8th issue

# 6G WAVES MAGAZINE

6G FLAGSHIP
UNIVERSITY OF OULU

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**6G Waves 8, Spring 2024**
ISSN 2670-2029 (print)
ISBN 978-952-62-4032-9 (print)
ISSN 2670-2088 (online)
ISBN 978-952-62-4033-6 (online)

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April 2024

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Research Council of Finland

FLAGSHIP PROGRAMME

6G Flagship is part of the Finnish Flagship Programme funded by the Academy of Finland.

# FOREWORD

***6G Flagship has been up and running for almost six years now. At the start, it was one of the two first Finnish science flagship programmes. Now, there are a total of 14 in different fields of science.***

All Finnish flagships strive to merge the best academic research excellence with the practical exploitation of the results. It has been the core driver and philosophy from the 6G Flagship proposal preparation in 2017.

Our core has been the long-term top-tier research carried out in strategic research areas (SRAs). The first three were wireless connectivity, devices and circuit technology, and distributed intelligence. These were soon complemented by a fourth, a more vertical application-oriented SRA, to focus on sustainable and human-centric wireless services.

Our early selections for technology focus now show a good fit for the current global 6G landscape. Last year, the International Telecommunication Union (ITU) released the IMT-2030 requirements and roadmap, highlighting the evolution of familiar 5G use cases like immersive and massive communications and hyper-reliable low-latency communications.

More interestingly, three new use cases have been identified: integrated sensing and communications (ISAC), integrated AI and communications, and ubiquitous connectivity. All these new and old topics were included in the 6G Flagship scope early on.

On top of actual 6G evolution, the critical role of microelectronics and semiconductor technologies has been freshly recognised in all continents. In Europe and North America, Chips Act programs invest in the skills and capabilities in the field. Our corresponding SRA has tackled certain corners of this from a 6G perspective.

Reflecting on our journey, one might wonder: was it all just a stroke of foresight at the beginning, or did we create the current landscape? Both are true, though the initial decision likely holds more weight. A decade from now, looking back with retrospective insight will offer fascinating perspectives on this question.

Given the great excitement about 6G technology, I hope you enjoy the current 6G Waves Magazine issue, which highlights some of the core stories over these past six years.

**Prof. Markku Juntti**
Centre for Wireless Communications
University of Oulu, Finland

## Editors' Greetings

With the 8th edition of 6G Waves, we wanted to bring you a unique combination of a retrospective glance with new analyses. This issue features a curated selection of articles from the inception of the 6G Flagship programme, complemented by contemporary insights. In these pages, our experts take stock of the journey, charting the milestones reached and projecting the trajectory of 6G technology.

Immerse yourself in a compilation that connects seminal decisions with the newest developments, navigating from 6G Flagship's origins into the future of 6G.

**Katja Longhurst**, **Ville Wittenberg** and **Sallamaari Syrjä**
6G Waves editors
6G Flagship, University of Oulu, Finland

# NATO DIANA ONBOARDS OULU'S 6G TEST CENTRE

***NATO's DIANA Board has approved Finland's proposal to establish two test centres and an innovation accelerator in Finland. A new test centre for 6G technology will be established in Oulu.***

The Ministry of Defence is the national responsible authority for the project, and the Technical Research Centre of Finland (VTT) coordinated the preparation of Finland's proposal in cooperation with the Ministry. The Ministry of Defence submitted Finland's proposal to the DIANA Board in July 2023.

## Innovative Test Centres and Accelerator

Technology test centres will be established at the University of Oulu and VTT's Otaniemi sites. Coordinated by the University of Oulu, the test centre will enable companies to test 6G network technologies. The Otaniemi test centre will focus on testing cyber-secure communication and quantum and space technologies. The test centres can, for example, evaluate concepts and technologies developed by companies and provide support for their development.

VTT will also set up a business accelerator in Otaniemi, Espoo, in cooperation with Aalto University and the University of Helsinki. The accelerator will focus on future communication systems and quantum technologies and provide training for companies in business development in the defence sector. The accelerator's services are targeted particularly at start-ups and SMEs with limited experience in the defence and security sector.

