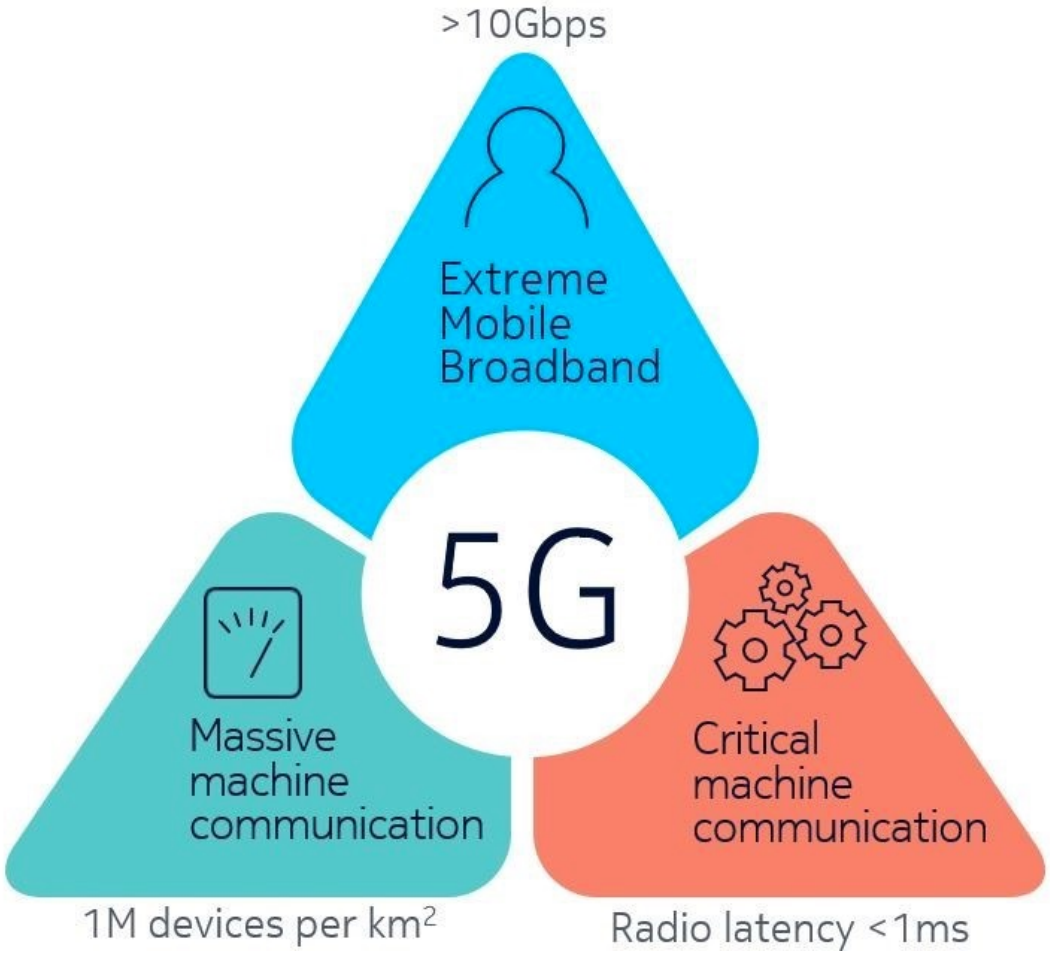
This material is based upon work supported by the National Science Foundation under Grant No. 1932418. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

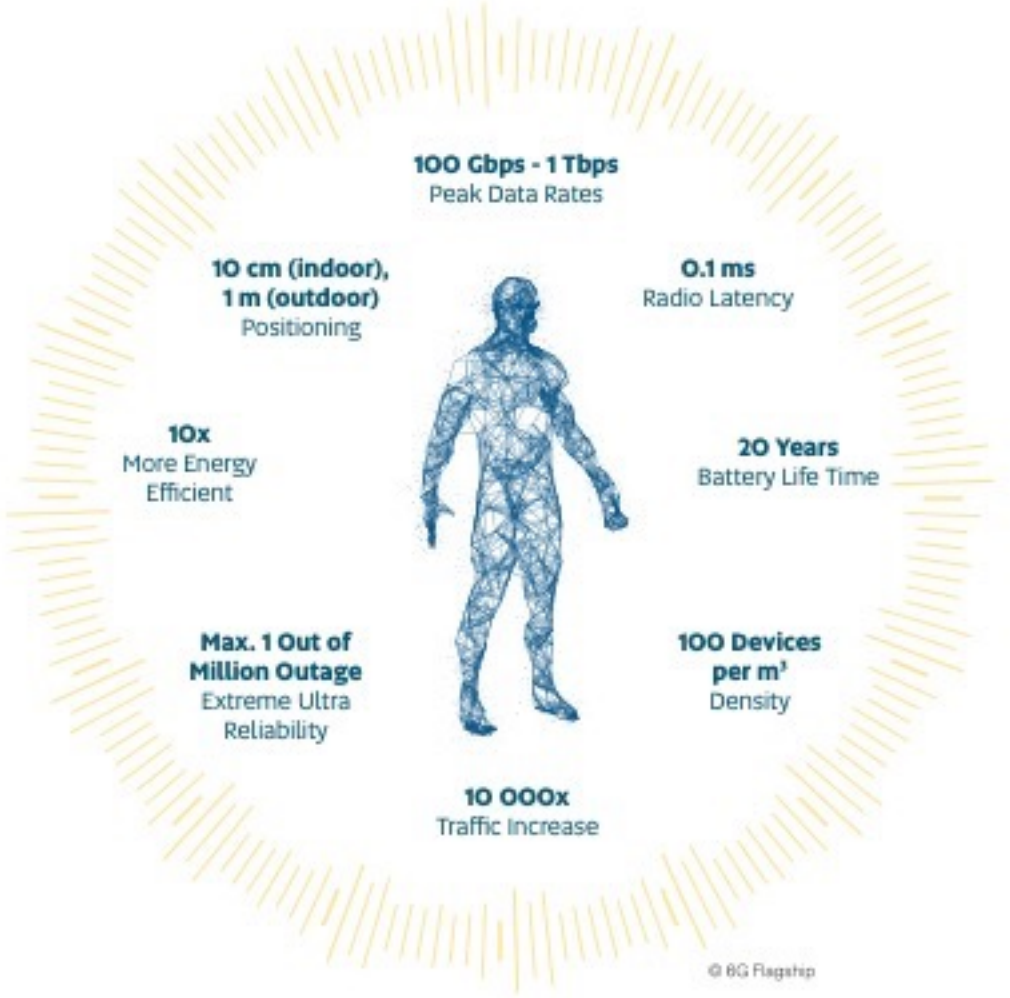
Scaling networks up and down: new network architectures for 6G

Henning Schulzrinne

Columbia University

Classical requirements pyramid





mostly PHY requirements!

The most important metric is missing!

Comcast *Median* Household Usage in GB/month

average: 500 GB/month
➔ $0.12/GB

BLS data (Internet services and electronic information providers)

