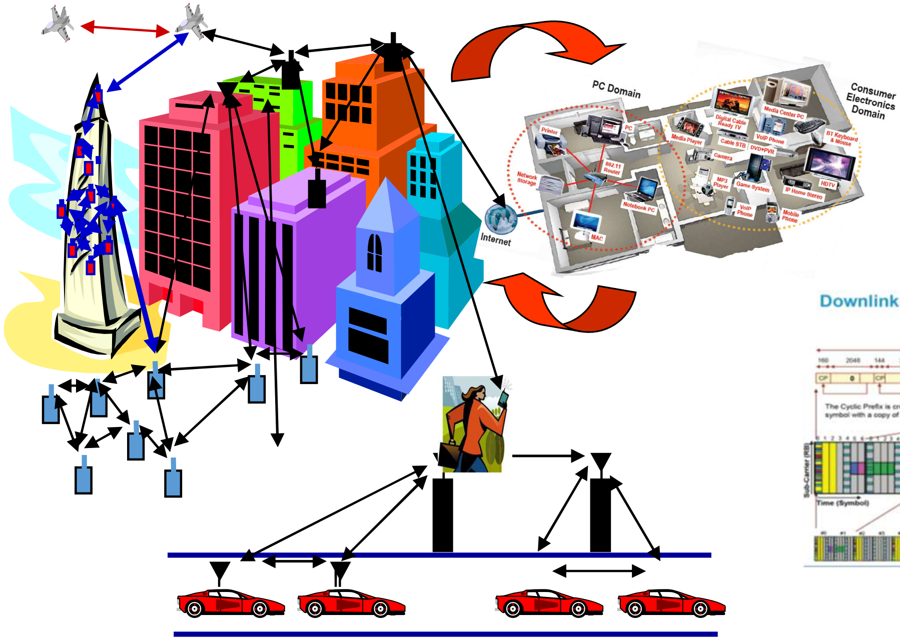
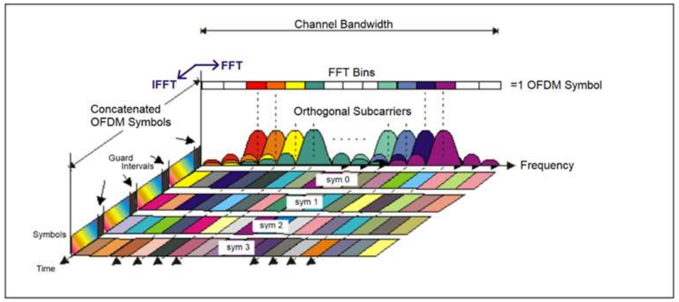
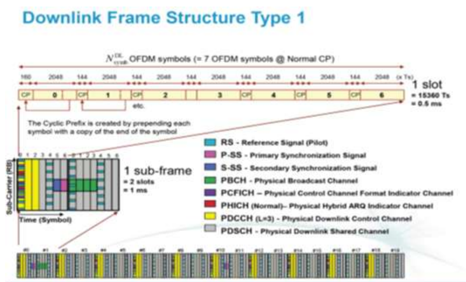
IEE IEE2650: Cellular Communications Technologies

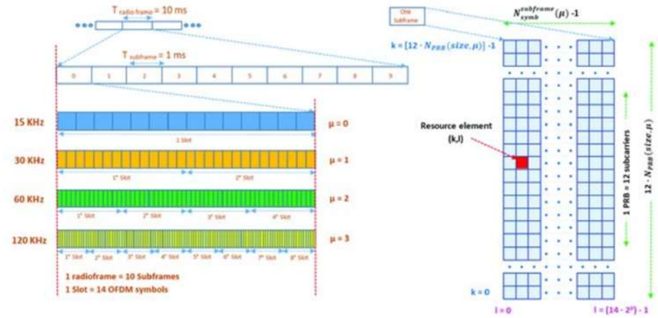
Muhammad Mahtab Alam, Professor





Frequency-Time Representative of an OFDM signal





Briefly about me

- Tallinn University of Technology (TTU), Estonia
  - Tenure Track Professor (Communication Technologies) at Thomas Johann Seebeck Department of Electronics. (April'18 – till date)
  - European Research Area-Chair (Holder) of H2020 COgnitive ELectronics (COEL) project. (Sep'16 – till date)
  - **Key Areas:** 5G and IoT -> Massive Machine Type Communication (NB-IoT), Ultra Reliable Low Latency Communication, Critical Communication, Wireless Communication, Body Area Networks.
- Research Scientist at Qatar Mobility Innovation Center, Qatar (2014 –2016)
- Charter Engineer (CEng) Status – Engineering Council United Kingdom (Mar'16)
- Assistant Prof. at University of Engineering and Technology, Pakistan (2013)
  - Lead the team of 20 members in EE Department of Swedish Engineering College
  - Accreditation from the engineering governing body (PEC)
- PhD (Signal Processing and Telecommunication) from Rennes1 University, INRIA/IRISA Lab, France (2009-2012).
  - Visiting PhD researcher – University College Cork, Ireland
- Research Assistant at CSDR-Aalborg University, Denmark (2007-2009)
  - DSP Firmware Engineer at Barco NV, Belgium (Aug'2008- Dec'2008)
- M.Sc Engineering in Applied Signal Processing and Implementation from Aalborg University (2005-2007)
- DSP Design Engineer at And-Or Logic Pvt. Ltd, Pakistan (2005)
- Streaming Networks Pvt Ltd (2004)

IEE2650 - Time table

Timetable | TalTech homepage ↗ | Intranet ↗ | ÕIS 1 ↗ | ÕIS 2 ↗ | Student Portal ↗ | Booking Rooms ↗ | ENG | EST

TALLINNA TEHNIKAÜLIKOOL TUNNIPLAAN | View timetable | Semesters | v 1.14.1 | Muhammad Mahtab Alam

Monday

15:00 - 16:30	IEE2650 - Cellular Communication Technologies	english	lecture	Muhammad Mahtab Alam (Tenured Full Professor)	Distance learning	1-16	*IAVM21*	View	

Thursday

10:00 - 11:30	IEE2650 - Cellular Communication Technologies	english	practice	Marika Kulmar (Early Stage Researcher)	U02-209	14	*IAVM21*	View	Praktikumid algavad teisest nädalast.

Friday

15:00 - 16:30	IEE2650 - Cellular Communication Technologies	english	practice	Marika Kulmar (Early Stage Researcher)	U02-209	2-13, 15, 16	*IAVM21*	View	Praktikumid algavad teisest nädalast.

Outline

- Course Syllabus
  - Course Information
- Wireless History
  - Generations of Cellular Communication Systems
- Current/Next-Gen Wireless Systems
  - Technologies and Use cases
- Summary

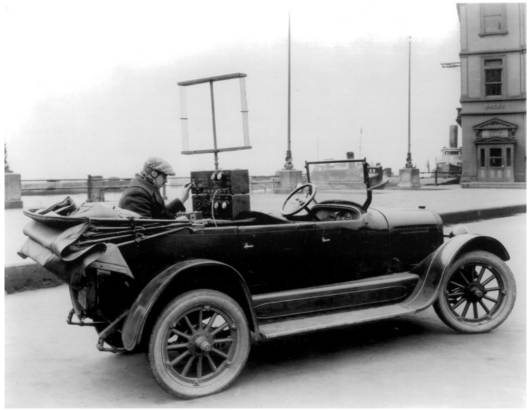
Lecture 1 Introduction: Wireless Evolution and Current State of Play

Wireless History

- **Ancient Systems: Smoke Signals, Carrier Pigeons, …**
- **Radio invented in the 1890s by Marconi**

1901: First radio reception across the Atlantic Ocean

1924: First Mobile Radio Telephone



- 1940s-50s: cellular concept discovered (AT&T)
- **1st Generation:** Analog:
  - AMPS: FDMA with 30 KHz FM-modulated voice channels.
  - **1983**: The first analog cellular system deployed in Chicago:
  - FCC increased the cellular spectral allocation from 40 MHz to 50 MHz.
    - Two 25MHz channels: DL and UL
  - AT&T moved on to fiber optics in '80s.
- **2nd generation:** digital: **early 90s**
  - higher capacity, improved cost, speed, and power efficiency of digital hardware

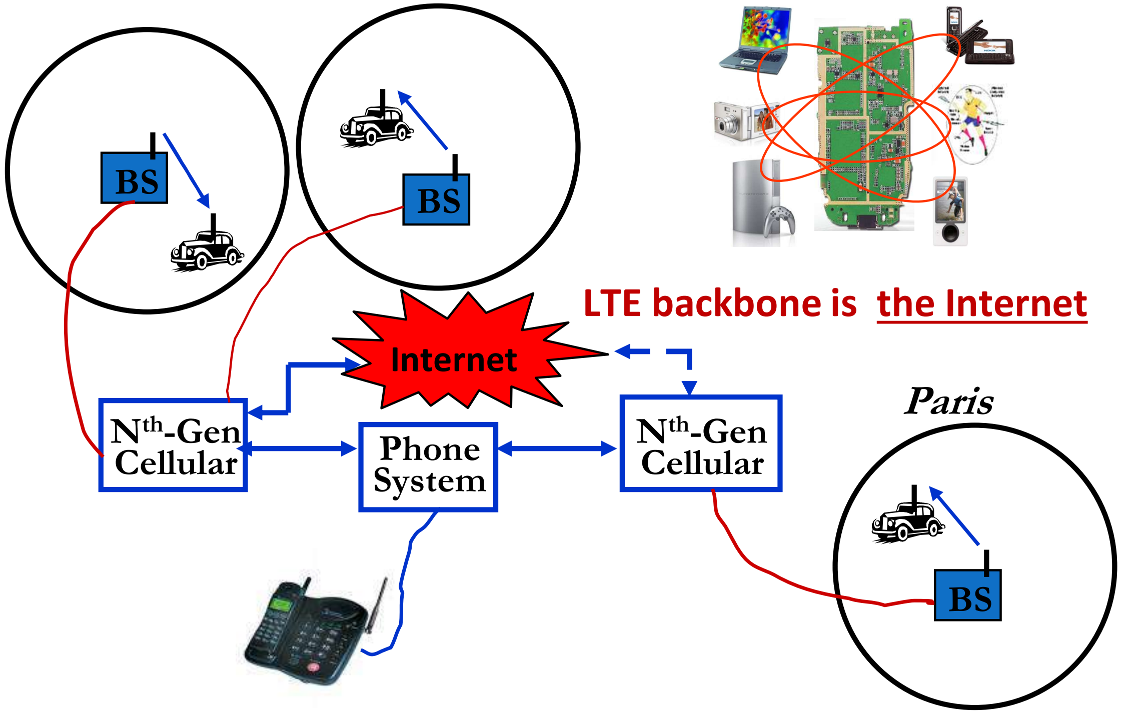
Mobile Networks Generation From 1G to 4G

Comparison of Mobile Network Generations (1G–4G)

Feature	1G (1980s)	2G (1990s)	3G (2000s)	4G (2010s)
Technology	Analog Cellular	Digital (GSM, CDMA)	UMTS, CDMA2000, HSPA	LTE, WiMAX
Data Speed	~2.4 kbps	9.6 kbps – 384 kbps	Hundreds of kbps – 2 Mbps+	100 Mbps – 1 Gbps+
Service	Voice Only	Voice + SMS (Text)	Voice + Data (Internet)	High-speed Data/Multimedia
Switching	Circuit	Circuit	Packet + Circuit	Pure Packet Switching (IP)
Core Network	PSTN (Public Switched Telephone Network)	PSTN	Packet Network	IP-based Network
Quality	Poor, Low Capacity	Improved, Encryption	Good, Mobile Broadband	High Quality, Broadband
Multiplexing	FDMA (Frequency Div.)	TDMA/CDMA	CDMA	OFDM (Orthogonal Freq.)

