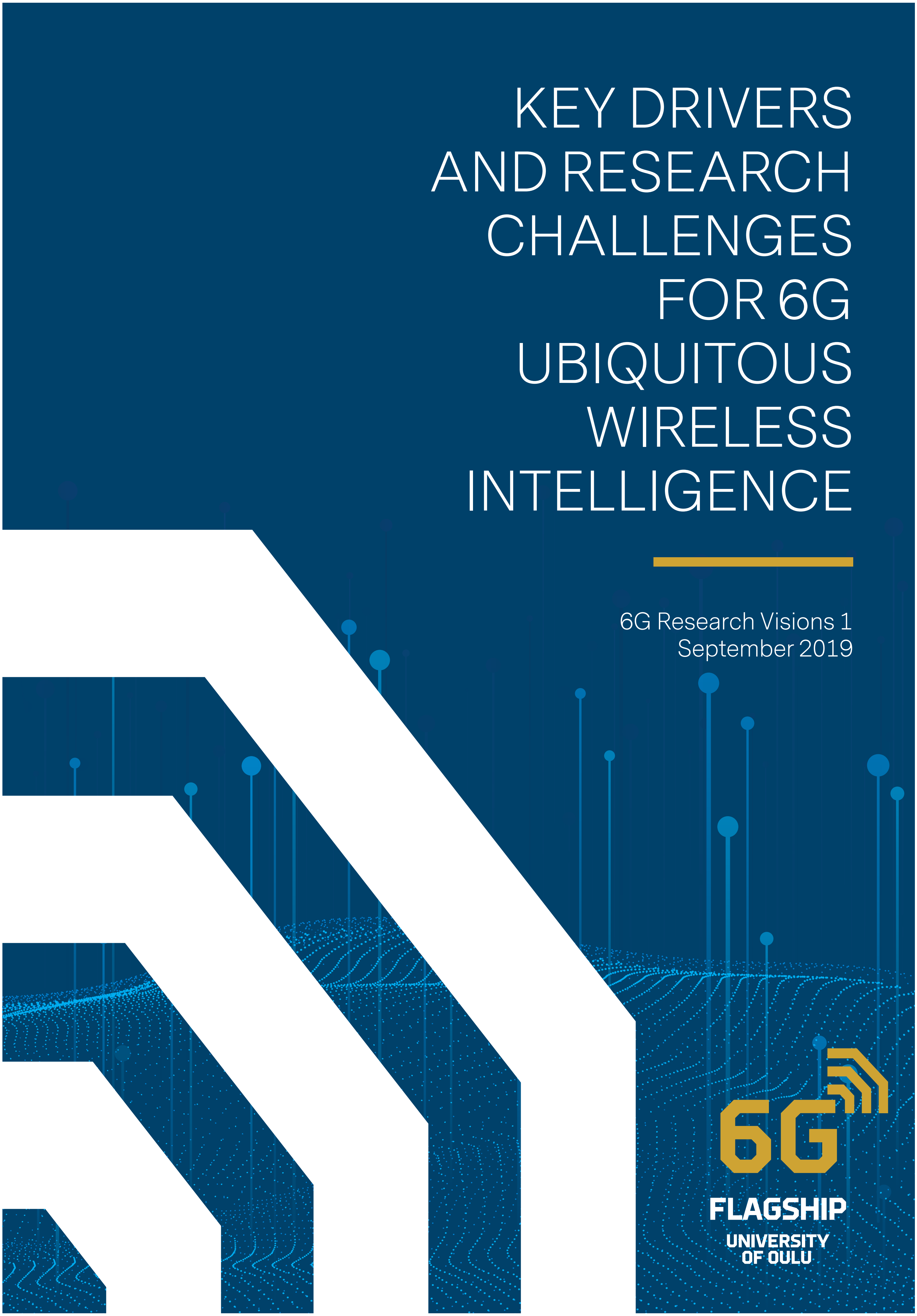

KEY DRIVERS AND RESEARCH CHALLENGES FOR 6G UBIQUITOUS WIRELESS INTELLIGENCE

6G Research Visions 1
September 2019

6G FLAGSHIP
UNIVERSITY OF OULU

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6G Research Visions 1
Key Drivers and Research Challenges for 6G Ubiquitous Wireless Intelligence
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EXECUTIVE SUMMARY

Our future society will be increasingly digitised, hyper-connected and globally data driven. Many widely anticipated future services, including eHealth and autonomous vehicles, will be critically dependent on instant, virtually unlimited wireless connectivity. Mobile communication technologies are expected to progress far beyond anything seen so far in wireless-enabled applications, making everyday lives smoother and safer and dramatically improving the efficiency of businesses.

As fifth generation (5G) research is maturing towards a global standard, the research community must focus on the development of beyond-5G solutions and the 2030 era, i.e. 6G. It is not clear yet what 6G will entail. It will include relevant technologies considered too immature for 5G or which are outside the defined scope of 5G. More specifically, the way in which data is collected, processed, transmitted and consumed within the wireless network will be a key driver for 6G.

The first 6G Wireless Summit in March 2019 launched the process of identifying the key drivers, research requirements, challenges and essential research questions related to 6G. This white paper is the first version for the annually revised series of 6G research visions and can be phrased in one vision statement from the first 6G Wireless Summit: Ubiquitous wireless intelligence.

It is envisioned that we will need new KPI drivers besides the current 5G technical KPIs. Societal megatrends, United Nations (UN) sustainability goals, lowering carbon dioxide emissions, emerging new technical enablers as well as ever increasing productivity demands are critical drivers towards 2030 solutions.

Totally new services such as telepresence and mixed reality will be made possible by high resolution imaging and sensing, accurate positioning, wearable displays, mobile robots and drones, specialized processors, and next-generation wireless networks. Current smart phones are likely to be replaced by pervasive XR experiences with lightweight glasses delivering unprecedented resolution, frame rates, and dynamic range.

6G research should look at the problem of transmitting up to 1 Tbps per user. This is possible through the efficient utilization of the spectrum in the THz regime. Extended spectrum towards THz will enable merging communications and new applications such as 3D imaging and sensing. However, new paradigms for transceiver architecture and computing will be needed to achieve these – there are opportunities for semiconductors, optics and new materials in THz applications to mention a few.

Artificial intelligence and machine learning will play a major role both in link and system-level solutions of 6G wireless networks. New access methods will be needed for truly massive machine-type communications. Modulation and duplexing schemes beyond Quadrature Amplitude Modulation (QAM) and Orthogonal Frequency Division Multiplexing (OFDM) must be developed and possibly it is time to start looking at analogue types of modulation at THz frequencies.

Security at all levels of future systems will be much more critical in the future and 6G needs a network with embedded trust. The strongest security protection may be achieved in the physical layer. During the 6G era it will be possible to create data markets, and thus, privacy protection is one key enabler for future services and applications.

6G is not only about moving data around – it will become a framework of services, including communication services where all user-specific computation and intelligence may move to the edge cloud. The integration of sensing, imaging and highly accurate positioning capabilities with mobility will open a myriad of new applications in 6G.

INTRODUCTION

The arrival of the 5G mobile communications technology is already showing signs of becoming a major factor in driving productivity and is expected to be the key enabler for long-envisaged, highly integrated and autonomous applications in many sectors. This new wave of technology will accelerate the digitalisation of economies and society. Historically, a new mobile "generation" appears approximately every ten years, with 6G expected to emerge around 2030. The first release of 5G New Radio (NR) – 3GPP Release 15 – was ready in 2018, and global commercialization of 5G is currently taking off. 5G performance and use cases will continue to evolve in the coming releases. 6G will take onboard new technologies and satisfy communication demands going beyond the 5G evolution. Now is the perfect time to identify future communication needs, performance requirements, system and radio challenges, and major technical options for 6G to establish the research goals towards the 2030s.

The first 6G Wireless Summit[1] was organized in Levi, Finland, in March 2019 with almost 300 participants from 29 countries, including major infrastructure manufacturers, operators, regulators as well as academia. The event was organised by the Finnish 6G Flagship Programme[2]. The 6G vision statement captures the essence of many of the key messages from the event: Ubiquitous Wireless Intelligence; Ubiquitous – services follow users everywhere seamlessly; Wireless – wireless connectivity is part of critical infrastructure; Intelligence – context-aware smart services and applications for human and non-human users.

Following the summit, a workshop was organized with 70 selected participants to commence the drafting of the first 6G white paper. Each year, the white paper will be updated following the annual 6G Wireless Summit. The goal for this first edition was to identify the key drivers, research requirements, challenges and essential research questions related to 6G. The format of the white paper is deliberately short avoiding lengthy background and justifications; it is targeted primarily at technical experts working in the field. At the highest level, the workshop identified major drivers for 6G (Figure 1): sustainability, society, productivity and technology.

Is it naïve to say "From 5G Engineering to 6G Humanity" or is it imperative?

In 2016, the UN released 17 Sustainable Development Goals[3] (SDGs) for the 2030 Agenda. These goals were developed against a backdrop of a growing and ageing global population, increasing urbanization and a world in which the climate is changing. If adhered to, the UN SDGs are expected to drive policy and influence government spending in many economies, creating global demand. It is estimated that the world's population in 2019 is 7.6 billion people, and that this will grow to 8.5 billion by 2030, 9.7 billion by 2050 and 11.2 billion by the end of the current century. As of 2018, 55% of the world's population lives in urban areas, a proportion that is expected to increase to 68% by 2050[4]. By 2030, the world is projected to have 43 megacities with more than 10 million inhabitants, most of them in developing regions. However, some of the fastest-growing urban agglomerations are cities with fewer than 1 million inhabitants, many of them located in Asia and Africa.

[1] www.6gsummit.com [2] www.6gflagship.com

[3] See https://www.un.org/sustainabledevelopment/sustainable-development-goals/.

[4] Source UN Department of Economic Affairs 2018 Revision of World Urbanization Prospects.
Available online https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html.

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Figure 1. From 5G Engineering to 6G Humanity – Breaking down the four areas driving 6G research.

Urbanization calls for super-efficient ICT services throughout society, which will become more and more automated in all sectors to significantly increase productivity, reduce carbon dioxide emissions and generate cost savings for public expenditure. The future services must be available 24-7, ubiquitously. The services developed for the future urban areas need to be transformed for the needs of remote, often rural and very poor areas in order to tackle the UN SDGs. At the same, as societies become heavily dependent on ICT services, they become extremely vulnerable to various types of security threats and attacks. The global threats[5] can no longer be ignored when developing future 6G technologies. Further to the societal and SDG drivers, we have included some examples of technology trends and drivers for increased productivity. 5G is envisioned to solve our communication challenges set for 2020s and beyond. However, the first 5G NR release only covers a subset of 5G targets and envisioned use cases.

New requirements and technologies are continuously emerging. Some are expected to enter future releases of 5G whereas far more rich requirements and technologies will need to wait for a clean slate of 6G specifications. Some of the emerging and promising directions in technology, described further in later chapters, are listed in Figures 2 and 3.

[5] Source World Economic Forum: The Global Risks Report 2019. Available online http://www3.weforum.org/docs/WEF_Global_Risks_Report_2019.pdf.

