Toward 6G Networks: Use Cases and Technologies

- Full digital and connected World : Move from personal communication to Full IoT
  - Data-centric, data-dependent and automated society
  - Automatic industry manufacturing processes
  - Autonomous transportation systems (road,ocean, air…)
  - Smart city, home with millions of sensors
  - New systems operated by artificial intelligence in local cloud and fog environments
  - move from personalized communication toward the full realization of the Internet of Things (IoT) paradigm
    - connecting the computing resources, vehicles, devices, wearables, sensors, and even robotic agents

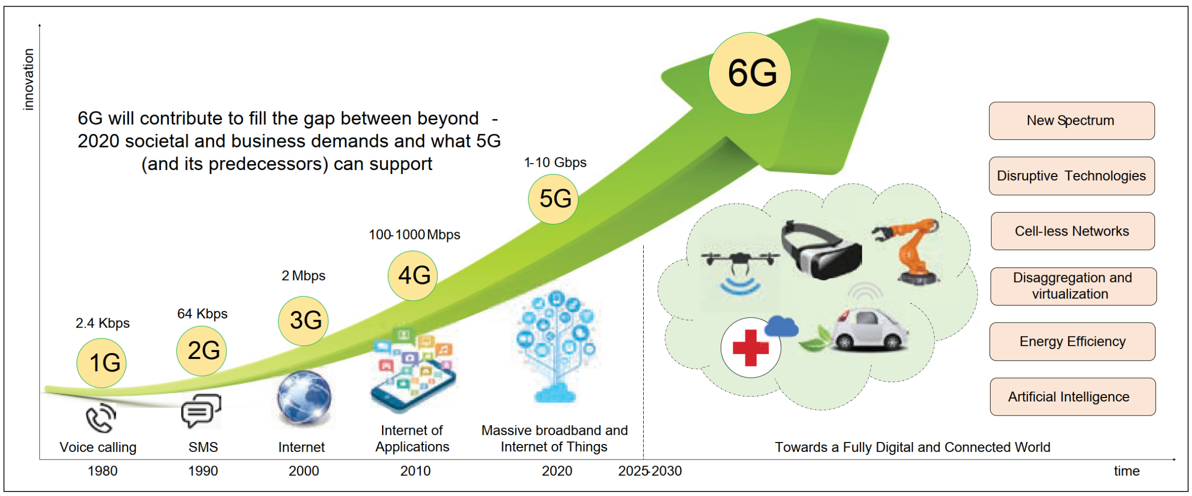


Figure 1. Evolution of cellular networks, from 1G to 6G, with a representative application for each generation.

- 5G a significant step toward a low-latency tactile access network
  - New frequency bands, mmWave
  - Advanced spectrum usage and management
  - redesign of core network
- Resource requirement of data centric and automated process may exceed 5G system
  - throughput in terabit per second
  - latency < ~x00 us
  - connected nodes in 10^7 per km^2
- Envision in 6G:
  - Novel disruptive communication technologies(新的破壞性通訊技術)
    - terahertz and optical communications
  - Innovative network architectures(創新的網路架構)
    - 3D coverage calls for new cell-less architectural
    - disaggregation and virtualization of the networking equipment
  - Integrating intelligence in the network(整合智能網路)
    - bring intelligence from centralized computing facilities to end terminals
    - distributed learning models
    - Unsupervised learning and knowledge sharing for realtime network decision.

6G Use Cases

- meet stringent network demands (e.g., ultra-high reliability, capacity, efficiency, and low latency) in a holistic fashion, in view of the foreseen economic, social, technological, and environmental context of the 2030 era.