Future Cellular Phones

Burden for this performance is on the backbone network

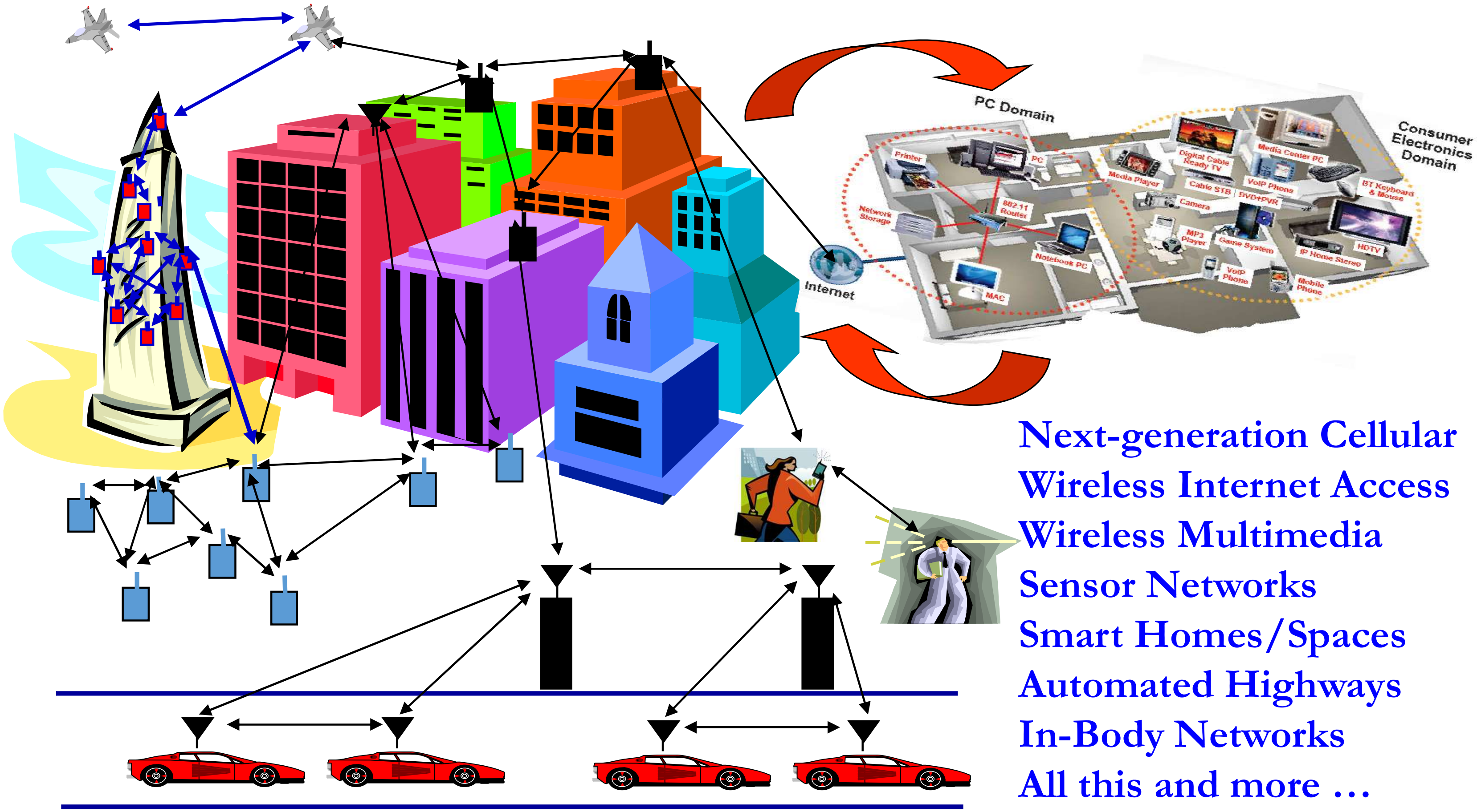


Much better performance and reliability than today

- Gbps rates, low latency, 99% coverage indoors and out

Future Wireless Networks

Ubiquitous Communication Among People and Devices



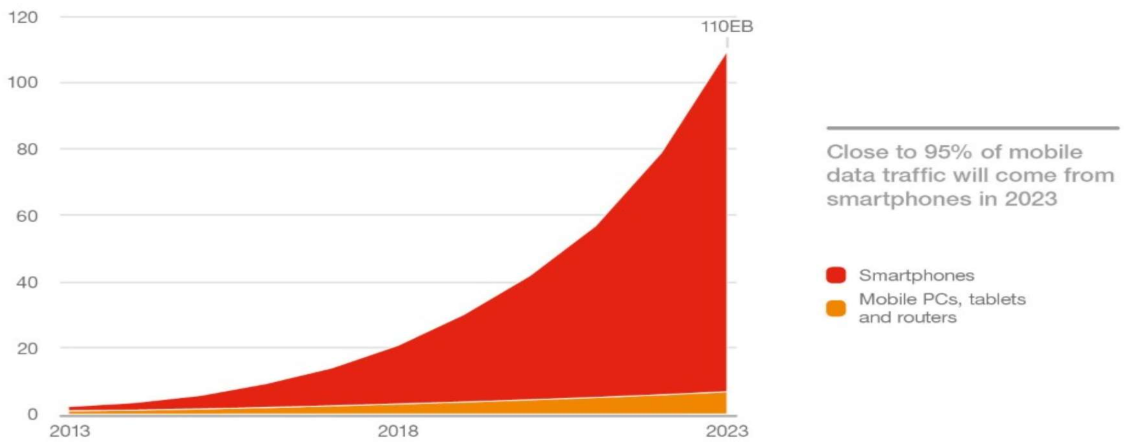
Next-generation Cellular
Wireless Internet Access
Wireless Multimedia
Sensor Networks
Smart Homes/Spaces
Automated Highways
In-Body Networks
All this and more …

Ericsson's Mobility Stats

- Mobile subscriptions worldwide Q3 2017
  - In Q3, 95 million new mobile subscriptions were added
  - resulting in a total of 7.8 billion.
  - LTE becomes the dominant mobile access technology in 2017
- In 2023, there will be 9.1 billion mobile subscriptions
  - 8.5 billion mobile broadband subscriptions
  - 1 billion 5G subscriptions for enhanced mobile broadband

Mobile subscriptions by technology (billion)

Global mobile data traffic (ExaBytes per month)



[Source] ERICSSON Mobility-report November-2017

Figure 9: Global mobile network data traffic (EB per month)

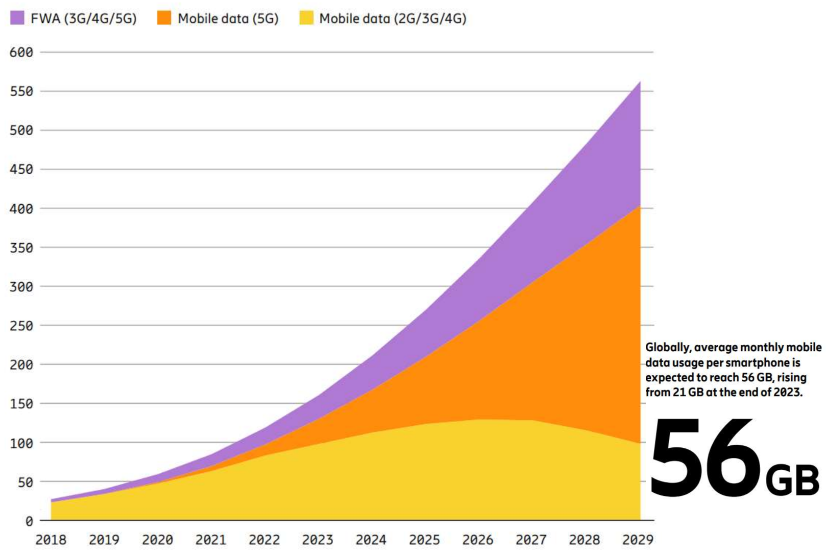
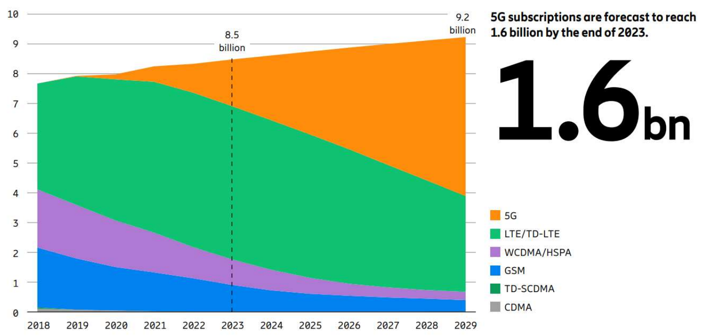
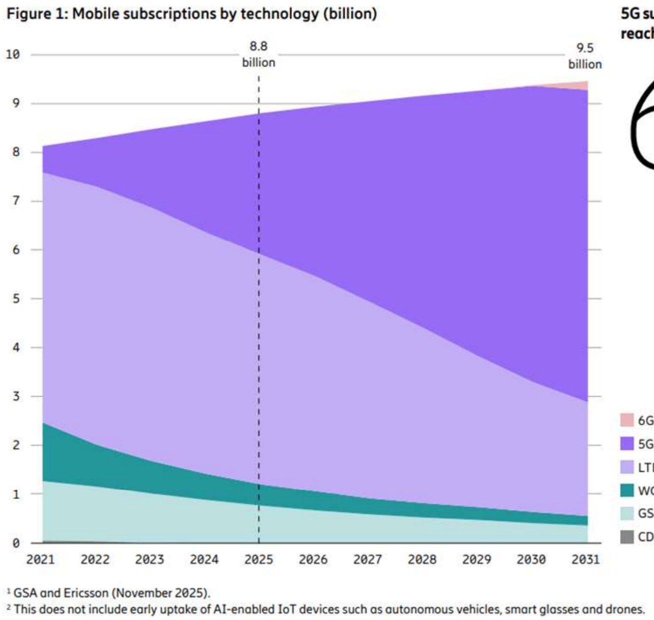