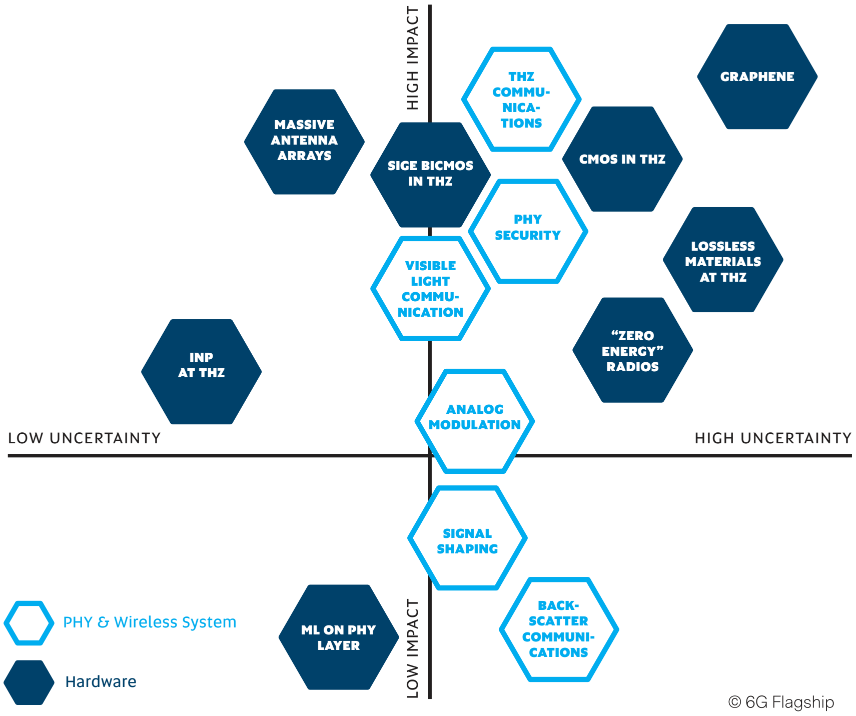

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Figure 2. New wireless hardware and physical layer technologies.

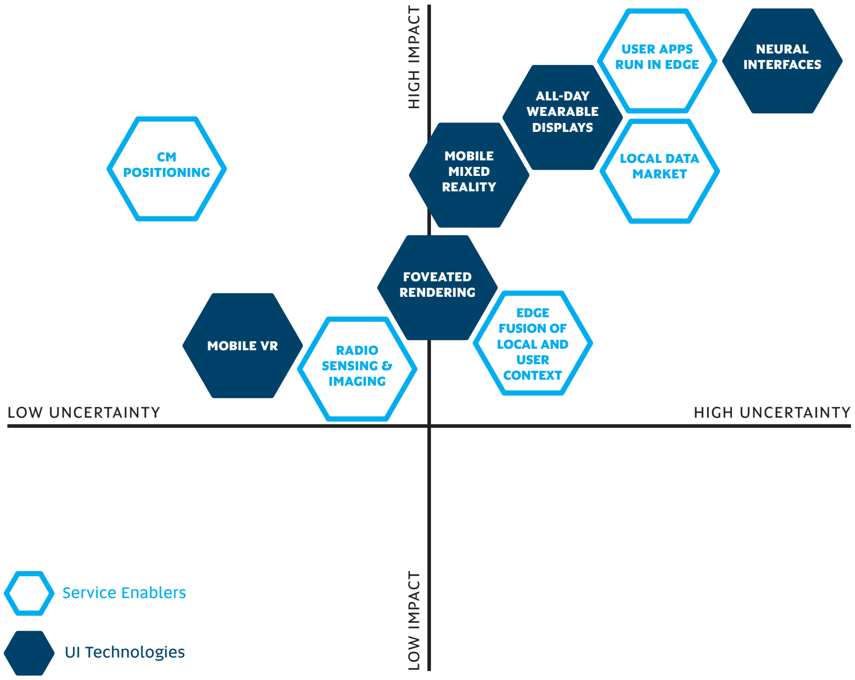

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Figure 3. Possible technologies for user interface and service enablers.

In the remainder of this white paper, key areas for investigation are identified to make the 2030 vision for Ubiquitous Wireless Intelligence a reality. The goal is also to identify essential research questions within the areas of interest. It is acknowledged that this does not form a comprehensive list, rather a starting point reflecting the discussions at the first 6G Wireless Summit as well as views from the 6G Flagship programme. Future editions of this white paper will complement the missing areas not discussed at the summit.

SOCIETAL AND BUSINESS DRIVERS FOR 6G

5G was primarily developed to address the anticipated capacity growth demand from consumers, as well as the productivity demands from industry, and to enable the increasing importance of Internet of Things (IoT). The technical success of 5G has relied on new developments in many areas and will deliver a much wider range of data rates to a much broader variety of devices and users. 6G will require a substantially more holistic approach to identify future communication needs, embracing a much wider community to shape the requirements of 6G. This includes identifying the trends, demands and challenges facing future societies, as well as the global forces shaping our future world to avoid merely commercially driven system definitions. Even though 5G development was shaped by demands from a range of vertical industry sectors, the emphasis has remained on deployments driven by mobile network operators (MNOs). 6G will introduce super-efficient short-range connectivity solutions that are likely to be driven by new players in the market resulting in new ecosystems outside traditional MNOs. Having a more inclusive view outside of MNOs will help shape the needs of 6G.

Drivers from society, including the UN sustainability goals, will shape 6G.

Societal and business drivers will increasingly shape 6G development, including political, economic, social, technological, legal and environmental (PESTLE) drivers as highlighted in Figure 4. To ensure that the benefits of smart city services and urbanization are fully shared and inclusive, policies to manage urban growth need to ensure access to infrastructure and social services for all, focusing on the needs of the urban poor and other vulnerable groups for housing, education, health care, meaningful work and a safe environment. The rise of always-connected omni-present systems, gadgets and sensors serving digital automation of critical processes will set high requirements for trustworthiness and resilience. The ubiquitous connectivity and contextual awareness of 6G networks is expected to promote ICT accessibility and use for the social and economic development of people with specific needs, including indigenous people and people living in rural areas. Future 6G architectures will foster digital inclusion and accessibility also unlocking rural economic value and opportunities.

High energy efficiency to reduce the overall network energy consumption is a critical requirement for 6G. The choice, use, reuse and recycling of materials throughout product lifecycles will enable the total cost of ownership to be reduced, facilitate the extension of network connectivity to remote areas, and provide network access in a sustainable and more resource-efficient way. Extensive research has been conducted into possible health effects of exposure to many parts of the frequency spectrum including mobile phones and base stations. All reviews conducted so far have indicated that exposures below the limits recommended in the ICNIRP (1998) EMF guidelines[6], covering the full frequency range from 0-300 GHz, do not produce any known adverse health effects (UN WHO[7]). The introduction of novel 6G technologies will initiate the need to review the status of the science and identify gaps in knowledge needing further research to make better health risk assessments.

[6] ICNIRP guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz) published in: Health Physics 74 (4):494-522; 1998. https://www.icnirp.org/cms/upload/publications/ICNIRPemfgdl.pdf.

[7] WHO - World Health Organization. Extremely low frequency fields. Environmental Health Criteria, Vol. 238. Geneva, World Health Organization, 2007. https://www.who.int/peh-emf/en/

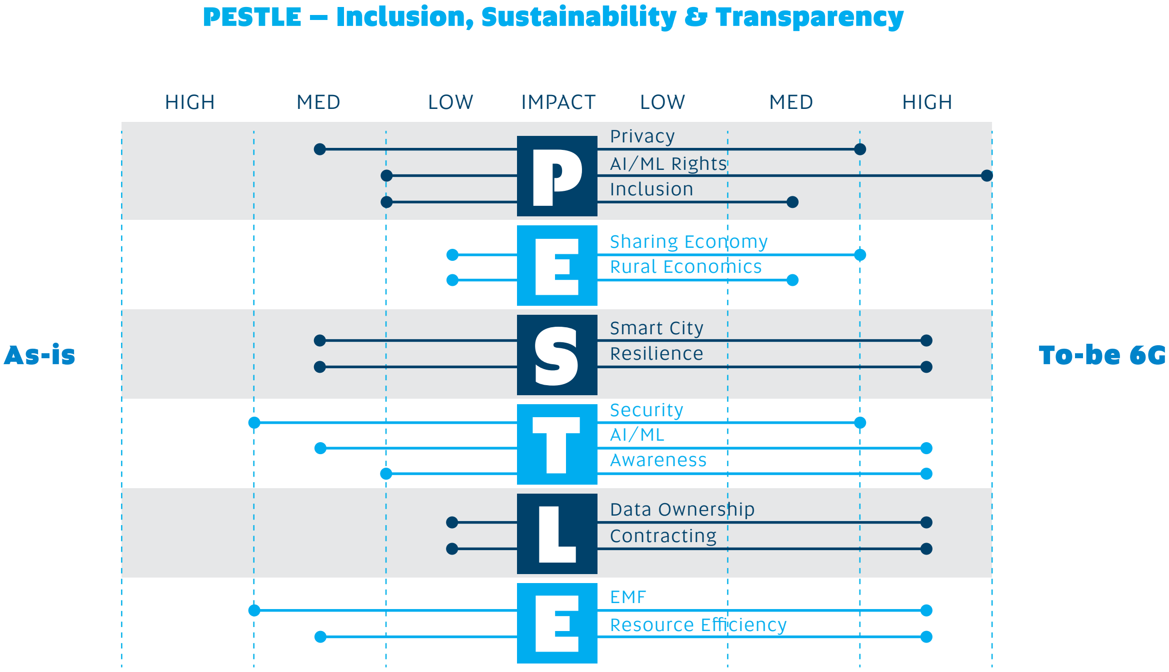

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Figure 4. 6G PESTLE (Political, Economic, Social, Technological, Legal and Environmental) analysis results highlight inclusion, sustainability and transparency.

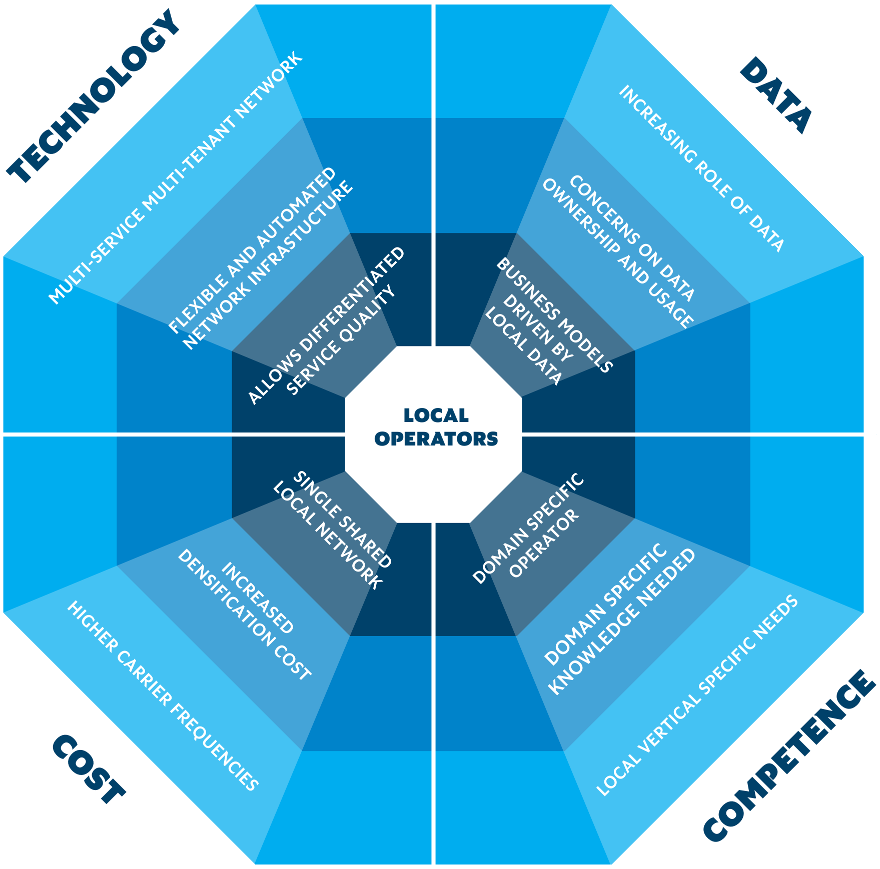
We are moving towards a data sharing / data market economy where issues with data ownership and contractual policies require special attention.