***Our 6G Test Centre provides global partners of NATO's DIANA programme with a testing facility for products and solutions for dual-use applications in telecommunications and defence services.***

## 6G Test Centre in Oulu: A Hub for Advanced Research

The 6G Test Centre in Oulu will provide advanced wireless communications facilities, services and processes for research and business testing. The University of Oulu will manage the test centre in cooperation with VTT.

"We have a long history in military communications research since the late 80's. In recent years, the role of dual-use technologies has dramatically increased making defence vertical a natural extension to the 6G Flagship research portfolio," says Matti Latva-aho, Director of 6G Flagship.

"The 6G Test Centre will serve as an advanced global test centre providing services for the development and testing of future dual-use technologies for NATO's DIANA partners and defence industry actors," says Jukka Riekki, Dean of the Faculty of Computer Science and Electrical Engineering at the University of Oulu.

"Our new 6G Test Centre will be a research and service centre for high-tech wireless telecommunications and communications. From a research and product testing perspective, we already have the capability and capacity to offer our facilities and expertise to partners. We will make use of our own 5G/6G test network and laboratories as appropriate, and we will also have new separate facilities for the test centre," adds Hannu Nikurautio, Research Director at the University of Oulu's 6G Flagship, responsible for strategic research in the defence sector.

# NATO DIANA ACCELERATOR AND TEST CENTRES IN FINLAND

**The Ministry of Defense – the national authority responsible for the project**

**VTT – coordinator of the implementation**

### NATO's DIANA accelerator

**Theme:** Next-generation communication systems and quantum technologies
**Location:** Helsinki metropolitan area
**Leader:** VTT LaunchPad startup incubator
**Partners:** Aalto University, the University of Helsinki and other partners

### NATO's DIANA test centre

**Theme:** 6G
**Location:** Oulu
**Leaders:** The University of Oulu and VTT
**Research environments:** 5G test networks (2025 ➔ also 6G test networks), sensor network environments, simulation environments, edge computing environments, interference-free test facilities.

### NATO's DIANA test centre

**Theme:** Secure Connectivity, Space and Quantum
**Location:** Espoo, Otaniemi
**Leader:** VTT
**Research environments:** test environments for communication technologies, quantum computers, cybersecurity development environments, and laboratory and cleanroom facilities for space technology development and testing.

**Funding providers and business partners**

The test centre will provide users with access to world-class, rare radio frequency measurement equipment. All measurements and testing related to the development of 6G technology can be carried out in one place. 6G antennas, radios, and radio-frequency integrated circuits (RFICs) can currently be studied in Oulu at up to 330 GHz. The test centre includes a large RF anechoic chamber and RFIC sensor stations, essential for successful radio testing.

## Emerging Technologies and Future Directions

"Our 6G Test Centre provides global partners of NATO's DIANA programme with a testing facility for products and solutions for dual-use applications in telecommunications and defence services. It will contribute to developing critical application areas, such as autonomous mobility and machine-to-machine communications," says Hannu Nikuratio.

The 6G frequencies and radio technology using large antenna arrays at the test centre enable research aimed at combining communications and observation. 6G networks, for example, aim to combine the capabilities of a mobile communications network and radar by using radio equipment to transmit data and detect objects in the environment and observe even small changes in them. The test centre will also provide a platform for integrating artificial intelligence into distributed solutions to manage the 6G network, control devices and implement user applications.

"The test centre's 6G network is based on 5G technology, which enables its use and functionality already today. The transition will be smooth. The network and test environments will undergo continuous updates to meet NATO and defence requirements and to provide services and technological solutions for critical needs," assures Nikurautio.

## Oulu's Pioneering Role in 6G Technology

"The location of this entity in Oulu and its coordination by the University of Oulu proves that Oulu is a pioneer in 6G technology and plays a key role in the further development of the new technology. We were the first in the world to start researching this [6G] even before 5G was commercially deployed. We have built up expertise in the 6G field over a long time. This is a good foundation to move forward," Jukka Riekki expresses his contentment with the progress.

