Beyond 5G?
What comes after that: 6G

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- Rollout of 5G is going to be far more costly than 4G
  - short distances signals can travel
  - greater density of equipment to transmit signals
  - astronomically high capital costs
  - lack of well-defined business models

What's leftover from 5G, what things did 5G not address

- **Speed and spectrum**
  - 5G networks already offer download speeds of up to 600 Mbps (4G generally operates at up to 28 Mbps)
  - Ideally:
    - 5G peak download speed: 20 Gbps (4G: 1 Gbps)
    - 5G peak upload speed: 10 Gbps
  - Actual speed:
    - Verizon 5G Home user with FWA can get 300 Mbps ~ 1 Gbps
    - T-Mobile says 450 Mb/s
    - Japan's NTT DOCOMO achieved > 25 Gbps during a 5G trial in 2018 involving a moving vehicle.
- 6G will target speeds of 1 Tbps
  - To get those speeds, signals will need to be transmitted above 1 THz, compared to GHz range where 5G operates

- 5G base stations are designed to handle up to a million connections (about 4,000 for 4G base stations)
- 5G latency – 1ms (50ms for 4G)
- 6G latency – almost zero

- Extreme densification of communications systems, enabling hundreds and even thousands of simultaneous wireless connections.
- Terahertz should need less power and have more capacity.
- Problems - Obstructions become more of an issue the higher up the spectrum - wavelengths are physically smaller.
- Shorter reach.

6G Cases

- 6G will enable rapidly changing collaborations on vast scales between intelligent agents solving intricate challenges on the fly and negotiating solutions to complex problems.
- Self-driving vehicles through a major city will need to be aware of their location, their environment and how it is changing, and other road users such as cyclists, pedestrians, and other self-driving vehicles. They will need to negotiate passage through junctions and optimize their route in a way that minimizes journey times.
- Significant computational challenge - it will require cars to rapidly create on-the-fly networks and then abandon them almost instantly. Interactions will therefore be necessary in vast amounts, to solve large distributed problems where massive connectivity, large data volumes and ultra low-latency beyond those to be offered by 5G networks will be essential.
- Similar applications - network optimization, financial-market monitoring and planning, health-care optimization, and "nowcasting" - ability to predict and react to events as they happen.

https://www.technologyreview.com/s/613338/ready-for-6g-how-ai-will-shape-the-network-of-the-future/

Post-Smartphone Era?

- While the 5G era is expected to make the smartphone less of a centerpiece of our lives than it is today, 6G will be a post-smartphone era.
- With everything capable of being connected, almost every object will be data driven, with true artificial intelligence capabilities a standard feature and augmented reality interfaces that pop up when needed and then disappear.
- The notion that we once had to carry a gadget to control other objects or communicate will seem quaint to the 6G generation.

- The way we consume data will be changing. Today, most of our data is consumed using a smartphone. But if we have virtual or augmented reality glasses with 5G, it could be these or other devices that are consuming that data.
- In that scenario, our relationship with our carrier is no longer buying a smartphone, but perhaps buying a bay station and allowing each home or office building to in essence become its own communications operator for the massive number of devices and data flowing through this next generation connectivity.

Flying Base Stations?

- Without all the cumbersome processing equipment tied to base stations, not only could they become lightweight, they could conceivably be mobile themselves.

- "Backhaul" is the transfer of data and voice traffic that needs to take place on the back end, to make that content available through the transmitter by customers. Up until recently, engineers thought that countless thousands of miles of fiber optic pipes would need to be laid to enable the colossal amount of backhaul that 5G would require.
  - mmWave - could be leveraged as an alternate backhaul mechanism, for when carving up the Earth to lay new pipes simply isn't practical. A fixed fiber connection wouldn't be necessary for a transmitter and base station to go live.

6G Requirements

KPI	5G	6G
Traffic Capacity	10 Mbps/m^2	$\sim$ 1-10 Gbps/m^3
Data rate DL	20 Gbps	1 Tbps
Data rate UL	10 Gbps	1 Tbps
Uniform user experience	50 Mbps 2D everywhere	10 Gbps 3D everywhere
Latency (radio interface)	1 msec	0.1 msec
Jitter	NS	1 μsec
Reliability (frame error rate)	10^{-5}	10^{-9}
Energy/bit	NS	1 pJ/bit
Localization precision	10 cm on 2D	1 cm on 3D