Access to data and data ownership are increasingly major factors in value creation, and limiting such access is a means of control. Creating a system that transforms how data is collected, prioritized, and shared can create strong drivers for future value, but may also lead to serious privacy and ethical concerns over the location and use of data. Furthermore, how the data itself can be used becomes a key question. The contractual rights and obligations of the different members of a communications ecosystem may describe how the information and data may be used. The challenge, however, will be the mapping of these rights and obligations to the data collected and used by highly adaptive autonomous systems, or smart devices, to create the services of the future.

The transition to ever higher frequencies with smaller radio ranges and the increasing role of indoor networks will boost network sharing in cities and indoor spaces, and – especially – drive the "local operator" paradigm.

For the foreseeable future, operation in the lower frequency bands (below 4 GHz), currently used for mobile communication networks, are expected to remain stable and dominated by MNOs[8] due to long-term spectrum licenses. With 6G however, new bands that target super-efficient short-range networks for both indoor environments and outdoor city spaces will become common (Figure 5). These local networks will target verticals with specialized demand and will be deployed by different stakeholders opening the market to new players, new investments and new ecosystems[9]. Building several overlapping ultra-dense networks will rapidly become infeasible and will lead to different stakeholders deploying a single network within a facility to serve multiple user groups and services. Via softwarization and the virtualization of network functions and opening of interfaces, sharing economy concepts will be utilized not only for the high platform business layers but also widely in network connectivity and data context layers. Challenges related to prioritising of traffic continue, as in the network neutrality regulation debate. Changes in the ownership of spectrum access rights, networks, network resources, facilities and customers will result in several combinations as different facilities will have varying requirements and infrastructures. New incentives will arise partly through regulation. The global harmonization of the spectrum will still be a challenge to be solved with the joint effort of all stakeholders.

6G will penetrate deeper into society and lives of people than anything we have seen so far. It will be very complex and besides communication deals with data collection, processing and ubiquitous intelligence. To avoid excessive operating costs, 6G software will be run on cloud technology utilising a very high level of automation. This will require advances in regulation.



© 6G Flagship

Figure 5. Drivers toward local operator paradigm.

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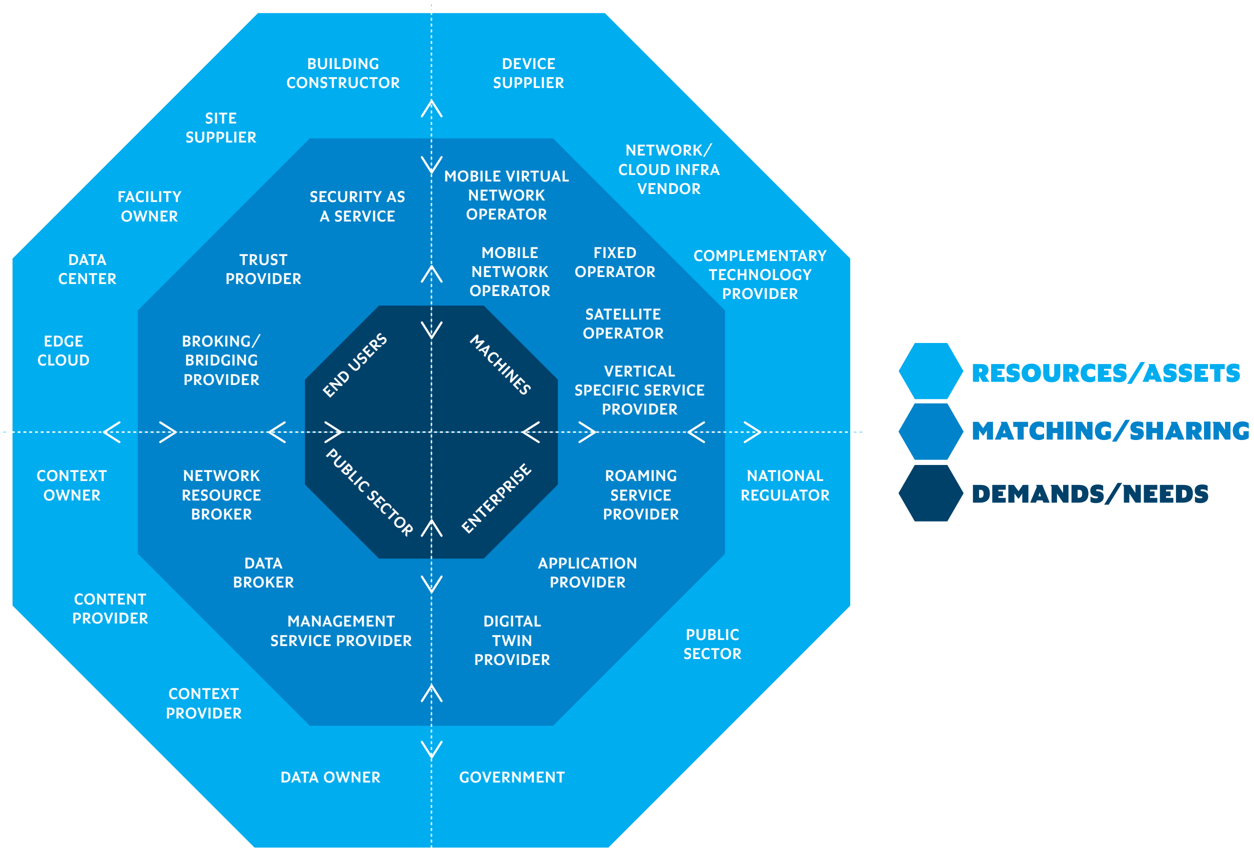
[8] A. Weber, D. Scuka, Operators at crossroads: Market protection or innovation?, Telecommunications Policy, Volume 40, Issue 4, 2016, Pages 368-377.

[9] P. Ahokangas, M. Matinmikko-Blue, S. Yrjölä, V. Seppänen, H. Hämmäinen, R. Jurva, M. Latva-aho, "Business Models for Local 5G Micro Operators," IEEE Transactions on Cognitive Communications and Networking, 2019.

Stakeholder roles in 6G will change compared to the current mobile business ecosystem and new roles will emerge.

As a sharing economy, future 6G ecosystems will change the existing roles and introduce new stakeholder roles resulting in a complex ecosystem as outlined in Figure 6. While the MNO market dominance is expected to continue in 5G, future 6G connectivity solutions will be driven by new players in the market. Stakeholders representing the different demands and needs originating from human and machine users, and specific to the public sector or enterprises in different verticals, are shown in the middle quadrangle in Figure 6. The resources and assets needed to meet the range of needs will be provided by different stakeholder roles providing physical infrastructure (facilities, sites), equipment (devices, networks), and data (content, context), under the regulatory framework set by the policy makers as depicted in the outer quadrangle. Demands and resources are brought together through the matching/sharing stakeholder roles[10] including different kinds of operators (local or vertical-specific operators, fixed operators, mobile network operators, satellite operators), resource brokers, and various service/application providers, such as trust/security providers.



© 6G Flagship

Figure 6. Stakeholders in a future 6G ecosystem.

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[10] R. Amit, X. Han, Value Creation Through Novel Resource Configurations in a Digitally Enabled World. Strategic Entrepreneurship Journal, 11, 2017, 228-242.

Overall, the stakeholder roles in 6G are expected to change compared to the current mobile business ecosystem and totally new roles will emerge. It is expected that especially the drivers listed in Figure 5 will fundamentally change the ecosystem and open new opportunities for different kinds of stakeholders in 6G. The matching and sharing of resources to meet the demands will take place through new activities to ensure inclusion, sustainability and transparency. Ultimately, the emergence and shape of new 6G ecosystems will be dependent on regulations which promote or hinder these developments.

Research questions

Q1: What are the key societal requirements for 6G?

Q2: How can ecosystem stakeholders and roles, and their ecosystem configurations be categorized in 6G?

Q3: How, why and what platform-based ecosystem business models could emerge in the 6G sharing economy?

Q4: How could artificial intelligence (AI) and machine learning (ML) transform the platform-based ecosystems, business models and services in future 6G systems?

Q5: What is the minimum viable regulation needed for 6G to respond to societal requirements?

Q6: How can novel mechanisms and business models be developed which support inclusion, and access in remote areas?

6G USE CASES AND NEW DEVICE FORMS

While smartphones have become an indispensable part of our lives, rapid advances in new display technologies, sensing and imaging devices, and low-power specialized processors are ushering in a new era in which our devices will become seamlessly integrated with our senses and motoric control. Virtual (VR)[11, 12] augmented (AR)[13], and mixed reality (MR) technologies are merging into XR, which encompasses wearable displays and interaction mechanisms that create and maintain perceptual illusions. Users will accept an alternative version of reality that enhances their ability to consume media, search the Internet, explore real and virtual worlds, collaborate on work projects, connect with family and friends, and engage in restorative activities.

Smart phones are likely to be replaced by pervasive XR experiences through lightweight glasses delivering unprecedented resolution, frame rates, and dynamic range.

XR experiences are likely to be delivered by lightweight glasses that project images onto the eyes at an unprecedented resolution, frame rate, and dynamic range. Furthermore, feedback will be provided to other senses via earphones and haptic interfaces. The necessary supporting technologies include: 1) imaging devices such as light field, panoramic, depth-sensing, and high-speed cameras; 2) biosensors for monitoring health conditions such as the heart rate, blood pressure, and neural activity; 3) specialized processors for computer graphics, computer vision, sensor fusion, machine learning, and AI, either in the device or in the surrounding network infrastructure; 4) wireless technologies including positioning and sensing. Sensing and imaging devices can capture our entire life experiences as well as detailed physical environments, whereas virtual worlds continue to increase in fidelity. These advances in combination with the requirement to distribute computation (because the computation demand exceeds small devices such as glasses) highlight demand for performance from wireless networks that is not yet available.

Telepresence will be made possible by high resolution imaging and sensing, wearable displays, mobile robots and drones, specialized processors, and next-generation wireless networks.

For centuries people have looked for ways to feel closer over great distances. From the postal service to the telegraph to the telephone to video chatting, our expectations for remote communication and interaction continue to evolve. Telepresence, as a surrogate for actual travel, is finally becoming a reality with the unprecedented speed of development in the supporting technologies: high-resolution imaging and sensing, wearable displays, mobile robots and drones, specialized processors, and next-generation wireless networks. A sense of presence may be achieved through real-time capture, transmission, and rendering of a 3D holographic representation of each participant in a meeting, or by combinations of graphical representations, such as avatars, and movement data that is captured by sensors. Perceptual illusions are created by XR devices that convince a geographically distributed group of people that they are in the same location, which could be a real or virtual environment.

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[11] J. Bailenson, Experience on Demand, What Virtual Reality Is, How It Works, and What It Can Do, W. W. Norton and Company, 2018.

[12] S. M. LaValle, Virtual Reality, Cambridge University Press, 2019.

[13] D. Schmalsteig, T. Höllerer, Augmented Reality: Principles and Practice, Mendeley Ltd., 2015.

With autonomous systems and robots, people can even effect changes in the remote world. People may communicate through familiar mechanisms such as speech and body language, or through specialized devices, analogous to a PC mouse, optimized for comfort, precision, and efficiency in 3D worlds[14]. Exemplary applications include education over distances, collaborative design, telemedicine, telecommuting, advanced 3D simulation and training, and defence.

Autonomous vehicles for ecologically sustainable transport and logistics are made possible by advances in wireless networks and in distributed AI and sensing.