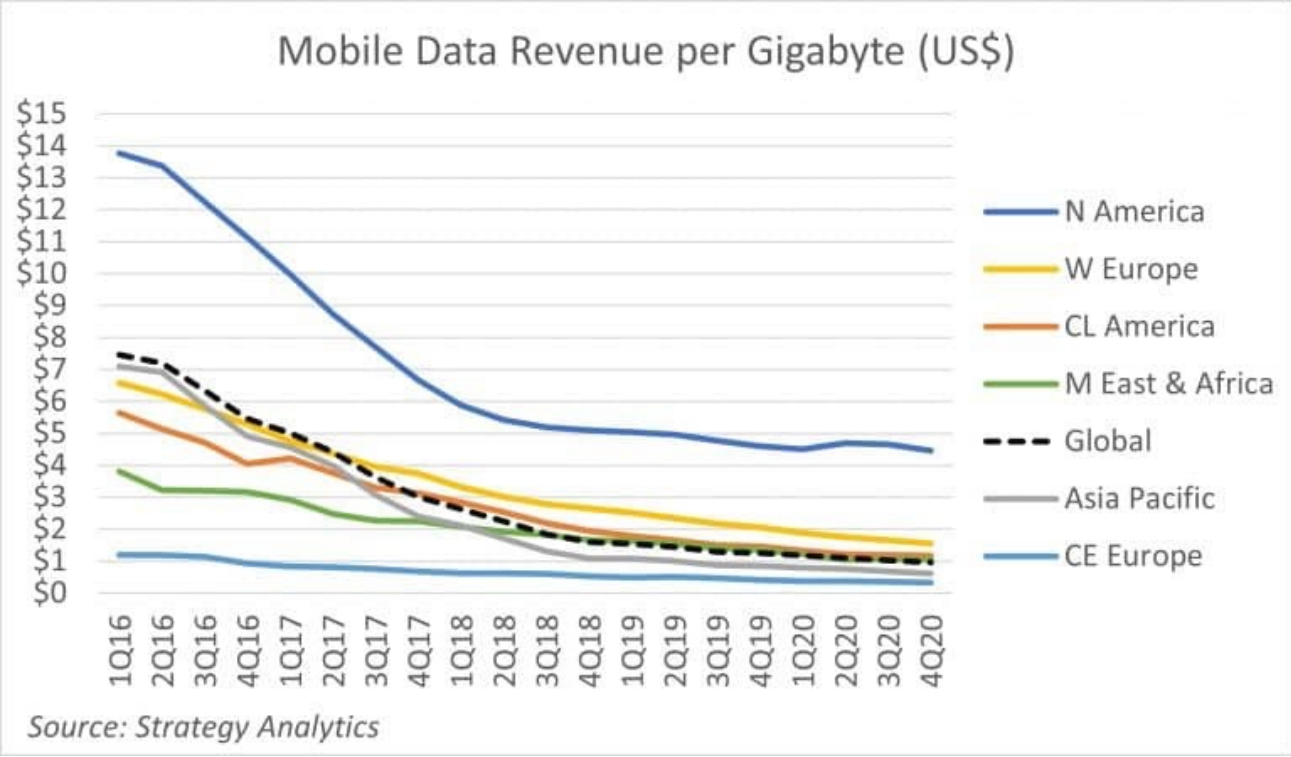
roughly 35% AAGR since 2017

400
350
300
250
200
150
100
50
0

Oct-08 Feb-09 Jun-09 Oct-09 Feb-10 Jun-10 Oct-10 Feb-11 Jun-11 Oct-11 Feb-12 Jun-12 Oct-12 Feb-13 Jun-13 Oct-13 Feb-14 Jun-14 Oct-14 Feb-15 Jun-15 Oct-15 Feb-16 Jun-16 Oct-16 Feb-17 Jun-17 Oct-17 Feb-18 Jun-18 Oct-18 Feb-19 Jun-19 Oct-19 Feb-20 Jun-20 Oct-20 Feb-21 Jun-21 Oct-21

GB/month

Without cost (and price) decrease, no advanced applications

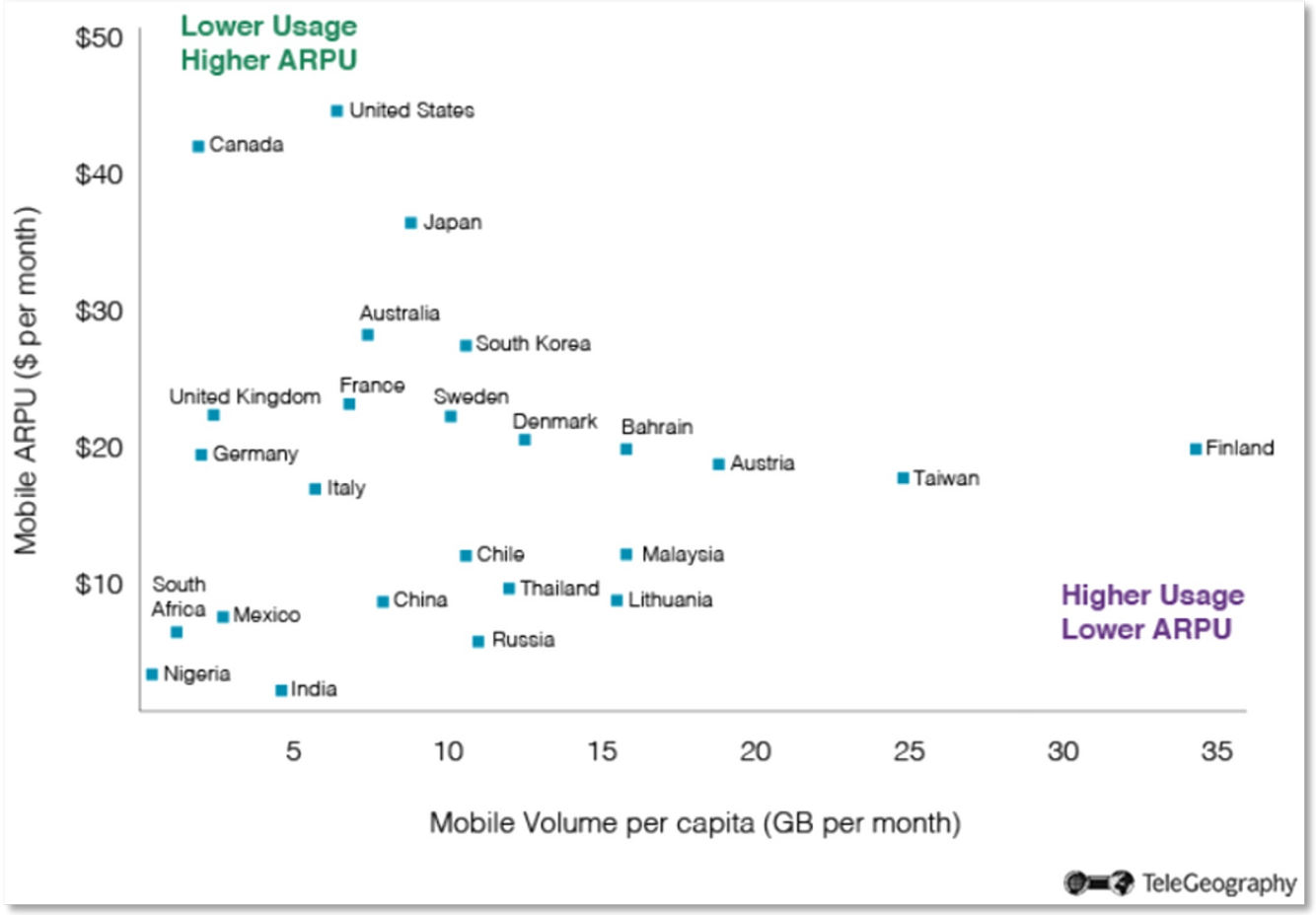


STADIA

Resolution	Data usage
Up to 4K (Stadia Pro only)	Up to 20 GB/hr
Up to 1080p	Up to 12.6 GB/hr
Up to 720p	Up to 4.5 GB/hr

➔ The key performance metric is $/GB (and maybe $/km^2 coverage)

