DUFF & PHELPS

Spectrum Update

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TECHNOLOGY FUTURES INC.

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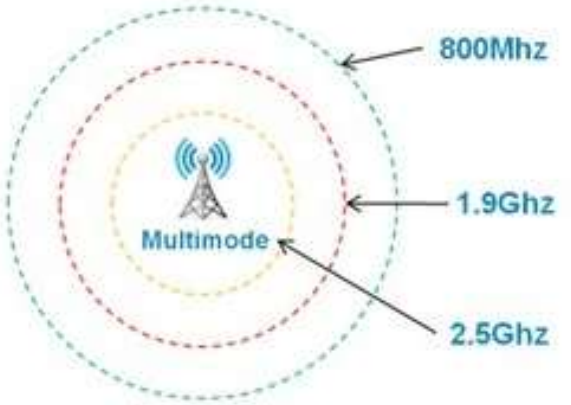
Speaker:

Ruben Miranda, ASA

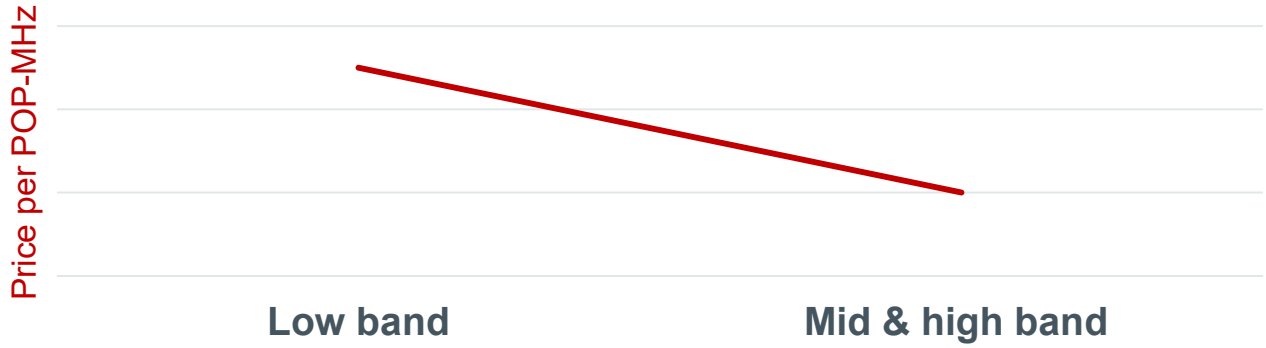
Director, Duff & Phelps LLC

Key Takeaways from Previous Sessions
Spectrum for Wireless Communications

- Historically, carriers relied on low-band spectrum to maximize coverage.
  - Propagation (travels farther)
  - Penetration (in-building coverage)
  - Exclusivity (no interference)



- Because of this emphasis on coverage, it followed that, *all things being equal*, spectrum's intrinsic value was historically worth more at low frequencies, and less at high frequencies.



Key Takeaways from Previous Sessions
Spectrum for Wireless Communications

- A regression analysis presented in 2018 altered that thinking.
  - Regressed Auctions 66 & 73 (pre 2014) vs Auctions 97 & 1002 (post 2014) – looked at income, age, paired vs non-paired, type, & density
  - All else held equal, the type (low band vs mid&high-band) resulted in a coefficient swing of $1 per POP-MHZ **in favor of mid & high-band**
- What is happening?!?
  - We didn't know in 2018, but clearly something else besides propagation and coverage was being considered in auction prices
  - mmWave analysis was expected to yield an answer....did it?

Spectrum Prices
FCC Auctions for mmWave Spectrum in 2019

- Auction 101
  - 28 GHz frequency
  - 2 different blocks of 425 MHz channels
  - Closed Jan 2019 (Verizon 72%)

$0.011/MHz-POP

- Auction 102
  - 24 GHz frequency
  - 7 different blocks of 100 MHz channels
  - Closed June 2019 (AT&T 49%, T-Mobile 40%)

$0.009/MHz-POP

- Auction 103
  - 37 GHz / 39 GHz / 47 GHz
  - 34 different blocks of 100 MHz channels
  - 48 rounds as of 1/14/2020

$0.007/MHz-POP

Spectrum Defined
"Information Superhighway"

Alan Gutierrez (1994)

Spectrum Defined

Highway Analogy

Spectrum Defined

Highway Analogy

How do we move more cars and trucks (data bits)?