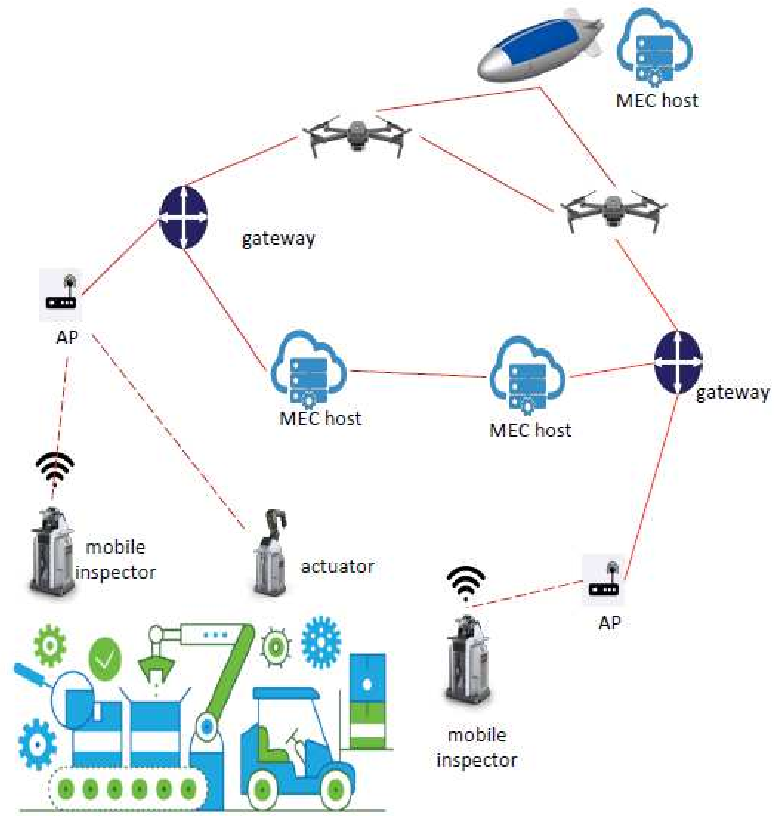
TABLE I: Comparison of 5G and 6G KPI's; NS= Not Specified.

E. C. Strinati, S. Barbarossa, J. L. Gonzalez-Jimenez, D. Kt´enas, N. Cassiau, L. Maret, C. Dehos, *"6G: The Next Frontier,"* 2019.

6G Innovations

- New architecture including a new data plane, a new control plane, and a new management plane (incorporating self-configuration and self-optimization capabilities, leveraging on the strong support of AI).
- A pervasive introduction of AI at the edge of the network.
- 3D coverage - design of a 3D communication infrastructure incorporating terrestrial and aerial radio access points and mobile edge hosts makes possible to bring cloud functionalities on demand, where and when needed.
- New physical layer incorporating sub-THz and VLC.

E. C. Strinati, S. Barbarossa, J. L. Gonzalez-Jimenez, D. Kt´enas, N. Cassiau, L. Maret, C. Dehos, *"6G: The Next Frontier,"* 2019.



6G network architecture should be designed to handle communication, computation, caching and control (C4) resources as parts of a single system.

E. C. Strinati, S. Barbarossa, J. L. Gonzalez-Jimenez, D. Kt´enas, N. Cassiau, L. Maret, C. Dehos, *"6G: The Next Frontier,"* 2019.