Even with the advent of telepresence, the movement of people and goods remains a critical challenge as both population and globalization increase. The world in 2030 and beyond envisions many millions of networked autonomous vehicles operating with different degrees of coordination to make transport and logistics as efficient as possible. These vehicles may include autonomous cars that move people between their homes and workplaces or schools, and autonomous trucks or drones that deliver goods. By 2030, online consumer shopping is expected to dominate in developed countries, causing a need to deliver millions of packages from warehouses to individual homes. Efficiency is important not only for improved global productivity but also for achieving sustainability targets by reducing fossil fuel consumption. Even more pressing than efficiency is safety: with the rise of the use of autonomous vehicles there should be no rise in harm to humans. In fact, the goal should be to reduce today's current global death and injury rates from transport and logistics networks. Advances in sensors, sensor fusion, and control systems continue to improve safety, but this comes at the expense of stronger network requirements.

Each vehicle in a future network will be equipped with many sensors, including cameras, laser scanners, possibly THz arrays for 3D imaging, odometry, and inertial measurement units. Algorithms must quickly fuse data from multiple sources and make rapid decisions about how to control the vehicle while considering a locally generated map of its immediate environment, its place in that environment, information on other vehicles, people, animals, structures or hazards that might lead to collision or injury. Interfaces must also be developed that alert passengers or supervisors to potential risks so that appropriate actions can be taken to avoid accidents. For the network of vehicles to function efficiently and safely, wireless networks must deliver ultra-high reliability, in addition to low latencies and a high bandwidth. A more comprehensive set of use cases are presented in the 6G Flagship Vision Video[15].

Research questions

Q1: What are the functional, performance and ergonomic requirements for next generation XR systems?

Q2: How to distribute computation and data between different components in future XR systems?

Q3: How can human perception-based quality of experience (QoE) criteria be defined and measured for next generation XR devices?

Q4: What novel opportunities can next generation networks and devices offer to interaction between people?

Q5: What are the considerations for communication reliability and traffic safety for autonomous vehicles?

[14] J. J. LaViola Jr., E. Kruijff, R. P. McMahan, D. Bowman, I. P. Poupyrev, 3D User Interfaces: Theory and Practice, 2nd Ed., Addison-Wesley, 2017.

[15] https://www.youtube.com/watch?v=T6ubRoZCeVw&list=PLFhJqSbEBkRSbtfHKX5ju0tsGt3bld-nM&index=2&t=0s

6G SPECTRUM AND KPI TARGETS

Many of the Key Performance Indicators (KPIs) used for developing current and emerging 5G technologies are valid also for 6G. However, the KPIs must be critically reviewed and new KPIs must be seriously considered. For technology driven KPIs, some leading vendors have released their initial drafts for the Beyond 5G and 6G requirements as depicted in Figure 7.

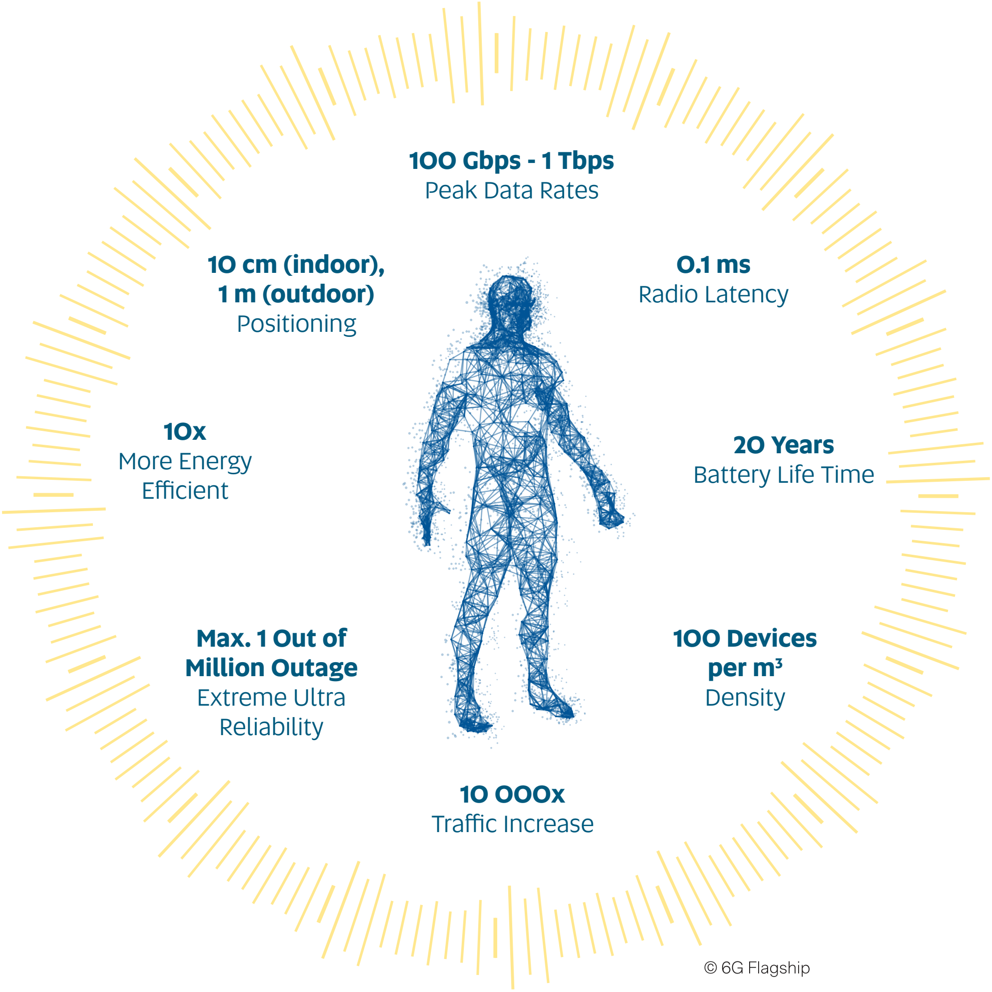

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Figure 7. Generic 6G targets presented by academia and industry in different fora.

The beyond 5G (B5G) and 6G targets in most of the technology domains once again point to an increase in the respective capability by a factor of 10-100, in line with the previous mobile cellular generation upgrades.

Some of the potential 6G KPIs including the previously discussed technology KPIs are listed in Figure 8. There are several KPI classes that are currently difficult to define and will be improved in future releases of the white paper.

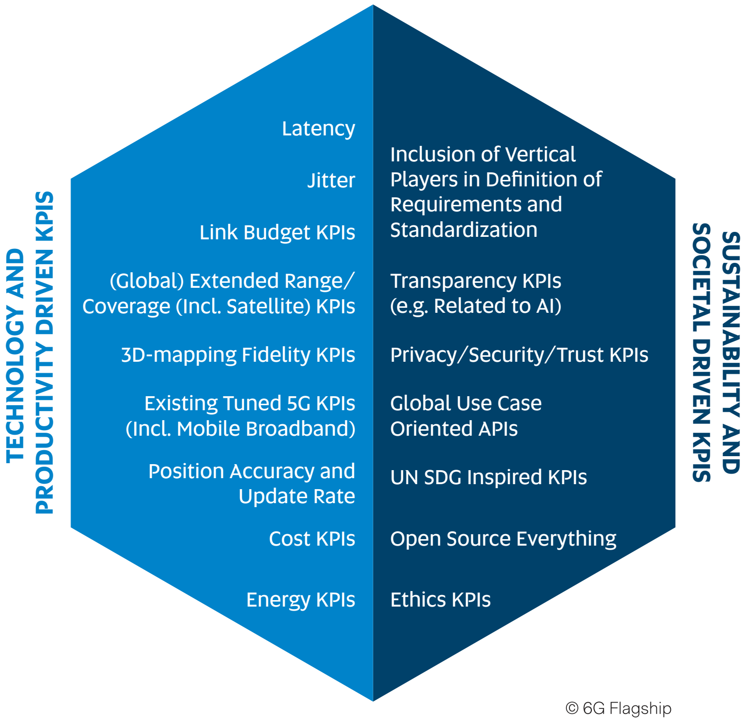

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Figure 8. Initial 6G KPIs.

An example of assessing these new metrics is related to UN SDG KPIs. Some activities have already been performed[16, 17], but further studies are encouraged to define the KPIs and to set target values. Digitalization accelerates progress towards achieving the SDGs – but business-as-usual will not achieve the SDGs on time. It is estimated that carefully designed digital solutions, including next generation wireless, targeting SDG KPIs will offer the required scale and speed for breakthroughs.

6G research should include the challenge of transmitting up to 1 Tbps per user.

Future wireless networks are expected to support a wide variety of sometimes conflicting requirements. 6G is expected to be the first wireless standard requiring hyper-fast links with the per link peak throughput exceeding the terabit per second (Tbps) mark. 6G use cases such as wireless factory automation will require very sophisticated operations such as communication with ultra-high reliability and ultra-low latency, high-resolution localization (at the centimetre level), and high-accuracy inter-device synchronicity (within 1 µs). The 6G reliability and latency requirements are expected to be diverse and use case specific. One of the most extreme is industrial control where only one erroneous bit in a billion transmitted bits with a 0.1 ms latency is permitted.

We can anticipate that the data traffic and the numbers of connected things will increase substantially for 6G. Device density may grow to hundred(s) of devices per cubic meter. This poses stringent requirements on area or spatial spectral efficiency and the required frequency bands for connectivity.

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[16] https://www.pwc.com/m1/en/publications/documents/delivering-sustainable-development-goals.pdf.

[17] https://www.huawei.com/minisite/gci/assets/files/Huawei_2018_SDG_report_en.pdf.

Security, privacy and reliability are important emerging KPIs. 6G will need to be hyper-secure with demanding requirements for industrial and high-end users, while simultaneously being low cost and of low complexity for Internet of Things (IoT) applications.

For future networks, wider radio bandwidths will be needed but can be found only at sub-THz and THz bands. The utilization of that spectrum provides many challenges, but also opportunities. Therefore, radio hardware research will primarily focus on this spectrum area although 6G will also utilize all existing and future bands at lower frequencies as enablers for mobile cellular large-area coverage. Super-efficient, short-range connectivity solutions will be key for the 6G, an area in which the higher-frequency bands can play a role in the future. The molecular absorption has a substantial impact on the path loss especially at longer distances (~1…10 dB/km at frequencies up to 400 GHz)[18]. However, for local connectivity the impact is still small compared to the free space loss and the THz radio spectrum can be divided into favourable spectrum windows between atmospheric absorption peaks above 500 GHz (Figure 9). Penetration through various materials and reflections from surfaces are other factors to be considered when categorizing the radio spectrum in addition to technological boundaries.