Network cost and price are highly variable

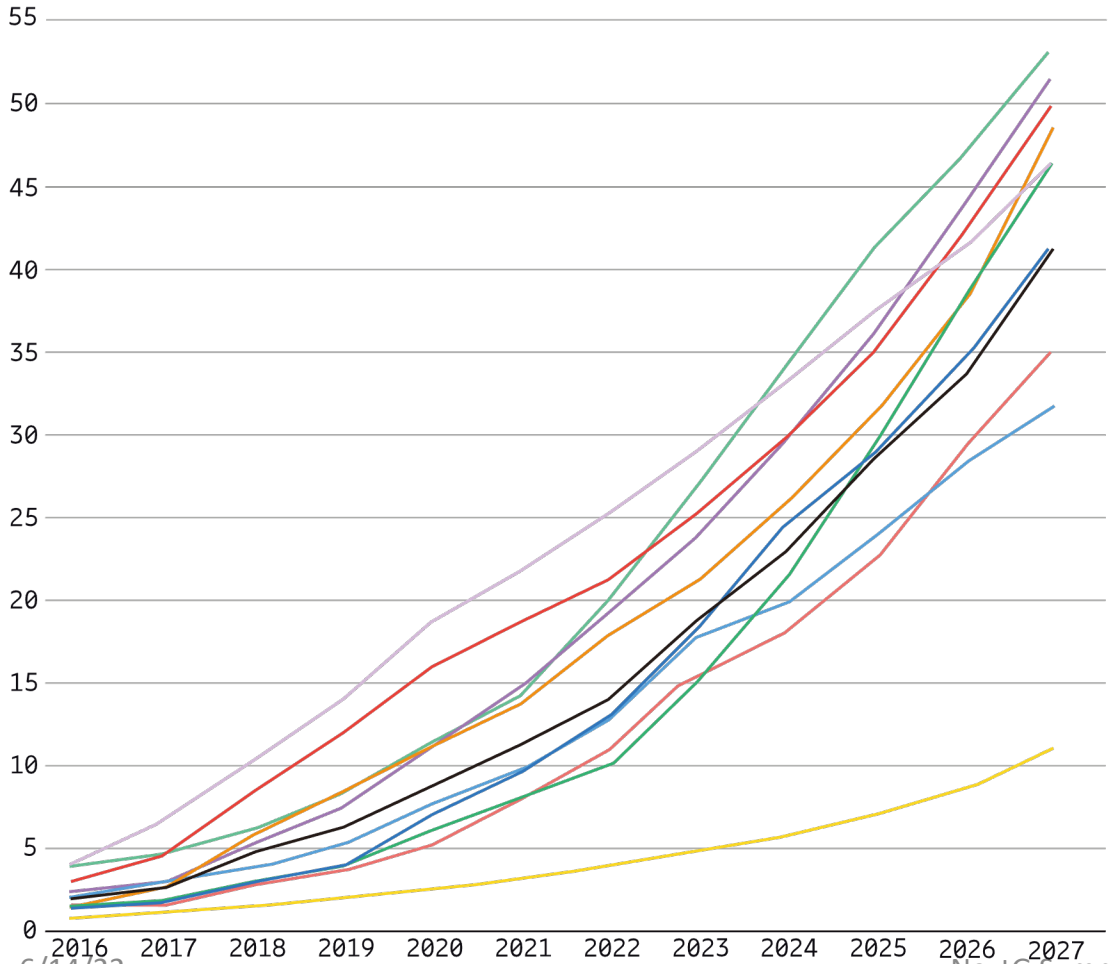


avg. about 5.1 GB/month
T-Mobile: 10 GB tethering

March 2020

Mobile data usage

Ericsson Mobility Report Nov. 2021



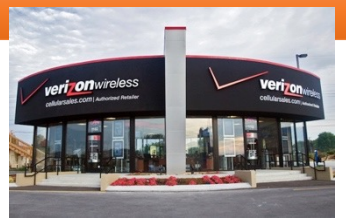
Regions	2021	2027	CAGR 2021–2027
North America	14.6	52	24%
Western Europe	15.2	51	23%
India	18.4	50	18%
North East Asia	13.9	48	23%
South East Asia and Oceania	8.0	46	34%
GCC	22	46	13%
Middle East and North Africa	9.6	41	27%
Global average	11.4	41	24%
Latin America	7.9	35	28%
Central and Eastern Europe	9.9	32	22%
Sub-Saharan Africa	2.9	11	25%

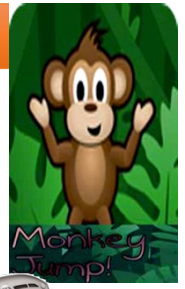
US ARPU (2022) = $35
➔ $2.40/GB

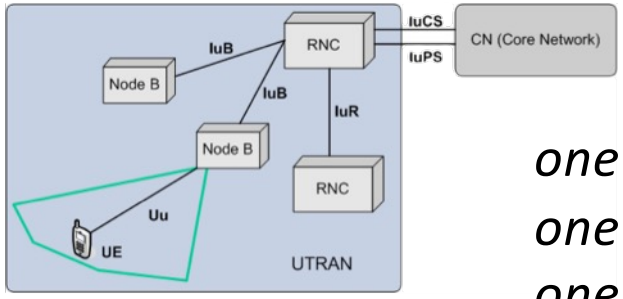
~20 times more expensive per GB than home (“Wi-Fi”)

Networks 1G through 4Gish

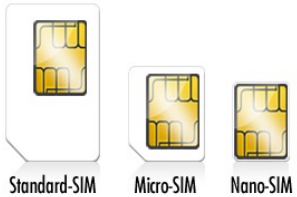
national carrier







one subscriber,
one phone,
one provider



What exactly is a carrier?

AMERICAN TOWER®
40k towers each (US)

CROWN CASTLE

FiberLight

lightower

zayo

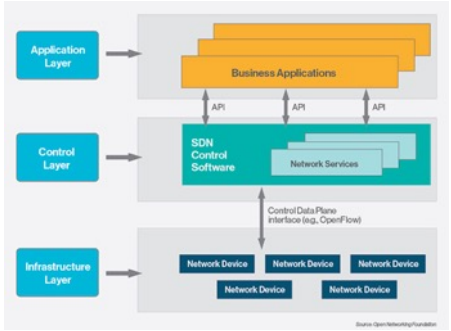
Spectrum DB

Google play

Level3
Cogent

comcast

LTE-U
802.11n
LTE



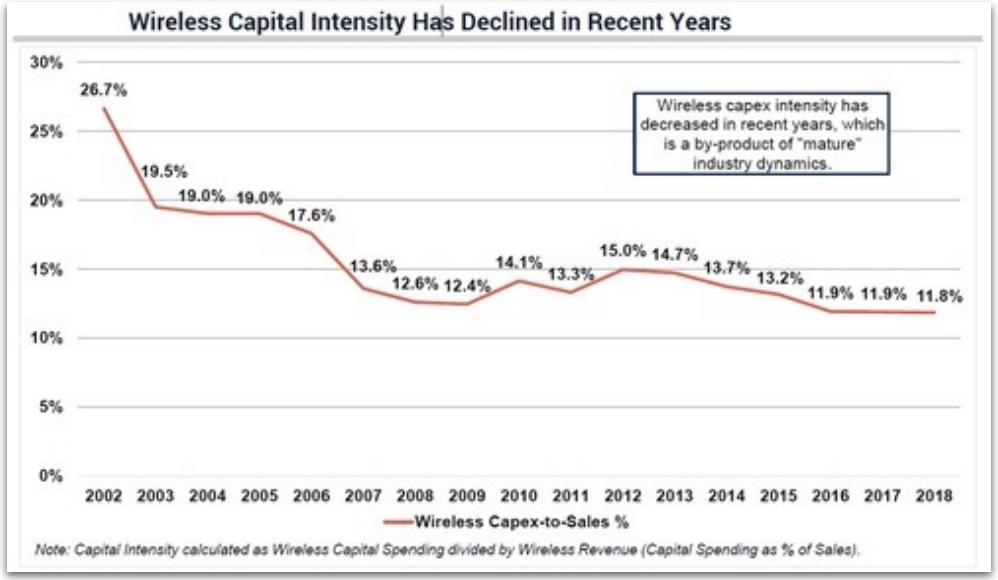
ERICSSON

Investment incentives for 5G are modest – are they going to be better for 6G?

Some of the world's first real 5G networks are coming online this year, sparking plenty of buzz and noise. However, a wide range of industry experts are cautioning that North American wireless network operators don't appear poised to invest in 5G networks like they did with 3G and 4G.

"We're negative on the prospects for a 5G investment 'cycle' from wireless operators -- at least over the near- and intermediate-term," wrote the Wall Street analysts at Jefferies Research. "Based on our analysis, we believe that the conditions for an acceptable return on investment (ROI) on 5G infrastructure are poor. Moreover, the 5G investment ROI looks drastically lower than the ROI associated with prior wireless investment cycles -- specifically 3G and 4G."

Why? It all comes down to flagging revenues in a saturated market. "The wireless service market is now a mature business," the analysts continued. "As such, operators' motivations for major capital investments will be reduced. To be clear, we still believe that 5G infrastructure deployment will happen. We expect that it will simply be a cutover of existing 4G investments to 5G technology. Most



Cell towers as cost driver (or revenue source)

349,344
cell towers in U.S. in 2019.

Total number of CELL TOWER SITES (cell towers, rooftops, water towers, flag-poles, billboards, etc.) in United States:
1,082,544

$70,655
Average revenues a cell tower generates per year.

WHAT ARE CELL TOWER LEASES WORTH IN 2022?