## NATO's DIANA Initiative and Dual-Use Innovations

NATO's DIANA (Defence Innovation Accelerator for the North Atlantic) aims to identify future challenges in the defence sector and find technologically innovative solutions with companies. DIANA focuses on new technologies such as artificial intelligence, autonomy and quantum technologies that are dual-use, i.e. that can be commercially exploited in both the civil and defence sectors.

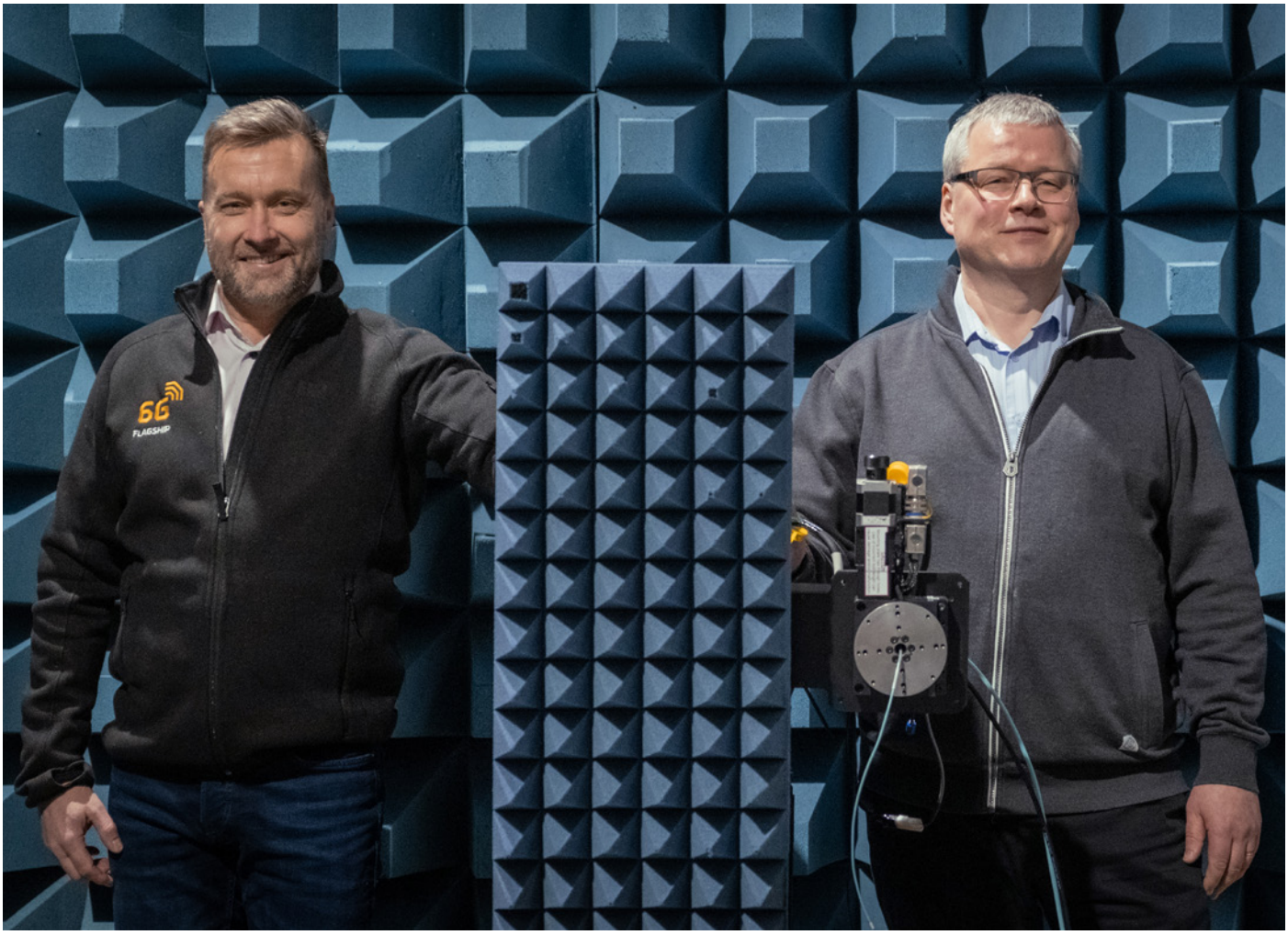
Most dual-use innovations are currently market-driven in the civil sector. This requires new mechanisms to identify promising technology developers and more robust integration of the defence sector into commercial innovation ecosystems.

