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6G: Towards a Fully Digital and Connected World

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6G Wireless Summit, Levi, Finland
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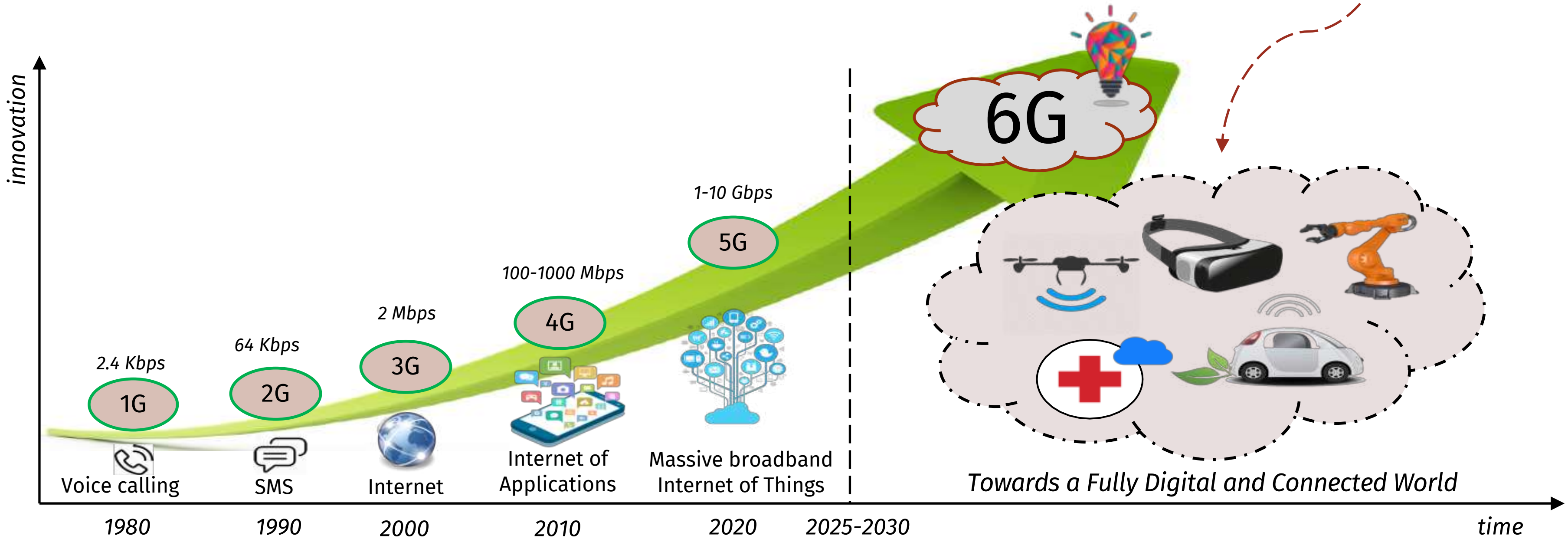
Outline

- Introduction and Motivations
- 6G Key Performance Indices (KPIs)
- 6G Potential Applications
- 6G Enabling Technologies
  - *Disruptive Communication Technologies*
  - *Novel 6G Communication Enabler*
  - *Innovative Network Architectures*
  - *Integrating Intelligence in the Network*
- Conclusions and Research Directions

Introduction and Motivations

- From 1G to 5G, passing through UMTS and LTE innovations, each generation of mobile technology has tried to meet the **needs** of network operators and final consumers
- The rapid development of **data-centric** and **automated processes** may exceed even the capabilities of emerging 5G systems, thereby calling for a new wireless generation



Introduction and Motivations

5G is always associated with trade-offs: 6G will contribute to **fill the gap** between beyond-2020 societal and business demands and what 5G (and its predecessors) can support

- Consider **potential applications** for future connected systems and estimate the key requirements in terms of throughput, latency, connectivity and other factors.
- Identify **use cases** beyond the performance of 5G systems under development today.
- Survey **emerging technologies** that are not available in networks today but have significant promise for future 6G systems (including developments at all layers of the protocol stack)