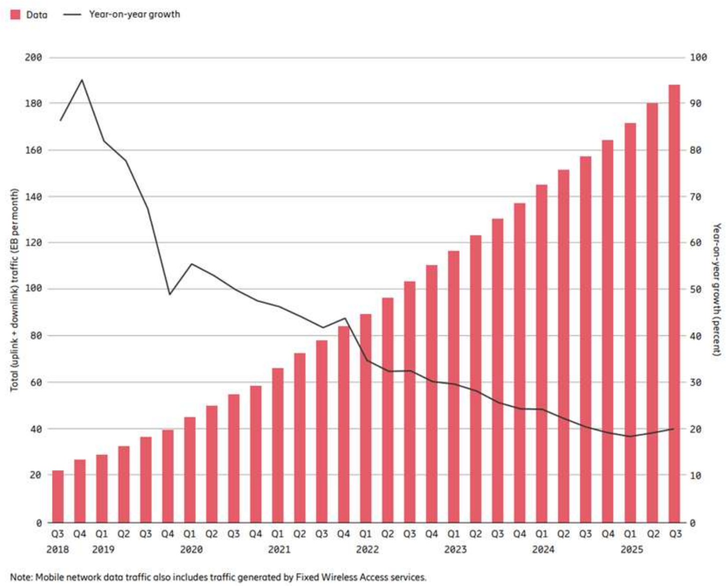
Figure 1: Mobile subscriptions by technology (billion)

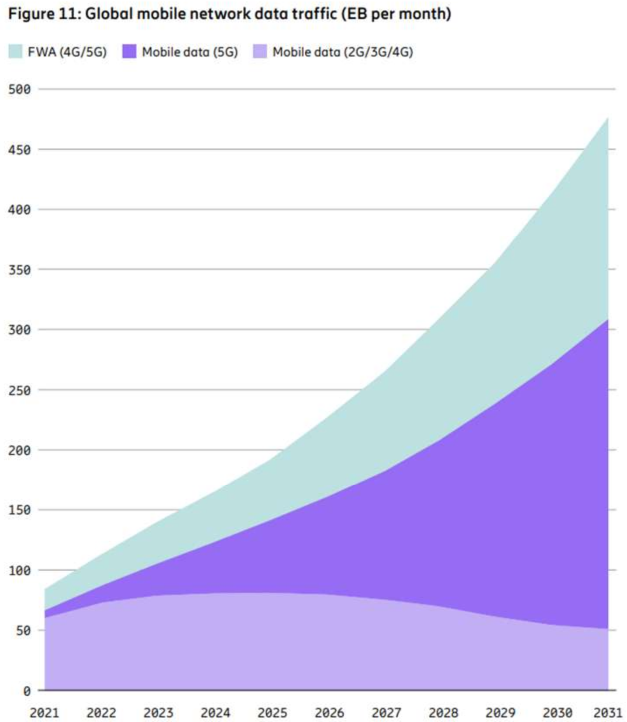


[1] 1 GSA and Ericsson (November 2023).
[2] A 5G subscription is counted as such when associated with a device that supports New Radio (NR), as specified in 3GPP Release 15, and is connected to a 5G-enabled network.
[3] Mainly CDMA2000 EVDO, TD-SCDMA and Mobile WiMAX.

Ericsson’s Mobility Report (November 2025)



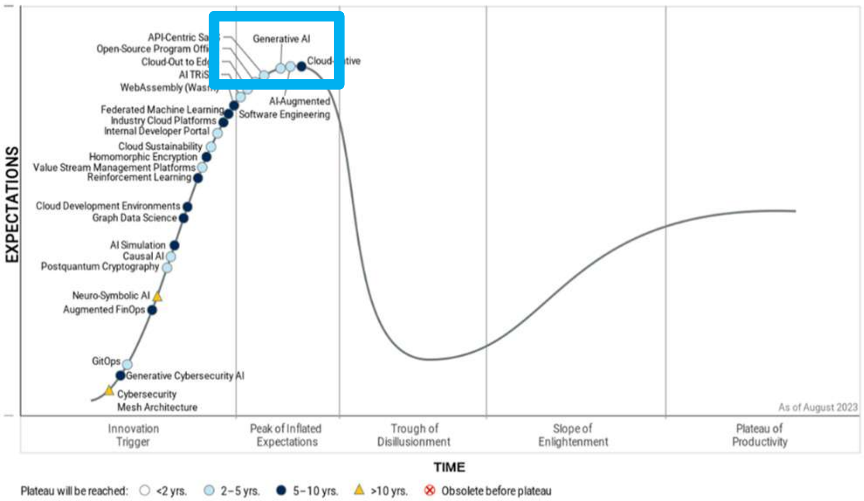




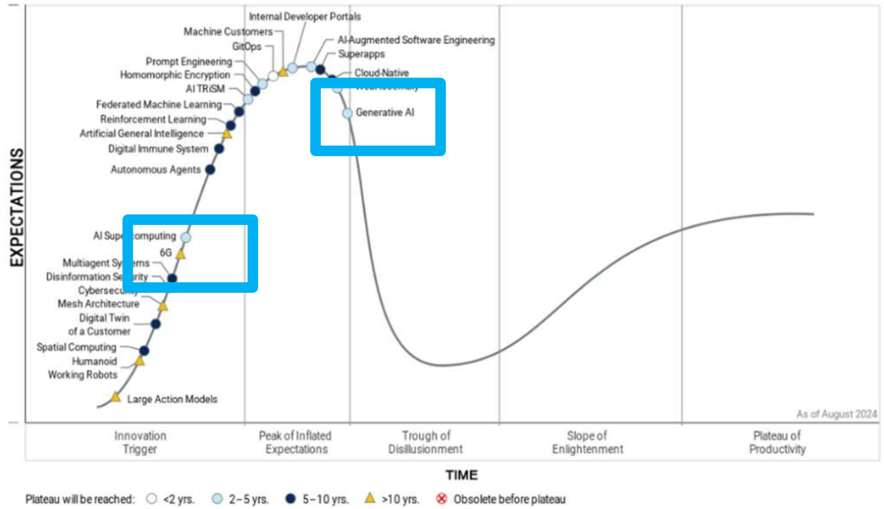
Source: https://www.ericsson.com/4aca6f/assets/local/reports-papers/mobility-report/documents/2025/ericsson-mobility-report-november-2025.pdf

Emerging Trends of Innovation

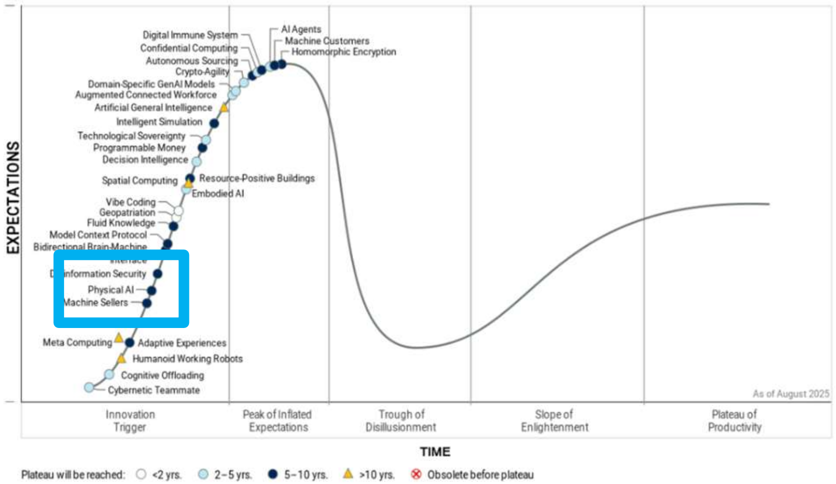
Hype Cycle for Emerging Technologies, 2023



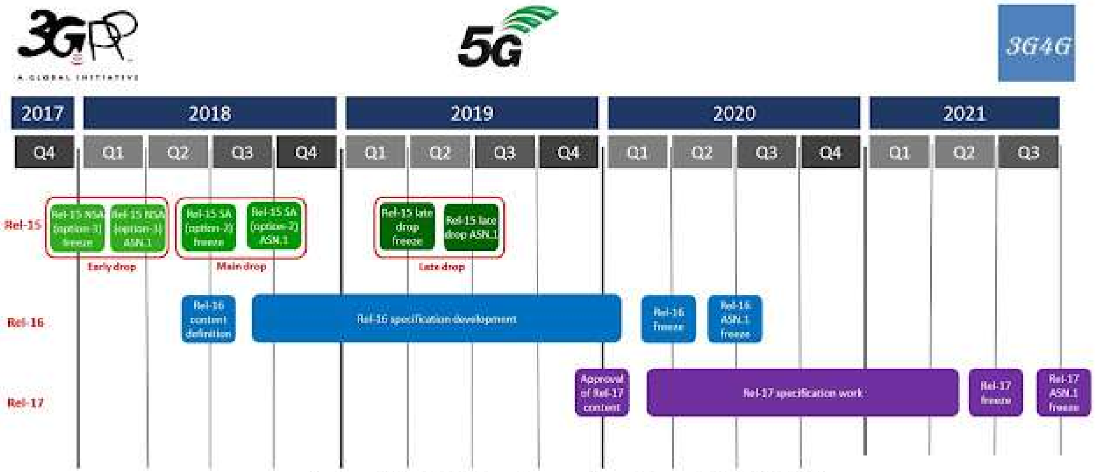
Hype Cycle for Emerging Technologies, 2024



