Key Drivers and Research Challenges for 6G

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World’s First 6G Research Program

6G Enabled Wireless Smart Society & Ecosystem

- National Flagship for 2018-2026
- Volume 251 M€
- Operated by University of Oulu
- Collaboration with Nokia, VTT, Aalto University, BusinessOulu, OUAS.

1. Wireless Connectivity
   Ultra-reliable low-latency communications vs. 1 Tbps
   Enabling Unlimited Connectivity

2. Devices & Circuits
   THz communications materials & circuits
   Enabling Unlimited Connectivity

3. Distributed Computing
   Mobile edge intelligence
   Enabling Time Critical & Trusted Apps

4. Services & Applications
   Multidisciplinary research across verticals
   Enabling Disruptive Value Networks

6G Flagship was elected as Finland’s high-tech Flagship, by Finnish Government through Academy of Finland.
Key Figures for the Two First Years of Operation

Staff
- 315 International staff
- 56 nationalities 50.1% of staff
- 18.4% of female staff
- 47 Doctoral degrees
- 6G White Paper downloads: 100,403

Peer-reviewed publications
- 1020

Joint publications with collaborators
- 671

Joint publications with companies
- 90

Companies investing in research portfolio
- 85

Total funding
- € 49.9M + 12M industry inkind
• To support companies in **finalisation of the 5G standard** by carrying out technology and system pilots.

• To develop/co-create the **fundamental technology components** to enable 6G systems.

• To speed up **dependable, robust and secure digitalisation of society** via 5G and 6G.
5GTN as a Co-Creation Platform

Radio coverage in the urban area

5G NR (<6GHz) NSA integrated

800MHz @26/28GHz 10Gbps

Hybrid Beamformer

NB-IoT/LTE-M1

LTE small cells

WiFi, BLE, LoRa

Dedicated SIM Cards

www.5gtn.fi
5G Test Network development towards 6G

Co-Creation Platform

Unlimited Wireless Connectivity
Always connected, new radios

Productized Services
Full set of services to utilize 5G & 6G

Co-Creation Infra
Tailored projects with 3rd parties

5G Test Network development towards 6G

5G NTN

Wireless Connectivity
Testing Devices & Solutions
5G NTN Community
Services
Vertical use cases

5G NTN Community

3G
LTE
5G PoC
5G NR
5G+
5G+ ... 6G
6G

700 MHz
2.1 GHz
2.3 GHz
2.6 GHz
3.5 GHz
3 ... 5 GHz
26 ... 28 GHz
NVR @ xxx GHz ... THz

2030
Vision for 2030

Our society is data-driven, enabled by near-instant, unlimited wireless connectivity.

6G will emerge around 2030 to satisfy the expectations not met with 5G, as well as, the new ones fusing AI inspired applications in every field of society with ubiquitous wireless connectivity.

Click here for our vision video
Wireless connectivity is driving major societal changes:

1G - 2G
1980s – 2000s
Millions of voice users

– 2020s
Billions of Mobile Broadband users

3G - 4G
– 2040s
Trillions of connected objects & intelligence

Applications range explodes and new value chains emerge:

- Logistics
- Retail
- Agriculture
- Industry 4.0
- Health
- Sustainable energy
- Automotive & transportation

Verticals specific service providers are needed to complement MNOs offerings.
Radio Spectrum Policy Enabling Future Innovations

Flexible and novel spectrum regulation policy is key to enable development of future verticals and ecosystems.

Seamless joint-operation of all access networks

Operator dominated closed ecosystems

Verticals driven open ecosystems
Example: Japanese Vision for Society 5.0
6G White Paper Process

- World’s first 6G Wireless Summit (300 participants) gathered all major telecom players to throw ideas around, in Levi, Finland in March 2019 (www.6gsummit.com).
- 19’ Summit launched 6G White Paper development with 70 experts from around the world representing different stakeholders.
- 20’ Summit (610 participants) attracted 310 experts to White Paper writing.
- 12 White Papers will be published end of June a: www.6gchannel.com/6g-white-papers/
The 6G research vision is based on three cornerstones:

1. **6G technologies** will bring to life the data-driven and hyper-connected future society.

2. **Major drivers for 6G** include sustainability goals and societal challenges on top of productivity targets and technology enablers.

3. **Numerous business and societal players** together create the new 6G infrastructure, products and services.


Published 6.9.2019
Many of the KPIs used for 5G are valid also for 6G. However, the KPIs must be critically reviewed and new KPIs must be seriously considered.
Initial 6G Key Performance Indicators (KPIs)

Generic 6G targets presented by academia and industry in different fora.

