5G and the Wireless Ecosystem: toward a disruption?
(an economist's perspective)

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~~5G~~ 6G (or xG) Vision : Pervasive Computing

Digital Economy is the future !

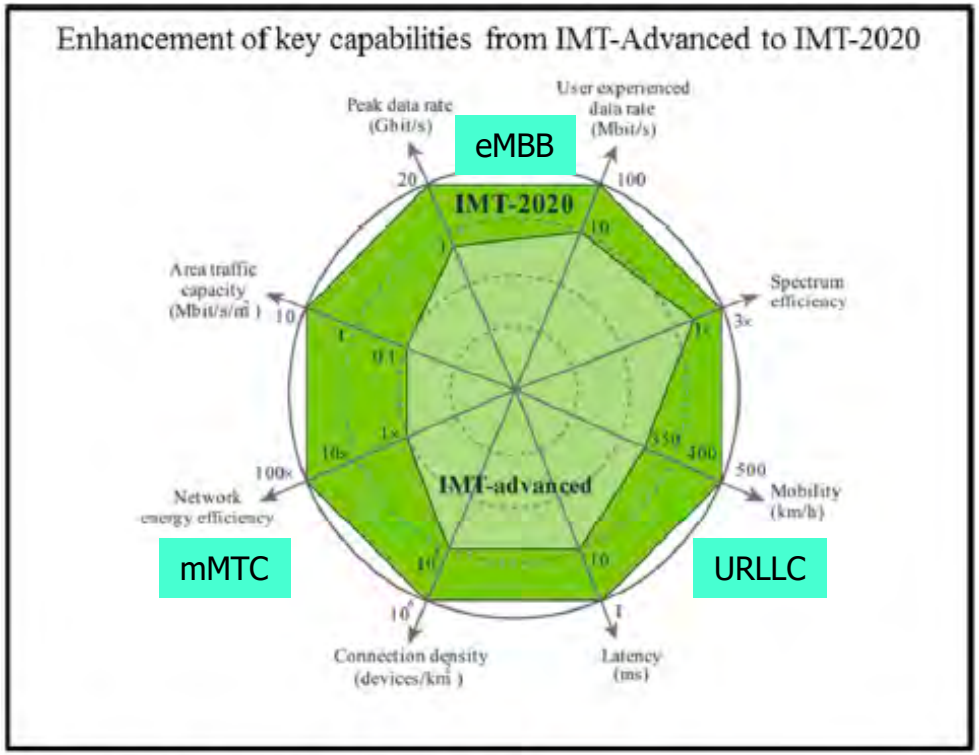
- Global transformation: all economies, all sectors (at different rates)
- ICTs accelerate, amplify, and augment changes. Disrupt.
- Digital & ”analog” elements of society/economy (laws, institutions, processes, skills, behavior, ...) must co-evolve

Everything, everywhere, always connect(able) to computing and networked resources

- 5G is the networking infrastructure to enable
- Clouds, IoT, BigData, AI, robots, Autonomous vehicles, Augmented Reality....”everything as a Service” (XaaS)
- Smart-X smart highways & vehicles; greener energy grids; healthcare; supply chains; natural resource mgmt.; finance & payments, etc.
- *Real and Virtual World Convergence*

5G is (vision of) the networking infrastructure to enable!

5G vision: Order magnitude performance improvement



Source: ITU Recommendation ITU-R M.2083-0 (2015)

Figure 2: 5G Network Improvements

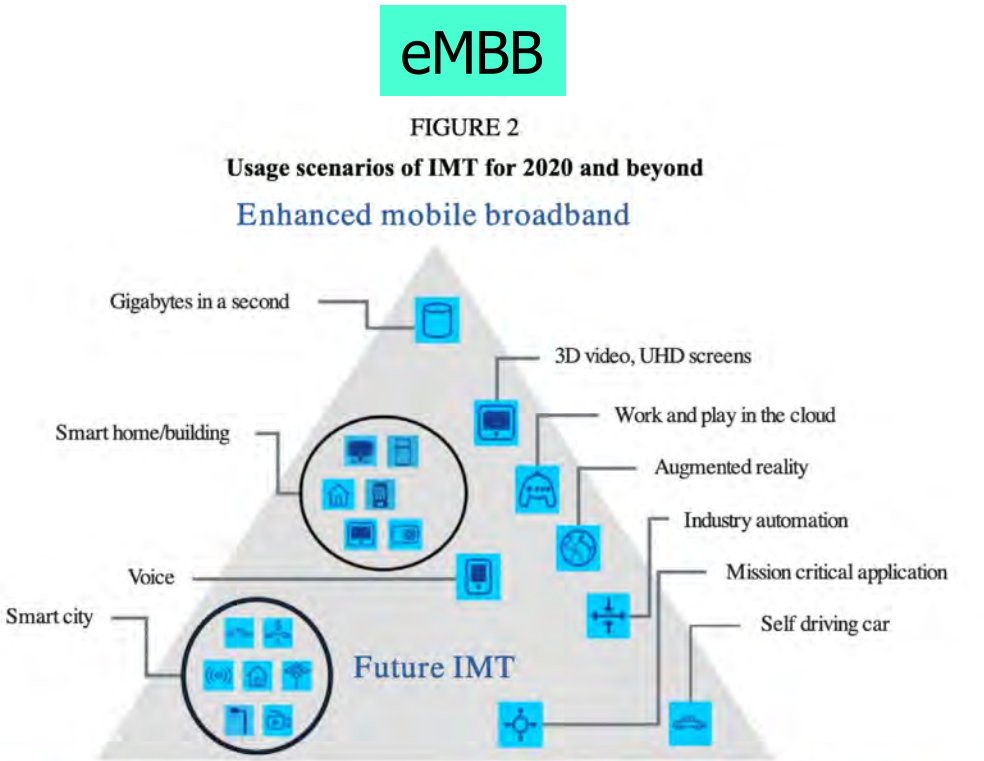
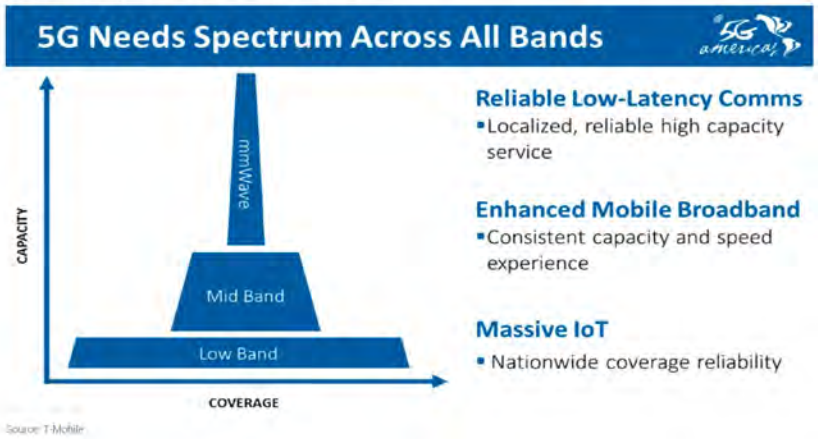