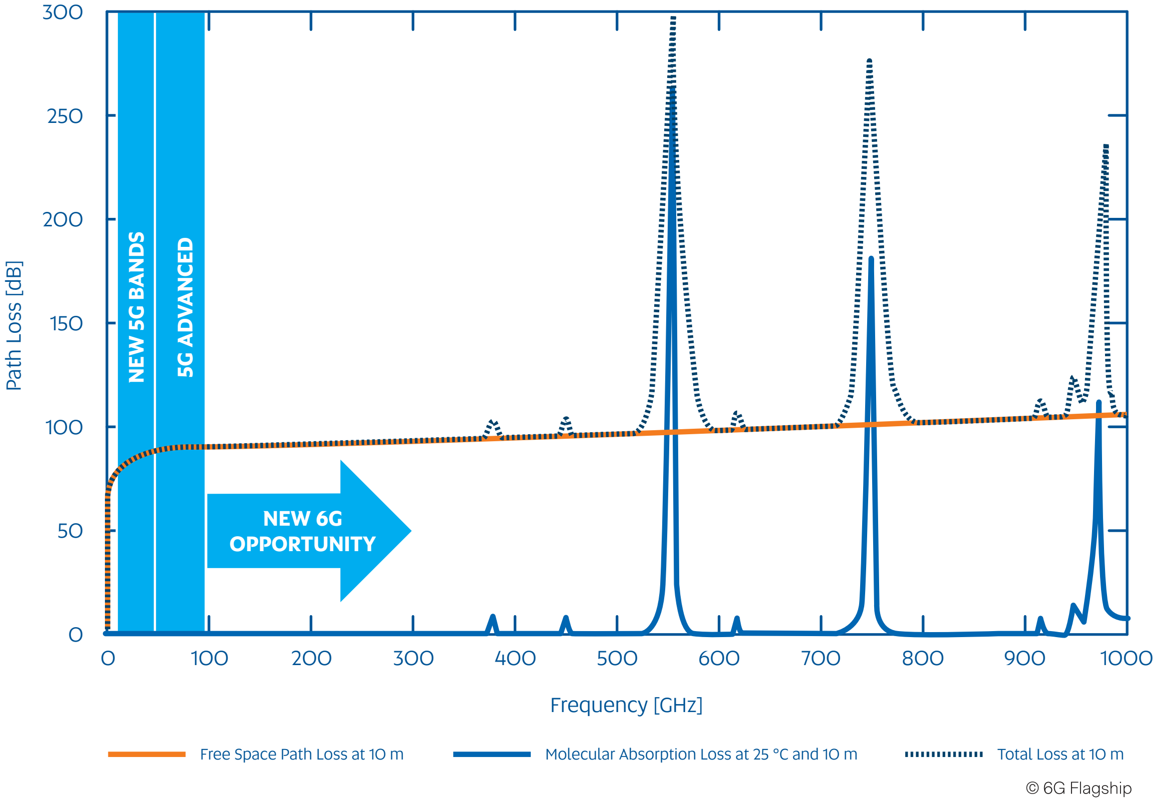

Figure 9. Spectral windows, the effect of free space loss and water vapor absorption at a distance of 10 m.

The basic properties of frequency bands available for 5G and 6G are given in Table 1. One should note that the increase in free space loss is quite small when moving into the THz region from 30 GHz onwards. If the antenna area is kept constant, the free space loss is compensated for by the increase in the antenna gain. Rather than the free space loss, the downside of higher frequencies is increased complexity and parallelism in RF hardware and the reduced beam width that creates problems with signal acquisition and beam tracking in mobile applications.

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[18] Terranova Deliverable D3.2, "Channel and Propagation Modelling and Characterization", project report, August 2018.

FREQUENCY BAND	**0.3-3 GHz**	**3-30 GHz**	**30-300 GHz**	**0.3-3 THz**	**3-30 THz**
WAVELENGTH	100-10 cm	10-1 cm	10-1 mm	1000-100 µm	100-10 µm
DOMINANT PROPAGATION MECHANISM	LOS, Reflection, Diffraction, Scattering, Penetration	LOS, Reflection, Diffraction, Scattering	LOS, Reflection	LOS, Reflection	LOS, Reflection
DOMINANT ATTENUATION EFFECTS	Free Space Loss	Free Space Loss -Transmission Loss Through Materials High at Upper Band	Free Space Loss/ Molecular Absorption -O_2 @60 GHz -H_2O > 24 GHz	Free Space Loss/ Molecular Absorption -High H_2O Peaks	Free Space Loss/ Molecular Absorption -High H_2O Peaks
SUPPORTED LINK DISTANCES	10 km	1000 m	100 m	<10 m	<1 m
TX POWER LIMITING FACTOR	Regulation	Regulation	Technology	Technology	Technology
APPROXIMATE SYSTEM BANDWITH	up to 100 MHz	400 (or 800) MHz	Up to 30 GHz	Up to 300 GHz	> 100 GHz

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Table 1. Spectrum bands for 5G and 6G.

The utilization of the spectrum in the THz regime needs to be arranged based on absorption and reflection properties.

Many current IoT scenarios are range, cost and battery-limited and will not scale up easily to higher frequencies. Conversely, data-rate-intensive scenarios, such as transferring holographic videos, require bandwidth not available even in the current mm-wave spectrum. The utilization of the spectrum in the THz regime needs to be arranged based on absorption and reflection properties of sub-bands to optimize use and reuse for communications and other applications. Specifically, in scenarios supporting multiple applications, the overlap of harmonic products must be prevented by careful frequency planning. Because sensitivity in weak signal detection is one of the key bottlenecks, preventive actions should preferably be considered already in frequency regulation, something that has not been seen across large span of bands before.

Research questions

Q1: How to assess and quantify the metrics towards UN SDG KPIs?

Q2: What is an adequate radio channel model for 6G communication applications, and is it possible to unify the model for whole range from GHz to THz?

Q3: What are feasible bands and what technologies are needed above 100 GHz for commercial use?

Q4: What are proper metrics for data privacy and security?

Q5: What are the real needs and requirements for future spectrum allocation and related policies?

RADIO HARDWARE PROGRESS AND CHALLENGES

The first 5G implementations will operate in frequency bands below 6 GHz for mobile applications and in mm-waves for fixed wireless access. The focus for new hardware technologies for 5G research has been primarily on the adoption of new spectrum at mm-wave bands, first in the 24-40 GHz region and then gradually moving up to 100 GHz carrier frequencies. A great deal of research is still required to enable mm-waves for mobile users including hardware and algorithms for flexible multi-beam acquisition and tracking in non-line-of-sight (NLOS) environments. Energy efficiency for massive multiple-input multiple-output (MIMO) antenna implementations is still a huge challenge. Due to the higher path loss, additional antenna gain is needed, and communication needs to utilise directive links implemented with phased arrays[19]. Bulk complementary-metal-oxide-semiconductor (CMOS) and CMOS silicon-on-insulator (SOI) technologies provide adequate performance and meet requirements for most applications using off-chip antennas. Antenna elements are still large compared to radio frequency integrated circuits (RFIC). Silicon-germanium bipolar CMOS (BiCMOS) is a good option especially when approaching and exceeding 100 Gbps data rates and 100 GHz carrier frequency.[20].

The role of directive transmission and reception becomes even more evident when carrier frequencies are further increased towards 1 Tbps link speeds. At the same time, it becomes more difficult to use CMOS transistors at frequencies well above 100 GHz. On one hand, it is still beneficial to keep exploring the potentiality of CMOS technology to support frequencies above 100 GHz. On the other hand, new or sometimes conventional but better performing hardware technologies, such as silicon germanium (SiGe) or indium phosphide (InP), allow spectrum utilization on a broader scale with an improved RF performance. Both physical and technological boundaries of electronic hardware and the fundamental laws of propagation will become bottlenecks or, at least, they will slow down the development.

Extended spectrum towards THz enables merging communications and new applications, such as 3D imaging and sensing.

Short wavelengths and wider available bandwidths above 100 GHz will enable increased data rates but also angular and ranging precision not seen before for imaging and radar applications for localization, 3D imaging and sensing. Therefore, hardware needs, bounds and opportunities for ultra-high-speed low-cost communications and advanced sensing systems should be studied together on an unprecedented scale (see Figure 10)[21].

The physical space needed for radio solutions will be reduced radically as the frequency increases: an antenna array of 1000 antennas will fit into an area of less than 4 cm^2 at 250 GHz. The surface area of current mobile devices could host several tens of thousands of antennas. This will lead to new challenges with integrated electronics becoming quite large compared to the corresponding antennas. Large antenna arrays, required to achieve a decent range for communications or sensing will result in extraordinarily narrow pencil beams. These could provide better security by pointing the messages just at the correct targets, however at the same time they are prone to misalignment.

[19] T. Tuovinen, N. Tervo and A. Pärssinen, "Analyzing 5G RF System Performance and Relation to Link Budget for Directive MIMO," in IEEE Transactions on Antennas and Propagation, vol. 65, no. 12, pp. 6636-6645, Dec. 2017.

[20] P. Rodríguez-Vázquez, J. Grzyb, B. Heinemann and U. R. Pfeiffer, "A 16-QAM 100-Gb/s 1-M Wireless Link With an EVM of 17% at 230 GHz in an SiGe Technology," in IEEE Microwave and Wireless Components Letters, vol. 29, no. 4, pp. 297-299, April 2019.

[21] P. Hillger, J. Grzyb, R. Jain and U. R. Pfeiffer, "Terahertz Imaging and Sensing Applications with Silicon-Based Technologies," in IEEE Transactions on Terahertz Science and Technology, vol. 9, no. 1, pp. 1-19, Jan. 2019.

Probably the biggest challenges are related to energy consumption. In low rate sensing applications there is a need for zero-energy, self-contained battery-less solutions with energy harvesting. At the other end, the toughest visions and unexpected applications requiring broadband processing without a doubt will call for huge improvements in power efficiency.

Generating RF power at THz is difficult and water absorption is harmful even outside the absorption peaks. However, such absorption can be also utilized: seeing through clothing but not the body or observing the absorption characteristics of various gases for environmental sensing. One interesting opportunity is also the increased reflectiveness of surfaces at shorter wavelengths. While penetration through materials will become an even more severe issue, the possibility to utilize reflections more effectively exists.

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

The limitations imposed by the laws of physic and the relevant technologies utilizing them will also enable the new generation of wireless technology in 6G. The speed of transistor both in analogue and digital signal processing becomes an issue when the targeted data rates of signal processing and utilized carrier frequencies approach the fundamental limits of mainstream and affordable technologies.

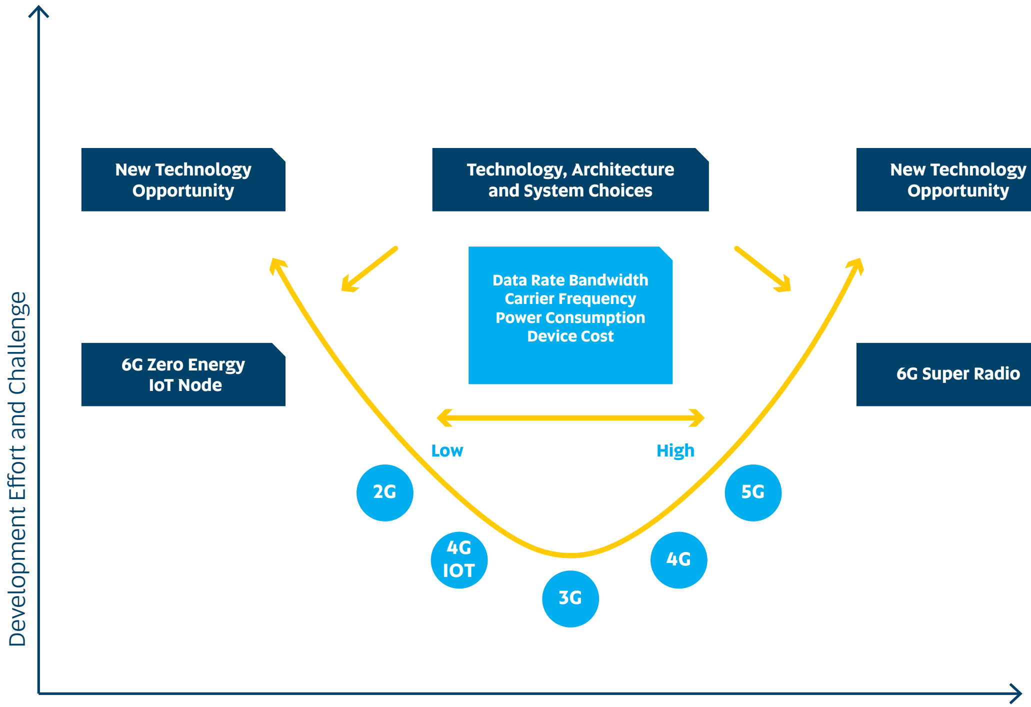

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Figure 10. 6G moving towards extremes: how to keep costs and complexity appropriate at both ends?