1. Have them go faster
2. Add more lanes

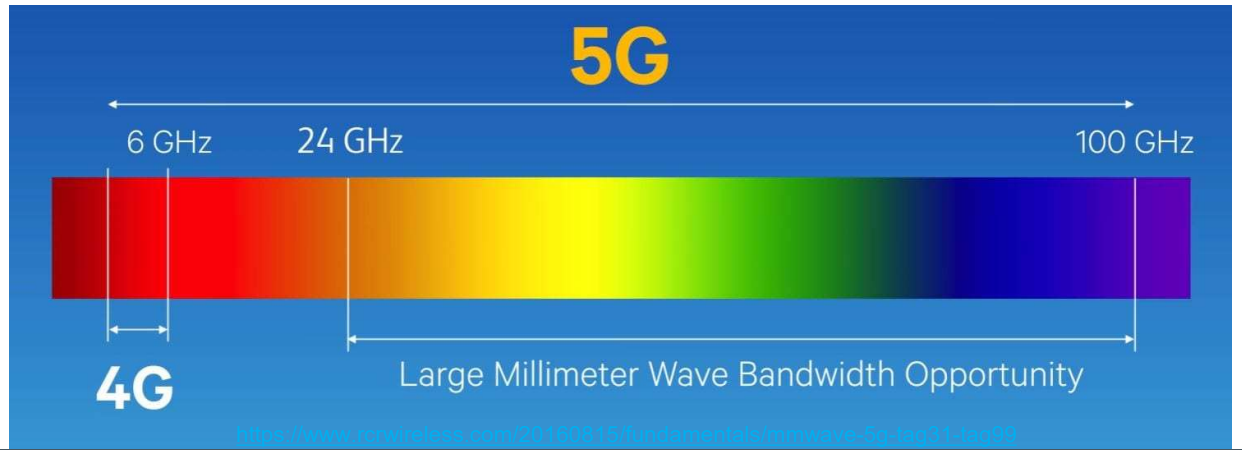
Spectrum Defined
Increasing Data Throughput

- Solution #1: Make the bits go faster
  - Cars and trucks have a hypothetical speed limit in their current form
  - “Where the rubber meets the road”
  - Friction and drag at high speeds become a bottleneck
- Radio transmitters and handset modems in their current form also have a bottleneck; a theoretical maximum rate at which information can be transmitted over a communications channel of a specified bandwidth.
  - Known as the Shannon-Hartley Theorem or Shannon Limit
  - Measured using spectral efficiency = Mbps per MHz *(mph per lane)*
  - Very hard to increase this number

Spectrum Defined
Increasing Data Throughput

- Solution #2: Add more lanes
  - Average auctioned license bandwidth in the United States is 10 to 20 MHz
  - Need new frequencies to carve out MASSIVE new channels
    - » Example: 10x increase in channel size (10-20 MHz → 100-200 MHz)