Exhibit 14:

5G will require spectrum across different frequencies



Source: T-Mobile

.. We realize the future as we move toward the horizon

5G: global CAPEX $872B. (1.7 x 4G CAPEX 2019-2030)

Exhibit 8:

Master 5G comparison table for the four markets

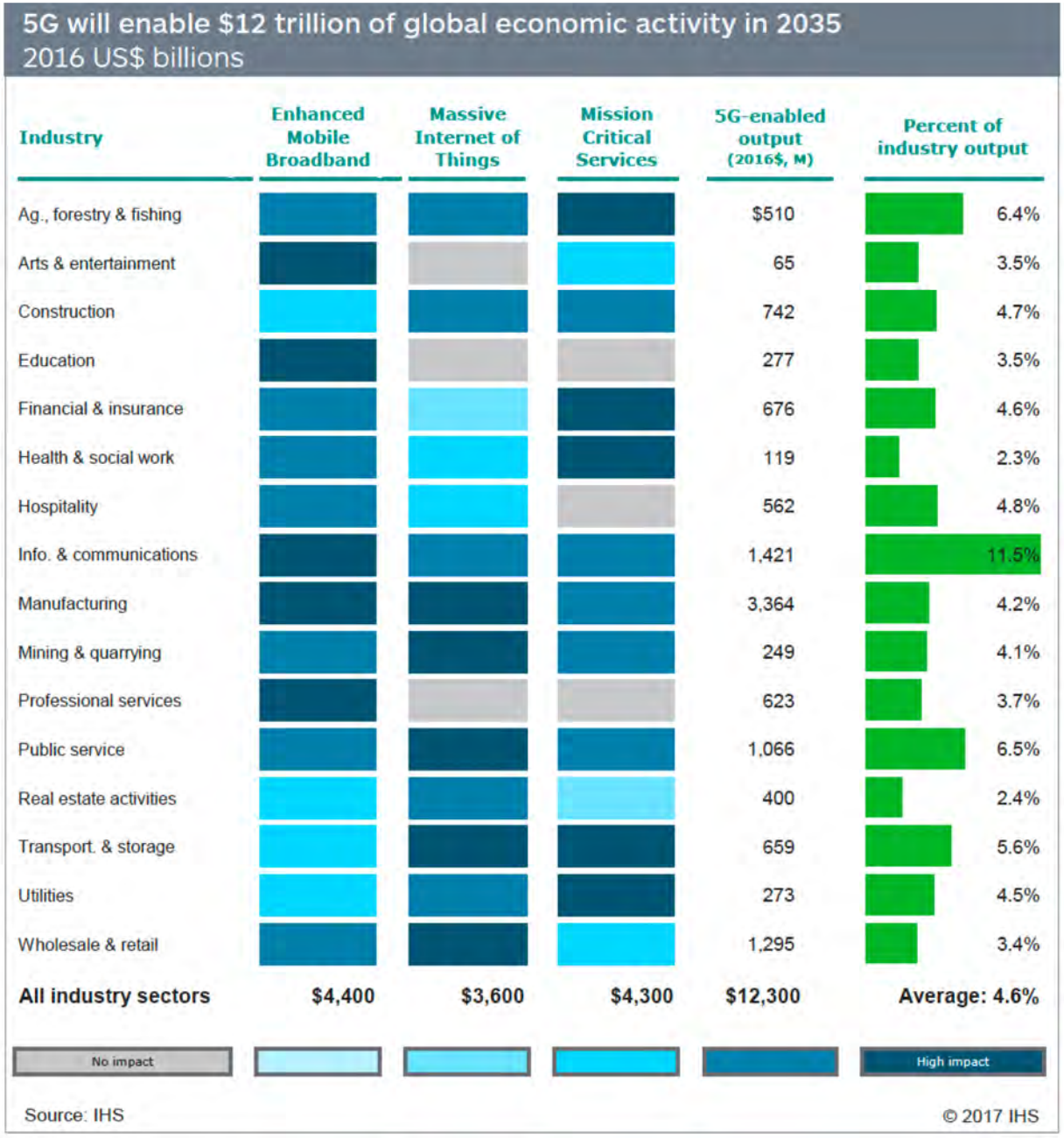
Country					
Spectrum	Mid band	3.3-3.6 & 4.8-5.0GHz; maybe 2.6GHz	3.5-4.2GHz; maybe 2.5GHz;	3.42-3.7GHz	3.6-4.2, 4.4-4.9GHz
	mmWave	24.75-27.5; 37-42.5GHz	24, 28, 37, 39, 47GHz	26.5-28.9GHz	27.6-29.5GHz
	Low band	NA	600MHz	NA	NA
Spectrum allocation timing		Late 2018	mmWave in 4Q18 and 19; Mid band will be later	Jun-18	1Q19
Spectrum cost (US$bn)		NA	26.0	7.4	NA
5G capex (US$bn)		421	239	50	129
Expected service launch		2020	4Q18	1Q19	4Q19
Focused application in early stage		IoT	Fixed-wireless	IoT	IoT
Potential market structure changes		Network sharing: CU and CT	Merge: T-Mobile and Sprint	NA	New entrant: Rakuten
Infrastructure plays		Tower, Data Centers, Construction Vendor	Tower, Data Centers, Fiber, Spectrum Holders	NA	NA
Potential incremental revenue (US$ bn)		60.2	76.3	6.8	12.2
as % telecom service revenue		32%	23%	21%	12%
as % mobile service revenue		45%	42%	32%	21%

Source: Morgan Stanley Research

"$9B 5G Fund for Rural Broadband"
(FCC announced, Dec2019)

5G Global Economic Impacts

$Trillions of Smart-X potential growth across entire economy



* many such studies.... all are *bets* on a future that depends on lots more than 5G...