On average, wireless carriers entered into new lease with landowners at an average of $1,050/mo. on a nationwide basis. There is a wide variation though in what landowners are offered. Generally, most offers are between $500/mo. and $1,500/mo. for new ground leases for telecommunication towers. The average lease rate for all ground leases in our database in 2022 is just under $1,300/mo. It hasn't changed from 2021 but is up from 2018 when it was $1,220/mo. These averages include rural, suburban, and urban towers including newly-built 5G towers.

cellular revenue per cell site:
$190B US total → $175k

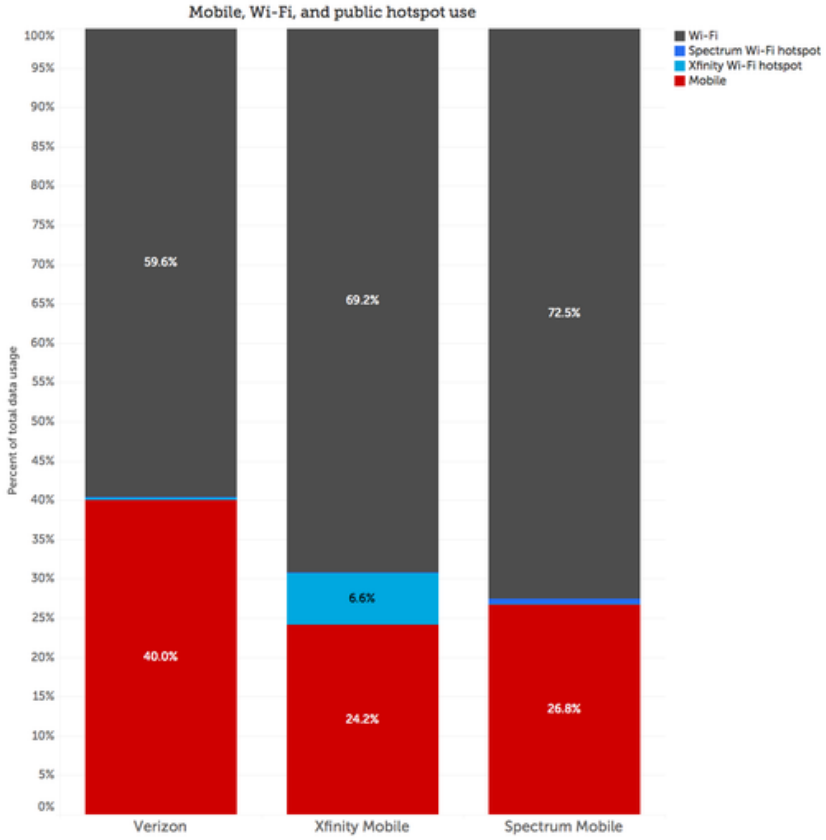
* Cost does not include radio equipment and backhaul!

https://www.celltowerleaseexperts.com/cell-tower-lease-news/cell-tower-industry-facts-figures-2016

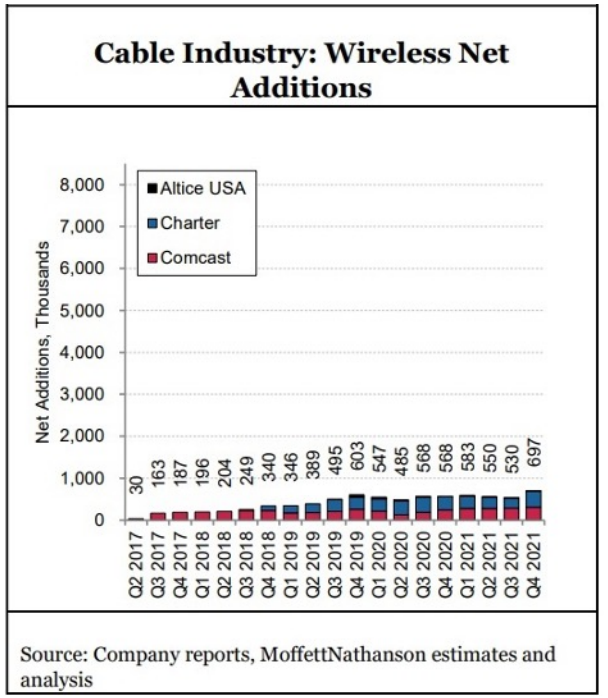
New operator models – cable (HFC) industry