DIANA

**DIANA accelerators and test centres worldwide**
*diana.nato.int/test-centres.html*

**DIANA website**
*diana.nato.int*

**6G Test Centre website**
*6gtc.com*



# RESILIENCE

## AT THE CORE OF MOBILE 6G EVOLUTION

***The upcoming 6G technology era is expected to significantly advance connectivity, creating a new era of unparalleled speed and reliability. One crucial factor that must be considered is resilience. As we prepare for the next generation of mobile networks, the ability to recover quickly from disruptions and challenges becomes critical.***

Reflecting on our journey, the 6G Flagship programme's foundational commitment — as chronicled in articles like "Let's Set our Minds Free!", "6G Is the Glue that Binds Everything Together" and "Going From Device-Centered To Human-Centered Technology" — have been instrumental in paving the way for the resilience-focused development we are now undertaking. Our early initiatives in exploring new spectrums and establishing the 6G Wireless Summit were important starts for global research collaboration on 6G. These combined efforts serve as the foundation for our current and future progress.

### Foundations of Resilience in Mobile 6G

The endorsement of the Joint Statement for 6G in February 2024 was a key milestone for 6G's resilience and security, setting foundational principles of security, openness, and resilience. This commitment by ten countries, Finland, the United States, Australia, Canada, the Czech Republic, France, Japan, the Republic of Korea, Sweden, and the United Kingdom, highlights a larger consensus on developing superior, future-ready networks.

In addition, the infusion of autonomous systems powered by artificial intelligence is set to play a crucial role. These systems will dynamically adapt to changing conditions, identify vulnerabilities, and implement real-time corrective measures. The outcome is a network that can learn and adapt, reducing downtime and guaranteeing a seamless service without interruptions.

### Challenges on the Horizon

However, the road to a resilient 6G network has hurdles. As the internet's connectivity grows, cybersecurity concerns become even more significant. The need for advanced encryption, secure key management, and real-time threat detection mechanisms is more pressing than ever. Great speed comes with great responsibility, and securing these lightning-fast networks is paramount.

Nature, too, poses challenges. Extreme weather events, natural disasters, and geological disturbances can wreak havoc on traditional infrastructures, including telecommunication infrastructure and energy grid. Designing 6G networks that can withstand these challenges becomes critical to ensure connectivity even in adverse conditions.

## Strategies for a Robust Future

To fortify the foundations of resilience, strategic measures are imperative. Redundancy and diversity in network components are touted as key strategies. This ensures that alternative routes can swiftly step in if one part of the network falters, mitigating disruptions.

Edge computing, a buzzword in tech circles, is not just a trend but a resilience strategy. Bringing computational power closer to users reduces latency and enhances responsiveness, thus fortifying the network against potential disruptions in centralised data centres.

> ***Resilience in the world of 6G is not a solo act; it's a global symphony.***

Dynamic spectrum sharing, another crucial strategy, allows for flexible allocation of frequencies. This adaptability ensures the network can weather changing demands and incumbent spectrum needs, optimising spectrum usage in real time.