- 100 Gbps - 1 Tbps: Peak Data Rates
- 10 cm (indoor), 1 m (outdoor): Positioning
- 10x: More Energy Efficient
- Max. 1 Out of Million Outage: Extreme Ultra Reliability
- +40 dB: Link Budget
- 0.1 ms: Radio Latency
- ±10 ns: Jitter
- 20 Years: Battery Life Time
- 100 Devices per m²: Density
- 10 000x: Traffic Increase
Stakeholder roles in 6G will change compared to the current mobile business ecosystem and new roles will emerge.
Towards Local Operator Paradigm

Transition to higher frequencies and increasing role of indoor networks will boost network sharing in cities and indoor spaces, and drive the “local operator” paradigm.
6G is not only about moving bits: it will become a framework of services, including communication service.

In 6G, all user specific computation and intelligence may move to edge cloud.

Integration of sensing, imaging and highly accurate positioning capabilities with mobility opens a myriad of new applications in 6G.

Trust and privacy are key prerequisites for successful 6G service platform.
Due to COVID-19 Summit was organized virtually
12 Thematic white papers written by 310 global experts:

- 6G Drivers and UN SDGs
- Validation and Trials for Verticals
- Machine Learning in Wireless Communications
- Networking
- Broadband Connectivity for 6G
- RF & Spectrum
- Connectivity for Remote Areas
- Business of 6G
- Edge Intelligence
- Security and Privacy
- Critical and Massive MTC towards 6G
- Localization and Sensing
White paper proposes to take UN SDGs as the basis for the development of 6G.

Three-fold role of 6G is envisaged:

1) a provider of services to support communities and countries towards reaching the UN SDGs,

2) a measuring tool for data collection to help the reporting of indicators with hyperlocal granularity, and

3) a reinforcer of new ecosystems based on 6G networks developed in line with the UN SDGs.

New 6G indicators needed.
1) White Paper on 6G Drivers and UN SDGs

Pillars of 6G Vision

- Hyper-local specialization
- Local specialization
- Wide
- Regional
- Global

... Intelligence Everywhere, Data Everywhere, Sensing Everywhere, Actuating Everywhere, Processing Everywhere, Connectivity Everywhere

Societal ambitions based on UNSDGs

Development of technical framework to support UN goals

UN SGSs

© 6G Flagship
2) 6G White Paper on Vertical Services Towards 2030’s

- What are the features within specific vertical that require **new capabilities beyond 5G**.

- Some key performance indicators (**KPIs**) are proposed for research purposes within a vertical.

- Key value indicators (**KVIs**) are also discussed.

- In terms of future trialing and validation, golden references for vertical specific testing are proposed.

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Specific Verticals
- Industry
- Future Mobility
- Health
- Energy
- Finance and Banking
- Public Safety
- Agribusiness
<table>
<thead>
<tr>
<th>Vertical</th>
<th>Link Data Rate</th>
<th>Latency</th>
<th>Link Budget</th>
<th>Jitter</th>
<th>Density</th>
<th>Energy Efficiency</th>
<th>Reliability</th>
<th>Capacity</th>
<th>Mobility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industry mMTC</td>
<td>&lt; 1 Mbps</td>
<td>&lt; 100 ms</td>
<td>+10 dB</td>
<td>100 μs</td>
<td>100/m³</td>
<td>High</td>
<td>1-10⁻⁶</td>
<td>&lt; 10 Gbps</td>
<td>240 km/h</td>
</tr>
<tr>
<td>Industry eURLLC</td>
<td>&lt; 5 Mbps</td>
<td>&lt; 100 μs</td>
<td>+20 dB</td>
<td>&lt; 1 μs</td>
<td>10/m³</td>
<td>Nominal</td>
<td>1-10⁻⁹</td>
<td>&lt; 100 Mbps</td>
<td>240 km/h</td>
</tr>
<tr>
<td>Mobility</td>
<td>&lt; 10 Gbps</td>
<td>&lt; 100 μs</td>
<td>+20 dB</td>
<td>100 μs</td>
<td>100/m³</td>
<td>Nominal</td>
<td>1-10⁻⁷</td>
<td>1 Tbps</td>
<td>1200 km/h</td>
</tr>
<tr>
<td>eHealth</td>
<td>&lt; 1 Gbps</td>
<td>&lt; 1 ms</td>
<td>+10 dB</td>
<td>100 μs</td>
<td>1/m³</td>
<td>High</td>
<td>1-10⁻⁹</td>
<td>&lt; 10 Gbps</td>
<td>240 km/h</td>
</tr>
<tr>
<td>Energy</td>
<td>&lt; 1 Mbps</td>
<td>&lt; 500 μs</td>
<td>+40 dB</td>
<td>&lt; 1 μs</td>
<td>10/m³</td>
<td>Nominal</td>
<td>1-10⁻⁶</td>
<td>&lt; 100 Mbps</td>
<td>N/A</td>
</tr>
<tr>
<td>Finance</td>
<td>&lt; 1 Gbps</td>
<td>&lt; 10 ms</td>
<td>varies</td>
<td>N/A</td>
<td>1/m³</td>
<td>High</td>
<td>1-10⁻⁹</td>
<td>&lt; 10 Gbps</td>
<td>Low</td>
</tr>
<tr>
<td>Public Safety</td>
<td>&lt; 1 Gbps</td>
<td>&lt; 1 ms</td>
<td>+20 dB</td>
<td>100 μs</td>
<td>1/m³</td>
<td>Nominal</td>
<td>1-10⁻⁷</td>
<td>&lt; 10 Gbps</td>
<td>240 km/h</td>
</tr>
<tr>
<td>Agribusiness</td>
<td>100 Mbps</td>
<td>&lt; 10 ms</td>
<td>+40 dB</td>
<td>100 μs</td>
<td>100/km²</td>
<td>Nominal</td>
<td>1-10⁻⁷</td>
<td>1 Gbps</td>
<td>240 km/h</td>
</tr>
</tbody>
</table>