All major US cable operators are offering cellular service

hybrid model:
MVNO + Wi-Fi + CBRS



LightReading, 7/19



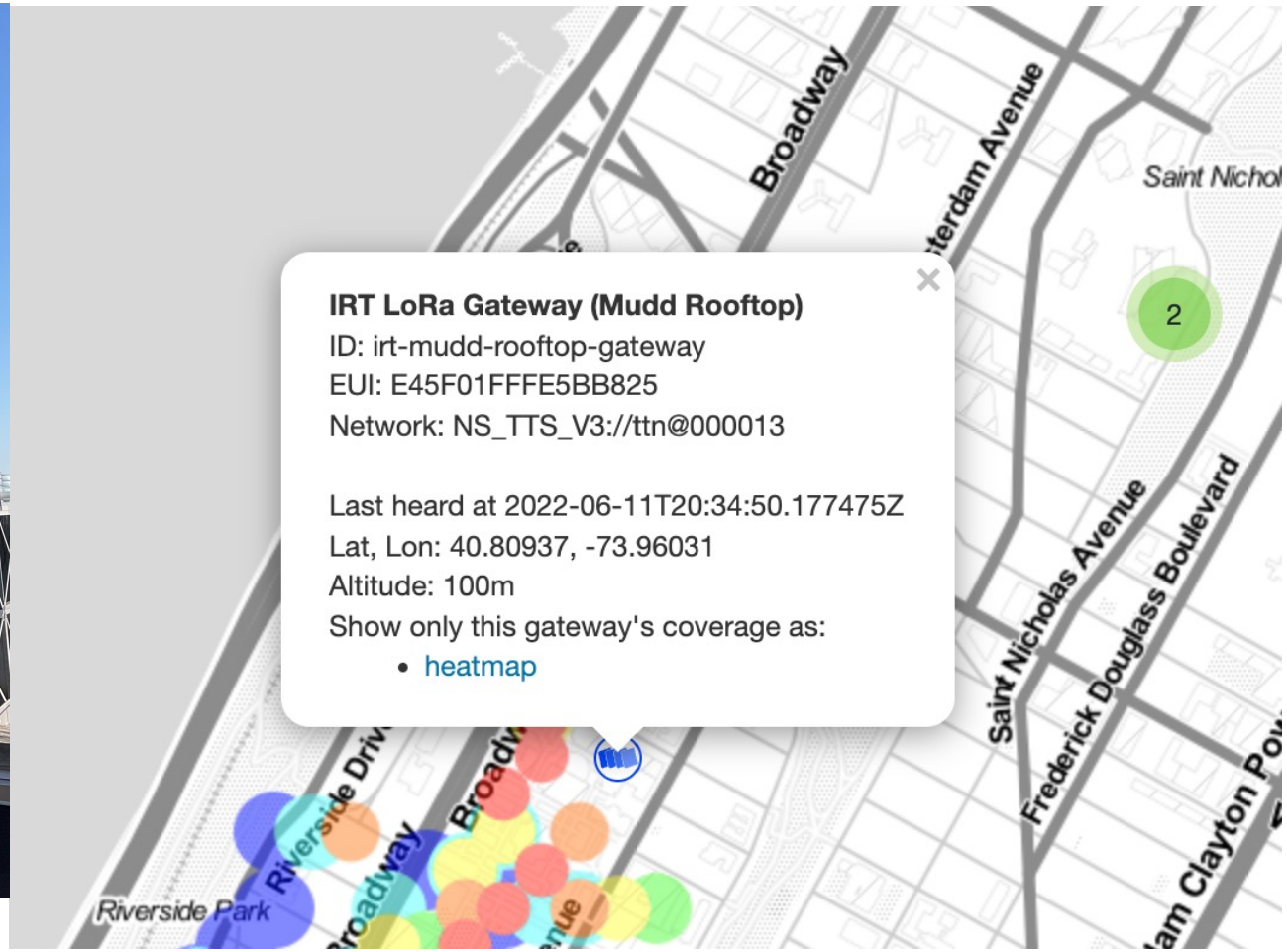
Comcast	4M
Charter	3.56 M
Altice	186k

LightReading, 3/22

The Things Network

The Things Network

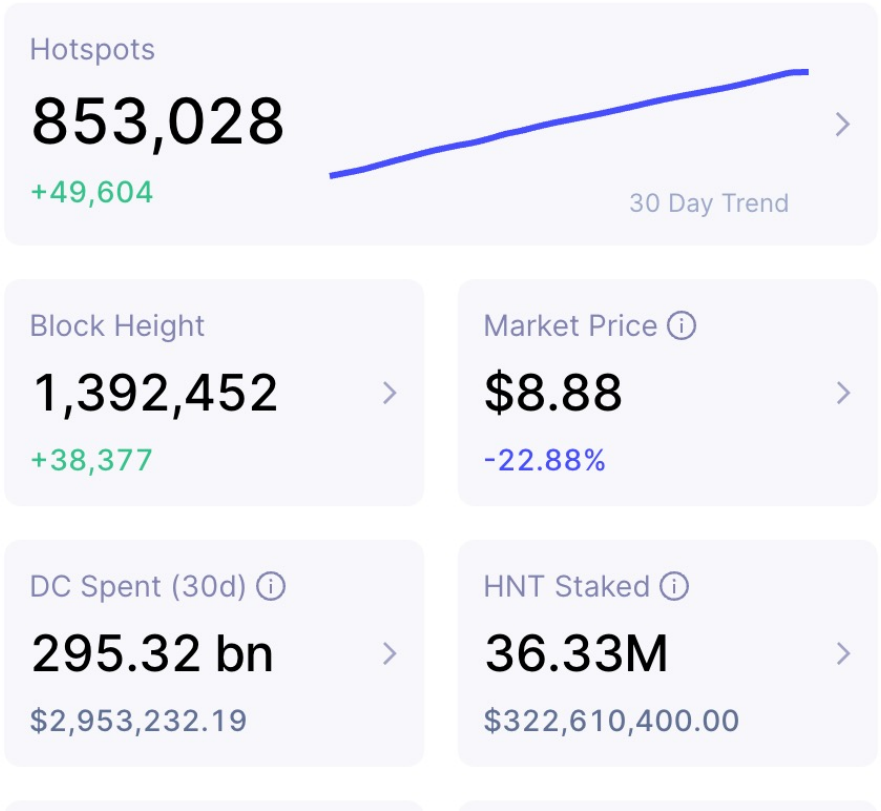
April 2022 (Columbia U.)



Helium LoRa model for IoT

Helium: **0.001c per 24-byte message (→ $416/GB)**

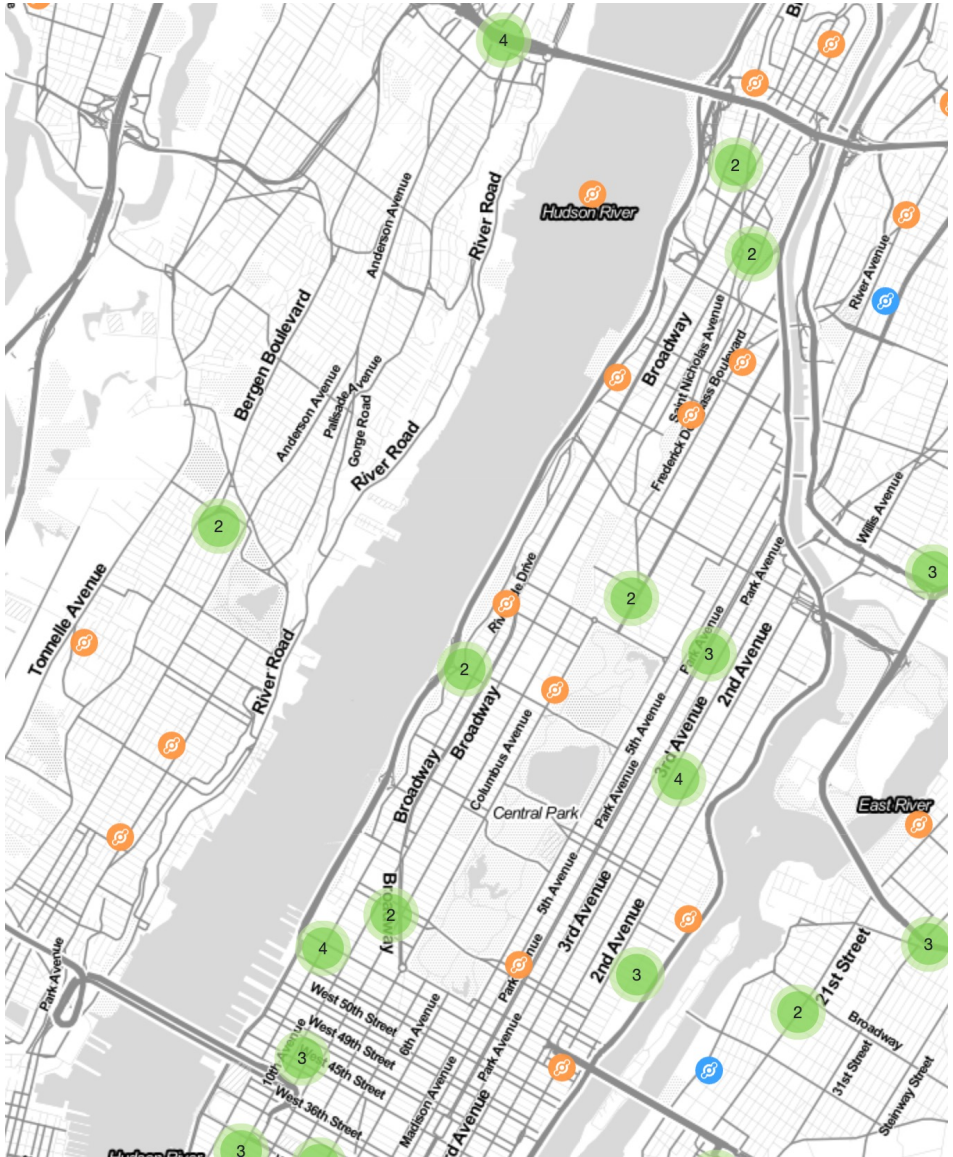
→ $3.46 per month and hotspot
5W of energy → $0.37 electricity



Dish Network will be the first major carrier to use the Helium Network's blockchain-based incentive model – with customers deploying their own 5G hotspots using Citizens Band Radio Service (CBRS) spectrum.