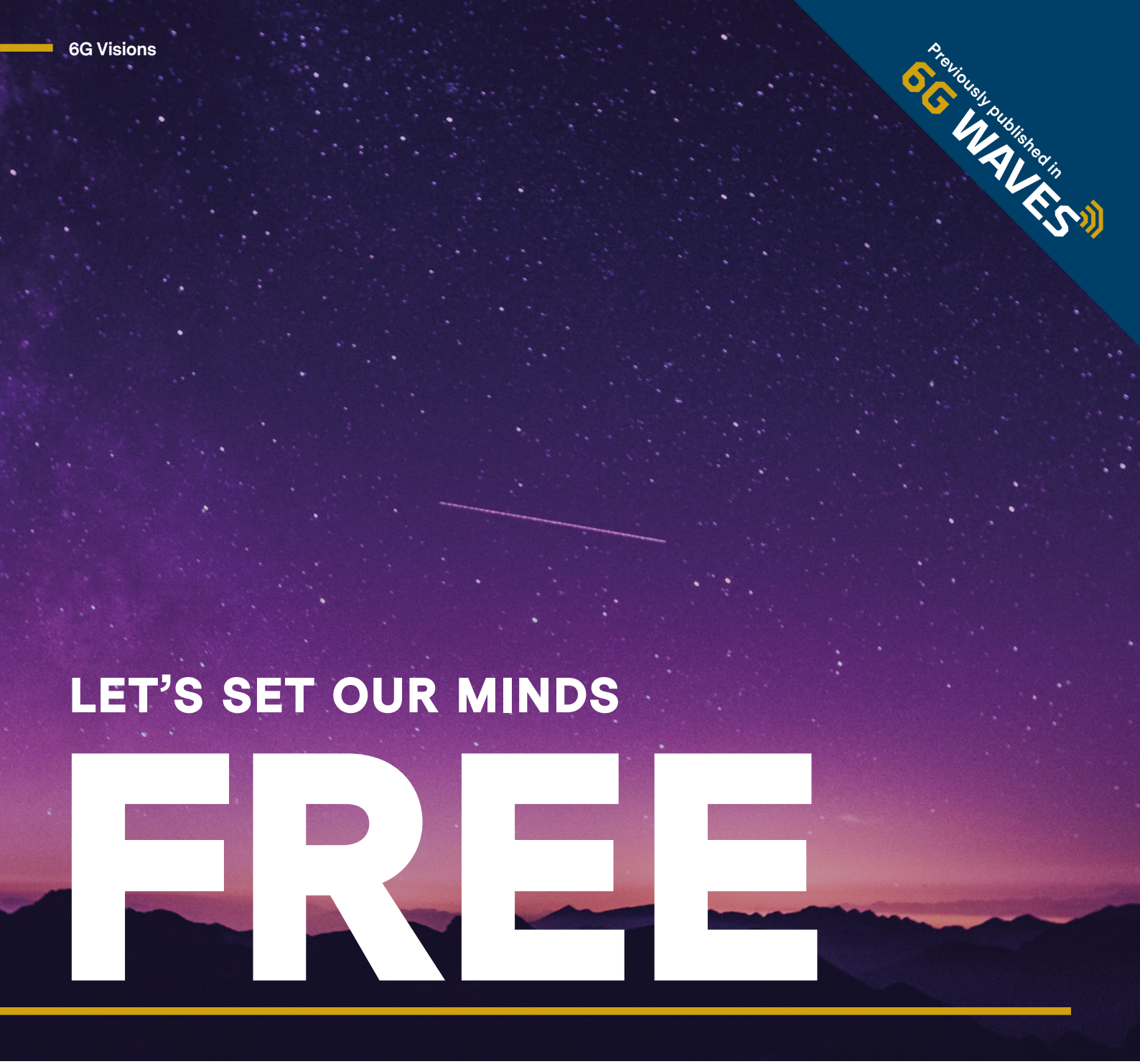
## Global Collaboration and Standards

Resilience in the world of 6G is not a solo act; it's a global symphony. Collaboration on a global scale and establishing interoperable standards are a must. Shared best practices, harmonised regulations, and collaborative research efforts will be the pillars of a resilient 6G future. The journey toward 6G is not just about speed; it's about building networks that can stand tall amidst the challenges of our ever-evolving digital landscape.