Novel Services
- XR and Holography
- Autonomous Driving
- Massive Robotics

QoS requirements

Application and Transport Layer
- ML-as-a-service
- Personalized ML models
- Opportunistic networking
- Client-centric networking

Network Layer
- Enable the Intelligent Internet of Things
- ML-enabled QoS optimization
- Centralized DNN handover optimization
- Multi-hop cellular networks

MAC Layer
- Predictive resource allocation
- Federated echo state learning

Physical Layer
- Replace mathematical models with ML
- Autoencoder
- End-to-end modeling
- Online learning

Data Synthesis with GANs
- Standardized data formats
- Open datasets
- Data synthesis with simulation
- Massive datasets
Key features:

- Network softwarization and service based architecture
- E2E cloud-native mobile communication system
- New IP architecture to support high precision services
- High-precision end-to-end telemetry and cross-segment analytics for autonomous 6G networking
5) Broadband Connectivity in 6G

Key Enablers for 6G

- **Enablers at the infrastructure level** based on the evolution of massive multiple-input multiple-output (MIMO) and holographic radio, intelligent reflecting surfaces (IRS), user-centric and scalable cell-free networking, integrated access and backhaul, and integrated space and terrestrial networks;

- **Enablers at the spectrum level** to realize THz communications and visible light communications (VLC);

- **Enablers at the protocol/algorithmic level**, providing innovations in the field of coding, modulation, waveform, and duplex, interference management using non-orthogonal multiple access (NOMA) and rate splitting, machine learning-aided algorithms, coded caching, wideband broadcast, and full-coverage broadband connectivity.
## 5) Broadband Connectivity in 6G

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Potential 6G solutions</th>
<th>Open research questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable service quality in coverage area</td>
<td>User-centric cell-free massive MIMO</td>
<td>Scalable synchronization, control, and resource allocation</td>
</tr>
<tr>
<td>Coverage improvements</td>
<td>Integration of a spaceborne layer, ultra-massive MIMO from tall towers, intelligent reflecting surfaces</td>
<td>Joint control of space and ground based APs, realtime control of IRS</td>
</tr>
<tr>
<td>Extremely wide bandwidths</td>
<td>Sub-THz, VLC</td>
<td>Hardware development and mitigation of impairments</td>
</tr>
<tr>
<td>Reduced latency</td>
<td>Faster forward error correcting schemes, wider bandwidths</td>
<td>Efficient encoding and decoding algorithms</td>
</tr>
<tr>
<td>Efficient spectrum utilization</td>
<td>Ultra-massive MIMO, waveform adaptation, interference cancellation</td>
<td>Holographic radio, usecase based waveforms, full-duplex, rate-splitting</td>
</tr>
<tr>
<td>Efficient backhaul infrastructure</td>
<td>Integrated access and backhauling</td>
<td>Dynamic resource allocation framework using space and frequency domains</td>
</tr>
<tr>
<td>Smart radio environment</td>
<td>Intelligent reflecting surfaces</td>
<td>Channel estimation, hardware development, remote control</td>
</tr>
<tr>
<td>Energy efficiency</td>
<td>Cell-free massive MIMO, suitable modulation techniques</td>
<td>Novel modulation methods with limited hardware complexity</td>
</tr>
<tr>
<td>Modeling or algorithmic deficiencies in complex and dynamic scenarios</td>
<td>ML/AI based model-free, data-driven learning and optimization techniques</td>
<td>End-to-end learning/joint optimization, unsupervised learning for radio resource Management</td>
</tr>
</tbody>
</table>