Cell-Tower-Lease-Industry-Facts-and-Figures.png

Helium in Manhattan

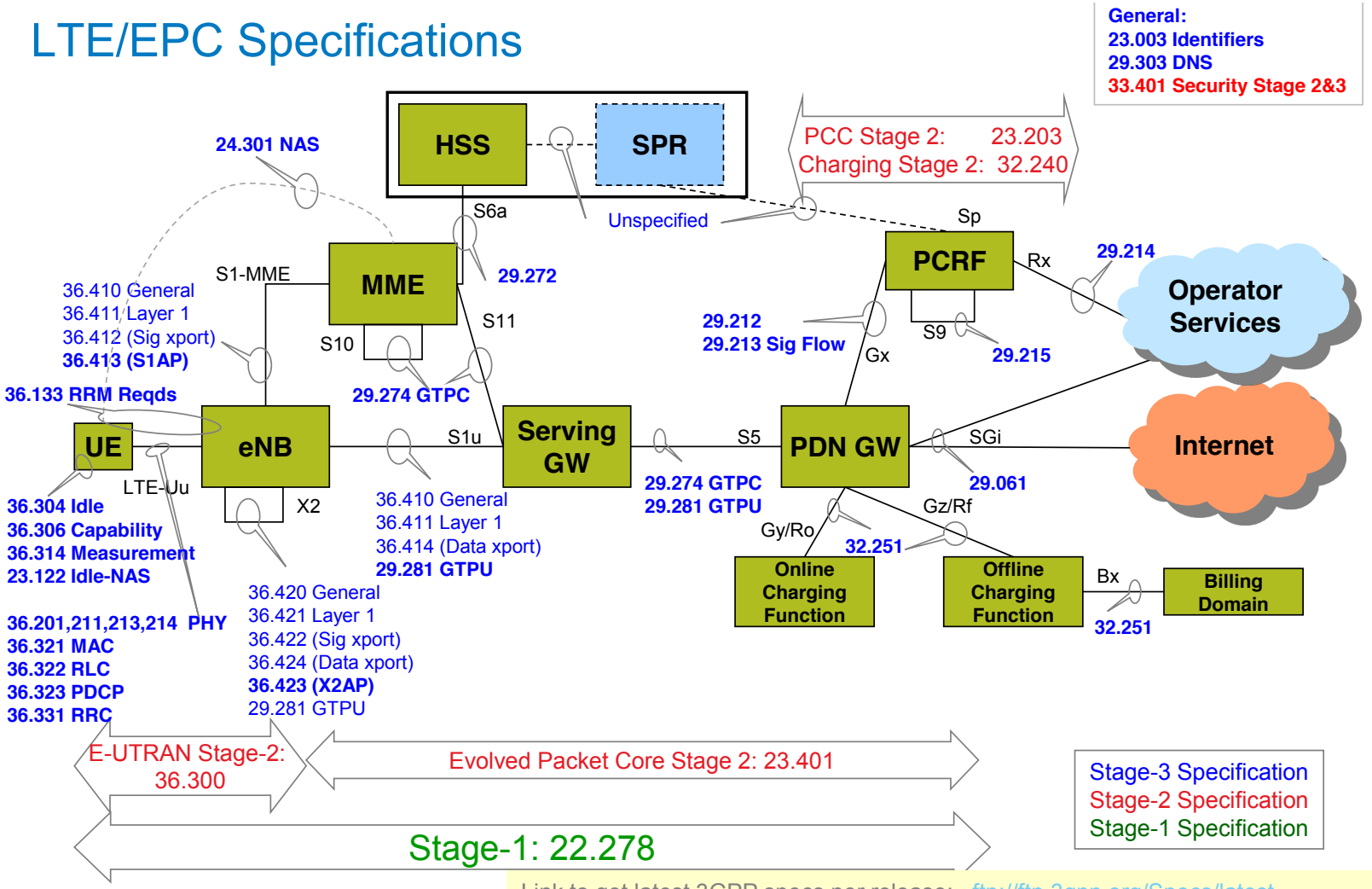


But blockchain models are volatile

https://www.coinbase.com/price/helium

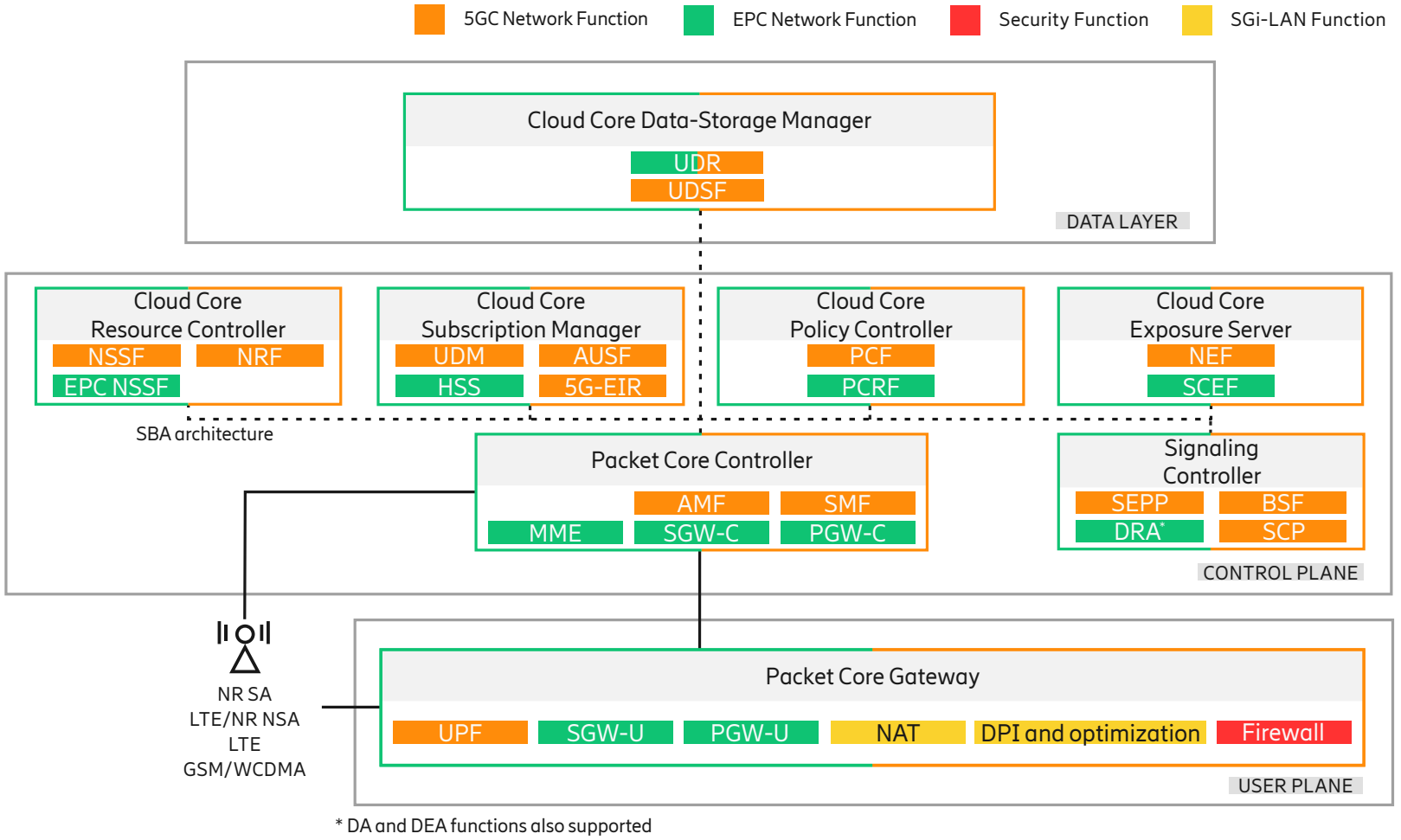
LTE EPC

LTE/EPC Specifications



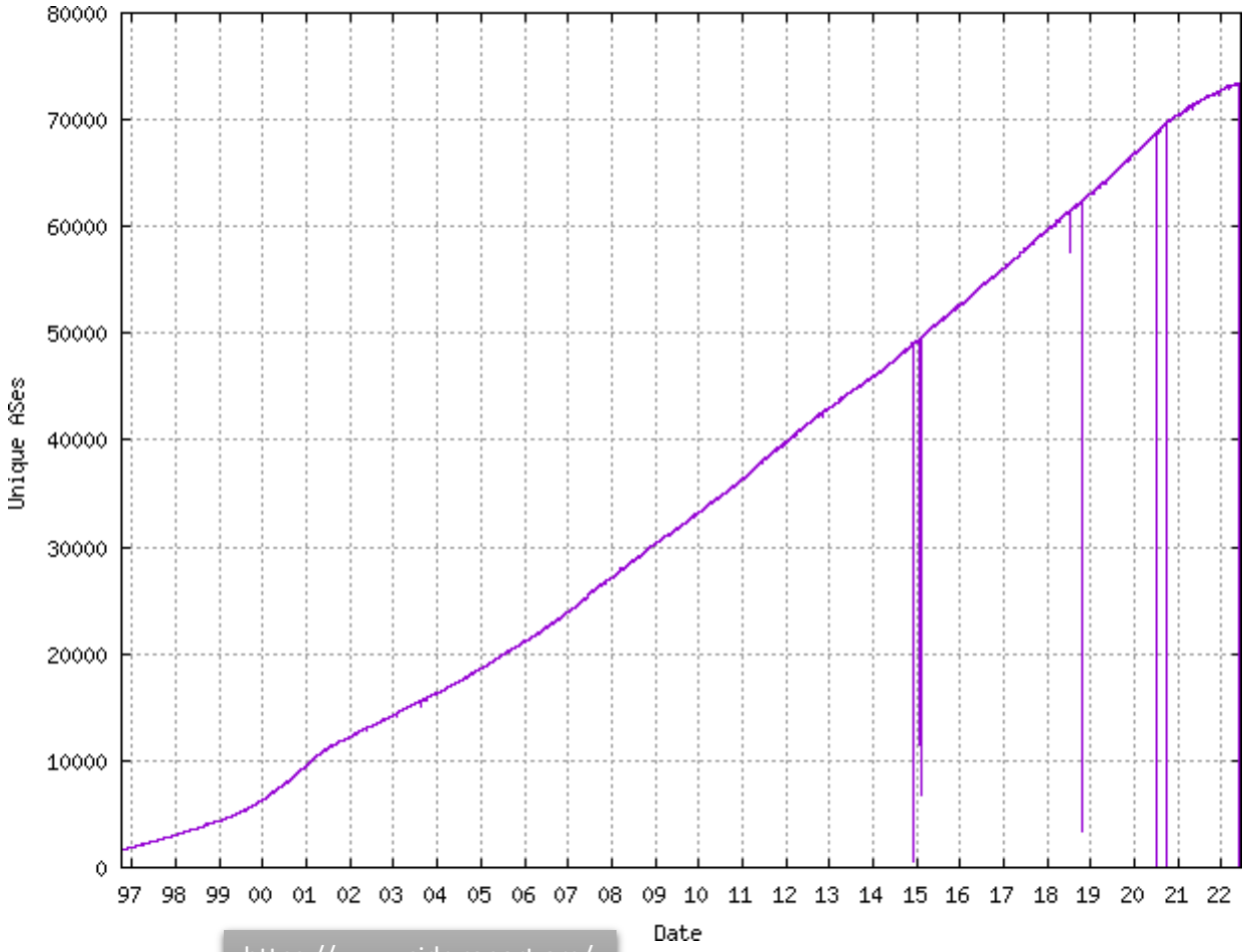
Link to get latest 3GPP specs per release: ftp://ftp.3gpp.org/Specs/latest
Link to find out what a spec covers: http://www.3gpp.org/Specification-Numbering