IHS (2017) study:

"5G will enable $12.3 trillion in sales, generating $3.5 trillion in additional global output that will support 22 million jobs by 2035"

"Annual global investment of $200B per year"

Meeting the 5G challenge

- **Small cells: CAPEX increases, backhaul challenge**
  - Enable Spectrum reuse, MEC, Energy efficiency, mmW spectrum
  - When cells smaller, spectrum more fungible (e.g. mid-band, high-band, etc.)
  - Spectrum smaller share of per-cell cost (site, power, backhaul, etc.)
- **Intelligent Core Network : Softwarization & Virtualization**
  - Expanded flexibility, customizability, scalability ("network-as-a-service"). Accessibility of cloud services.
  - Delocalization control ➔ realize scale/scope economies.
  - via aphabet soup of tech: NFV, SDN, MEC, Slicing
- **Shared Spectrum : *everyone* wants more so have to share**
  - DSA: dynamic, granular shared RF in all dimensions (time, space, context, …)
  - Heterogeneous users/uses/networks co-exist. Active/passive uses.
  - 5G is *NOT* just 3GPP (LTE) but also WiFi (802.11x), satellite, etc.
  - Regulatory ➔ markets: continuum from licensed to unlicensed (e.g., CBRS)

Future BB Competition: intensifying competition

- **Specialized and Local Facilities-based Entry** **(new)**
  - Venues: Stadiums, Campuses, Shared-tenant-networks
  - Small cells (access/site control bigger issue)
  - Shared costs, virtualize infrastructure/functionality (delocalized, network-as-a-service)
  - End-user deployed ⇔ new vector for competition (e.g., WiFi, Muni-nets, etc.)
- **MVNO competition intensified** **(seen this before, but new flavor)**
  - 3 MNOs with excess capacity ➔ robust wholesale market.
  - Edge providers integrate forward for enhanced control of user experience. Rise CDNs.
  - 5G vertical niches as SmartX drives need to vertically-integrate. New specialized MVNOs
- **Fixed-Mobile Convergence** **(been coming for a while)**
  - Intensified intermodal competition. Mobile closer substitute to fixed.
  - Revenue drivers: Cord-cutting, OTT rise. Falling prices mobile.
  - Rise WiFi (Google *Project Fi*, Comcast *Xfinity*). 5G traffic more nomadic, less fast-mobile.
  - Smaller cells ⇔ CAPEX looks more similar for fixed/mobile
  - Converged Landscape: MNOs are smaller part of overall picture

Will the Internet survive Covid-19? (press coverage March 2020....)

COVID-19: How Cable's Internet Networks Are Performing

Select your state to display network information.

National

Downstream Growth (% of usage)

20.1 % OVERALL SINCE 3/1 — 4.3 % WEEKLY 3/21 - 3/28

Upstream Growth (% of usage)

27.7 % OVERALL SINCE 3/1 — 7.3 % WEEKLY 3/21 - 3/28

Network Performance (% of network)

95.9% Normal Peak Usage
3.7% Elevated Peak Usage
0.3% Substantially Elevated Peak Usage
0.1% Significantly Elevated Peak Usage

Internet Service Providers

CHARTER COMCAST COX GCI MIDCO VYVE

FierceVideo

VIDEO CABLE

Cable

Comcast claims video-on-demand is hitting record highs

by Ben Munson | Mar 31, 2020 11:09am

telecompaper

HOME : WIRELESS : BROADBAND : VIDEO GENERAL IT : INDUSTRY RESOUR

GENERAL

Comcast says peak internet traffic up 32% since start of March

Tuesday 31 March 2020 | 16:43 CET | News

Comcast, the largest ISP in the US, said its peak internet traffic has increased 32 percent since the start of March, but the usage remains within the overall capacity its network. The increase in

Bloomberg | Quint

Internet Traffic is Surging But The Pipes Aren't Bursting Yet

Daniele Lepido Thomas Seal Natalia Drozdiak

Published on March 20 2020, 4:22 PM

COVID-19 PANDEMIC

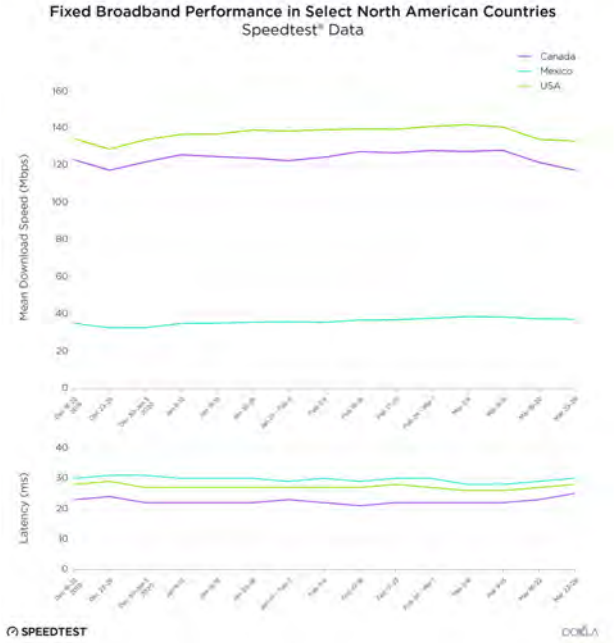
Netflix urged to slow down streaming to stop the internet from breaking

by: CNN Wire

Posted: Mar 19, 2020 / 08:48 AM CDT / Updated: Mar 19, 2020 / 08:50 AM CDT

The European Union is urging Netflix and other streaming platforms to stop showing video in high definition to prevent the internet from breaking under the strain of unprecedented usage due to the coronavirus pandemic.