### KPIs

<table>
<thead>
<tr>
<th>KPI</th>
<th>5G</th>
<th>6G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak data rate</td>
<td>20 Gb/s</td>
<td>1 Tb/s</td>
</tr>
<tr>
<td>Experienced data rate</td>
<td>0.1 Gb/s</td>
<td>1 Gb/s</td>
</tr>
<tr>
<td>Peak spectral efficiency</td>
<td>30 b/s/Hz</td>
<td>60 b/s/Hz</td>
</tr>
<tr>
<td>Experienced spectral efficiency</td>
<td>0.3 b/s/Hz</td>
<td>3 b/s/Hz</td>
</tr>
<tr>
<td>Maximum bandwidth</td>
<td>1 GHz</td>
<td>100 GHz</td>
</tr>
<tr>
<td>Area traffic capacity</td>
<td>10 Mb/s/m²</td>
<td>1 Gb/s/m²</td>
</tr>
<tr>
<td>Connection density</td>
<td>10⁵ devices/km²</td>
<td>10⁷ devices/km²</td>
</tr>
<tr>
<td>Energy efficiency</td>
<td>not specified</td>
<td>1 Tb/J</td>
</tr>
<tr>
<td>Latency</td>
<td>1 ms</td>
<td>100 μs</td>
</tr>
<tr>
<td>Reliability</td>
<td>1-10⁻³</td>
<td>1-10⁻⁹</td>
</tr>
<tr>
<td>Jitter</td>
<td>not specified</td>
<td>1 μs</td>
</tr>
<tr>
<td>Mobility</td>
<td>500 km/h</td>
<td>1000 km/h</td>
</tr>
</tbody>
</table>

Possible Transmission KPI's
Extended spectrum towards THz enables merging communications and new applications, such as 3D imaging and sensing.

New paradigms for transceiver architecture and computing will be needed to achieve 1 Tbps.

New opportunities for semiconductors, optics and new materials in THz applications.
7) Connectivity in Remote Areas

- Digital divide is increasing, and it is most emphasised in rural and remote areas.
  - These places may lack of power grid and backhaul (fibre), and may be low ARPU areas.

- The solution must be **affordable** and **provide sufficient data rate and availability**. Furthermore, it should be easy to use and adaptable to different cultures.

- Affordable and sufficient service solutions do not call just for technical solutions but also for novel regulation and cooperation between various stakeholders (we do not mention financing challenges).

- Technically, it uses mobile cellular (or alike) solutions in places where people live and work (digital oases as we call them) and various backhaul solutions including large cells, relay technology and satellite technology, …
8) Essential choices for developing business of 6G futures

**Technology trends and enablers**

- **Security & privacy**
  - Local edge and sub-network security
  - Digital trust
  - Security autonomies

- **Digital value platforms**
  - Human-machine interface
  - Augmented Intelligence
  - Digital twins
  - Holopresence

- **Cognitive network management**
  - Resource brokerage & open APIs
  - Zero human touch cognitive MANO
  - Context-aware network orchestration

- **Core network**
  - Cloud native
  - Hyper-specialized virtualization & slicing
  - Ubiquitous sub-nets

- **Local edge cloud**
  - Caching and edge computing
  - Time-sensitive critical local intelligence
  - Ubiquitous augmented cognition

- **Access**
  - Private local virtual open access
  - Non-terrestrial networks
  - Self-optimizing commns and multi-sensing

**Business model elements**

**Opportunities**
- Private networks
- Unmet local service needs
- Human-machine Interface
- Serve "experiential" consumers

**Value**
- Real-time trustworthiness
- Immersive human experience
- Network as a multi-sensor
- Local data & intelligence
- Resource marketplace

**Advantage**
- Extreme capacity
- Security, privacy, & trust
- Transaction platform
- Ubiquitous cognition access

**Scalability**
- Dataflow design & arch.
- Zero-touch automation
- Specialized tail of services
- Open collaboration

**Replicability**
- Cloud native platform
- Native 5G support
- Service agility
- Modularity & complementary

**Sustainability**
- Sharing economy
- UN SDG impact
- Empowered users and communities
- Connecting the unserved
8) Essential choices for developing business of 6G futures