Success of large-scale communications has been based on CMOS and – in most demanding RF specifications – on BiCMOS-based semiconductor technologies that have provided continuous reduction of cost per function and increased speed both in analogue and digital processing. Is this assumption still valid in the future? The increased speed available from smaller transistors is not easily available as the speed of the interfaces, even inside silicon, becomes the dominant bottleneck, especially in CMOS. This is further challenged by the more limited power delivery capability of nanoscale technologies[22], which leads to increased parallelism in all phases of signal processing. Unfavourable thermal effects, low breakdown voltages and limited battery capacity are evident obstacles on the way towards Tbps communications. However, it is challenging to envision the full replacement of silicon technologies and all opportunities to stretch the use of the mainstream technologies will need further research from devices to transceiver architectures.

The size of one antenna element will become small as the half-wavelength distance between array elements will be a few hundred micrometres even on the lower THz regime – scale that enables integration of antenna arrays inside silicon. As the size of an antenna element becomes smaller than the associated electronics, new approaches to the transceiver architecture will be needed. To avoid tens or hundreds of thousands parallel transceiver frontends with antenna elements, advanced lens-based systems are likely to play a significant role.

There are opportunities for semiconductors, optics and new materials in THz applications.

Material properties and unwanted parasitic effects typically get worse with increased frequency. Therefore, a lot of focus is currently on silicon-germanium heterojunction bipolar transistors (HBT) that outperforms CMOS. Additionally, faster III-V semiconductor technologies, for example indium phosphide, deserve more attention. The challenge of packaging and integration of various technologies from lens to digital technology is one of the key research questions. Photonics, a dominant technology in upper THz regime and solution for the highest speed interfaces, is a viable technology for 6G. As the so-called THz gap is narrowing down, electronics and optics bring complementary opportunities both for very high-speed interfaces and for visible light communications. This is one opportunity in the 6G context for short range links with specific but inexpensive optical components and system solutions[23].

Open-source platforms – a dream or a must to make the next generation hardware and software solutions happen?

It is evident that the complexity both in RF transceivers and in digital signal processing will need to increase substantially from 5G to achieve the vision. A highly relevant question is, therefore, how we can achieve these goals and demonstrate the advanced capabilities not only as stand-alone solutions but also as complete systems. This calls for open-source platforms that enable low-level algorithmic development, and possibly go much deeper into specific technologies than any open-source software or hardware has done before.

[22] Hua Wang, Fei Wang, Huy Thong Nguyen, Sensen Li, Tzu-Yuan Huang, Amr S. Ahmed, Michael Edward Duffy Smith, Naga Sasikanth Mannem, and Jeongseok Lee, "Power Amplifiers Performance Survey 2000-Present", https://gems.ece.gatech.edu/PA_survey.html.

[23] T. Kawanishi, "THz and Photonic Seamless Communications," in Journal of Lightwave Technology, vol. 37, no. 7, pp. 1671-1679, April, 2019.

Research questions

Q1: How can electrical and optical technologies merge and specialize for different applications around the so called ‘THz gap’?

Q2: Will silicon-based technologies perform well in THz/Tbps systems and what other technologies are needed?

Q3: How can sufficient output power and steerable antenna arrays for communications and sensing beyond 10 m be implemented at frequencies well above 100 GHz?

Q4: Can tunable antennas and other RF solutions be implemented at frequencies above 100 GHz and can machine learning help in this problem?

Q5: How can the mutual requirements of communications, sensing, substance detection and imaging coexist in the THz region?

PHYSICAL LAYER AND WIRELESS SYSTEM

No single solution addresses the needs of all vertical applications. The hugely varying system requirements, such as massive broadband, ultra-reliable low-latency communication (URLLC), massive machine-type communication (mMTC) and extreme power efficiency, mean many solutions will be required. Case-by-case system optimization will be needed and compatibility across different use cases must be redefined. The current 5G new radio (NR) network is not yet capable of meeting all the demanding design needs of existing and emerging URLLC requirements, such as ultra-high reliability, ultra-low latency, ultra-secure networks. Motivated by this, we examine the prospects for future physical layers and wireless systems. In addition to the terrestrial networks, also infrastructures based on satellite and unmanned aerial vehicles (or similar aerial platforms) will be needed to support the coverage and capacity requirements.

The energy and power consumption become particularly challenging when combined with the data explosion and the fact that more and more data is packed and processed in tiny devices. At the same time, also the complexity of transceiver processing and end-user applications may increase lead to excessive energy consumption without careful design over all layers for energy efficiency[24].

Artificial intelligence will play a major role both in link and system level solutions of 6G wireless networks.

Meeting all the challenging requirements identified requires a hyper-flexible network with configurable radios. AI and machine learning will be used in concert with radio sensing and positioning to learn about the static and dynamic components of the radio environment. This will be used to predict link loss events at high frequencies, to proactively decide on optimal handover instances in dense city networks and to determine optimal radio resource allocations for base stations and users, just to give some examples. The future wireless networks must be able to seamlessly interface with terrestrial, satellite and airborne networks. Visible light communication is foreseen as a key enabler to achieve Tbps data rates in indoor scenarios.

New air interface enablers are needed and must be developed to meet these requirements (see Figure 11). Most require the extensive use of ML and AI algorithms to improve the time varying performance of the air interface. The concept of semantic communications (using the meaning of the messages for making the connectivity and networking more efficient), is an important emerging area of research which is closely connected to semantic AI. An important question is whether AI could be used to design optimal air interfaces on the fly for a given environment and set of specific requirements. This suggests AI inspired air interfaces. However, their true performance, in particular, power and energy efficiency in real use cases is an open research problem.

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[24] E. C. Strinati, S. Barbarossa, J. L. Gonzalez-Jimenez, D. Ktnas, N. Cassiau, and C. Dehos, “6G: The next frontier,” arXiv:1901.03239 [cs], Jan. 2019.

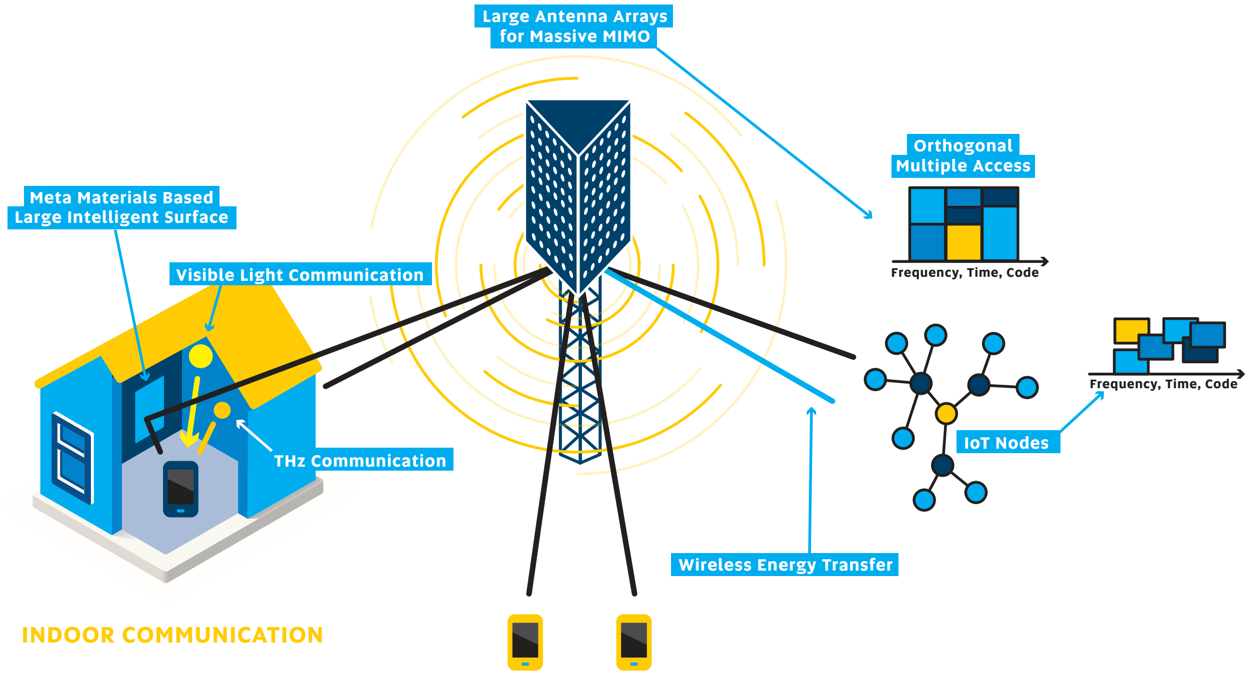

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Figure 11. Challenges of future wireless.

New grant-free access methods are critical for truly massive machine-type communication.

Extending a trend that began in 5G, 6G systems will have to flexibly enable mMTC use cases, supporting a massive number of low-power and low-complexity devices while attaining high spectral efficiency. Such requirements are especially demanding for the Internet of Things, where devices sporadically generate short packets and the overhead for resource allocation may outweigh the actual exchange of information. Modern random-access solutions for data delivery based on proper protocol design and leaning on successive interference cancellation[25,26] may become a key enabler in this direction. Indeed, already adopted in some satellite standards, they have been shown to approach the performance of scheduled access while implementing a truly grant-free approach. Furthermore, modern random-access protocols leverage the joint design of the physical and the MAC layers to boost the achievable throughput. These may prove to be useful for short-range connectivity solutions, i.e., in non-cellular domain.

To fully profit from such a tight integration, optimizations of the data frame structure as well as the forward error correction design should be considered. Attention must be devoted to the choice of the modulation scheme, which needs to be robust with respect to limited knowledge of the channel state, and on the extension of the 5G channel coding options towards short, low-rate packets.

[25] M. Berioli, G. Cocco, G. Liva, and A. Munari, "Modern Random Access Protocols," NOW Publisher, 2016.

[26] F. Clazzer, A. Munari, G. Liva, F. Lazaro, C. Stefanovic, and P. Popovski, "From 5G to 6G: Has the Time for Modern Random Access Come?" in Proc. 6G Wireless Summit, Levi (Finland), Mar. 2019.

Signal shaping is a way to achieve record-high spectral efficiency.

Achieving enhanced performance in bit rates will require the use of very high constellation modulation. However, these high order constellations are sensitive to non-linearities in the transmission medium. Signal shaping for quadrature amplitude modulation (QAM) may be able to overcome some of these challenges. Signal shaping comes in two varieties: geometric and probabilistic. Both geometric and probabilistic QAM constellation shaping are expected to achieve record-high bits/s/Hz/polarization in optical and THz wireless communication systems.

Analogue modulation schemes in 6G?

Orthogonal frequency-division multiplexing (OFDM) has proven to be very efficient for broadband connectivity. It has been proposed earlier also for multiband OFDM versions of ultra-wide-band (UWB) systems at 60 GHz with greater than 500 MHz bandwidths. When the transmission bandwidths are taken to extremes, such as several or even tens of GHz at a few hundreds of the GHz spectrum band, the classical transceiver design starts to fail, and multicarrier modulations do not work as with current technologies. More robust analogue modulation schemes will be needed instead.

The strongest security protection may be achieved at the physical layer.

Future optical wireless communication could rely on quantum key distribution (QKD) schemes that could provide some unique physical layer security features, thereby enabling the required hyper-secured networks for certain 6G applications and use cases. QKD provides a secure way of distributing secret keys between two users. In this way, the secrecy is ensured through quantum mechanics instead of complex computation. Furthermore, authentication by a physical layer signature, such as RF fingerprinting, and some other technologies, such as randomization of MIMO transmission coefficients, coding, etc., could potentially be used in 6G.