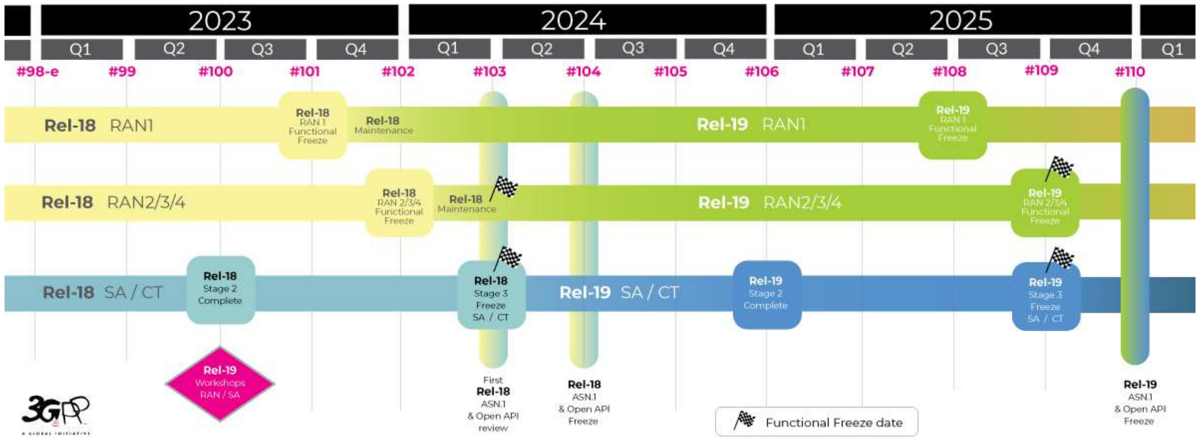
Hype Cycle for Emerging Technologies, 2025



Standardization Activities and Timelines



Designed by 3G4G, based on roadmap from 3GPP, July 2019



Source: https://www.3gpp.org/specifications-technologies/releases

What is 5G?

❑ 5G is a 5th generation network:

- that connects new industries
- enable new services
- empower new user experiences
- set new levels of cost and energy efficiency.

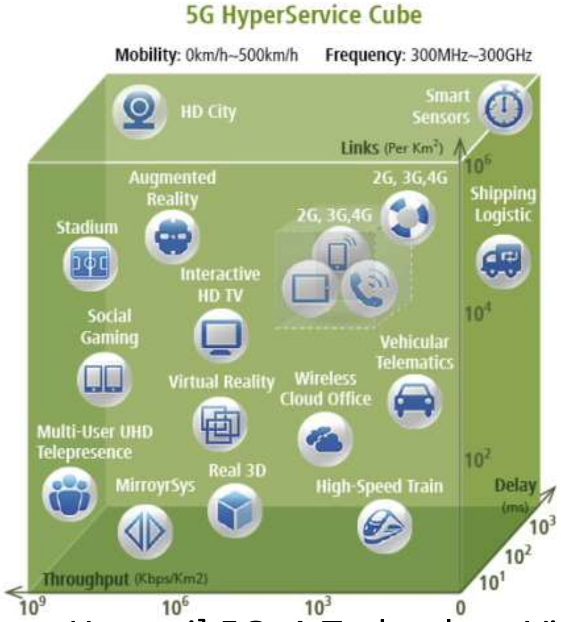
"Developing vertical applications for the future requires re-imagining of how we create and deliver data and services".

[Source]: Qualcomm Technologies, Inc.

Overview of 5G: Architectures – Services

The “5G HyperService Cube” a multi-dimensional overview

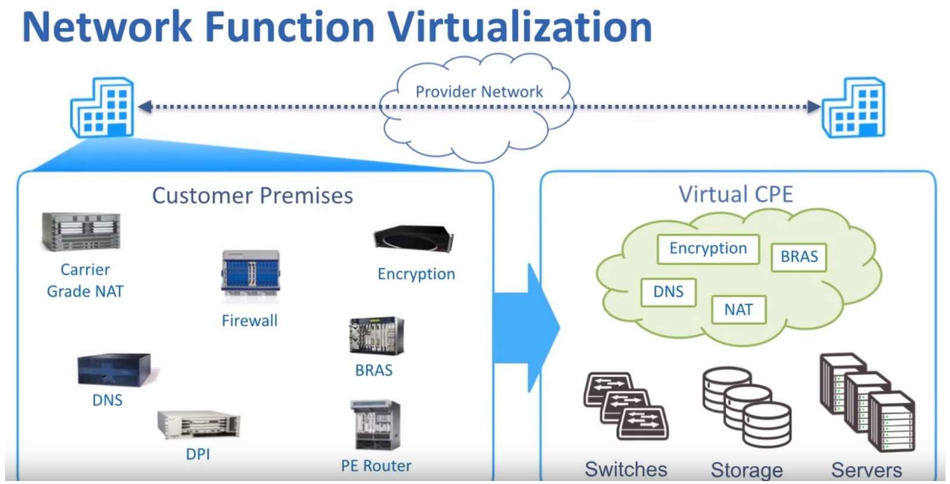
- throughput,
- latency
- number of connections



[Source - Huawei] 5G: A Technology Vision

Architecture elements are defined as virtualized network functions (NFV) that offer operators to provide services:

- Reduced hardware cost
- Flexible orchestration services



SDN is a solution for

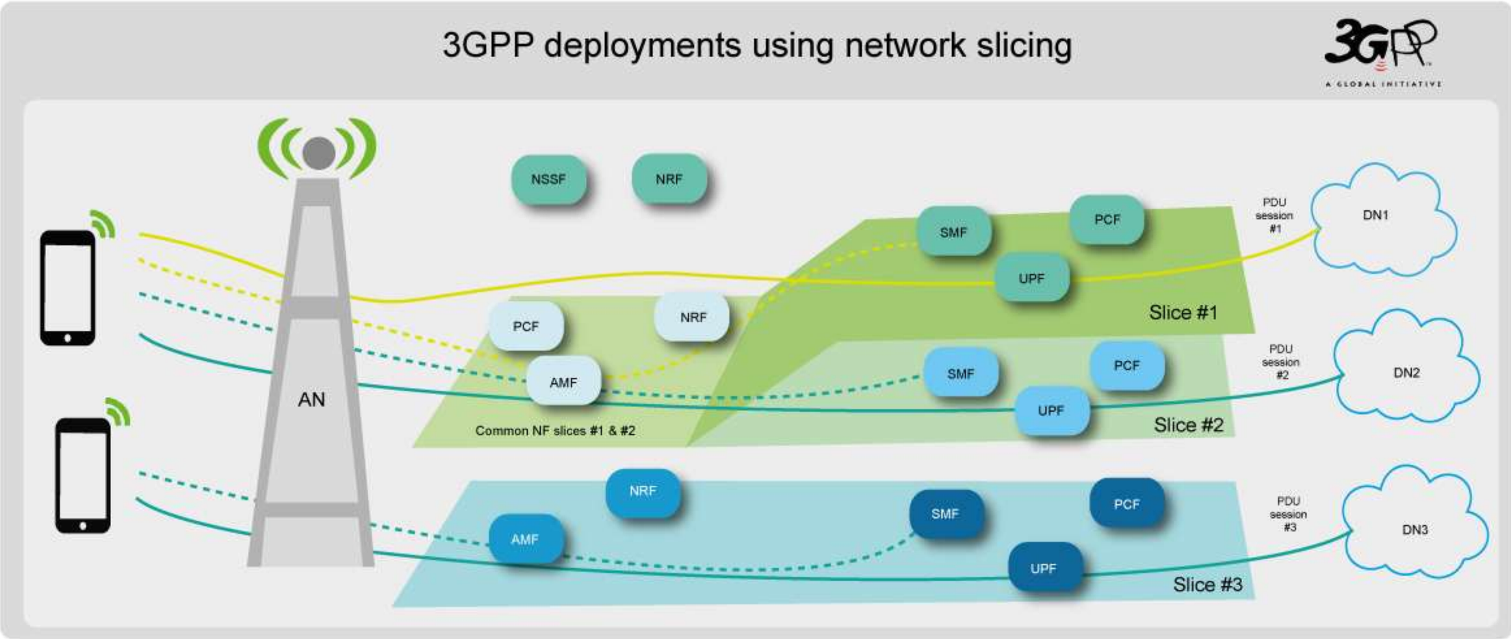
- High demand on resources
- Unpredictable traffic patterns
- Rapid network reconfiguration
- Incorporating business rules

5G Service-based Architecture

Virtual network architecture – Network Slicing!

- multiple logical networks from common shared physical infrastructure
- to meet the specific needs:
    - applications, services, devices, customers or operators