Ookla Speedtest Data : relatively stable performance (as of 3/30/2020)



ThousandEyes

State of Internet Health During COVID-19

Posted by Angelique Medina on March 23rd, 2020

"Despite massive traffic increases — particularly across consumer last-mile networks — **we have not seen a significant corresponding spike in Internet outages.**

TECH / CORONAVIRUS

The Internet Was Built To Withstand A Nuclear Bomb. It Will Survive The Coronavirus.

"Push comes to shove, we'll watch wonderful movies in standard definition."

Alex Kantrowitz
BuzzFeed News Reporter

Posted on March 13, 2020, at 2:21 p.m. ET

5G & Platforms in a (post) Covid World

Internet and Broadband rise to the challenge (mostly)

- Network traffic increase 30-40% during peak
  - Broadband, IXPs, Clouds, Applications, etc.
  - Increased video-conferencing, video-streaming, gaming
  - Drop in business traffic as work shifted to home helped
  - Cloud shift for VPNs helped
  - WiFi replaced cellular
- Congestion some, outages few
  - Local bottlenecks, Configuration errors, Older equipment
  - Applications (e.g., Zoom, Microsoft Teams) and Websites (e.g., employment sites) saw unanticipatible short-term growth.
- Cyberattacks increase, Privacy & Surveillance

Long-term effects (??)

- Accelerate traffic trends already under way : virtual life a step closer...
  - Shift to Clouds and CDNs, Private replace public networks, flatter topology
- More Telemedicine, FinTech (ePayments), Remote Collaboration, ...
- Demand shock & Supply Response – Government must lead
  - Digital Divide ➔ 5G should be for everyone. Push for Universal Service public subsidies
  - Supply response ➔ Economic recovery (??) and scarcity private capital. Revenue pressure.
- More (or less) regulation?
  - Digital platform antitrust, Network Neutrality, Privacy, etc.

Summing Up: 5G & Wireless Ecosystem....

Autonomy = Real/Virtual world convergence

5G = platform for Pervasive Computing

- Everything connectable does *not* mean everything should/will be connected
- Like the Internet, control & ownership will be distributed/decentralized

$Trillions of future Smart-X potential

- Transformation *will* be disruptive. Adjustment costs will be significant
- Realization depends on co-evolution of digital & *analog* elements

Covid-19, Climate Change, Globalization, ...

might not be threats in world without computers

but our ability to respond surely depends on continued advances

wlehr@mit.edu

Additional Material --- not used

Convergence of WLAN (802.11x) and Cellular (3GPP)

- Data rates
- Cell size
- Support for multi-APs and standalone deployment

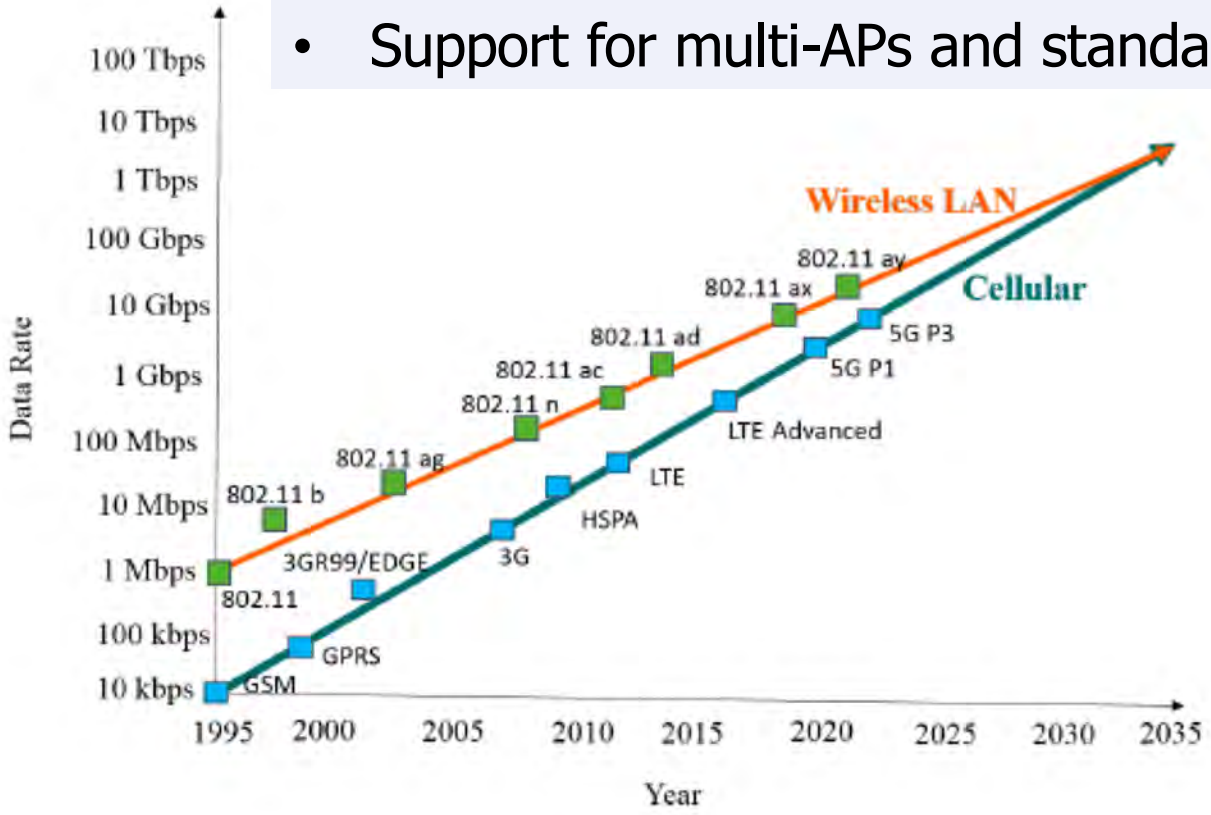


Fig. 1. Wireless Roadmap Outlook up to the year 2035.

