-3.5 GHz

Band 43: TDD, 3.6-3.65 GHz

FSS: C Band (3.625–4.200)

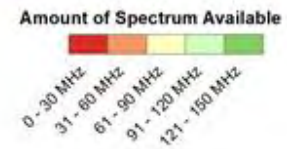
Source: Google

CBRS availability



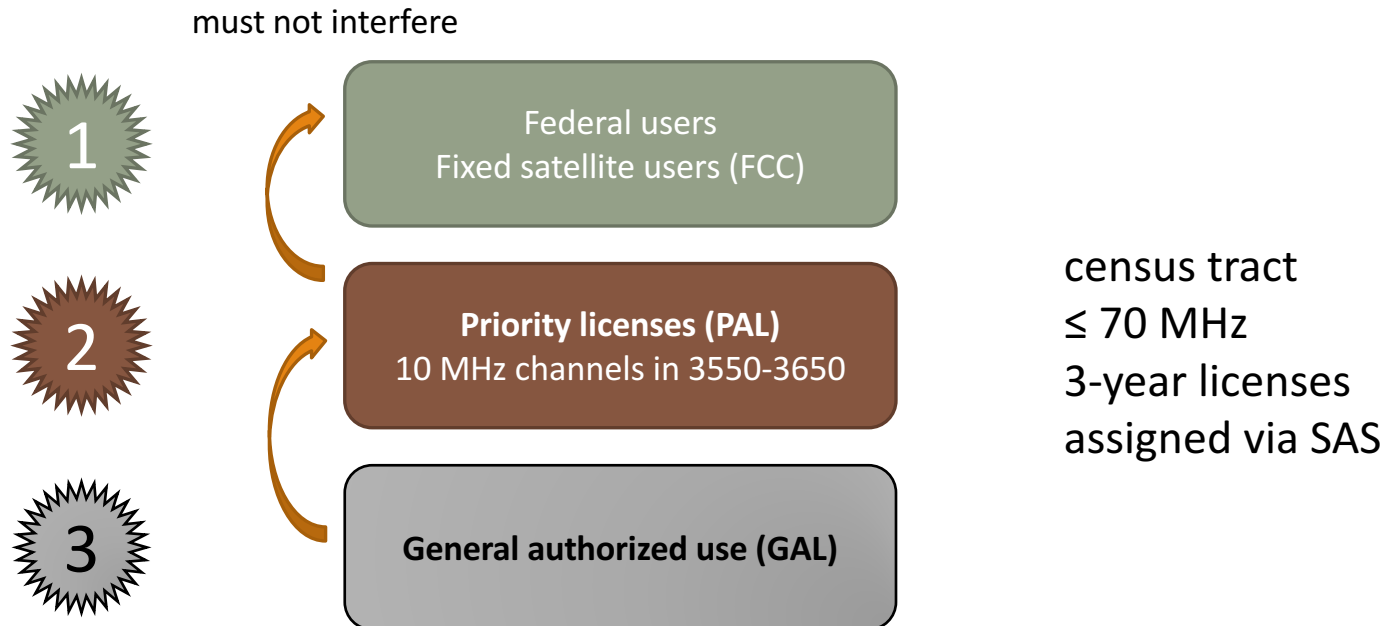
CBRS Incumbent Assessment (3550-3700 MHz)