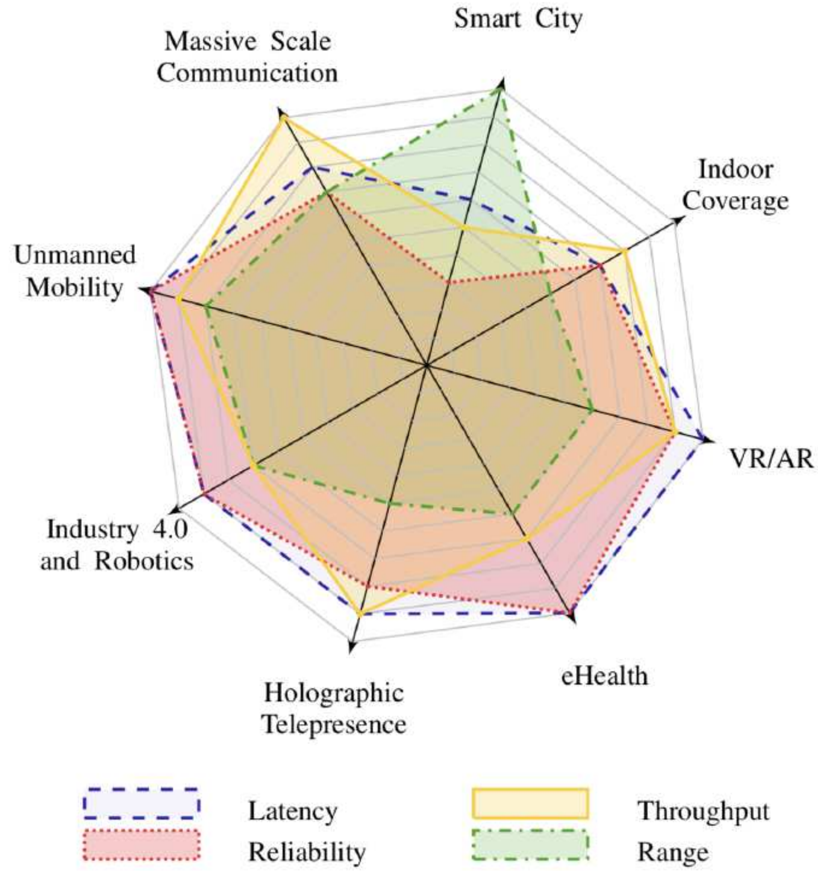


Fig. 2: Representation of the requirements (according to multiple Key Performance Indicators (KPIs)) of different 6G use cases.

M. Giordani, M. Polese, M. Mezzavilla, S. Rangan, M. Zorzi, "*Towards 6G Networks: Use Cases and Technologies*," 2019.

TABLE I
REQUIREMENTS OF 5G VS. BEYOND 5G VS. 6G.

	5G	Beyond 5G	6G
Application Types	• eMBB. • URLLC. • mMTC.	• Reliable eMBB. • URLLC. • mMTC. • Hybrid (URLLC + eMBB).	New applications (see Section II-C): • MBRLLC. • mURLLC. • HCS. • MPS.
Device Types	• Smartphones. • Sensors. • Drones.	• Smartphones. • Sensors. • Drones. • XR equipment.	• Sensors and DLT devices. • CRAS. • XR and BCI equipment. • Smart implants.
Spectral and Energy Efficiency Gains with Respect to Today's Networks	10x in bps/Hz/m^2	100x in bps/Hz/m^2	1000x in bps/Hz/m^3 (volumetric)
Rate Requirements	1 Gbps	100 Gbps	1 Tbps
End-to-End Delay Requirements	5 ms	1 ms	$<$ 1 ms
Radio-Only Delay Requirements	100 ns	100 ns	10 ns
Processing Delay	100 ns	50 ns	10 ns
End-to-End Reliability Requirements	Five 9s	Six 9s	Seven 9s
Frequency Bands	• Sub-6 GHz. • MmWave for fixed access.	• Sub-6 GHz. • MmWave for fixed access at 26 GHz and 28GHz.	• Sub-6 GHz. • MmWave for mobile access. • Exploration of THz bands (above 140 GHz). • Non-RF (e.g., optical, VLC, etc.).
Architecture	• Dense sub-6 GHz small base stations with umbrella macro base stations. • MmWave small cells of about 100 m (for fixed access).	• Denser sub-6 GHz small cells with umbrella macro base stations. • $<$ 100 m tiny and dense mmWave cells.	• Cell-free smart surfaces at high frequency supported by mmWave tiny cells for mobile and fixed access. • Temporary hotspots served by drone-carried base stations or tethered balloons. • Trials of tiny THz cells.

TABLE II
SUMMARY OF 6G SERVICE CLASSES, THEIR PERFORMANCE INDICATORS, AND EXAMPLE APPLICATIONS.

Service	Performance Indicators	Example Applications
MBRLLC	• Stringent rate-reliability-latency requirements. • Energy efficiency. • Rate-reliability-latency in mobile environments.	• XR/AR/VR. • Autonomous vehicular systems. • Autonomous drones. • Legacy eMBB and URLLC.
mURLLC	• Ultra high reliability. • Massive connectivity. • Massive reliability. • Scalable URLLC.	• Classical Internet of Things. • User tracking. • Blockchain and DLT. • Massive sensing. • Autonomous robotics.
HCS	• QoPE capturing raw wireless metrics as well as human and physical factors.	• BCI. • Haptics. • Empathic communication. • Affective communication.
MPS	• Control stability. • Computing latency. • Localization accuracy. • Sensing and mapping accuracy. • Latency and reliability for communications. • Energy.	• CRAS. • Telemedicine. • Environmental mapping and imaging. • Some special cases of XR services.