Dynamic end-to-end network slicing for 5G



Courtesy 3GPP

5G Radio Access Methods and Technologies

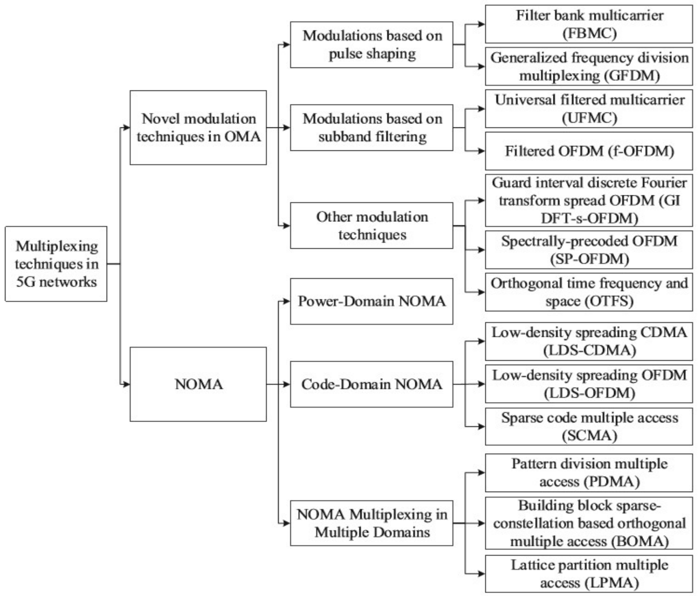
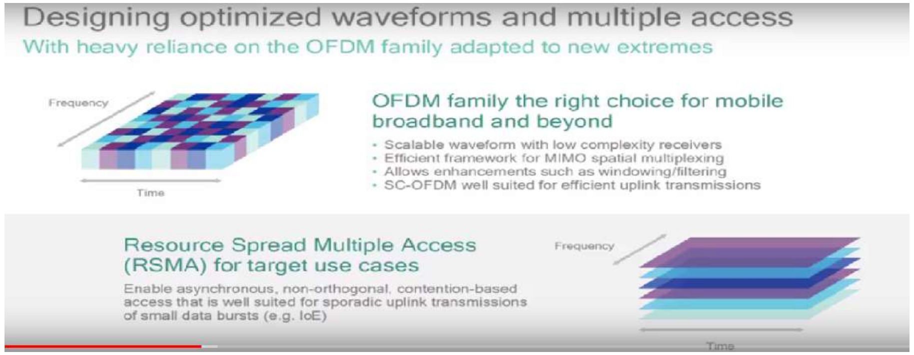
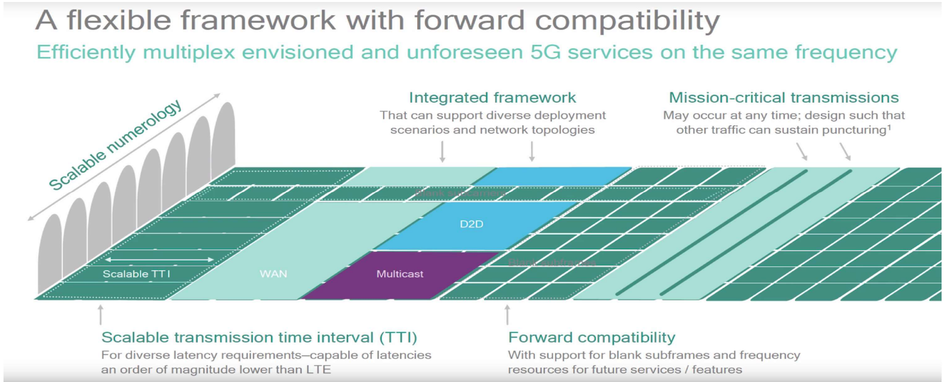
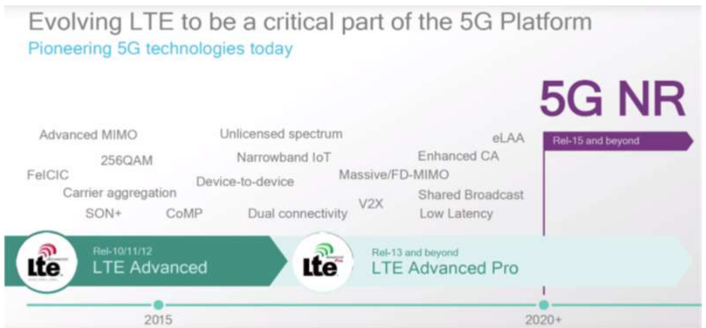


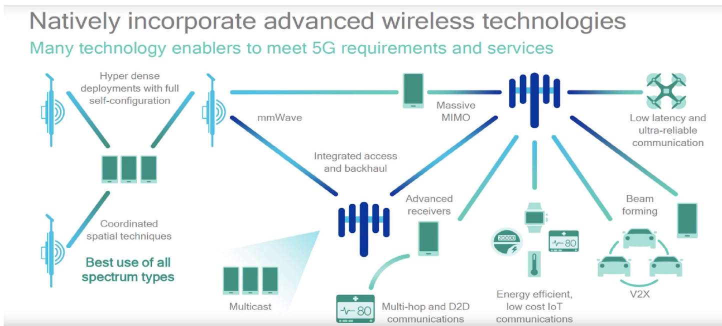
Fig. 1: A classification of the novel multiplexing techniques in 5G networks.

[Source]: Yunlong Cai et. al., "Modulation and Multiple Access for 5G Networks" , IEEE Communications Surveys & Tutorials, 2017.









[Source]: Qualcomm Technologies, Inc.

mmWave Channel Measurement Campaign by NYW

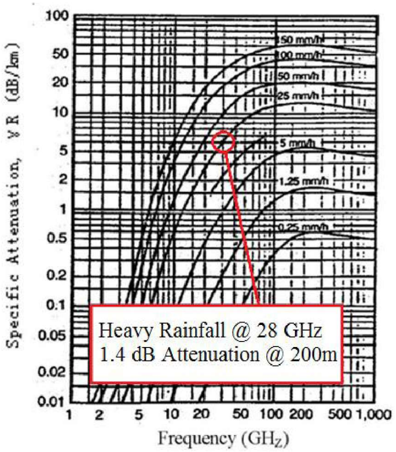


FIGURE 1. Rain attenuation in dB/km across frequency at various rainfall rates [26]. The rain attenuation at 28 GHz has an attenuation of 7 dB/km for a very heavy rainfall of 25 mm/hr (about 1 inch per hour). If cell coverage regions are 200 m in radius, the rain attenuation will reduce to 1.4 dB.

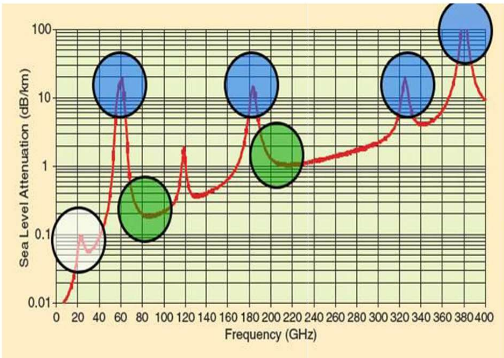
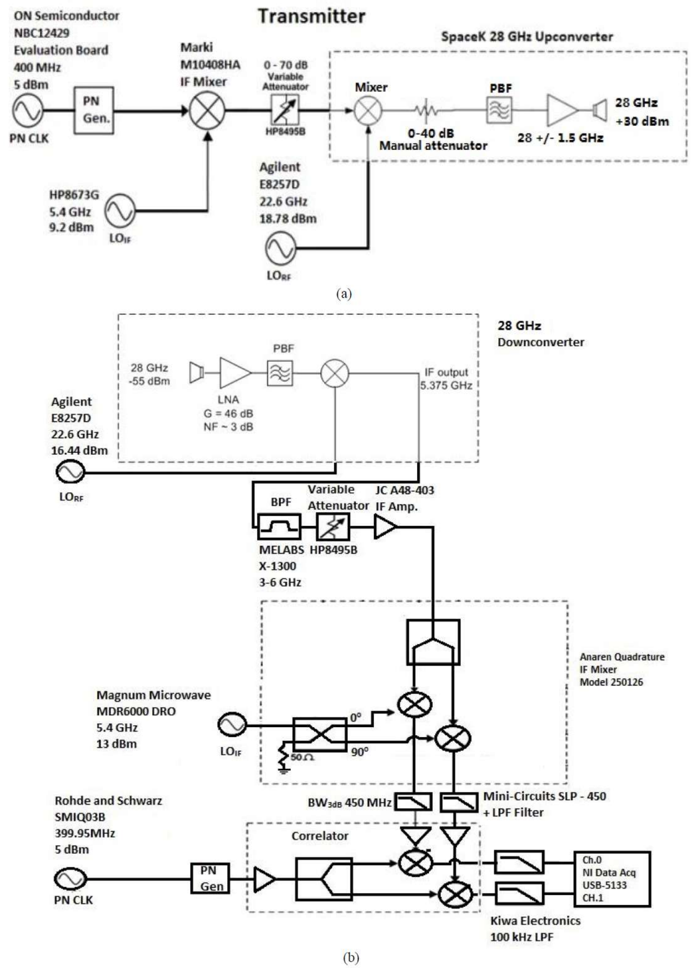


FIGURE 2. Atmospheric absorption across mm-wave frequencies in dB/km [1]. The attenuation caused by atmospheric absorption is 0.012 dB over 200 m at 28 GHz and 0.016 dB over 200 m at 38 GHz. Frequencies from 70 to 100 GHz and 125 to 160 GHz also have small loss.



T. Rappport et al., “*Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!”,* IEEE Access,

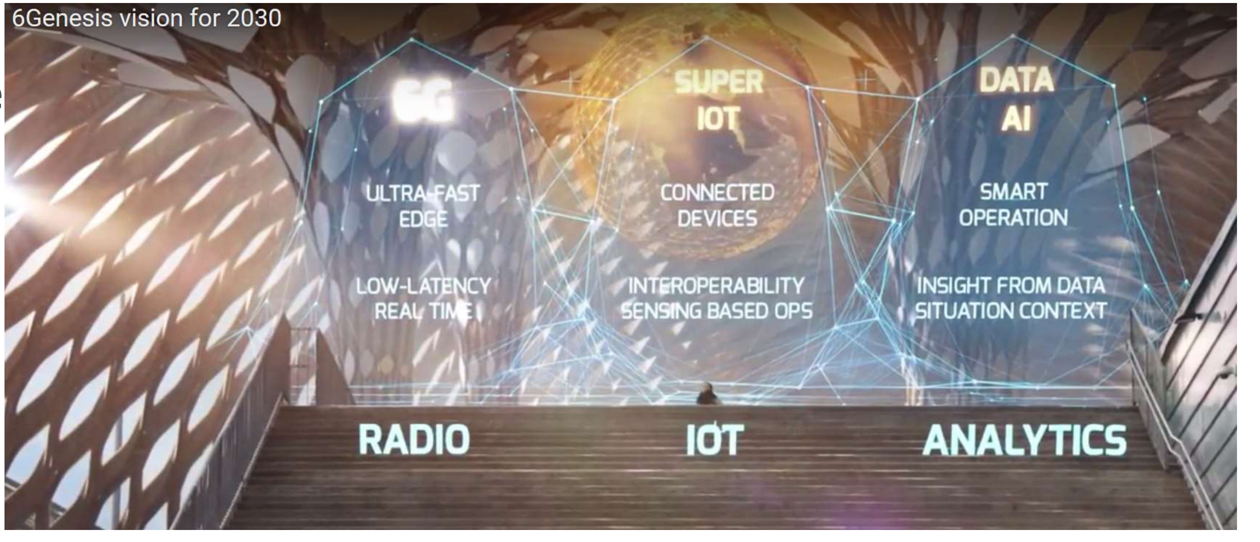
FUTURE – 6G?