New Spectrum

Disruptive Technologies

Cell-less Networks

Disaggregation/ virtualization

Energy Efficiency

Artificial Intelligence

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6G Use Cases

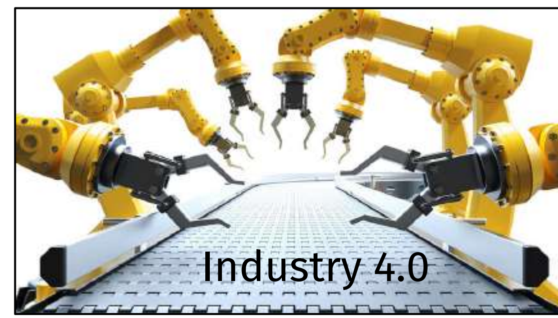

Massive Scale
Communication


Virtual Reality


E-Health

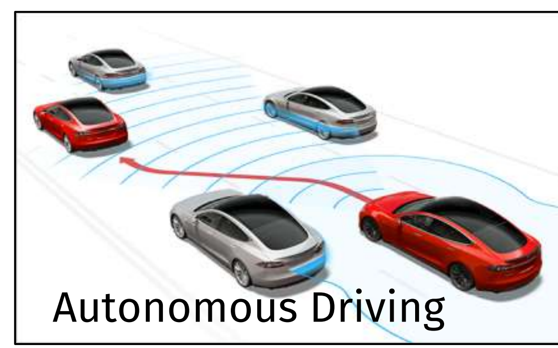

Tactile Internet


High-Speed Mobility


Industry 4.0


Smart Cities


Holographic Telepresence


Autonomous Driving

6G Applications and Use Cases

INDOOR COVERAGE

- 80% of the mobile traffic is generated indoor
- 5G current cellular networks never really targeted indoor coverage
  - ➢ High-frequencies **cannot penetrate** solid material
  - ➢ 5G densification through femtocells (proposed as a solution) presents **scalability** issues and high deployment and management costs for operators

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6G should target cost-aware indoor connectivity solutions autonomously deployed by end-users and managed by the network operators (e.g., **wireless relays** coupled with indoor communications)

6G Applications and Use Cases

MASSIVE SCALE COMMUNICATIONS

- 5G networks are designed to support more than 1’000’000 connections per km^2
- Mobile traffic will grow 3-fold from 2016 to 2021, pushing the **number of connected devices** to the extreme (> *500 billion connected things worldwide by 2030*)
- This will stress already congested networks, which will not guarantee the required QoS

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6G targets **capacity expansion** to offer high throughput and continuous connectivity, even when civil communication infrastructures may be compromised (**public safety** is main requirement)

6G Applications and Use Cases

eHEALTH

- OBJECTIVE: revolutionize the health-care sector, e.g., eliminating time and space barriers through remote surgery and guaranteeing health-care workflow optimizations.
- Current communication technologies cannot be applied in future health-care
  - **high cost** and **lack of real-time tactile feedback**
  - mmWaves can support low-latency, but do not guarantee **connection continuity**.

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6G enhancements will unleash the potential of eHealth applications through innovations like **mobile edge computing**, **virtualization** and **artificial intelligence**

6G Applications and Use Cases

INDUSTRY 4.0 and ROBOTICS

- OBJECTIVE: digital transformation of manufacturing through **Cyber Physical Systems (CPS)** and **Internet of Things (IoT)** services.
- Enabling, among other things, Internet-based diagnostics, maintenance, operation, and direct Machine to Machine (M2M) communications in a cost-effective, flexible and efficient way.
- CPS will **break the boundaries** between the physical factory and the cyber space computation.

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6G will foster the Industry 4.0 revolution through new **semiconductor** and **IC** innovations (e.g., **terahertz scale electronic** packaging solutions)

6G Applications and Use Cases

SMART CITY

- <u>OBJECTIVE</u>: life quality improvements, environmental monitoring, traffic control and city management automation
- Current cellular systems have been mainly developed for **broadband** applications
- Smart city applications build upon data generated by **low-cost** and **low-energy** consuming sensors, which efficiently interact with each other.