*Includes Federal Gov't, FSS, & Grandfathered Wireless



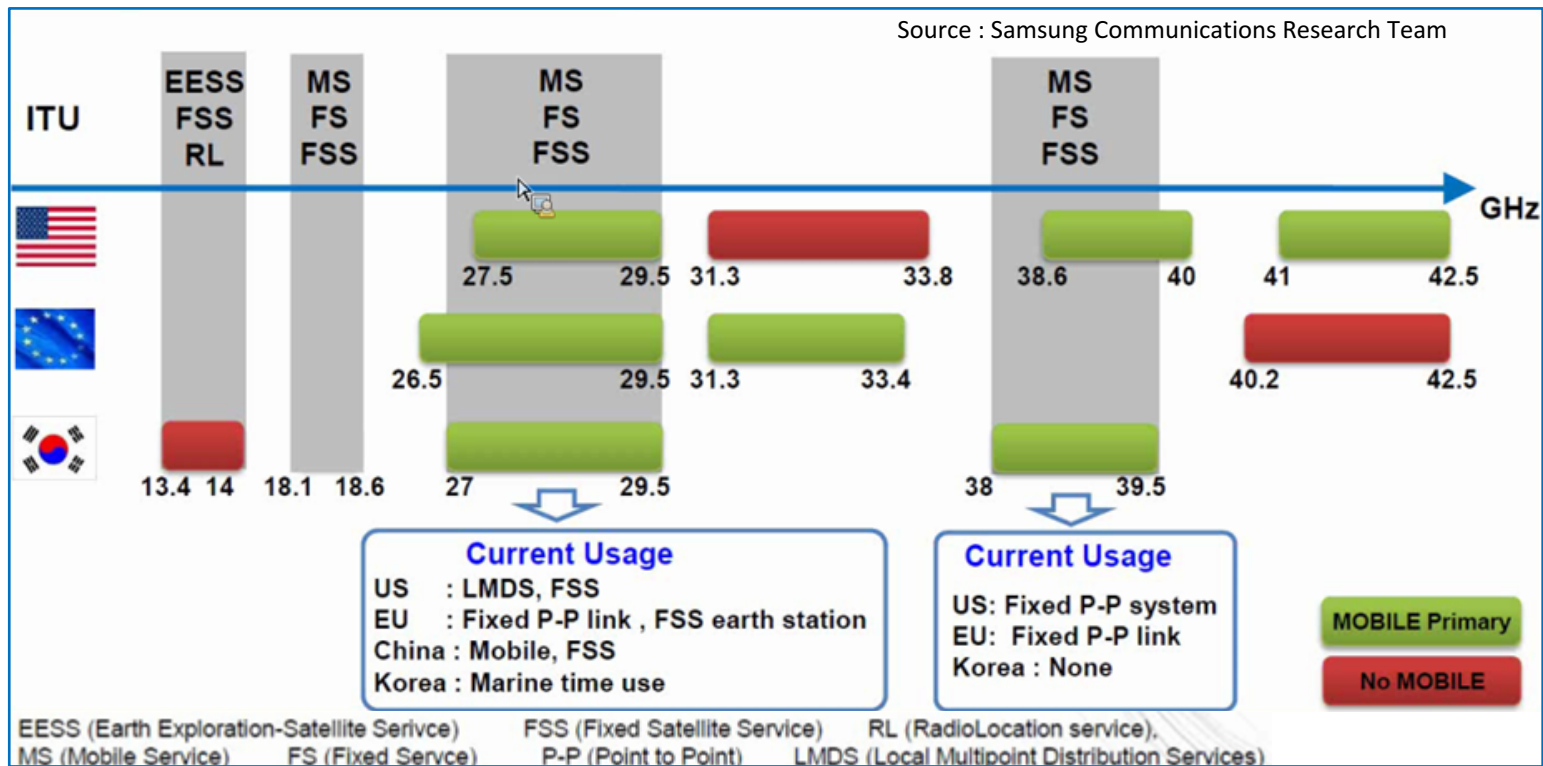
Source: CommScope

3.5 GHz user classes



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

30-40 GHz mmW overview



- Note: The Commission's Fixed Microwave (Part 101) and Satellite Communications (Part 25) service rules govern most of US mobile allocations shown above

MMW: Spectrum Frontiers R&O

Core Principles

- Identify substantial spectrum in MMW bands for new services
- Protect incumbent services against interference
- Flexible use: enable market to determine highest valued use
- Overlay auctions where no existing assignments
- Provide spectrum for both licensed and unlicensed use

R&O – 10.85 GHz added for mobile service (July 2016)

- Licensed bands (3.85 GHz): 27.5-28.35 GHz; 37-38.6 GHz; 38.6-40 GHz
- Unlicensed bands (7 GHz): 64-71 GHz

FNPRM – seeks comment on another 18 GHz & above 95 GHz

- 24.25-24.45 GHz; 24.75-25.25 GHz; 31.8-33.4 GHz; 42-42.5 GHz; 47.2-50.2 GHz; 50.4-52.6 GHz; 71-76 GHz; 81-86 GHz; bands above 95 GHz

Licensing, operating and regulatory rules

- Part 30: Upper Microwave Flexible Use Service (UMFUS)
- Geographic area licensing, area size, band plan, license term

Conclusions

5G is no one thing

- and some of the “things” may be secondary
- but reducing the cost per

New spectrum is one key differentiator for 5G

New bands may take 10+ years: policy negotiation + clearing/sharing + deployment

Each band has unique challenges, but some tools emerging

- reverse auctions for clearing
- spectrum databases, enabled by multiple radios and GPS