5G & 4G EPC



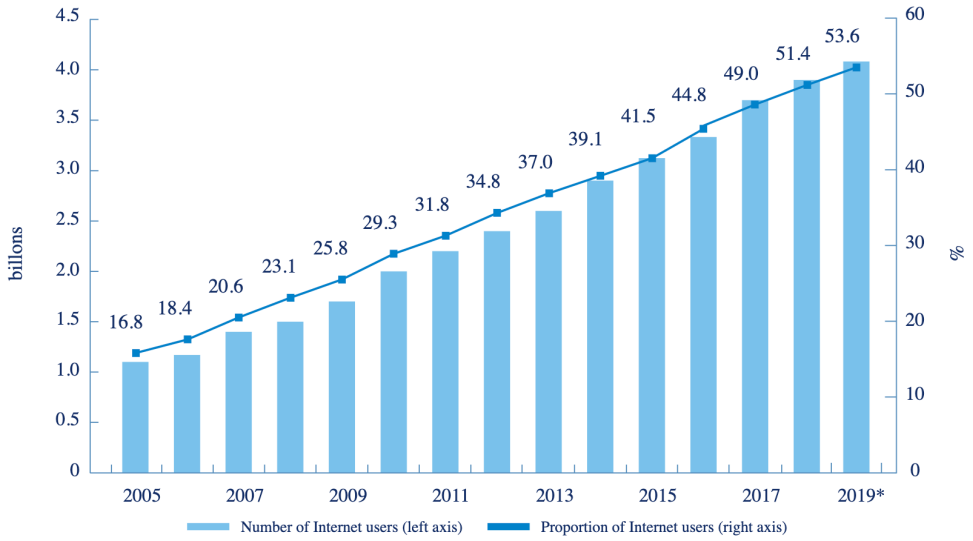
Ericsson, Oct. 2020

Users per ASN roughly constant



https://www.cidr-report.org/

Individuals using the Internet, 2005-2019*



roughly unchanged at 60k users per AS
(slight decrease in users / routing table entry)

https://itu.foleon.com/itu/measuring-digital-development/internet-us

Home networks are now small enterprise networks

The average U.S. household has 25 connected devices – more than double the 11 that the average household had in 2019, according to a new Deloitte report.

Largely self-managed:

- routing (mesh)
- device management
- device & user authentication

Scaling down is harder than scaling up

no PhD (or carrier training) needed!

large enterprise management

firewall
DNS
edge computing

mesh backhaul

identity management and trust still deficient

Network value is (much) more than PHY

Property	Requirements?	Example
Universality	Can I operate my system (almost) anywhere in the world?	Adaptive frequency use by region (device knows location)
Incremental system cost	How much does it cost to add the functionality to the system?	< $5 for IoT devices
Data cost	Can I build "free" data systems, even if restricted? Can I leverage cheap landline BW?	< $0.10/GB for in-home use
Network architecture	Can I build my own network?	peer-to-peer → mesh → access point → cellular → long-range
User management	Can I design my own user management?	database + credential device-based model coupled to other systems (e.g., combined with other services)
System management	Can the system largely manage itself?	Frequencies & power, but also users and traffic restrictions

What made Wi-Fi successful?

- Scalable complexity – 802.11b/g/n to 802.11ax
- Architectural flexibility
  - peer-to-peer, access point, mesh, long haul Pt2MP & Pt2Pt
  - re-use cheap local wired network and shared (managed & firewalled) access
- Multiple authentication models
  - from open access to federated 802.1x RADIUS
- Minimal viable network functionality
  - Ethernet frames + IP
  - local multicast
- International usability
  - universal “bootstrap” band (2.4 GHz)
  - locally-discoverable spectrum availability

What's bad about having both Wi-Fi and (nG) cellular?

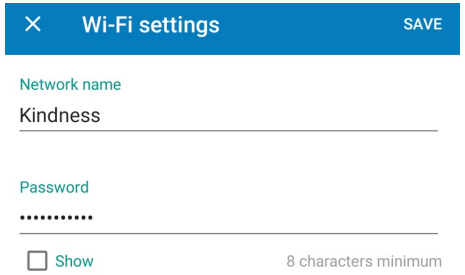
- System hardware complexity (e.g., for IoT devices)
- No seamless roaming
- Maintain multiple user identities
- Difficult to do consistent traffic restriction
  - cellular bypasses corporate firewall
- Inconsistent network behavior
  - e.g., IPv6 support
- More limited competition

Current authentication models

picket fence security

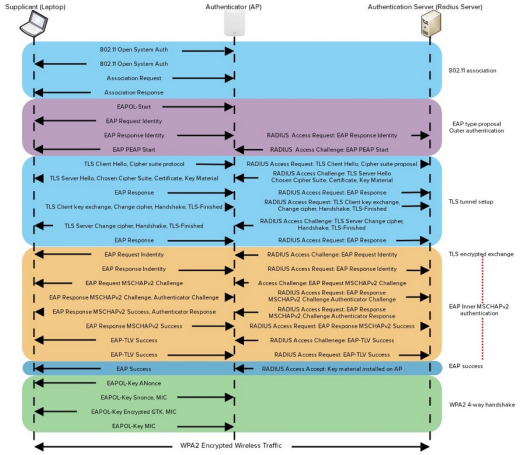
hard to scale to IoT

SCAN ME



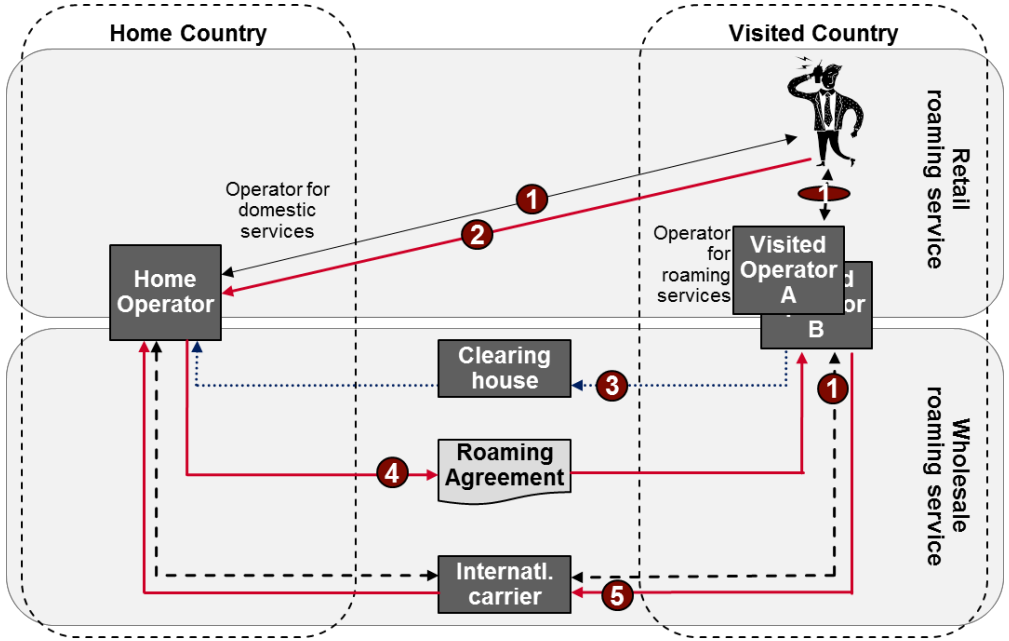
WPA2-Personal

802.1x



federated (RADIUS, DIAMETER)