### About the Writer

**Professor Matti Latva-aho is the Director of 6G Flagship at the University of Oulu, and an IEEE Fellow with a distinguished record in pioneering wireless communications research.**

Previously published in 6G WAVES



# LET'S SET OUR MINDS FREE

***6G research is gaining momentum all around the world now that 5G NR and its evolution path has become quite obvious. WRC'19 did not yet offer a significant spectrum regulatory booster towards 6G but that is exactly why 6G research will experience a Klondike gold rush during the next few years. No boundaries have yet been set for 6G requirements and therefore we have to set our minds free!***

Of course, researchers would need some funding to grease the wheels and several governments have already started building national 6G programmes. In Finland, we started already in May 2018. We felt that one of the first things to do is to set up an international forum for the growing 6G research community where all researchers, from any part of the world, can get together to define fundamental requirements and key drivers towards 6G. In the middle of the trade war between US and China, this is utterly important. As a result, 6G Wireless Summit was born.

We in 6G Flagship have taken a very ambitious path via open white paper expert groups which aim at defining critical research questions related to some of the key areas of 6G. Moreover, we have felt that our community must take United Nations' Sustainable Development Goals (UN SDGs) seriously and we should define key performance indicators (KPIs) aiming at reaching the UN goals. Not an easy task by any means!

This work has given rise to several serious questions on how to enable global coverage in an affordable manner to those

who are currently unconnected. This is a question related to several issues of economic, political, regulatory, business as well as technical challenges. Data security and privacy are also growing concerns together with ethical questions. So, 6G most definitely deals with many other issues besides wireless connectivity challenges.

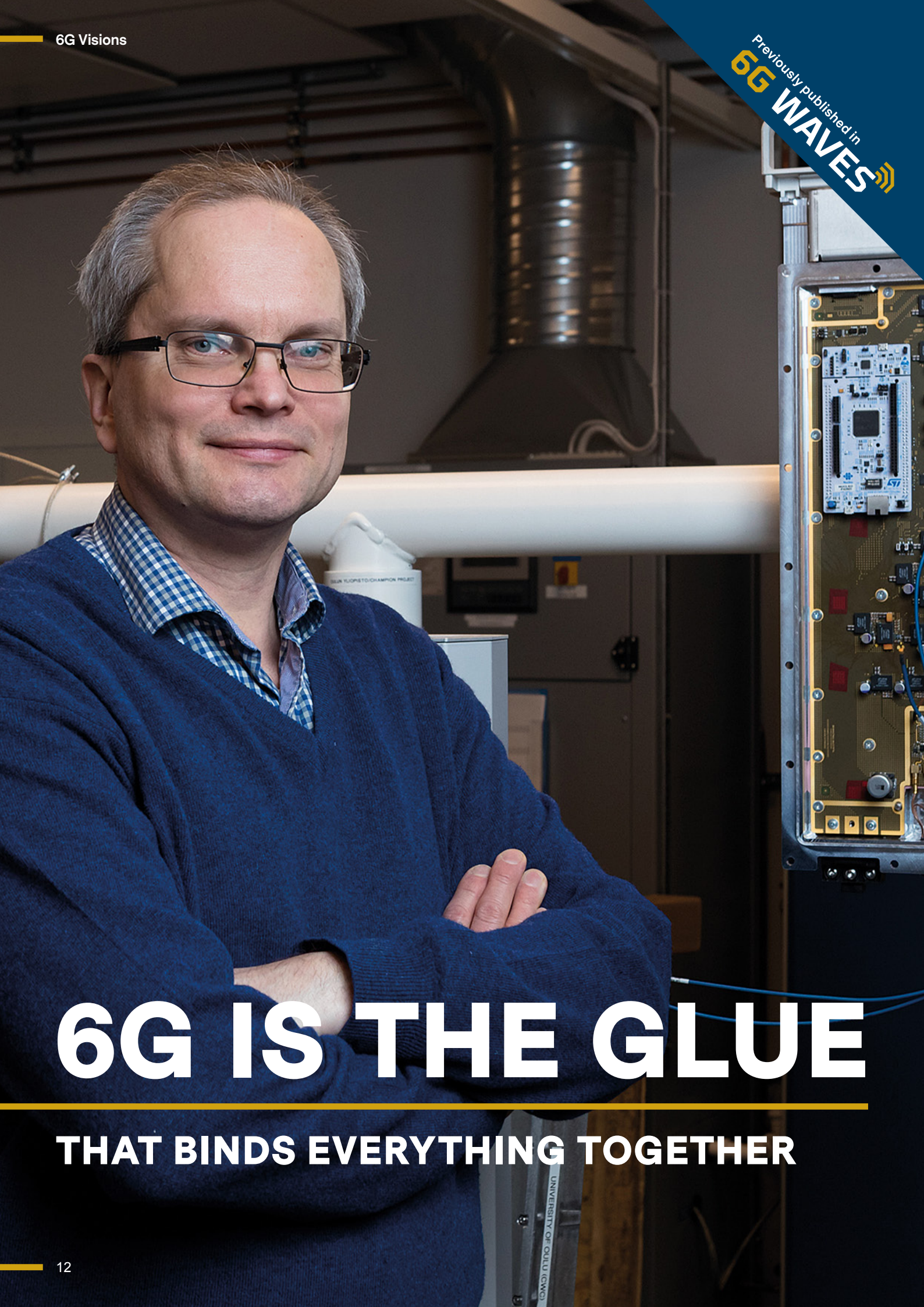
Another interesting, although obvious, venue towards 6G is responding to the ever-increasing demand for broadband wireless connectivity. An evident trend towards mmWaves and even beyond will change RAN technologies quite dramatically. Very accurate beamforming and physics of radio wave propagation will transform the way networks operating at high frequencies should be designed. Super-efficient short-range connectivity solutions are needed to offer Tbps speeds mainly in indoor as well as inside vehicles. In machine-type communications, the uplink capacity needs to be boosted with more limited transmitter capabilities compared to downlink direction. Again, a great challenge to be looked at as well as many other transceiver implementation-related research topics. After all, 5G has already shown needs to improve transceiver energy efficiency dramatically.