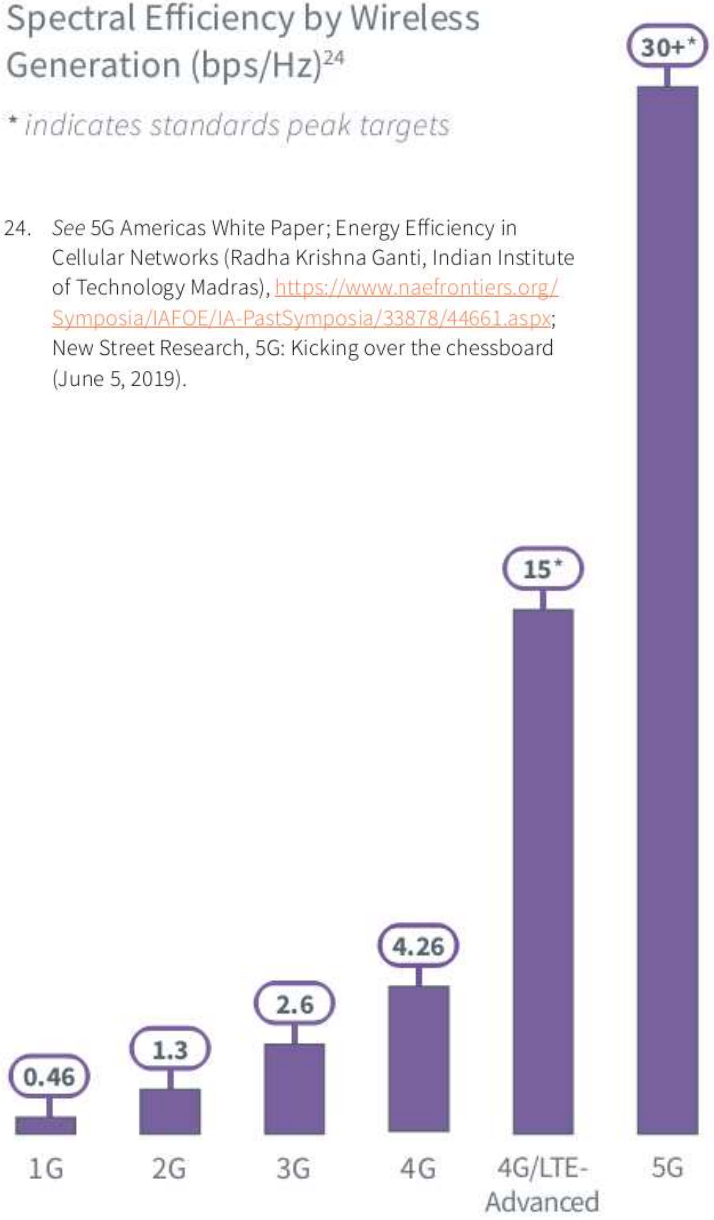
      = 10x increase in speed (at least)
  - Where are these frequencies? **In ultra-high millimeter wave (mmWave)**
  - Craig Moffett: "The standards of 5G were set for insanely wide blocks of spectrum. You can't find insanely wide blocks of spectrum anywhere but these stratospheric high frequencies."



Spectral Efficiency by Wireless Generation (bps/Hz)[24]

* *indicates standards peak targets*

24. *See* 5G Americas White Paper; Energy Efficiency in Cellular Networks (Radha Krishna Ganti, Indian Institute of Technology Madras), https://www.naefrontiers.org/Symposia/IAFOE/IA-PastSymposia/33878/44661.aspx; New Street Research, 5G: Kicking over the chessboard (June 5, 2019).



5G Will Drive Even Greater Spectral Efficiencies In Key Bands[33]

33. T-Mobile US, Inc. & Sprint Corporation Public Interest Statement Attachment, WT Docket No. 18-197 (June 18, 2018), https://ecfsapi.fcc.gov/file/10618281006240/Public%20Interest%20Statement%20and%20Appendices-%20A-J%20(Public%20Redacted)%20.pdf.