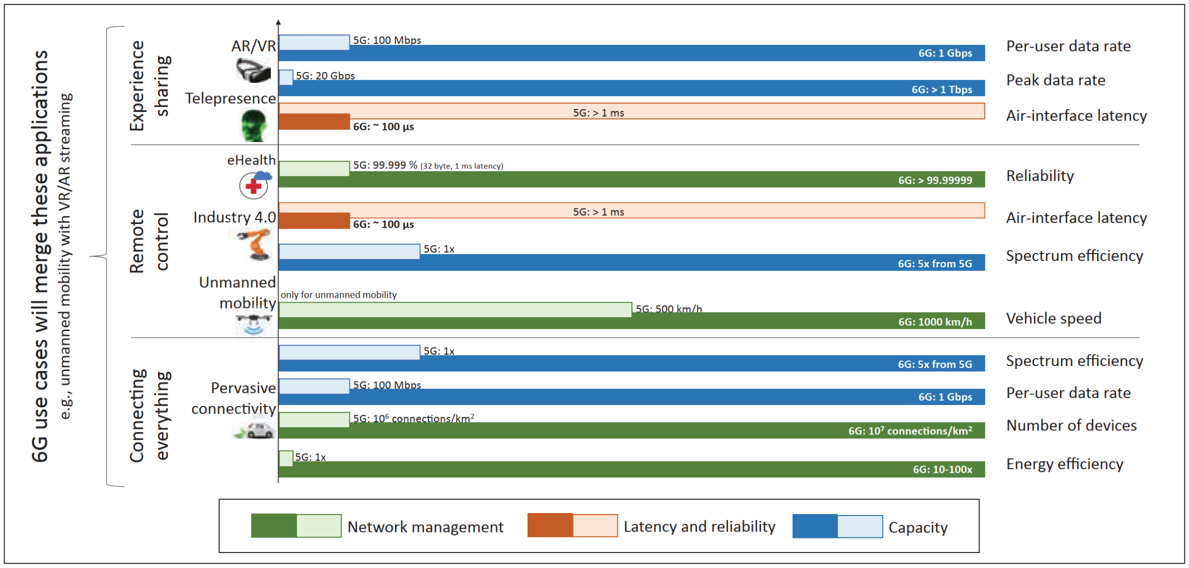


Figure 2. Representation of multiple KPIs of 6G use cases, together with the improvements with respect to 5G networks, using data from [1–9].

  - AR/VR: 100Mbps per user to 1G per user, 20Gbps total to 1Tbps from 5G to 6G
  - Holographic telepresence (teleportation)
    - 3D holographic display
    - latency < ~100 us
  - eHealth:
    - require from 99.999% to 99.99999% reliability
  - Pervasive connectivity:
    - higher overall energy efficiency (10–100x with respect to 5G)
    - provide seamless and pervasive connectivity in a variety of different contexts, matching stringent QoS requirements in outdoor and indoor scenarios with a cost-aware and resilient infrastructure
  - Industry 4.0 And robotics
    - microsecond delay jitter
    - gigabit-per-second peak data rates for AR/VR industrial
  - Unmanned Mobility
    - ultra-high-mobility scenarios (up to 1000 km/h) to guarantee passenger safety

6G Enabling Technologies

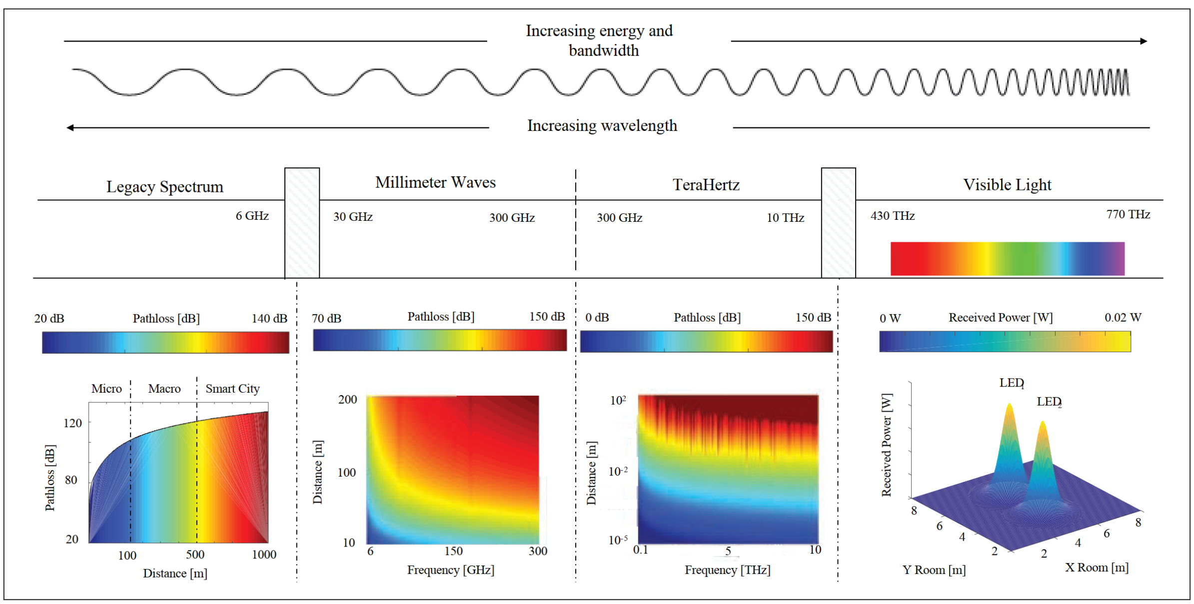
Tech	Cat	Potential	Challenges	Use Cases
New Spectrum	TeraHz	high BW, small antenna, focus beams	Circuit design, high propagation loss	Pervasive connectivity, industry 4.0, holographic telepresence