Source: Elayan, H., Amin, O., Shihada, B., Shubair, R.M. and Alouini, M.S., 2019. Terahertz band: The last piece of RF spectrum puzzle for communication systems. *IEEE Open Journal of the Communications Society*, *1*, pp.1-32.

Spectrum sharing

Citizen Band Radio Service (CBRS) 3.5GHz

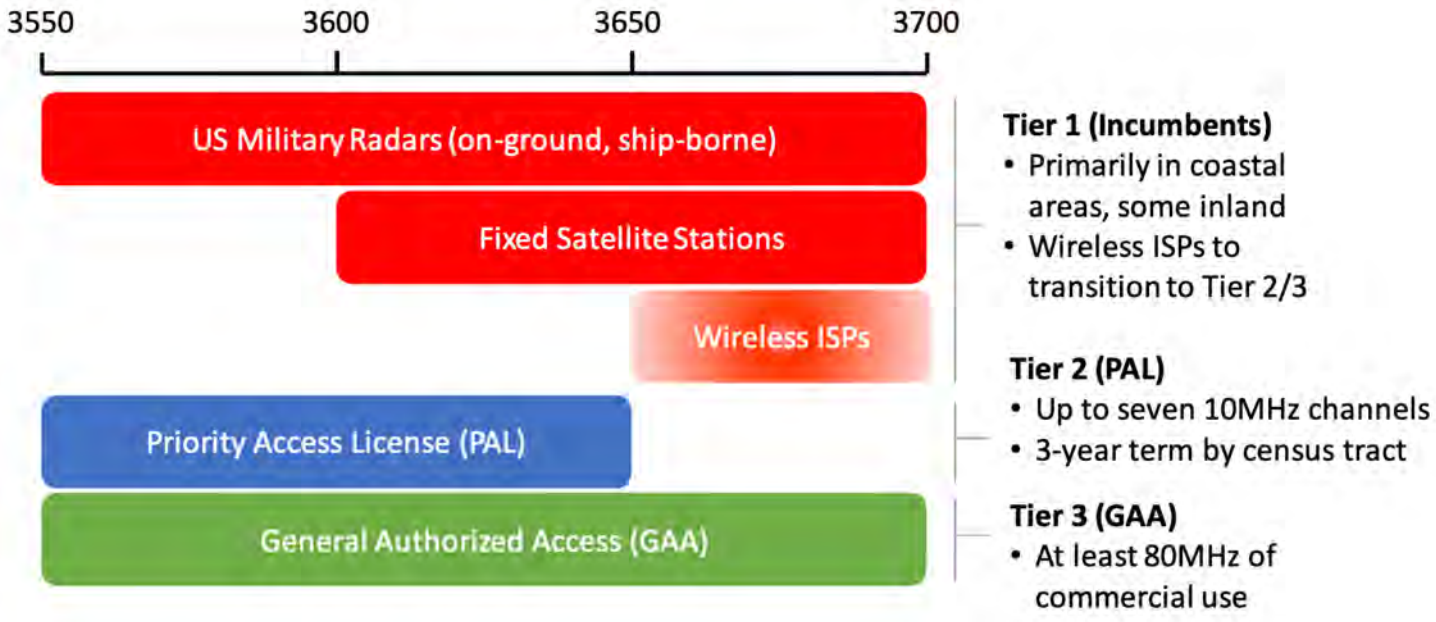


Figure 1. CBRS 3-Tier Shared Spectrum Licensing Structure

- High-value mid-band spectrum for 5G
- History:
  - WH (2010): "clear 500MHz Federal spectrum in 10 years". NTIA (2010) Fast-track report
  - FCC (2012) NPRM identifies CBRS. PCAST (2012) report.
  - FCC (2015) CBRS rules announced
  - September 2019, GAA commercial begins; June 2020 PAL auction

Citizen Band Radio Service (CBRS) 3.5GHz

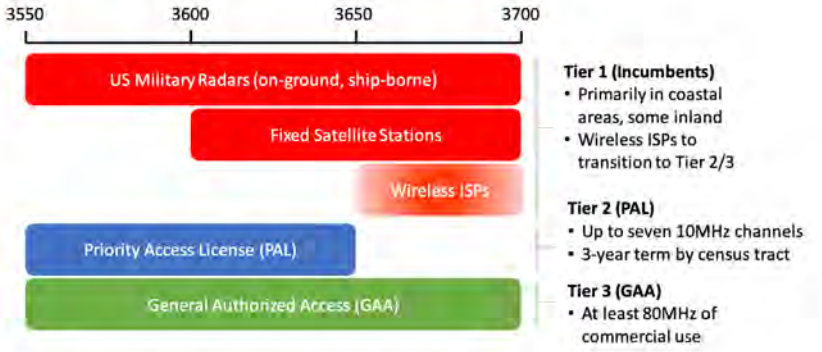


Figure 1. CBRS 3-Tier Shared Spectrum Licensing Structure

Business models

1. MNO capacity augmentation, e.g., using carrier aggregation
2. New CBRS MSO entrant (e.g., Cable, new) to build out new LTE network
3. Neutral Host RAN: manage interconnection, shared resources, multiple networks
4. Enterprise Private LTE: improvement over DAS, Wi-Fi