19%

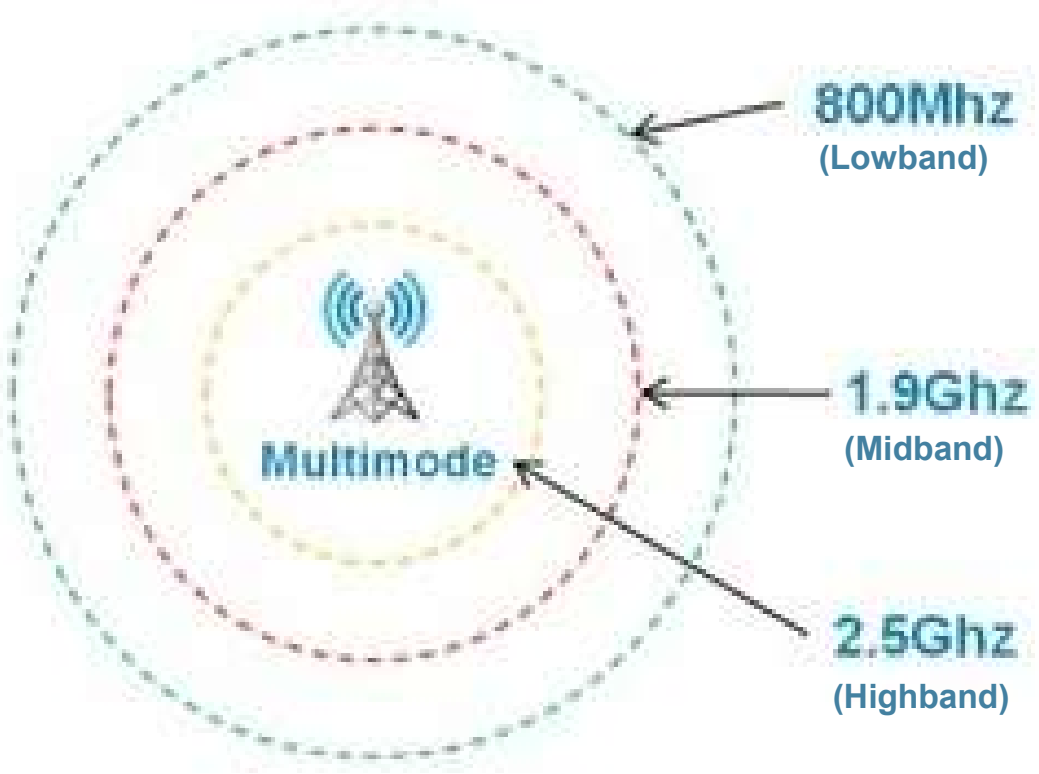
increase in low-band spectral efficiency.

52%

increase in mid-band spectral efficiency.

Source: "Smarter and More Efficient: How America's Wireless Industry Maximizes Its Spectrum." CTIA, July 9, 2019. https://www.ctia.org/news/smarter-and-more-efficient-how-americas-wireless-industry-maximizes-its-spectrum

Spectrum
5G Runs Better on Higher Frequencies



Per MHz channel

19% faster on 5G
(vs 4G LTE)

52% faster on 5G
(vs 4G LTE)

>100% faster on 5G
(vs 4G LTE)