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6G will seamlessly include support for user-centric M2M communication, promoting **ultra-long battery lifetime** combined with energy harvesting approaches

6G Applications and Use Cases

HOLOGRAPHIC TELEPRESENCE

- OBJECTIVE: remotely connect with an increasing amount of digital accuracy
- ISSUE: raw hologram, without any optimization nor compression, with colors, full parallax, and 30 fps, would require a daunting **4.32 Tbps** data rate.
- ISSUE: latency requirement will hit the **sub-millisecond**, and **thousands** of synchronized view angles will be necessary (2 tiles for 4K/8K HD, and 12 tiles for VR/AR)

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6G will develop architectures and network designs able to digitalize and transfer all the **5 human senses**, increasing the overall target data rate

6G Applications and Use Cases

UNMANNED MOBILITY *(Autonomous Driving)*

- OBJECTIVE: fully autonomous connected and intelligent transportation systems, offering safer traveling, improved traffic management, and support for infotainment applications (>7000B$)
- Unprecedented levels of communication **reliability** and low end-to-end **latency**, even in ultra-high mobility scenarios (up to an impressive 1000 km/h).
- Sensors (more than 200 per vehicle by 2020) will demand increasing **data rates** (in the order of **terabytes** per driving hour), saturating the capacity of traditional technologies.

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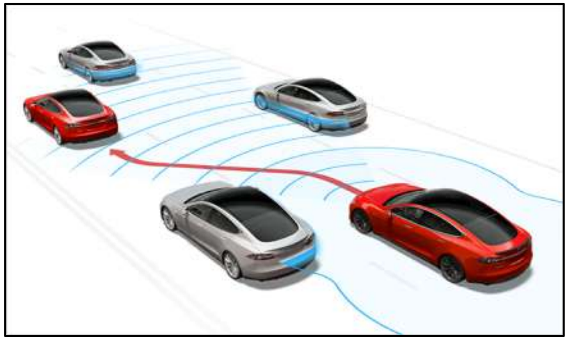
6G will pave the way for the coming era of connected vehicles through **hardware** and **software** advancements and new technologies to **eliminate** typical 5G latency/reliability/throughput **trade offs**



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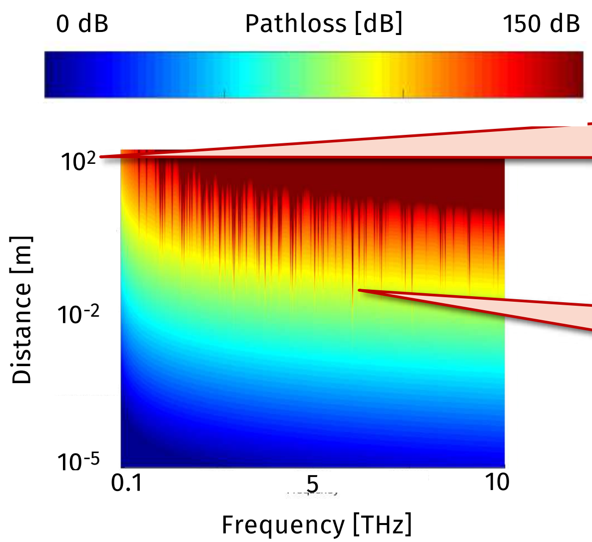
Disruptive Communication Technologies – **Terahertz**

- Frequency bands between **100 GHz** and **1 THz** → bring to the extreme the potentials and challenges of high-frequency communications.
- Huge data rates (possible to allocate contiguous chunks of up to **200 GHz** of spectrum)



PROPAGATION LOSS (compensated using **directional antenna arrays**, also enabling spatial multiplexing without increasing the interference)

MOLECULAR ABSORPTION (it is important to choose deployments in frequency bands **not** severely affected by molecular absorption)