W. Saad, M. Bennisy, and M. Chen, "*A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems*,"2019.

Shared Networks

- 6G networks will likely keep more detailed records of customers, so that providers can provide greater levels of personalization. These networks will probably partner with leading publishers to provide more customized and versatile services and solutions to customers across various 6G networks. They may even make it possible for customers to transfer data from one provider network to another.
- The interconnectedness of 6G networks could even be utilized on a global scale. This might dramatically improve latency by fostering strong connections that are independent of the region that the customer is connecting from. Customers in different parts of the world could connect with each other in real time with time delays that can be measured in microseconds.
- Migrating more data *to the cloud* to ensure it is accessible on a global scale.

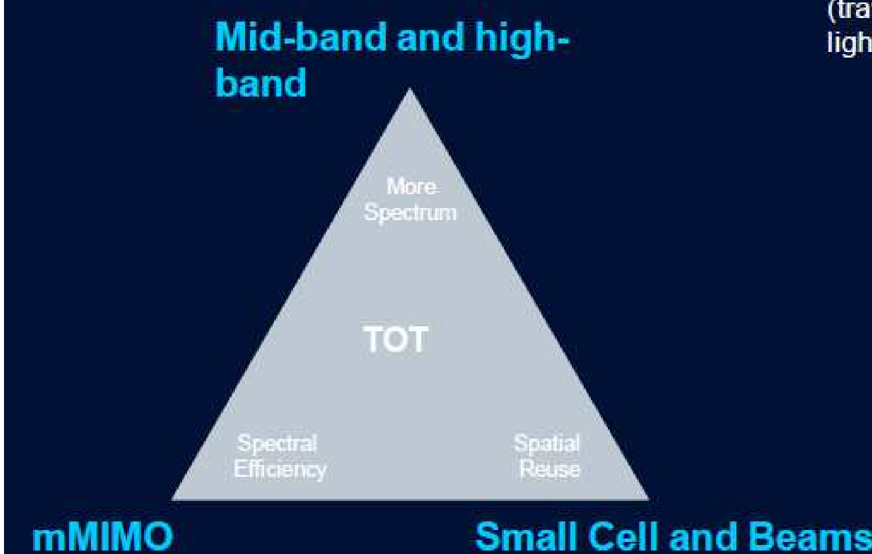
- 5G
- 6G
  - *Mobile* base stations (from small cells to tiny cells, dronecells)
  - Edge AI
  - Holographic communication
  - Connectivity to multi-sensory applications (extended reality, and haptic communication)
  - End of the smartphone era
  - Connectivity in 3D (wide-scale deployment of drones), integrate ground, aerial, and satellite networks
  - Shared networks

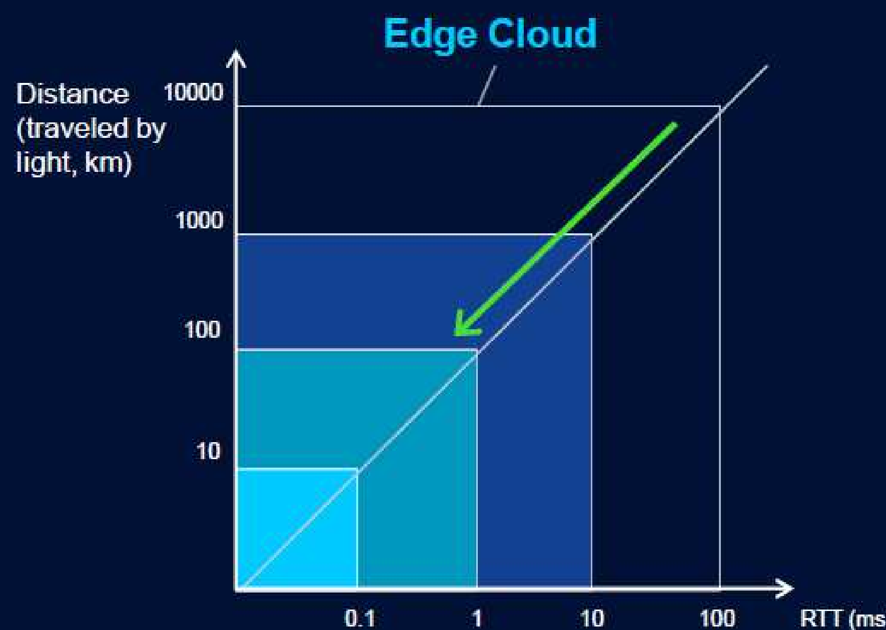
https://vtnews.vt.edu/articles/2019/06/eng-ece-saad-wireless-networks.html