Backscatter communications using RF power for connectivity and computation may enable hyper-low-power communications.

The overall network and system-level energy efficiency specifically, the number of bits per joule, needs to improve significantly to support the requirements of 6G. This requires the optimization of the radio resources so that a controlled balance between the transmit energy and required processing energy is systematically designed. The approach calls for coding, modulation, transmit and receive processing together with power and frequency allocation in an energy-efficient manner. Furthermore, hyper-low energy (sub mW) capabilities are needed in terminals and even more in low-power IoT nodes. Most of this can be achieved by appropriate RF and baseband hardware design, but low-power coding, modulation and physical layer (non-OFDM) also needs to be addressed. Backscatter communications and energy harvesting from environment and RF waveforms will also enable the long lifetime of IoT nodes with non-replaceable batteries. Additionally, backscatter communications using RF power for connectivity and computation may provide a pathway towards hyper-low-power communications.

6G wireless networks may shape the radio environment to their liking.

Driven by a revolution in electromagnetically tunable surfaces (e.g., based on metamaterials), 6G will control signal reflections and refractions from large intelligent surfaces (LIS). Open research problems range from the optimized deployment of passive reflectors and metamaterial-coated smart surfaces to AI-powered operation of reconfigurable LIS. Fundamental analysis to understand the performance of LIS and smart surfaces, in terms of the rate, latency, reliability, and coverage is needed. Another important research direction is environmental AI whereby smart surfaces learn and autonomously reconfigure their material parameters. Challenges include how to focus signals with different angles of incidence in large metamaterial surfaces require controllability of reflection/refraction coefficients. ML-driven smart surfaces in mobile environments may require continuous retraining, in which the access to sufficient training data, high computational capabilities, and guaranteed low training convergence are needed.

Holographic radio could be made possible with 6G by using LIS and similar structures. Holographic RF allows the control of the entire physical space and the full closed loop of the electromagnetic field through spatial spectral holography and spatial wave field synthesis. This would greatly improve the spectrum efficiency and network capacity and would help the integration of imaging and wireless communication.

Research Questions

Q1: How to design channel coding, modulation, detection and decoding with high rates, low latency, high reliability and large bandwidths?

Q2: How to decode Tbit/s communications (speed)? What kind of constellation shaping is needed?

Q3: How to design the systems to satisfy high-energy-efficiency and low-cost requirements? How will we enable true battery-less operations?

Q4: How to enhance information security, privacy and reliability via the physical layer technologies? Can quantum key distribution with optical (or microwave further in future) be practical?

Q5: How to design mm-wave/THz links, systems and transceivers efficiently? How will it be possible to compensate for or sustain phase noise? What are the roles of coherent, noncoherent, partially coherent systems? How will it be possible to realize mobile positioning, channel acquisition and tracking?

Q6: How to carry out massive MIMO and smart beam steering with active antenna arrays merged with lens antennas? How to design systems with large intelligent surfaces?

Q7: How to design efficient interfaces between high performance computation platforms and RF chains?

Q8: How to cope with very high speeds of trains and drones to support the connectivity? Can and should we still use multicarrier technology? Do we need new waveforms such as those based on special affine Fourier transform?

6G NETWORKING

6G needs a network with embedded trust.

By 2030, the digital and physical worlds will be deeply entangled, and people's lives will depend on reliable operation of the network. Major industrial value will be lost if networks fail. Whereas in the digital world an attack may compromise intangible assets, in the cyber-physical world physical assets could be stolen, incapacitated or harmed by digital attacks. Malicious cyber activity could lead to loss of property and life.

To counteract, we should embed ubiquitous trust model into the network[27], so that users can trust the communication over the network. Users here mean both individual and organizational entities. The trust model should ubiquitously collect evidence of misbehaviour and provide indirect reciprocity and non-repudiation of actions. For safety, trust and security-critical services, the network should provide embedded distributed denial of service (DDoS) mitigation and protection from other attacks with fast and accurate trace back to the resources used for the attack, as well as automated means of pushing the mitigation back towards the attacker. Devices should be able to see only expected traffic while non-expected traffic should be dropped by the network.

6G adopts the idea of ID/locator split and mainly relies on private addresses for devices.

Embedding trust into the network needs a more stable ID for devices and nodes than just an address that may be translated or dynamic. Each device should have at least a unique name or several names that the network will be able to translate into addresses as well as back to IDs as needed. Devices should be allocated either just a private address, or like classical IP hosts, they may have a globally unique address. When attached, the device should be able to control its own reachability. A natural consequence of the addressing principle is that end-to-end communication "layer" is separated from packet forwarding for the users. Like Software Defined OpenFlow networks, the network can use several forwarding protocols, such as IPv4, IPv6, Ethernet, and several tunnelling protocols.

This is illustrated in Figure 12 and described further as follows. End-to-end network connectivity is from one customer network to another across a wide area. Technology choices in each area are independent due to the generic flow abstraction created by the edge node. The end-to-end connectivity layer manages the willingness to communicate on top of the heterogeneous packet forwarding layer. The edge node has a registry of served hosts. It assigns and maintains stable IDs for all served hosts and translates IDs to addresses and addresses to IDs on request. The edge node collects evidence of behavior of all seen entities against the ID of the entity supporting and using the idea of reputation of the hosts and network entities.

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[27] R. Kantola, H. Kabir, P. Loiseau, Cooperation and end-to-end in the Internet, International Journal of Communication Systems, Wiley, 02/2017.

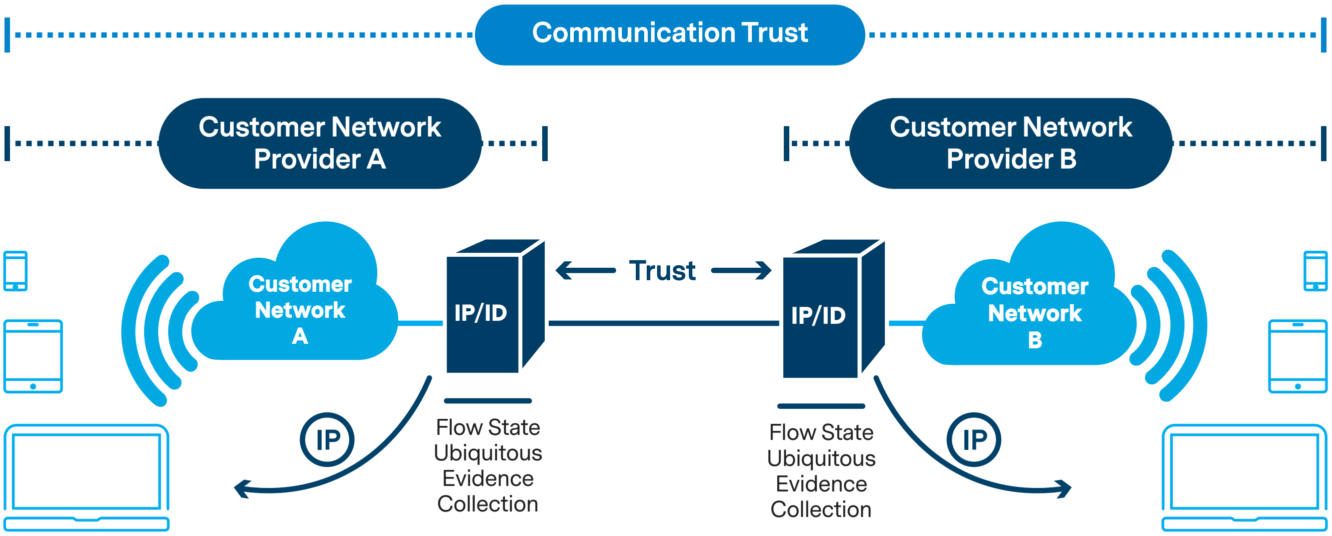

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Figure 12. Communication in 6G can be over a chain of trust.

6G will create data markets – privacy protection will be a key enabler.

Networks will generate an unprecedented amount of information about people (IoT, Industrial IoT, eHealth, Body area networks and so on). The IIoT will generate significant amounts of business sensitive and personal data. Internet companies have shown how lucrative the use of private information is. Private information collected from the physical world can be very sensitive and used against people's interests in many ways. We believe that to make 6G acceptable to society, the protection of private information will be a key enabler to realize its full potential.

A fair market requires that it is possible to protect business sensitive data. Users should ultimately be able to control and manage their private data with a simple and intuitive user interface. The ownership and control over personal data should be given to the person or the entity in question.

Some of the data generated by 6G devices and elements in both public and private networks has value for many societal functions and possibly to other private corporations than the one that collects the data. The 6G data markets offer a natural new business case. Clear rules for this market are needed, so that all types of actors, including ordinary consumers, can enter it.

6G needs an upgraded networking paradigm.

The current Internet paradigm is often referred to as "best effort" delivery. To address the need for differentiated service quality, 5G envisions slicing, in which network resources, capacity and features are tailored to the use case by applying traffic management, linking and computer resource allocation and a choice of virtualized network functions that control and process the traffic in the slice. A slice can offer the best effort to its users or apply some QoS schema for processing the packets.

In 6G, the 5G paradigm will be refined and expanded. One possibility is to virtualize (critical) end-to-end connectivity from devices through the mobile network to the packet data network and to the cloud. Under the 6G paradigm, the network seeks to maximize user welfare or Quality of Experience (QoE) by several technical means such as intelligent traffic management, edge computing, policies set by the user either proactively or per transaction or through traffic orchestration. The latter may, for example, use policies set by the user or by the operator for a group of subscribers who are each treated equally within that group. The network is neutral in the sense that it treats all applications in a slice equally and all users with the same type of subscription equally.

It is possible that by the time we reach 6G the net neutrality regulations will be updated and will mandate MNOs to offer value added security services to users under the users' control. Such a regulation would define reasonable and understandable liabilities for users who have been unable to take care of the security of their own devices in case they have been used in attacks against other users. At the same time, the network should provide a fair basis for service and application competition to maximize end user choice.

6G research will need to investigate alternative divisions of responsibilities between the private and public networks. The seamless integration of short-range connectivity solutions with large-coverage cellular systems will need to become more ubiquitous and given more impetus in development and standardization.

Artificial intelligence and block chains may play a major role in 6G networks.

Recently, there has been a growing interest in machine learning (ML) and artificial intelligence. ML relies on Big Data that is mined to gain information and knowledge. This approach is a reasonable candidate for detecting malicious behavior of a remote entity. There are also other needs in networking that require "intelligence" such as self-configuration or managing complexity. Besides Big Data, AI relies on an abundance of computing power. 6G will use the increasing computing power for coping with the higher bitrates but also for gaining added flexibility. This will increase power consumption dramatically unless tackled in the overall system design.

Another new technology attracting high hopes is block chain also known as distributed ledgers. Without a central authority, in a distributed manner, this technology allows storing and sharing information that does not change too often. The full record of the changes is also kept. This may give rise to new ways of organizing data markets or helping to maintain trust in an inter-operator setting.

Research questions

Q1: How to define a new networking paradigm that equally supports consumers, corporate and life and mission critical communications? What regulatory changes are needed to allow such innovation?

Q2: How to embed trust and security in the network? How can the style of isolation provided by virtualization be leveraged to secure end to end connectivity and communications?

Q3: What kind of data market business models are feasible and what technology is needed to support them? What will the architecture look like and how can the non-tech users easily make use of it?

Q4: What kind of network functionality, interfaces and protocols are needed to support the new splits of responsibilities between wide area and local area players and between consumer and vertical market players?