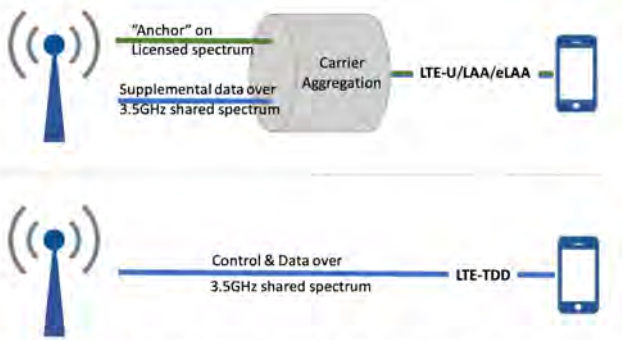


Figure 3. Mobile Operator Capacity Expansion using CBRS

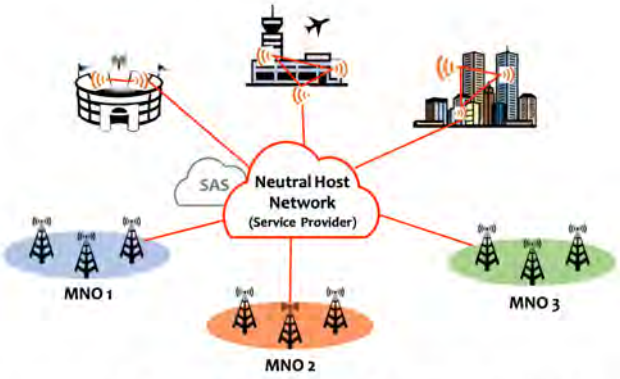


Figure 5. Neutral Host Network Provider using CBRS

Figure 6. Enterprise Private LTE Networks

PERSPECTIVE
https://doi.org/10.1038/s41928-019-0355-6
nature electronics

What should 6G be?

Shuping Dang*, Osama Amin, Basem Shihada and Mohamed-Slim Alouini

5G v. 6G (one perspective...)

- Service: 3D VR/AR v. Tactile
- Max data: 35Gbps v. 100Gbps
- Max spectrum: 90GHz v. 10THz
- Massive MIMO v. Intelligent surface

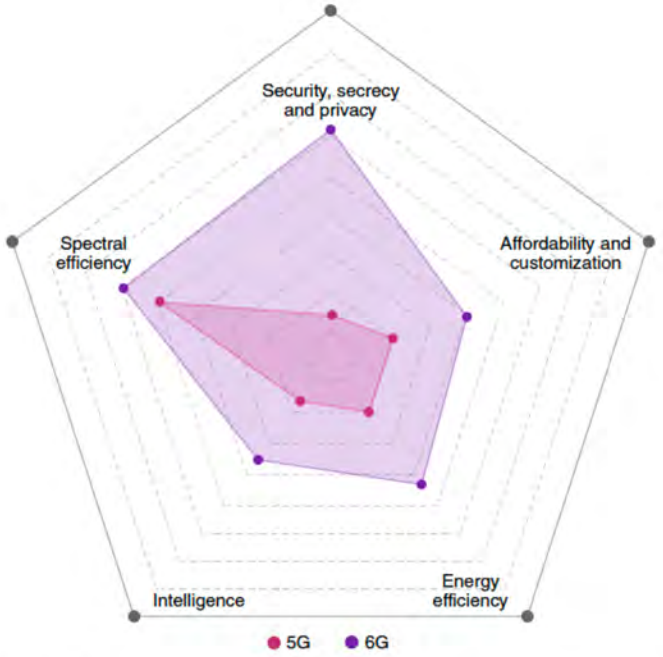


Fig. 3 | Qualitative comparison between 5G and 6G communications. The

Table 2 | Detailed comparisons of 1G to 6G communications

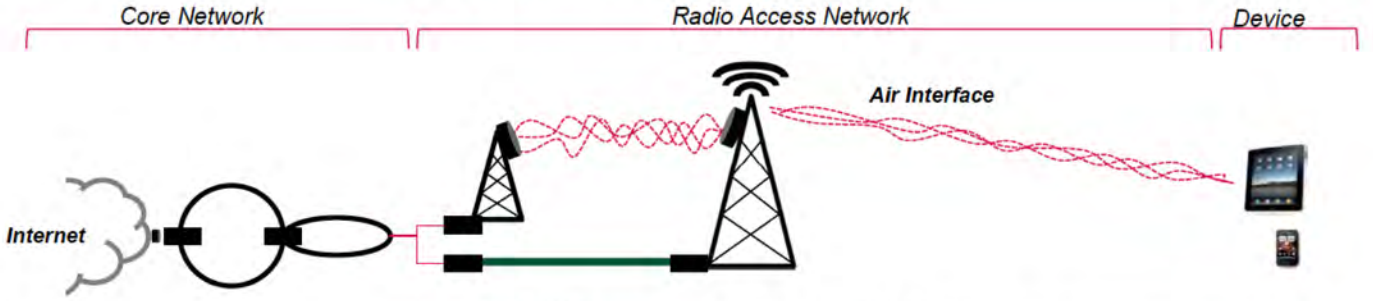
Features	1G	2G	3G	4G	5G	6G (supposed)
Period	1980–1990	1990–2000	2000–2010	2010–2020	2020–2030	2030–2040
Maximum rate	2.4 kb s^{-1}	144 kb s^{-1}	2 Mb s^{-1}	1 Gb s^{-1}	35.46 Gb s^{-1}	100 Gb s^{-1}
Maximum frequency	894 MHz	1,900 MHz	2,100 MHz	6 GHz	90 GHz	10 THz
Service level	Voice	Text	Picture	Video	3D VR/AR	Tactile
Standards	MTS, AMPS, IMTS, PTT	GSM, IS-95, CDMA, EDGE	UMTS, WCDMA, IMT2000, CDMA2000, TD-SCDMA	WiMAX, LTE, LTE-A	5G NR, WWWW	-
Multiplexing	FDMA	FDMA, TDMA	CDMA	OFDMA	OFDMA	Smart OFDMA plus IM
Architecture	SISO	SISO	SISO	MIMO	Massive MIMO	Intelligent surface
Core network	PSTN	PSTN	Packet N/W	Internet	Internet, Internet of Things	Internet of Everything
Highlight	Mobility	Digitization	Internet	Real-time streaming	Extremely high rate	Security, secrecy, privacy

VR, virtual reality; AR, augmented reality; MTS, Mobile Telephone Service; IMTS, Improved Mobile Telephone Service; PTT, push to talk; GSM, Global System for Mobile Communications; IS-95, Interim Standard 95; CDMA, code-division multiple access; EDGE, Enhanced Data rates for GSM Evolution; UMTS, Universal Mobile Telecommunications Service; IMT2000, International Mobile Telecommunications-2000; LTE-A, Long-Term Evolution Advanced; 5G NR, Fifth-Generation New Radio; WWWW, World Wide Wireless Web; FDMA, frequency-division multiple access; TDMA, time-division multiple access; OFDMA, orthogonal frequency-division multiple access; IM, index modulation; SISO, single-input single-output; PSTN, public switched telephone network; Packet N/W, packet-switched network.