- https://www.youtube.com/watch?v=fYLJP7C6q50

- Fastest growing mobile application today? (11m) – shopping (e-commerce), entertainment – but they are spending money – not productive
- 14m – consumer 3.0 (best effort network)
  - Human response time – 100ms (it was ok to have servers in central cloud)
- 17m – carrier grade reliability in LTE network – 99.8% (1 or 2 in 1000s call drop – now 5 9s and 9 9s)

Physics will continue to dictate network and cloud performance





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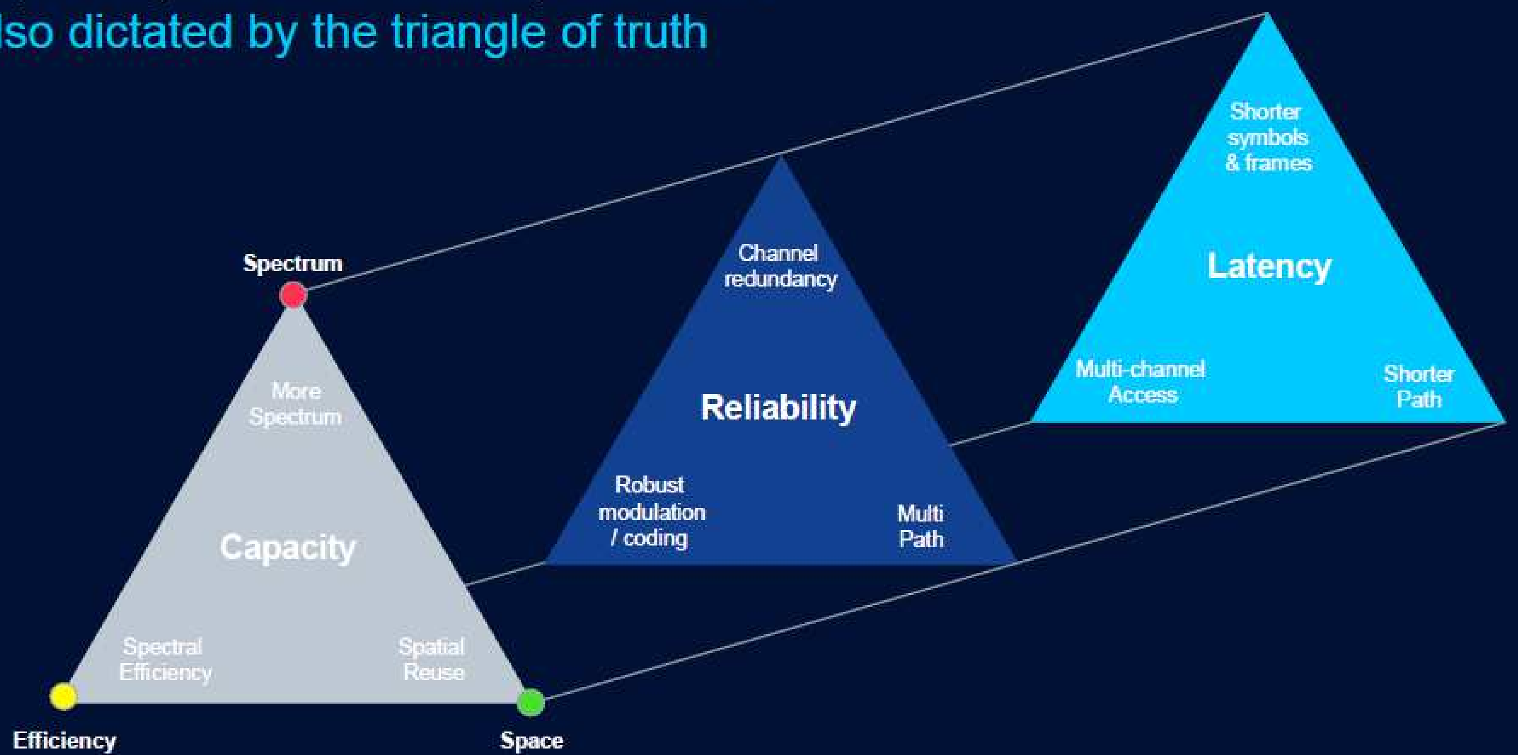
Improving the other critical parameters
Also dictated by the triangle of truth



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