A great promise of 5G has been a dramatic increase in different verticals. We may think of designing, optimizing and even operating future mobile systems or parts of them by better understanding different key verticals through questions such as: what is a typical radio propagation environment, what are the capacity requirements, how about reliability and latency constraints, energy and cost constraints, network operation and ownership principles, what about spectrum availability, and so worth. Thus, verticals must be driving some of the development efforts of future wireless systems. Otherwise the current "one solution fits all" approach will continue leading to rather inefficient solutions.

Our 6G Flagship Programme based in Oulu, Finland is looking at all of these challenges and many more in a vivid international research community of more than 300 researchers from more than 50 countries. We are constantly looking for new collaboration opportunities, offering visitor positions as well as recruiting new staff members to cover the most relevant and demanding areas of 6G development. We will keep you posted on our work via this biannual 6G Waves Magazine. Enjoy reading!

**Professor Matti Latva-aho**
Director of 6G Flagship

Previously published in 6G WAVES



# 6G IS THE GLUE

## THAT BINDS EVERYTHING TOGETHER

***5G and 6G will bring about enormous and to a large extent yet-unforeseen changes, applications and consequences in business, but they will also provide hugely exciting opportunities for researchers. And the University of Oulu is well-poised to be at the forefront of the research.***

"Last year the focus was on building the networks and basic technology in a sense," says professor **Markku Juntti**. "I think this year we will see more reinforcements in the application arena." There are many projects running at 6G Flagship that will take advantage of 5G infrastructure. "This year they will be pushing full speed ahead," Juntti says. "I am specifically expecting to see concrete examples of applications in logistics, pilot projects in ports and so on. New applications in the new frequencies, this is what we will see this year."