Tech	Cat	Potential	Challenges	Use Cases
New Spectrum	VLC	Low-cost hardware, low interference,unlicensed spectrum	Limited coverage, need for RF uplink	Pervasive connectivity, eHealth
PHY	Full duplex	Continuous TX/RX and relaying	Management of interference, scheduling	Pervasive connectivity, industry 4.0
PHY	Out-of-band channel estimation	Flexible multi-spectrum communications	Need for reliable frequency mapping	Pervasive connectivity, holographic telepresence
PHY	Sensing and localization	Novel services and context-based control	Efficient multiplexing of communication and localization	eHealth, unmanned mobility, industry 4.0
Network	Multi-connectivity and cell-less architecture	Seamless mobility and integration of different kinds of links	Scheduling, need for new network design	Pervasive connectivity, unmanned mobility, holographic telepresence, eHealth
Network	3D network architecture	Ubiquitous 3D coverage, seamless service	Modeling, topology optimization and energy efficiency	Pervasive connectivity, eHealth, unmanned mobility
Network	Disaggregation and virtualization	Lower costs for operators for massively-dense deployments	High performance for PHY and MAC processing	Pervasive connectivity, holographic telepresence, industry 4.0, unmanned mobility
Network	Advanced access-backhaul	integration Flexible deployment options, outdoor-to-indoor relaying	Scalability, scheduling and interference	Pervasive connectivity, eHealth
Network	Energy-harvesting and low-power operations	Energy-efficient network operations, resiliency	Need to integrate energy source characteristics in protocols	Pervasive connectivity, eHealth

Tech	Cat	Potential	Challenges	Use Cases
Intelligence	Learning for value of information assessment	Ontelligent and autonomous selection of the information to transmit	Complexity, unsupervised learning	Pervasive connectivity, eHealth, holographic telepresence, industry 4.0, unmanned mobility
Intelligence	Knowledge sharing	Speed up learning in new scenarios	Need to design novel sharing mechanisms	Pervasive connectivity, unmanned mobility
Intelligence	User-centric network architecture	Distributed intelligence to the endpoints of the network	Real-time and energy-efficient processing	Pervasive connectivity, eHealth, industry 4.0

Disruptive Communication technologies

- 6G networks: conventional spectrum (sub-6 GHz and mmWaves) + new frequency band(terahertz ,visible light communications)



Terahertz Communications

- between 100 GHz and 10 THz
- high-frequency connectivity enabling data rates(~x00 Gbps).
- main issues: propagation loss, molecular absorption, high penetration loss, RF and Antenna
  - propagation loss
    - directional antenna arrays (like mmWave)
    - spatial multiplexing with limited interference
  - molecular absorption: select the operating band not affected by.
  - limited to indoor-to-indoor scenarios
  - RF and antenna: ultra-small-scale electronic packaging solutions.

Visible Light Communication

- quickly switch between different light intensities to modulate a signal that can be transmitted to a proper receiver
- more mature than that on terahertz communications
- Applied in indoor application
  - limited coverage range
  - require an illumination source
  - suffer from shot noise from other light sources
- Need to be complemented by RF for the uplink
- Standard: IEEE802.15.3d and IEEE802.15.7
  - not included in Cellular network
  - targeting beyond 5G use cases
- Research for enable 6G mobile users to operate in the terahertz and VLC spectra
  - hardware and algorithms for flexible **multi-beam acquisition** and tracking in **non-line-of-sight (NLoS)** environments

Full-Duplex Communication Stack

- key on reducing the cross-talk between TX/RX
- enable concurrent downlink and uplink transmission increasing multiplexing capability
- 6G network careful planning to avoid interference

Novel Channel Estimation Techniques (e.g.,Out-of-Band Estimation and Compressed Sensing)

- Difficult to design **efficient procedures** for **directional** communication, considering very large BW in mmWave and Terahertz
- Out-of-band estimation(angular domain) improves relativeness of beam management
- Angle domain sparsity: exploit **compressive sensing** to estimate the channel using a reduced number of samples

Sensing and Network-Based Localization

- 6G networks will exploit a unified interface for localization and communications to improve control operations:
  - information to shape beamforming patterns, reduce interference, predict handovers, and innovative user services

Innovative Network Architectures

- Increasing BW requires higher capacity of backhaul networks, wide range of different communication tech increase the heterogeneity of the network.
- 6G Architecture