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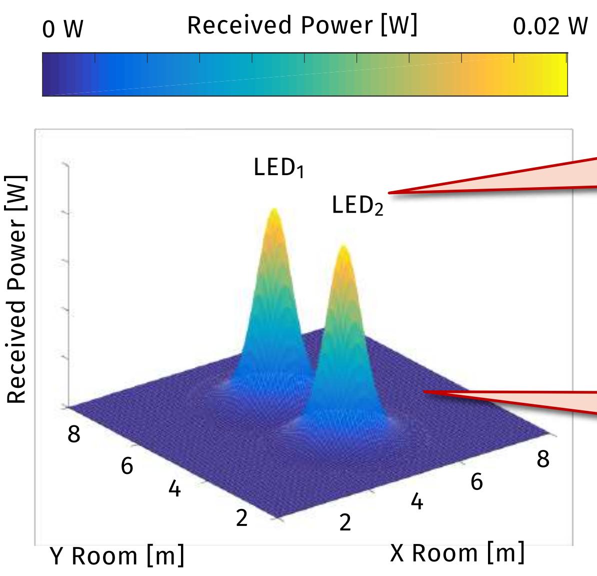
Disruptive Communication Technologies – **Visible Light Communications**

- Frequency bands between **430 GHz** and **770 THz** → complement RF communications by piggybacking on the wide adoption of **LED luminaries**
- VLC devices can switch between different light intensities to **modulate** a signal
- More mature research than THz (standard for VLC – IEEE 802.15.7 – has been defined)



INTERFERENCE (limited coverage **range**, require an **illumination source** and suffer from **shot noise** from other light sources)

MULTI-CONNECTIVITY: need to be complemented by RF for the **uplink**

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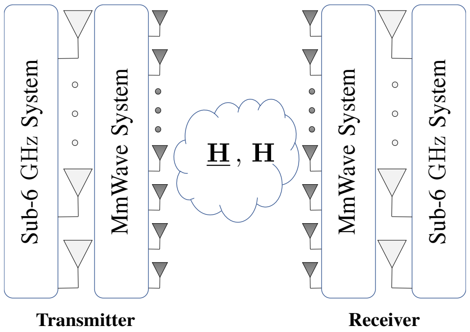
Disruptive Communication Technologies – **Full-Duplex**

- The transceiver in base stations and UEs will be capable of TX a signal while also TX
- Continuous downlink transmission with uplink acknowledgments or control messages → increase **multiplexing** and system **throughput** without using additional bandwidth.

Disruptive Communication Technologies – **OBB channel estimation**

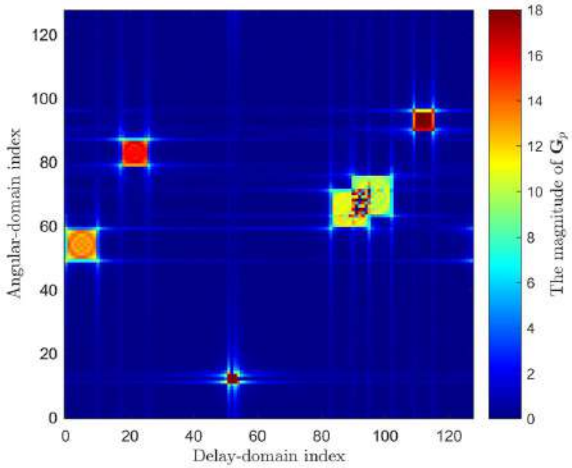
- IDEA: leverage channel state information acquired at a lower frequency as a form of side information on a higher frequency channel.
- Need to define a "**transformation function**" to relate the spatial correlation matrix derived at one frequency to another at a much different frequency



Disruptive Communication Technologies – **Channel Sparsity**

- Estimating the mmWave channel is equivalent to estimating the parameters of the channel paths, i.e., the AoA, the AoD, and the gain of each path.
- IDEA: exploit the **poor scattering** nature of the mmWave channel to formulate the mmWave channel estimation problem as a **sparse compressed sensing** problem: *the channel power is concentrated in a few entries of a virtual channel matrix*
- It is sufficient to estimate the AoAs and AoDs of the dominant paths to be resolved.