Spectrum

Example Speed Benefits of 5G by Frequency

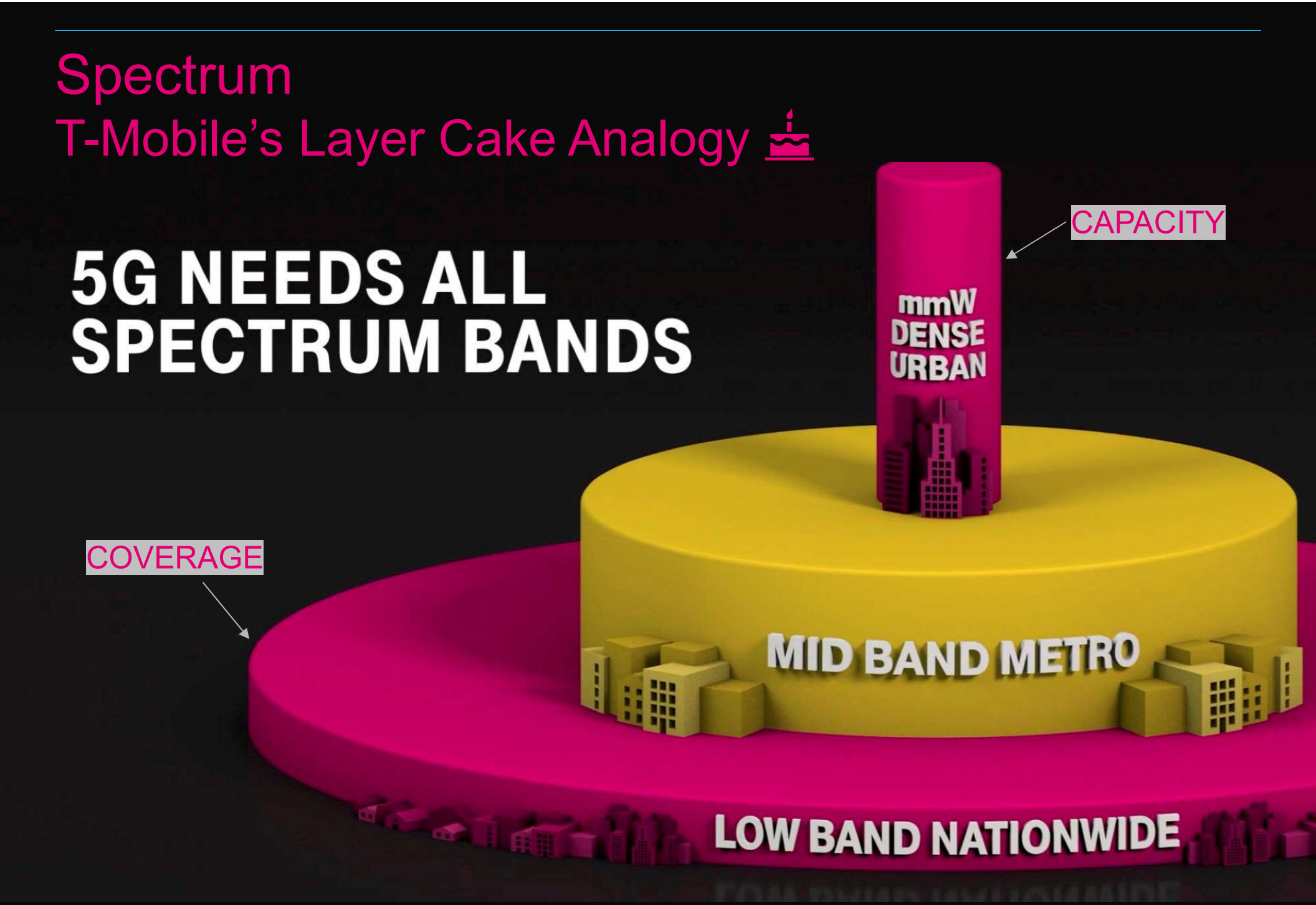
Type	Frequency (MHz)	Channel Width (MHz) [1]	4G LTE Spectral Eff. (Mbps/MHz)	4G LTE Speed (Mbps) [2]	5G Spectral Eff. (Mbps/MHz) [3]	5G Speed (Mbps) [2]
low	700	10	15.0	56.3	18.0	67.5
mid	1,700	10	15.0	56.3	22.5	84.4
high	2,500	10	15.0	56.3	22.5	84.4
mmwave	43,000	100	15.0	112.5	30.0	1,125.0

[1] Assumes max channel width for LTE of 20 MHz
[2] Assumes 50% allocated for download & 25% overhead
[3] Assume 19% increase for low-band, 50% increase for mid- and high-band, 100% for mmwave

- Speed Bump
  - 4G LTE (existing bands): 56.3 Mbps
  - 5G on mmWave: **1,125 Mbps**
  - **10x** increase in channel size, **19x** increase in speed!

Spectrum

T-Mobile's Layer Cake Analogy



Spectrum
Impact of Using mmWave

- Coverage or capacity….must compromise with 5G!
  https://arstechnica.com/information-technology/2019/04/millimeter-wave-5g-isnt-for-widespread-coverage-verizon-admits/
  - T-Mobile CTO Neville Ray wrote that millimeter-wave spectrum "will **never materially scale** beyond small pockets of 5G hotspots in dense urban environments" (4/9/2019)
  - Verizon CEO Hans Vestberg: "We will need to remind ourselves, **[mmWave] is not a *coverage* spectrum**"
  - Verizon Consumer Group CEO: "While we can deploy and we will deploy a 5G nationwide offering, the lower down the spectrum tiers you go, the more that will approximate to a good 4G service"

Conclusion

- Historic driver of price was propagation
  - Low band = more valuable
- The NEW drivers of price are
  - Spectral efficiency (higher bands = more valuable)
  - Availability (higher bands have the contiguous space)
  - Low band retains coverage value but not capacity value
  - The industry needs a new metric to decipher value ($/Mbps? $/POP-Mbps?)
- People are going to be disappointed in 5G!
  - Initial 5G rollouts in 2019 were almost entirely on low-band
  - Carriers promised “more to come”, which tells you a lot about what they expect from customers today
    - » “Where’s my gigabit service?”

Thank You