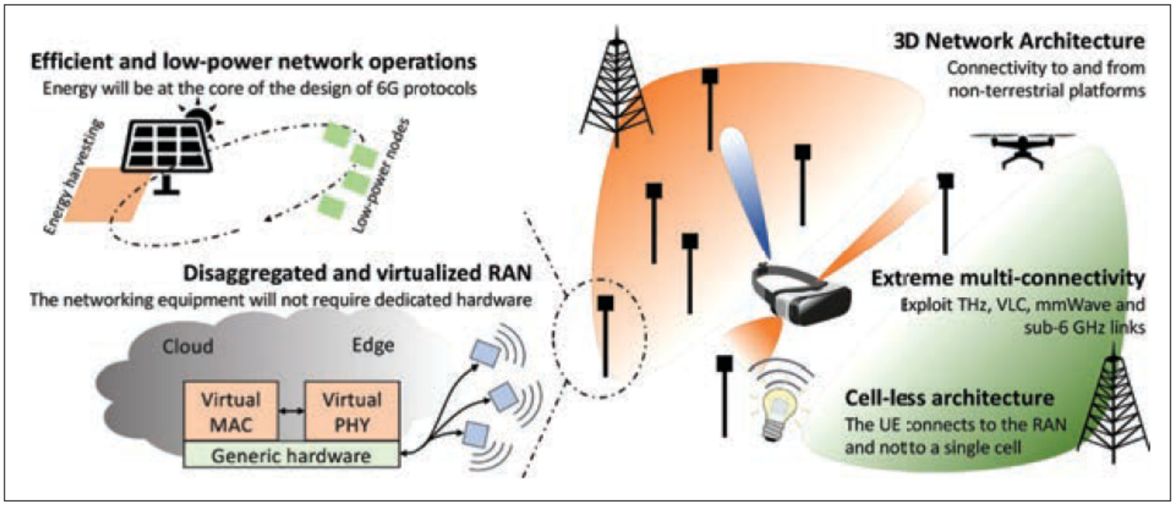


Figure 4. Architectural innovations introduced in 6G networks.

- Tight integration of multiple frequencies and communication technologies and cell-less architecture:
  - support a number of heterogeneous radios in the devices
  - multi-connectivity techniques extend cell boundary.
  - **cell-less** network procedures guarantee **seamless mobility** without overhead due to handovers
  - provide QoS guarantees
  - The devices be able to **seamlessly transition** among heterogeneous links **without manual intervention or configuration**
  - concurrently use different network, ex. sub 6G for control and TeraHertz for data.

3D Network Architecture

- 5G bi-dimensional space: network access points are deployed to offer connectivity to devices **on the ground**
- 6G 3D coverage:
  - complementing terrestrial infrastructures with non-terrestrial platforms(drones, balloons, satellites)
  - quickly deployed to guarantee seamless service continuity and reliability
  - Challenge:
    - air-to-ground channel modeling,
    - topology and trajectory optimization,
    - resource management, and energy efficiency

Disaggregation and Virtualization of the Networking Equipment

- Network toward disaggregation of once-monolithic networking equipment
- 3GPP not directly specific how to introduce virtualization concept.
  - 5G network currently not addressed the challenges related to the design of disaggregated architecture.
    - the higher control latency.
    - cyber attach for centralization, and to the security of virtualized network functions.
- 6G bring disaggregation to the extreme by virtualizing MAC and PHY in low-cost distributed platforms with just antenna and minimum processing.
  - decrease the cost of networking equipment, making massively dense deployment economically feasible.

Advanced Access-Backhaul Integration

- massive data rate requires increasing of 6G backhaul capacity.
- dense deployment of TeraHertz and VLC need backhaul connectivity to their neighbors and the core network
- Self-backhauling solutions : radios(TeraHertz) in the base stations provide both access and backhaul
- Challenge: networks will need higher autonomous configuration capabilities.

Energy-Harvesting Strategies for Low Power Consumption Network Operations

- necessary to design systems where both the circuitry and the communication stack are developed with energy awareness in mind
- energy-harvesting circuits to allow devices to be self-powered

Integrating Intelligence In the Network

- expect 6G deployments to be much denser(# of AP and users) and more heterogeneous (different tech and application characteristics), and have stricter performance requirements with respect to 5G.
- In 6G network, intelligence play more prominent role in prediction and classification tasks.
  - data-driven approaches can be seen as tools network vendors and operators can use to meet the 6G requirements

Learning Techniques for Data Selection and Feature Extraction

- fundamental to discriminate the value of information to maximize the utility for the end users with (limited) network resources
- machine learning (ML) strategies can evaluate the degree of correlation in observations, or extract features from input vectors and predict the a posteriori probability of a sequence given its entire history
- **unsupervised** and **reinforcement learning** approaches do not need labeling and can be used to operate the network in a
  truly autonomous fashion

Inter-User Inter-Operator Knowledge Sharing

- learning-driven networks, operators and users can also share learned/processed representations of specific network deployments and/or use cases
  - speed up the network configuration in new markets
  - better adapt to new unexpected operational scenarios

User-Centric Network Architecture

- ML-driven networks are still in their infancy(起步階段)
- user-centric network architecture:
  - end terminals will be able to make autonomous network decisions based on the outcomes without communication overhead to and from centralized controllers

- Distributed methods can process ML algorithms in real time, yielding more responsive network management.