Example of 6 dominant paths (the location of each square reflects the AoA and time delay of each path)



B. Wang, et al., "Spatial- and Frequency-Wideband Effects in Millimeter-Wave Massive MIMO Systems," in *IEEE Trans. Sig. Proc.*, vol. 66, no. 13, pp. 3393-3406, Jul. 2018.

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Innovative Network Architectures – **Disaggregation/virtualization**

- IDEA: **decouple** network/control plane (CP) and forwarding/user plane (UP).
  - SDN offers network **programmability** and **centralization** of the control
  - SDN is **agile** and **responsive** (traffic flow meets fluctuating needs and demands).
  - SDN is standards-based (e.g., *OpenFlow*) and **vendor-neutral**.
- IDEA: **replace** network services provided by dedicated hardware (e.g., network switches) with virtualized software.
  - NFV saves **capital** and **operating expenses**

NFV and SDN are **complementary** technologies
(SDN executes on an NFV infrastructure)

- C. J. Bernardos et al., "An architecture for software defined wireless networking," in *IEEE Wireless Communications*, vol. 21, no. 3, pp. 52-61, June 2014.
- R. Mijumbi, et al., "Network Function Virtualization: State-of-the-Art and Research Challenges," in *IEEE COMST*, vol. 18, no. 1, pp. 236-262, 2016

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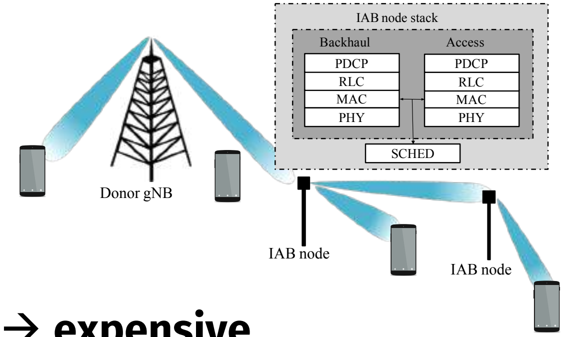
Innovative Network Architectures – **Access/Backhaul integration**



- Massive 6G data rates technologies → adequate growth of the **backhaul** capacity
- THz and VLC deployments will call for a massive increase in the density of access points, which should be provided with backhaul connectivity to the core network → **expensive**
- IDEA: deploy a fraction of BSs with traditional fiber-like backhaul capabilities and the rest of the BSs connecting to the fiber infrastructures **wirelessly.**
- 6G deployments will introduce new challenges and opportunities
  - The networks will need higher autonomous configuration capabilities
  - Out-of-band IAB can be realized to increase the overall network throughput.

- M. Polese, et al. , "End- to-End Simulation of Integrated Access and Backahul at mmWaves," *to appear on IEEE CAMAD*, Sep. 2018.
- M. Polese, et al., "Distributed Path Selection Strategies for Integrated Access and Backhaul at mmWaves", *to appear on IEEE GLOBECOM*, Dec. 2018

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Integrating Intelligence in the Network – **Learning**

- BACKGROUND: the signal received at multiple BSs renders a defining signature for the user location and its interaction with the surrounding environment.
- BACKGROUND: UEs typically move through predefined paths, and some movements are impossible due to the presence of obstacles, e.g., buildings, walls.
- IDEA: account for previous access statistics and use **machine learning** tools to predict the network behaviors (e.g., by remembering/observing consequences of previous decisions).

SUPERVISED LEARNING

The amount of data generated will be massive, thus **labeling** the data may be infeasible.

UNSUPERVISED LEARNING

Does not need labeling, used to autonomously build complex network representations

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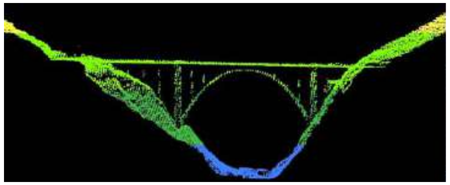
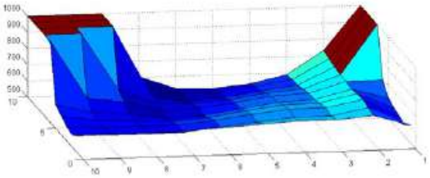
Integrating Intelligence in the Network – Knowledge sharing and learning