6G-Enabled Wireless Smart Society & Ecosystem (6Genesis) - http://www.oulu.fi/university/6gflagship

Centre for Wireless Communications (CWC) – University of Oulu

Key Components:

Mobility as a service



The goals:

Support industry in finalization of 5G

Develop the fundamental technology needed to enable 6G

Speed up digitalization in society

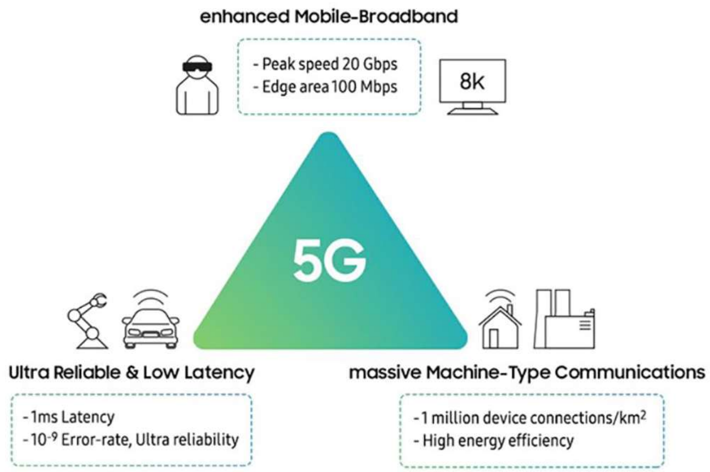
To place Finland at the leading edge of 6G

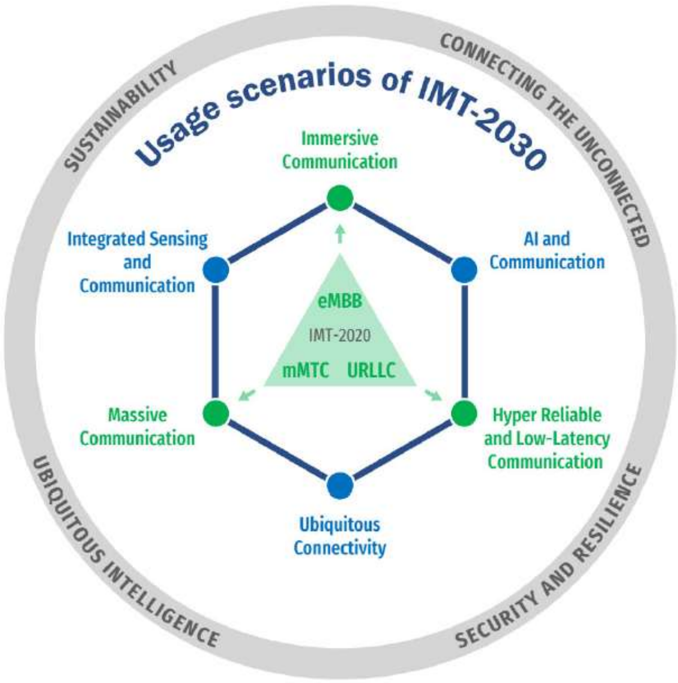
"Developing vertical applications for the future requires re-imagining of how we create and deliver data and services."

International Mobile Telecommunications 2030

The transition from 4G to 5G was based on:

- Enhanced Mobile Broadband (eMBB)
- Ultra reliable low latency Communication (uRLLC)
- Massive Machine Type Communication(mmTC)

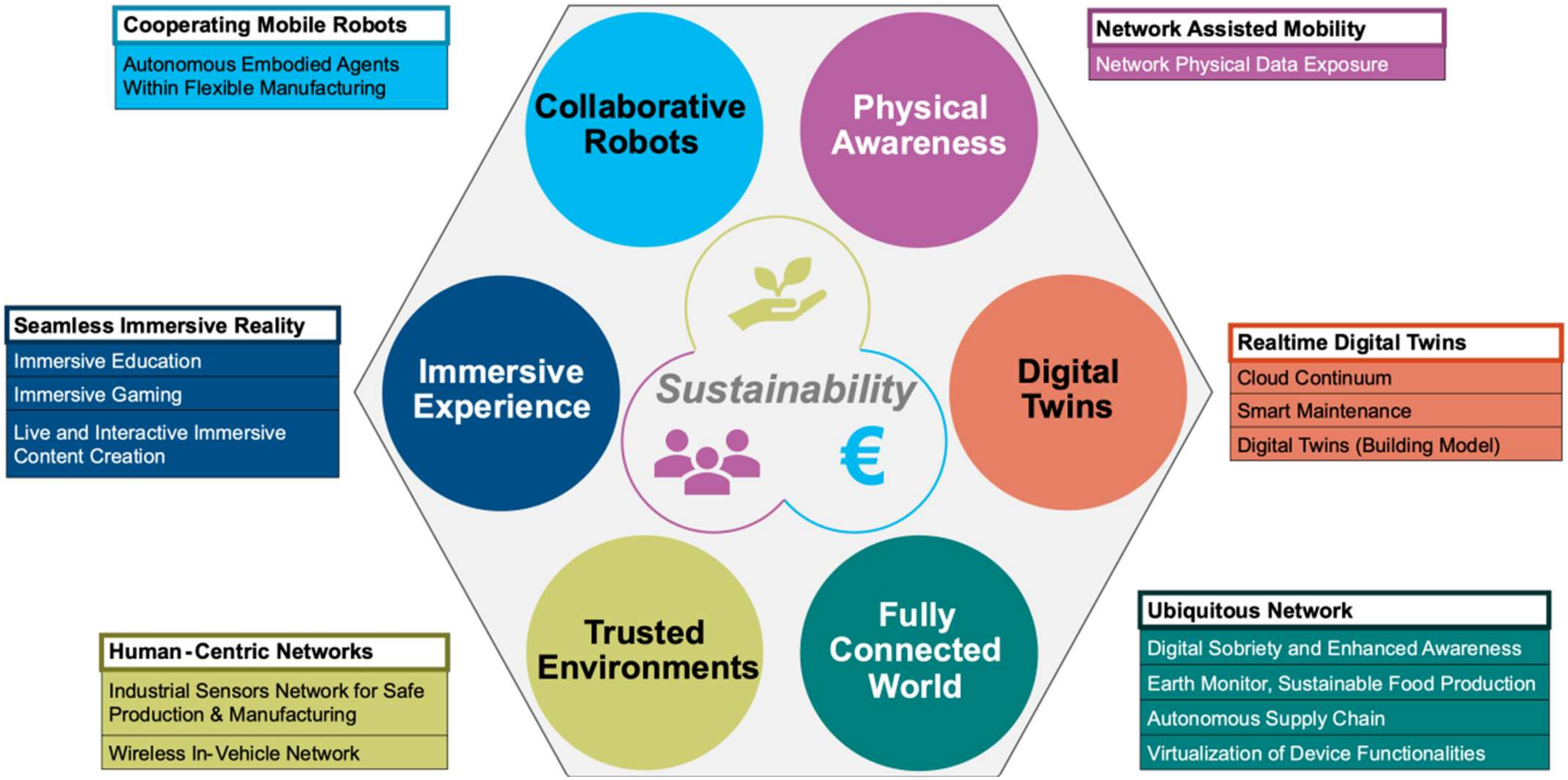




The transition from 5G to 6G is based on:

- Immersive Communication Network of Senses (Xtreme Reality, Holographic Vision)
- AI and Communications (Disaggregation and Distributed Intelligence)
- Hyper reliable and low latency communication (eRLLC)
- Ubiquitous Connectivity (Terrestrial and Non-Terrestrial Network Integration)
- Massive Communication
- Integrated Sensing and Communication (IS&C)

6G Usecases


Cooperating Mobile Robots
Autonomous Embodied Agents Within Flexible Manufacturing
Network Assisted Mobility
Network Physical Data Exposure
Collaborative Robots
Physical Awareness
Seamless Immersive Reality
Immersive Education
Immersive Gaming
Live and Interactive Immersive Content Creation
Immersive Experience
Sustainability
Digital Twins
Realtime Digital Twins
Cloud Continuum
Smart Maintenance
Digital Twins (Building Model)
Trusted Environments
Fully Connected World
Human-Centric Networks
Industrial Sensors Network for Safe Production & Manufacturing
Wireless In-Vehicle Network
Ubiquitous Network
Digital Sobriety and Enhanced Awareness
Earth Monitor, Sustainable Food Production
Autonomous Supply Chain
Virtualization of Device Functionalities

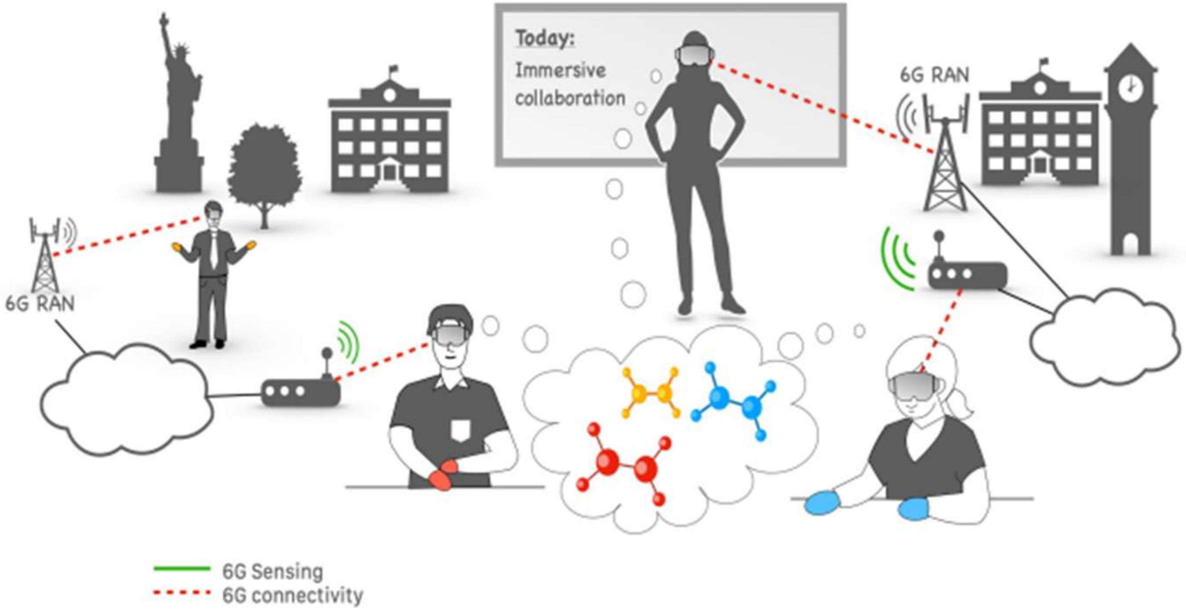
Seamless Immersive Reality

Problem(s) to be Solved/Challenges

- Enabling significantly improved quality of experience
- Living and working from anywhere
- Achieve seamless service continuity
- Ensure privacy protection

