6G: Towards a Fully Digital and Connected World

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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.

<table>
<thead>
<tr>
<th>Year</th>
<th>Innovation</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>Voice calling, SMS</td>
<td>2.4 Kbps</td>
</tr>
<tr>
<td>1990</td>
<td>SMS, Internet</td>
<td>64 Kbps</td>
</tr>
<tr>
<td>2000</td>
<td>Internet of Applications</td>
<td>2 Mbps</td>
</tr>
<tr>
<td>2010</td>
<td>Internet of Applications</td>
<td>100-1000 Mbps</td>
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<tr>
<td></td>
<td>4G</td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td>5G</td>
<td>1-10 Gbps</td>
</tr>
<tr>
<td></td>
<td>Massive broadband Internet</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Internet of Things</td>
<td></td>
</tr>
<tr>
<td>2025-2030</td>
<td>6G</td>
<td></td>
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</tbody>
</table>

Towards a Fully Digital and Connected World
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).
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6G Applications and Use Cases

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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

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 km²
- 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

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

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

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

- **OBJECTIVE**: 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.

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 $4.32 \text{Tbps}$ 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)

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

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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6G Technologies and Innovations

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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)
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**
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
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.

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

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.
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.

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.
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

Efficient and low-power network operations
Energy will be at the core of 6G protocols design

Disaggregated and virtualized RAN
The networking equipment will not require dedicated hardware

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

Extreme multi-connectivity
Exploit THz, VLC, mmWave and sub-6 GHz links

Cell-less architecture
The UE connects to the RAN and not to a single cell

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