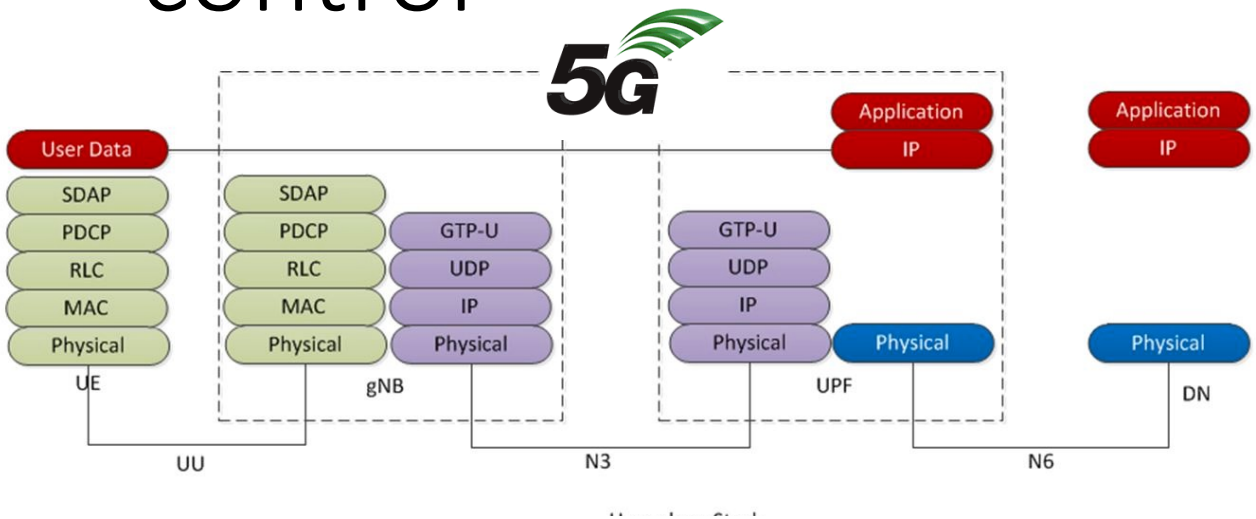
international roaming

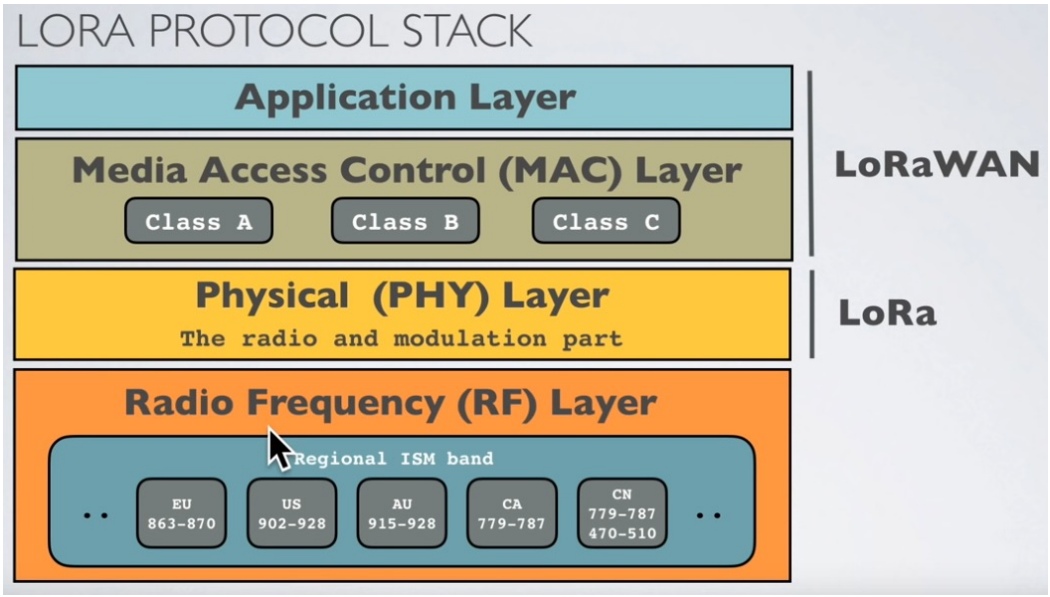


TAP: Transferred Account Procedure
Source: A.T. Kearney analysis

Roaming services
Traffic flow
Revenue flow
Data exchange

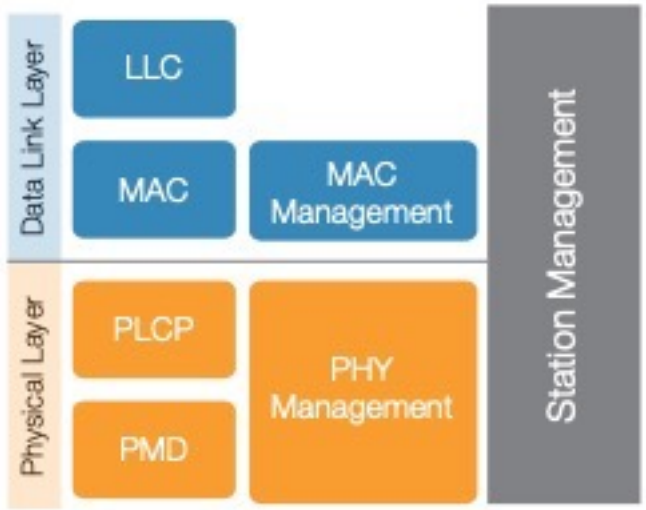
Stacks always focus on data – complexity is in control





LoRaWAN®

Wi Fi®



Requirements for simple networks

- Separate link layer from network architecture
  - Why can’t 5G (or 6G) NR operate on a home router, without a carrier?
  - Assume flexible spectrum access (geo database)
- Every interface must be testable and self-testing
- *Interface neutrality* = every control needs to be accessible to network consumer, not just operator (bounded by slice or authorization)
- Clean interfaces particularly at layer 2 and 3
- No configuration files, ever
- No hard-coded addresses (e.g., gateways), ever

What's needed for down-scalable networks?

- Better frequency coordination for CBRS GAA (and similar systems)
  - e.g., allow time-domain (slot?) coordination
- Support simple self-contained EPC that can run on AP
  - or OpenRAN with many *untrusted* participants → zero-trust networks
- Simplified roaming and settlement mechanisms
  - GSMA unlikely to scale
- May need new mobility models, but most new applications are likely nomadic and (somewhat) disruption-tolerant, not mobile and voice-like

Protocols matter, but programmability matters more

- Nobody wants to program raw protocols
- Most significant network application creation advances:
  - 1983: socket API → abstract data stream or datagram
  - 1998: Java network API → mostly names, HTTP, threads
  - 1998: PHP → network input as script variables
  - 2005: Ruby on Rails → simplify common patterns
- Many fine protocols and frameworks failed the programmer hate test
  - e.g., JAIN for VoIP, SOAP for RPC
- Most IoT programmers and factory automation specialists will not be computer scientists (and won't have a telecom background)
- Nobody learns ONAP in their CS BS

Two evolutionary paths for 6G

mostly not a PHY problem

lowest bandwidth cost

like 4G & 5G, just more
highest mobility

Conclusion

- The key performance metric is $/GB (and maybe $/km^2 coverage)
- The key challenge is incentivizing investment
- 6G needs an architecture re-think, not (only) better PHY
- Cleaner separation between media/complexity-dependent layers, common data transport and control planes
- Design scalable, IP-based control plane for everything from peer-to-peer mode to managed national cellular network
- Cleanly separate access from backbone
  - since likely continue to be both locally (enterprise) and third-party managed
- Opportunity to bridge the Wi-Fi - cellular chasm