KPIs

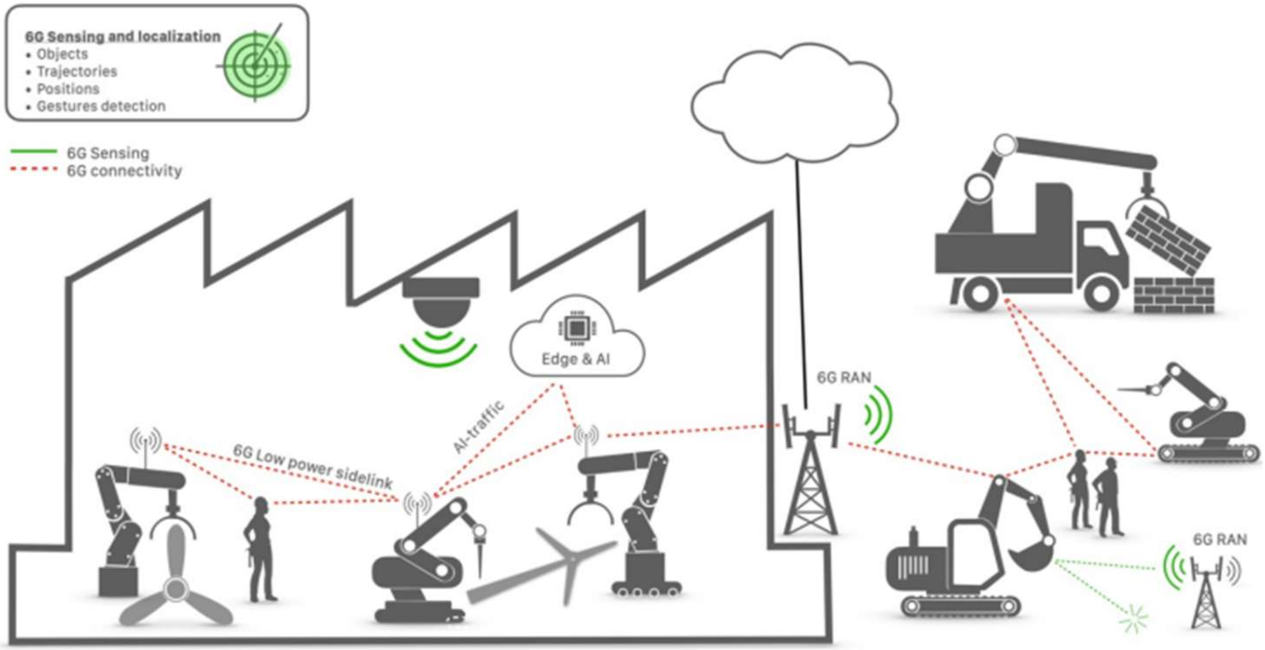
	KPI	Target Range	Justification
Communication	User-experienced data rate [Mb/s]	< 250	DL, also UL, for instance if the UE takes the role of a gateway
	Area traffic capacity [Mb/s/m²]	< 250 < 20	Indoor: per floor in a multi-story building Wide area: focus on immersive experience "on the go"
	Mobility	seamless HO	Pedestrian up-to vehicular speed for mobile passengers
	End-to-end latency [ms]	< 10 < 50 < 150	Split rendering Voice Collaboration
	Reliability [%]	99.9– 99.999	Depending on service and data stream
Positioning & New Capabilities	Positioning accuracy [cm]	≤ 10 horizontal ≤ 10 vertical	Some services may use network-assisted positioning; high positioning accuracy typically requires device-based sensors and sensor fusion.
	Sensing-related capabilities [Y/N]	Y	Some service scenarios may include JCAS or may apply sensor fusion of network and sensor data of connected devices
	AI/ML-related capabilities [Y/N]	Y	Device-embedded and/or provided by network



Cooperating Mobile Robots

Problem(s) to be Solved/Challenges

- Understanding and addressing the communication requirements of machines in the future
- Using limited resources efficiently
- Adapting to dynamic requirements of the market
- End-user access to custom manufacturing
- Safe and trustworthy interactions with tools that can make decisions



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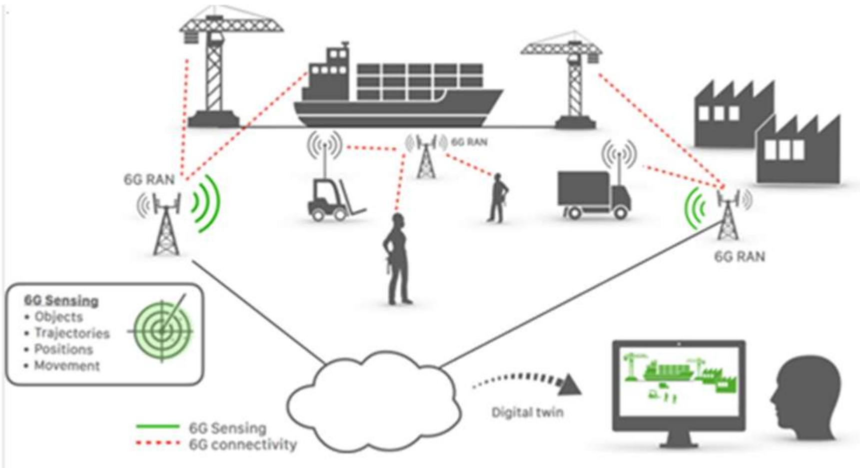
Realtime Digital Twins

This use case covers the following applications (non-exhaustive list)

- DT in a manufacturing plant
- DT for water management and improved traffic management (smart cities)
- DT aggregation of sub-DT to cover complex systems (e.g. full smart cities)
- DT for 6G network planning and operation itself
- DT in port operations.



Problem(s) to be Solved/Challenges

- Increase production quality and efficiency
- Prevent situations where humans are put at risk
- Guaranty the privacy & trustworthiness
- Accessibility of DT models

KPIs

	KPI	Target Range	Justification
Communication	End-to-end latency [ms]	order of ms	Very low latency for the Realtime aspect
	Reliability [%]	99.99999	Very high: The control of Realtime industrial processes requires very high service reliability. Can be lower for non-realtime DT
	User experienced data rate [Mb/s]	< 100	Low. It is expected video will be most demanding (up to 100 Mb/s)
	Connection density [devices/m²]	1-10	High to cope with the high-volume of sensors (with very dispersed data rate needs)
	Coverage [%]	99.99	Service coverage both outdoor & indoor
	Mobility [km/h]	< 100	
Positioning & New Capabilities	Location accuracy [cm]	≤ 10	High. Accurate Positioning to enrich the DT model
	Sensing-related capabilities [Y/N]	Y	Network-sensing: accuracy, resolution, and range to enrich the Digital Twin model
	AI/ML-related capabilities [Y/N]	Y	AI services can be provided by the service itself (embedded AI) or exposed by the 6G network (AI/ML provided by the network) but no AI-Native required (6G network AI).

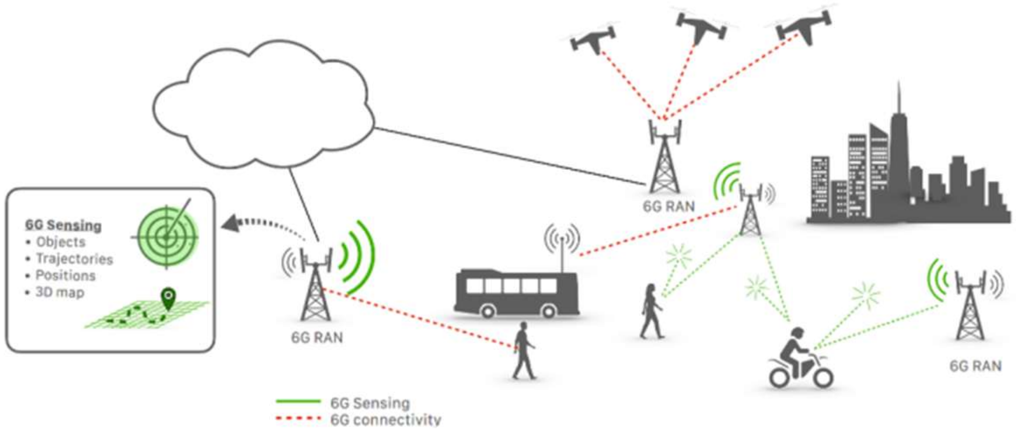
Network-Assisted Mobility

Problem(s) to be Solved/Challenges

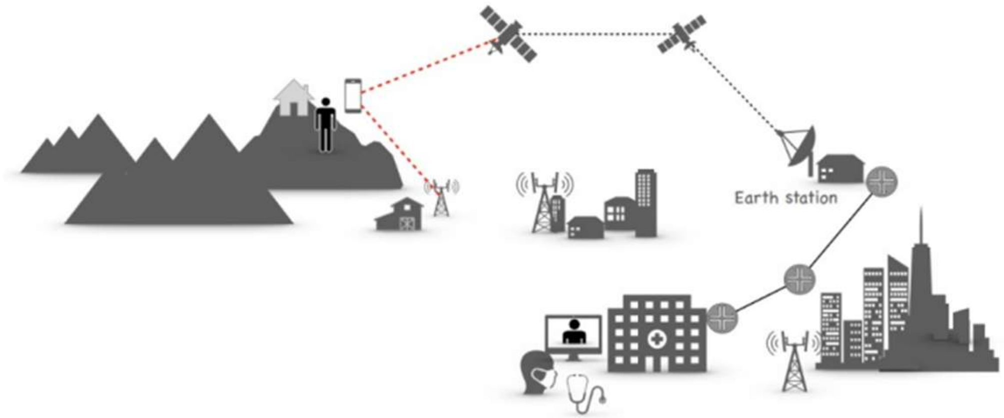
- Risk of accidents with intense and automated transport scenarios
- Energy consumption and generated emissions from transport
- Cost of transportation of goods and people
- Access to reliable transport
- Privacy in public spaces