What is 5G?

5G is not a single technical innovation, but rather a set of advances with spectrum

Network Architecture: 4G LTE vs. 5G



	Core Network	Transport	Tower / Access Point	Antenna	Air Interface Technology	Spectrum	Device
4G	Most computing resources **located in core**	**Legacy copper, wireless, or fiber backhaul**	**eNodeB** macro cell base stations	**MIMO** sends / receives limited # of signals simultaneously	**One size fits all waveform** with OFDM	**Carrier aggregation** maximum of five component carriers (100 MHz bw)	**Standard LTE chipsets** and battery life
5G	**NFV and SDN technologies, NSA, SA slicing**	**Fiber Fronthaul**	**Macro-sites+ Many small cells**	**Massive MIMO and adaptive beamforming**	**Rel 15 OFDMA with improved flexibility**	**Higher freq (mmWave) and wider bandwidths carrier aggregation**	**Multi-mode, low power 5G chipsets**

Greater Capacity

Faster Download Speeds

Lower Latency

Source: AV&Co. Research & Analysis

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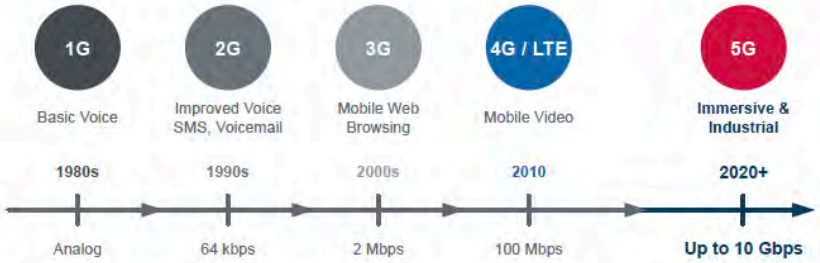
What is 5G?

5G is not a single innovation, but rather a set of advancements in spectrum usage



NOTE: Maximum theoretical downlink speed by technology generation, Mbps (10 Gbps is the minimum theoretical upper limit speed specified for 5G)
SOURCE: GSMA Intelligence.

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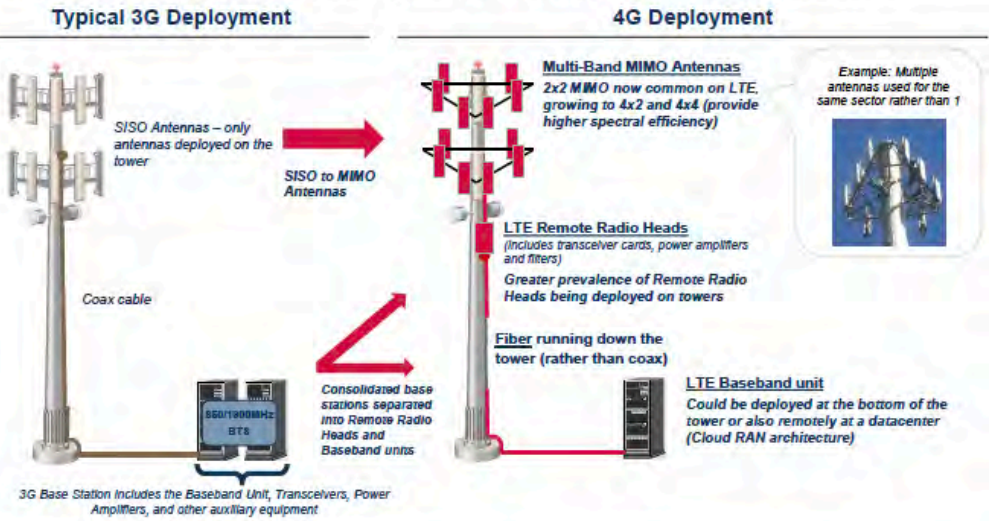
Networks are Evolving to Address Capacity Needs

Ongoing 4G activity includes new wrinkles on equipment configurations



The Trend Has Been *More* Equipment Being Placed on Towers

search & Analysis

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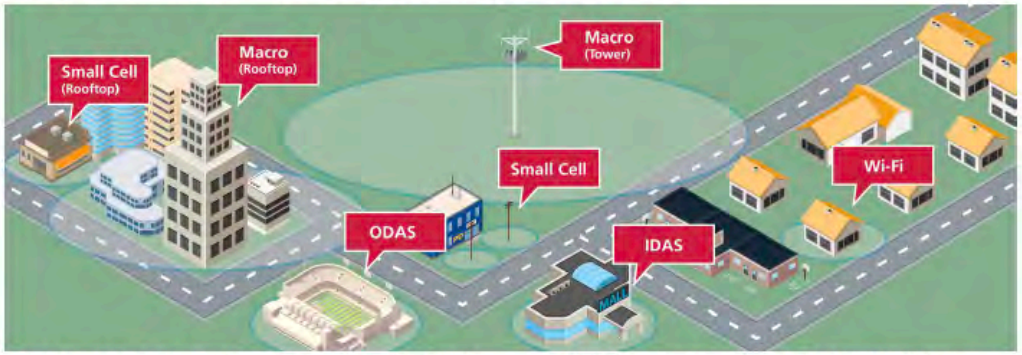
Ongoing Evolution of Wireless Networks

Heterogeneous Networks (Hetnets) and unlicensed LAA will continue to play an important role in urban deployments, as will shared spectrum for neutral host indoor intallations

Network deployments are expected to consist of multiple layers—traditional macro cell towers provide a blanket of coverage, while underneath this umbrella, a combination of other technologies are deployed to increase network capacity, particularly in dense urban areas