- 5G: At high frequency, the massive bandwidth and spatial degrees of freedom are unlikely to be fully used by any one cellular operator. Spectrum can be **shared**, in time and in space, with several *performance* and *energy* benefits:
  - *Reducing deployment costs*, if operators share bands and infrastructures
  - *Inter-operators access and interference coordination*

- 6G: operators and users may also be interested in sharing **learned representations** of specific network deployments and/or use cases
  - Speed up the network configuration in new markets
  - Better adapt to new unexpected scenarios which may emerge during network operations

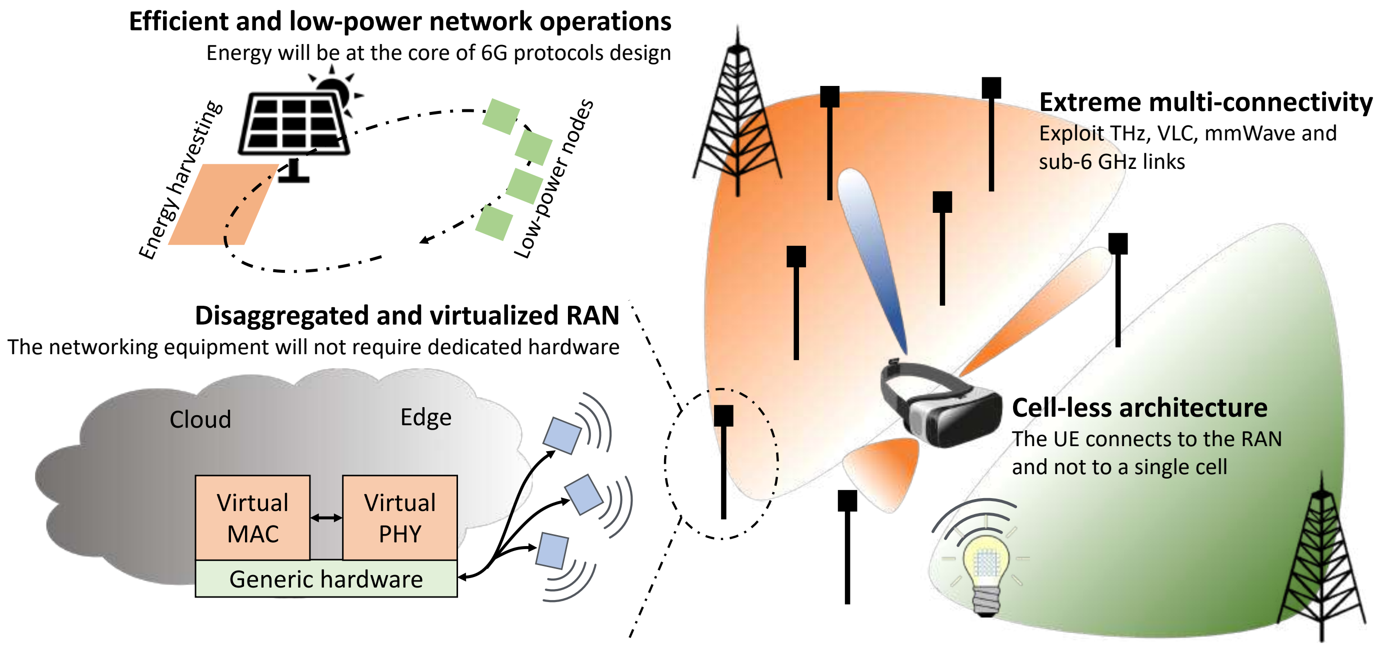




6G Challenges

- Integrate energy characteristics in protocols
  - Energy vs. high-deployment / MIMO

- Circuit design, high propagation loss
- Limited coverage, need for RF uplink
- Need for reliable frequency mapping



- Slower network operations/security concerns
  - CU/UP functions are tightly coupled

- Scheduling, need for new network design
- Scalability, and interference management

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