Megatrends

- UN SDGs
- Climate change
- Decentralization

Gaia

Drivers

Edge

Barriers

Power of platforms
Rights of AI and HMI
Regulation

Customer 6.0

Challenges

- Becoming of the sharing economy
- Disruptive business models
- Empowered user’s rights
Moving towards 6G intelligent solutions utilizing data-driven machine intelligence

Distributed computing environments, networking, and artificial intelligence brought together for real-time systems

Edge computing and ML/AI together to enable “Intelligent Internet of Intelligent Things”
The challenges in creating a trustworthy 6G are multidisciplinary spanning technology, regulation, techno-economics, politics and ethics.

In 6G, physical safety will more and more depend on information technology and the networks we use for communication. Therefore, we need trustworthy 6G.

The roles of trust, security and privacy are somewhat interconnected, but different facets of next generation networks. This white paper addresses their fundamental research challenges.
10) 6G White Paper: Research Challenges for Trust, Security and Privacy

Trust
- **End-to-end trust in 6G.** 6G network must support embedded trust for increased level of information security in 6G. Trust modeling, trust policies and trust mechanisms need to be defined. 6G interlinks physical and digital worlds making safety dependent on information security. Therefore, we need trustworthy 6G.

Security
- **Inherited and novel threats in 6G scale.** The diversity and volume of novel IoT devices and their control systems will continue to pose significant security and privacy risks and additional threat vectors as we move from 5G to beyond towards 6G system. The development towards cloud and edge native infrastructures is expected to continue in 6G networks, and we need holistic 6G network security architecture planning.
- **Post-quantum cryptography and security architecture for 6G.** The current 5G standard does not address the issue of quantum computing but relies on traditional cryptography.
- **Machine-learning as tool and risk in softwarized 6G.** Security automation opens new questions: machine learning can be used to make safer systems, but also more dangerous attacks.
- **Physical layer security in 6G** can also represent efficient solutions for securing less investigated network segments as first line of defense, and also should PhySec be a stand-alone security design or interactions with upper layers are mandatory in 6G networks.

Privacy
- **Privacy as exploited resource in 6G.** There is currently no way to unambiguously determine when linked, deidentified datasets cross the threshold to become personally identifiable. Courts in different parts of the world are making decisions about whether privacy is being infringed without formal measures of the level of personal information, while companies are seeking new ways to exploit private data to create new business revenues. As solution alternatives, we may consider blockchain, distributed ledger technologies and differential privacy approaches.
Critical and massive MTC are among the main enablers of digitalization of society towards the 2030-era.

Future use cases, for example connected industries, zero-energy IoT and Internet of Senses, will impose stringent requirements on 6G MTC connectivity.

5G KPIs will continue to be relevant while introducing new KPIs specific to 6G MTC.

For instance, the end-to-end cost, reliability, latency and energy consumption per successfully delivered bit will be of significant importance towards the 6G era.

This white paper presents a set of research directions covering end-to-end networking, energy optimized MTC devices, massive scalable MTC, URLLC enablers and privacy and security aspects towards meeting the stringent and diverse requirements of an MTC optimized 6G networks.
11) Critical and Massive MTC Towards 6G

Selected MTC Use Cases
- Connected Industries
- Swarm Networking
- Zero-energy IoT
- Internet of Senses
- Personalized Body Area Network
- Distributed Ledger Technology

6G MTC Requirements
- Dependability
  - (1-10⁻⁹) Reliability, 0.1 ms Latency, ...
- Sensing
  - Localization-accuracy, Positioning-as a service
- Efficiency
  - Energy efficiency, E2E efficiency, Cost-complexity efficiency, ...
- Throughput
  - Spectral-efficiency
- Scalability
  - Global Connectivity, Massively scalable, 3D connectivity
- Security, Privacy and Trust
  - Low-cost authentication and authorization, Long term/ Lightweight/ flexible/ distributed solutions
12) 6G White Paper on Localization and Sensing

Vision

6G will be intelligent context-aware network exploiting built-in localization and sensing features with no or limited human intervention.

Opportunity

6G will achieve high-accuracy positioning and high-resolution sensing/imaging enabling autonomous navigation and advanced XR applications with rich and accurate virtual imagery of the environment.
12) 6G White Paper on Localization and Sensing

- Enabling technologies for the 6G environment-aware communication systems
- Localization and sensing opportunities for future 6G systems.
- Open issues and technological challenges for the convergent 6G communication, localization and sensing system.
Thank you!!