- Macro sites expected to continue providing wide area coverage for high mobility users and be the core of wireless networks
- Multiple solutions including DAS, Rooftops, Wi-Fi and Small Cell networks expected to complement the coverage provided by towers in urban locations

ource: AV&Co. Research & Analysis

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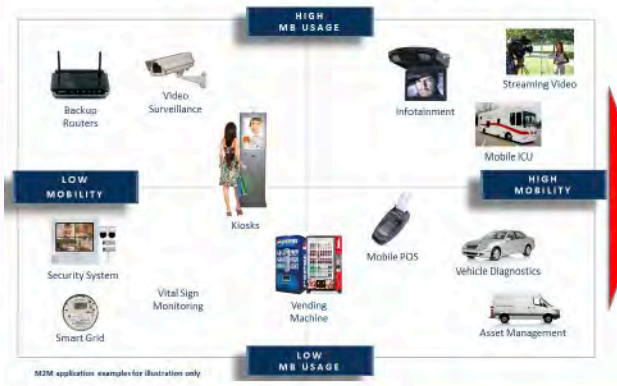
5G IoT Capabilities

The Internet of Things (IOT) is expected to experience rapid growth as 5G is deployed

Multitude of IoT use cases



Huge IoT Volumes

(U.S. numbers shown)

	2018		2023E
Total IoT traffic:	11X growth (65% CAGR)	→	560 PB/month
Total IoT devices:	4.5X growth	→	468M

Sources: AV&Co. Research & Analysis

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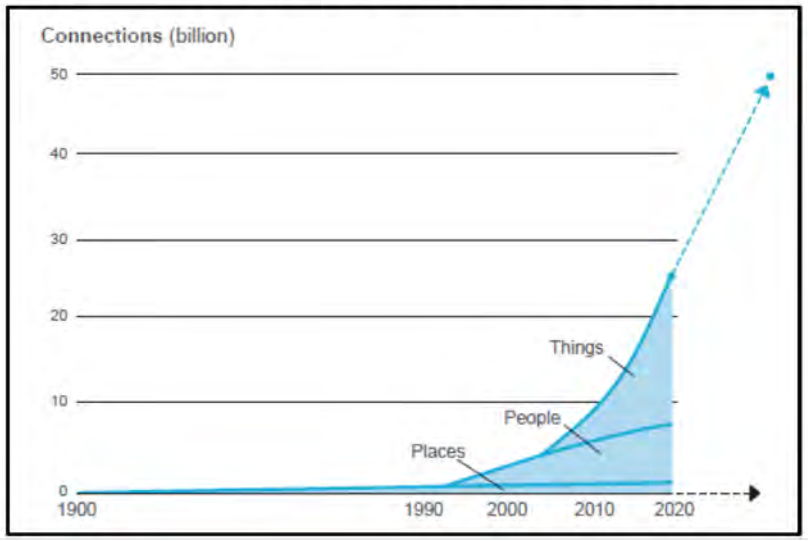
25

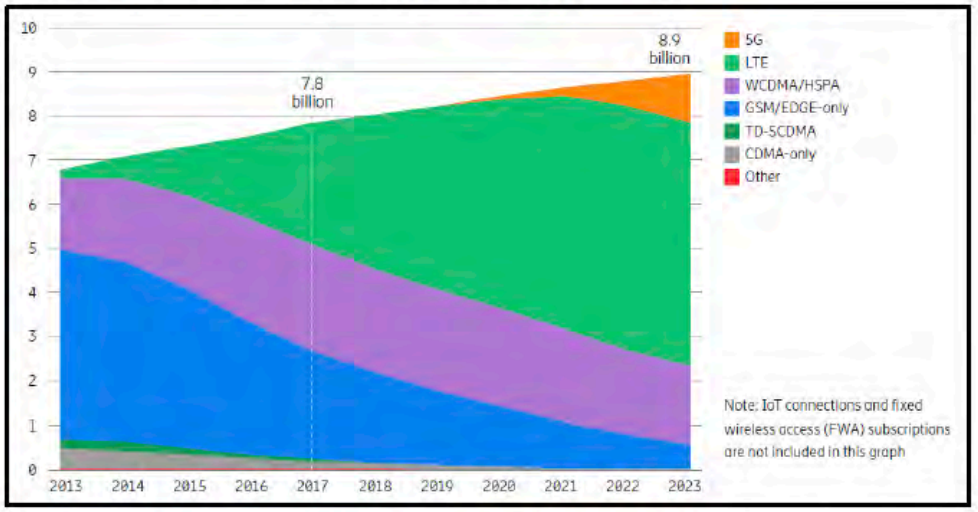
M2M connections dominate

Figure 3: Connections of Places Versus People Versus Things[5]



5G connections grow fast, small share still by 2023

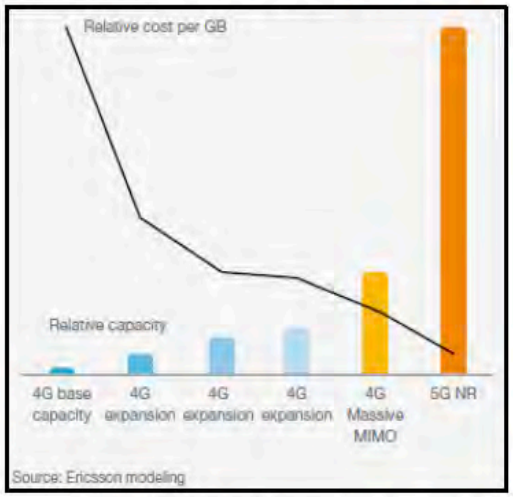
Figure 4: Mobile Subscriptions by Technology (Billions)[10]



The number of 5G connections will grow rapidly: GSMA estimates 1.2 billion connections by 2025.[11]

$/GB falling steeply

Figure 12: Reduced Cost per GB of 5G Compared to 4G



Similarly, an analyst firm predicts that the cost of delivering a gigabyte of data will drop from $1.25 with 4G to $0.16 with 5G.[21]

Source: Rysavy (2018), "LTE to 5G: the Global Impact of Wireless Innovation," 5G Americas/Rysavy Research White Paper, August 2018.