KPIs

	KPI	Target Range	Justification
Communication	Peak Data Rate [Gb/s]	–	Not expected to be a challenge
	User-Experienced Data Rate [Mb/s]	1-10 (<100)	Depends on service type: lower for warnings and assistance, higher for digital maps. (For sensor fusion exchange of data may be higher.)
	Spectrum Efficiency	–	Same as for communication services
	Area Traffic Capacity [Mb/s/m^2]	–	Not expected to be a challenge
	End-to-end latency [ms]	20	Similar to V2X services.
	Reliability [%]	99.99	Fraction of packets within latency bound E2E
	Coverage [%]	99.9	Fraction of defined service space (in 3D) within latency bound.
	Service availability [%]	99.99	Probability to get communication service (as defined with E2E latency) within service space when requested. (Can replace coverage and reliability)
	Connection density [devices/km^2]	10^4	Not expected to be a challenge
	Mobility [km/h]	Up to 300 seamless handover	Speed of vehicles (cars, drones, trains) in urban areas. Handover within latency bound
Positioning & New Capabilities	Location accuracy [m]	1 (3D) precision with 99.9% reliability within 99.9% of service space (0.1)	Reliable positioning with high availability important for use case, but likely multiple sources (e.g. from onboard sensors) can be combined to achieve more precise positioning. (Sensor fusion).
	Sensing-related capabilities [Y/N]	Y	Object detection probability, Object location accuracy/resolution, Object velocity accuracy/resolution, Object size accuracy/resolution.
	AI/ML-related capabilities [Y/N]	Y	Probability of a response time of compute/AI capabilities within a latency limit.



Ubiquitous Network



Problem(s) to be Solved/Challenges

- Digital inclusion
- Reduce educational and health-services gaps
- Enabler for earth monitoring
- Delivers increased network resilience, crucial in the event of disasters

KPIs

	KPI	Target Range	Justification
Communication	End-to-end latency [ms]	10-100	Depending on the service. It is targeting video calls/streaming. 'Real-time' interactions are not considered as part of this requirement (e.g., no remote surgeries).
Communication	Reliability [%]	99.9 –99.999	The reliability KPI could be associated with the expected service (e.g., given NTN coverage, what is the probability of successfully fallback from TN to NTN and achieving a data rate of at least 100 kb/s). Success rate for this should be high.
Communication	Availability [%]	98.5	Tightly connected to reliability (qualifying the success of transmission) is the availability of connectivity (qualifying the percentage of time the service can be delivered). Appropriate combination of full coverage and capacity to deliver video streaming-like services is required. Reaching new areas can promote new use cases/businesses/ services. As there is no viable alternative, those services will fully rely on this connectivity (e.g., Health services require high reliability and availability of the connectivity). Also, Maintainability requirements need to be high for them not being a cause for downtime. Moreover, the ecosystem needs to be designed in a fully reliable and resilient way in case of emergencies. As deployment cannot be defined through design, KPIs such as 'seconds of system downtime upon handover' could be implemented.
Communication	User experienced data rate [Mb/s]	0.1 –25 Downlink/ 2 Uplink	Good quality video streaming should be delivered (not extreme experience). The data rate refers to a single UE, measured on the device. Based on current standards, from 0.1 (sensor data) to 25 Mb/s (4K video, based on current video requirements) are the expected bit rates, at least for Downlink. It may be revisited based on the evolution of video standards by 2030.
Communication	Connection density [devices/m²]	0.1	Connection density is not a stringent requirement, as it does not target massively connected deployments. Also, connection densisty for rural areas are low. However, urban settings could require 0.1 devices/m², in case of crisis scenario.
Communication	Coverage [%]	- Up to 10-15 km range (cell radius) for TN - 99.9% earth human environment on earth area coverage with TN/NTN	Coverage means both extending the range of terrestrial networks, reaching larger cell size, but also the percentage of coverage of a given area, combining the different types of access, TN and NTN.
Communication	Mobility [km/h]	up to 120	Mobility related to seamless handover between TN and NTN. It should support terrestrial vehicle speed's
Positioning & New Capab.	Location accuracy [m]	Low (≈ 10)	Global coverage option is not prone to high accuracy requirements.
Positioning & New Capab.	Sensing [Y/N]	N	Sensing usually not needed, except for some specific cases (during a crisis to obtain information)
Positioning & New Capab.	AI/ML-related capabilities [Y/N]	N	AI services can be provided offline, utilizing big data analytics. It might require AI capabilities to tweak routes, or other outcomes to minimize disruption time.

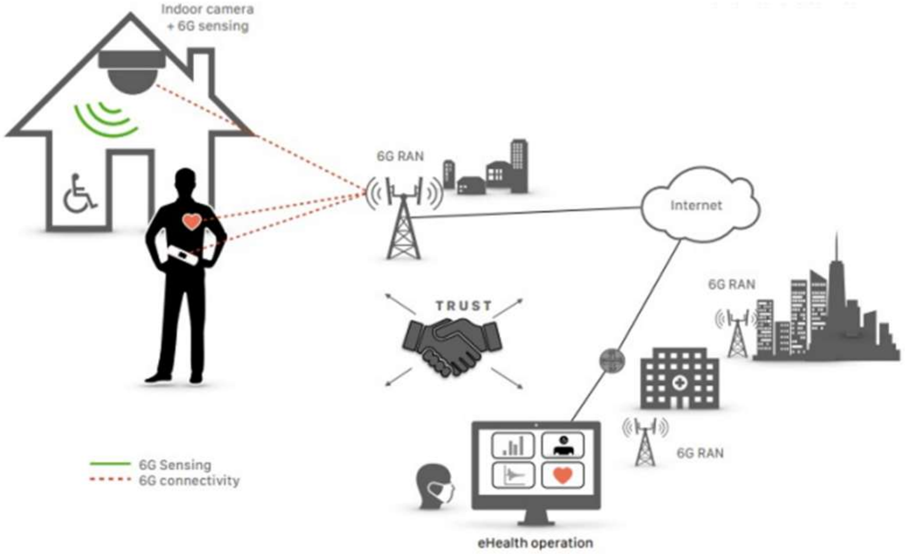
Human-Centric Networks

Problem(s) to be Solved/Challenges

- Extended access to high-end health monitoring and diagnosis
- Deliver safe environments for increased well-being, mental health, safety, inclusion, and autonomy
- Safety, health, and peace of mind for hard-hat workers, as well as visitors of big public events

KPIs

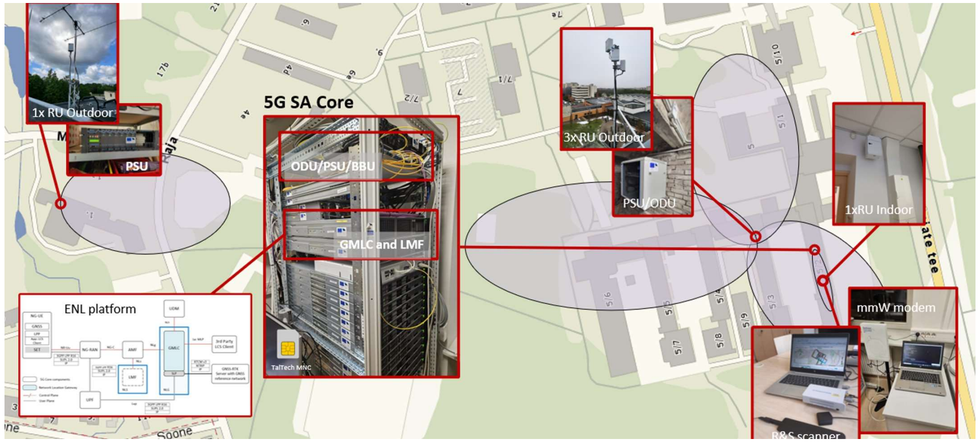
	KPI	Target Range	Justification
Communication	User experience data rate [Mb/s]	–	
Communication	End-to-end latency [ms]	< 250 < 1000	For AGVs and care robots, e.g. in homes for the elderly and in hospitals. Initiating an intervention in case of an evolving critical situation in a crowd.
Communication	Reliability [%]	99.9 – 99.999	High service availability is key for this use case.
Communication	Connection density [devices/m²]	1 to 10 < 0.001	Indoor per floor Outdoor
Communication	Coverage	–	
Communication	Mobility	pedestrian, slow vehicular	
Positioning & New Capabilities	Location and positioning accuracy [m]	< 10 < 0.3 to < 1 < 0.1	Location accuracy Positioning accuracy Relative positioning accuracy, e.g. collision avoidance
Positioning & New Capabilities	Sensing-related capabilities [Y/N]	Y	Relevant for most of the scenarios
Positioning & New Capabilities	AI/ML-related capabilities [Y/N]	Y	Relevant for most of the scenarios

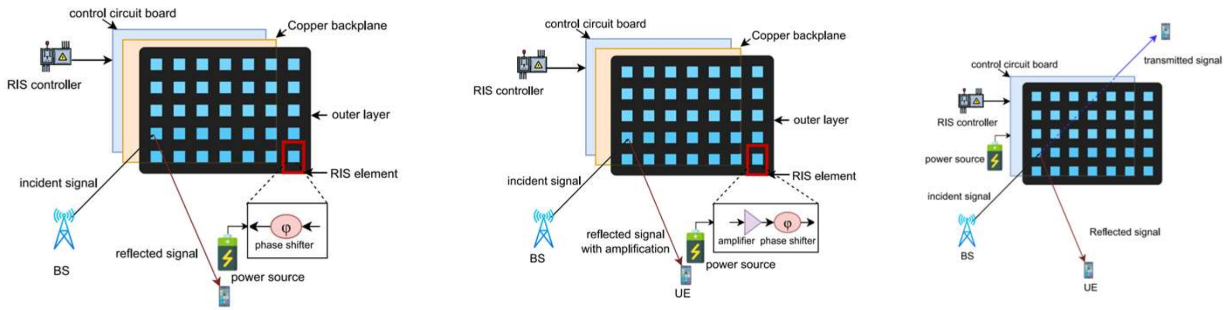


6G Standardization

ComSys Research Group Research in 6G

- Radio Access Techniques (RATs)
- Reconfigurable Intellegent Surfaces
- Integrated Sensing, Localization
- mmWave Aerial communications, sensing and localization





(a) Passive Reflective RIS

(b) Active Reflective RIS

(c) Transmissive/STAR RIS which can be active or passive