Q5: How can virtualization be enhanced and improved to support maximum flexibility of networks at a low cost for both non-critical and critical communications?

Q6: What new computing and software technologies can be leveraged in 6G?

NEW SERVICE ENABLERS

6G is not only about moving data: it will become a framework of services, including communication services.

Up to the 5G cellular system, the focus in cellular development has been on the communications aspects, while other services, such as positioning, have had low priority: they have been introduced quite late into the system design. This has not led to optimal performance or the full utilization of system capabilities. Future services, such as mixed reality, will be so difficult to produce and require so many component enablers, such as positioning, 3D mapping, fusion of digital content with physical model, and extremely high-speed communication at low latency, that the co-design of the necessary enablers is not only desirable – it is critical for a good mixed reality performance. Dense, wireless networks, with high-frequency antenna arrays and a lot of computing power at the edge, offer natural enablers for such integrated services. The challenge is to make these happen in an energy efficient manner.

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

AI is witnessing an unprecedented surge from the wireless community driven by recent breakthroughs in deep learning, the increase in available data, and the rise of smart devices.[28] Imminent use cases for AI (particularly for reinforcement learning) revolve around creating self-learning networks and systems that can autonomously manage resources and control functions. In addition, with the proliferation of a new breed of autonomous devices sensing, communicating, and acting within their local environments. It is inpractical to transmit a massive amount of local data to the centralized cloud for training and inference. This calls for new neural network architectures and their associated communication-efficient training algorithms over wireless links, while making real-time and reliable inferences at the network edge. Such architectures also pose new challenges: limited access to training data, low inference accuracy, lack of generalization, and limitations of processing power and memory for edge devices.[29]

Edge computing[30] opens new possibilities for running computation intensive, low-latency user applications on the infrastructure side (Figure 13). An example of such computations would be foveated rendering for mobile virtual reality experiences. Another example would be fusion of the physical and digital world (matching virtual content with 3D point cloud) for mixed reality applications (Figure 14). A third interesting possibility is a local and instant information service: the edge cloud could provide fast discovery of people, services, devices, resources and any dynamic and highly local information near the user that cannot be collected by centralized search engines. Such an edge information service platform could be used in the creation of a local and dynamic marketplace for services, things and information. Extreme cases for edge computation would be a thin user client, essentially a light low-energy device capable of interacting with human senses or neural system, with all the user specific computing occurring in edge cloud.

[28] Z. Zhou, X. Chen, E. Li, L. Zeng, K. Luo and J. Zhang, "Edge Intelligence: Paving the Last Mile of Artificial Intelligence with Edge Computing," in Proceedings of the IEEE.

[29] J. Park, S. Samarakoon, M. Bennis, and M. Debbah, “Wireless Network Intelligence at the Edge,” to appear in the Proceedings of the IEEE [Online]. ArXiv preprint: https://arxiv.org/abs/1812.02858.

[30] N. Abbas, Y. Zhang, A. Taherkordi and T. Skeie, "Mobile Edge Computing: A Survey," in IEEE Internet of Things Journal, vol. 5, no. 1, pp. 450-465, Feb. 2018.

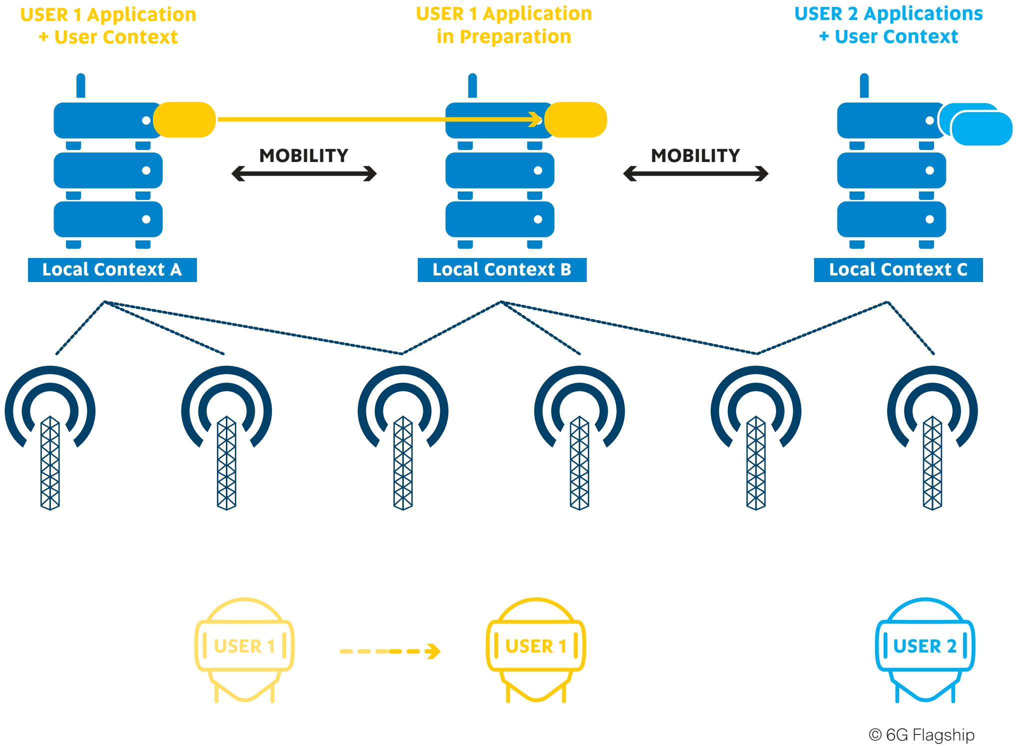

Figure 13. User applications and their mobility using edge technology.

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

Diverging from current networks, future communication systems will become pervasive across multiple industry verticals and thus enable a plethora of services that require positioning, such as assets tracking, context-aware marketing, transportation and logistics systems, augmented reality and health care. In fact, traditional localization methods relying on GPS satellites and cell multilateration are limited or even impractical in urban and indoor deployment scenarios. Very high carrier frequencies, large bandwidths, massive antenna arrays, densification and device to device communication are upcoming technologies which are mostly celebrated for their communication benefits, whereas their inherent localisation potential is typically neglected. For instance, while 3D beamforming allows for better spectrum utilization and signal quality overall, it also enables precise positioning for IoT applications.

RF-based sensing is another localisation opportunity enabled by high carrier frequencies of future networks. For instance, 3D THz imaging can improve traffic safety with accurate position determination and object detection. 3D mapping based on optical or radio technologies will be a crucial component in future mixed reality systems and would be a natural part of the future edge services. 5G and beyond systems supporting large bandwidths (in the order of hundreds of MHz) with massive antenna arrays would also offer the potential to carry out high-accuracy RF positioning and tracking. However, full application of such technologies still suffers from sufficient transmitter-to-receiver isolation: it is likely that next generation access points will be able to communicate while simultaneously resolving reflections from distinct targets. Spectral environmental sensing at THz frequencies is another interesting new opportunity. It allows aspects such as the detection and identification of harmful or poisonous gases in the environment.

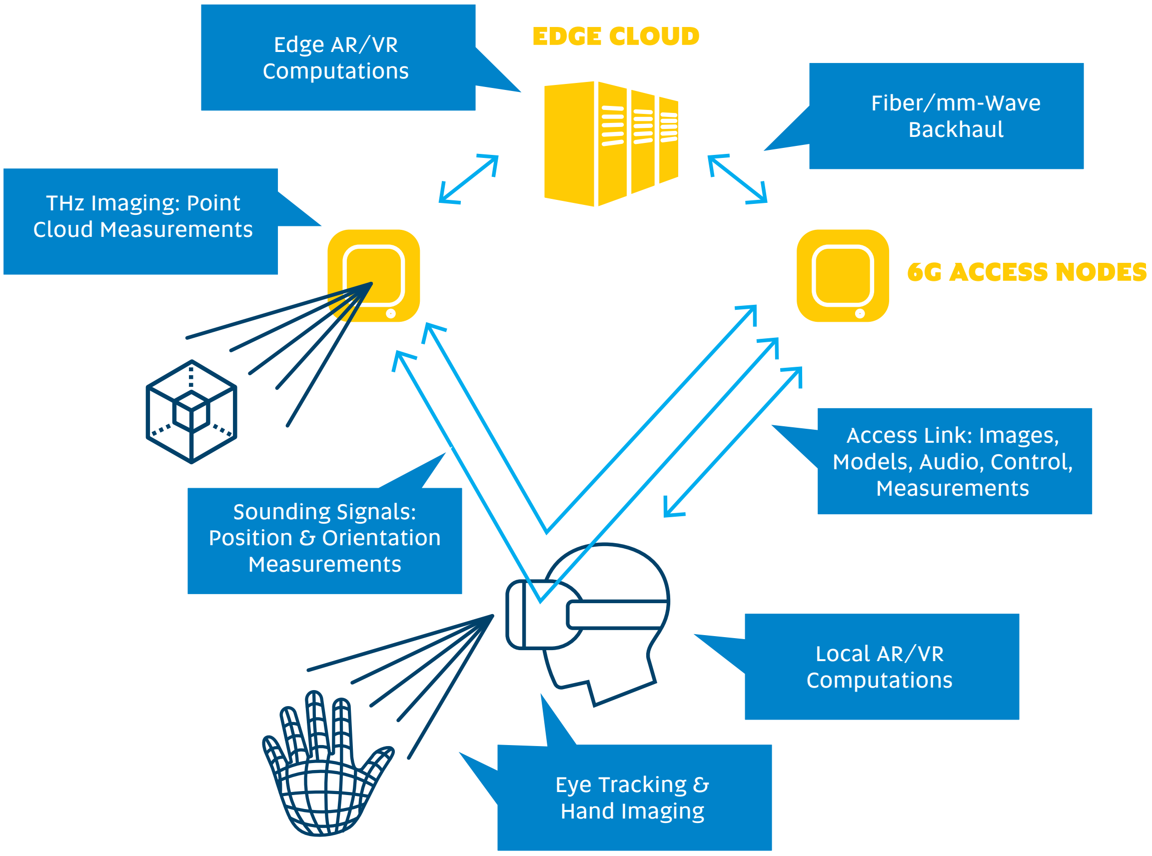

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Figure 14. 6G networks can handle positioning, 3D point cloud mapping, and mixed reality data fusion in the edge.

Trust and privacy are key prerequisites for a successful 6G service platform.

The enablers discussed above will process and store personal and very sensitive information about the users. As an example, imagine that your banking or authentication application is running on the network edge, instead of your personal mobile device. It is inconceivable that anyone would agree to run such applications in the network without utmost focus on trust, privacy, and information security[31]. This is a somewhat different goal from the security of the communication system. The requirement for privacy and security for the service enablers is higher as they process personal data without protection of E2E encryption, such as a VPN (obvious if the user applications run on the edge). The edge services issue is reminiscent of cloud services but adds the challenge of mobility since the user applications and context in the edge need to follow the user.

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[31] P. J. Sun, "Research on the Tradeoff Between Privacy and Trust in Cloud Computing," in IEEE Access, vol. 7, pp. 10428-10441, 2019.

Research questions

Q1: How to build trust, security and privacy solutions for mobile edge services and sensitive services such as accurate positioning?

Q2: How to reach cm-level positioning accuracy in outdoor and indoor spaces?

Q3: How to provide network-based 3D sensing/imaging capability for mixed reality services?

Q4: What user applications would benefit greatly from edge services and how?

Q5: How to provide edge services that have low latency, have access to local information and that follow the user constantly (i.e. have mobility even across network boundaries)?

Q6: What would the role of edge AI be for service management and system orchestration? What new requirements (e.g. stemming from privacy, security, locality or distribution) does the edge-native environment set on current AI methods, and how can the current AI methods fulfill these requirements?

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