Juntti says that 6G will be a pervasive element in research, technology and society. "It's the glue that binds a lot of things together. It has an impact on all the areas of ICT, naturally, but also on many other industries and businesses. 5G already will revolutionize many businesses, which will take advantage of the massive amounts of data from networked sensors, which will number in the billions. The amount of data and analytics in 5G will bring huge opportunities to all the sciences and industries, not to mention 6G."

Autonomous cars, AI, smart homes and connected appliances are standard fare when talking about 5G and beyond. What are the things Juntti expects will happen and become part of our everyday lives? "Measuring, monitoring and real-time analytics of data will change healthcare and lead to earlier reliable diagnostics," Juntti says. "Autonomous cars? Maybe in some form, but I don't think we will have so-called level-5 self-driving cars in all circumstances and on all roads. But they will observe their surroundings, transfer information to other cars or some database that is accessible to all. I'm sure there will be things like commercial local bus routes that will be operated by a driverless vehicle with a pre-defined path."

Then there is information security. All of these things require not only low latencies and massive computational capacities but networks and devices people can trust. "That's the whole thing," Juntti says. "No one will use our wonderful networks and shiny devices if they can't trust them. We've seen that any given technology that has benevolent uses is also susceptible to malevolent uses. So, information security is extremely important and that cannot be over-emphasized."

Juntti elaborates why the University of Oulu is an excellent place for exploring and studying future development of wireless networks. "One of the key factors in this is the business ecosystem that exists in Oulu," he says. "We wouldn't be able to do ground-breaking research without such close ties to industry, as all engineering sciences are applied in the end."

For Juntti, university training has personal and global significance. "I enjoy teaching and that's one of the most rewarding aspects of my job," Juntti says. "I really want to encourage young people to come and study with us. That's how change comes about, through people who study and graduate and then go out into the world. There are students from Oulu who are working in all the continents of the world – aside from Antarctica. So far."

**Read more**

*6gflagship.com/news/professor-markku-juntti-6g-is-the-glue-that-binds-everything-together*

Previously published in 6G WAVES

# GOING FROM DEVICE-CENTERED TO HUMAN-CENTERED TECHNOLOGY

***In 6G research, the year 2030 gets touted around a lot. By that time–still futuristic but ever approaching–the world will be a very different place, with ubiquitous, reliable and real-time connectivity and the planet will be the better for it. "Maybe," says Dr. Ian Oppermann, New South Wales Government Chief Data Scientist and Industry Professor at University of Technology Sydney.***

Obviously, Oppermann is all for digitalization and technological advancement, and in fact thinks there is no alternative path for us, if we are to survive as a species. However, there are important decisions to be made and serious conversations to be had about things like data, consent, privacy and trust.

"The big difference in the vision for 6G, when compared with 4G or 5G, is the movement away from being device-centered to being human-centered," Oppermann says. "People are put in the center both as sources of data as well as users of data. At the moment we get to decide what kind of world we want for us in the future, a world where we inevitably will be revealing more and more data about ourselves."

Already, we are creating very rich digital footprints as we use our devices. We constantly use sophisticated technology, casually exchanging information about ourselves for personalized services, the problems of which we are just working out. It is very easy to imagine benign applications now and in the future with, say, zero energy devices woven into our clothes, but it is getting increasingly more difficult to imagine every scenario where our personal information might be useful.

"It all comes down to the increasing number of ways we generate and use data. Think of a smart home, where the lights turn on and off as you move from room to room, where the heating is controlled intelligently by the number of people at home. That's already divulging your exact location and that you are with someone else," Oppermann describes.

"Imagine you have a smart toilet that analyzes your urine chemistry and gives you recommendations for what to eat, based on your phosphate levels. Maybe that information gets shared with your fridge and it suggests you should eat more bananas. There are many questions about this scenario, beginning with 'Can I trust this service?' And 'Who is responsible if this is not good advice?'"

## "Trust is a must in 6G"

Another convenient piece of technology might be a drone hovering above your home, providing you with an ad hoc mobile network (great), but in addition the drone can record your location (dubious, but OK) and perhaps measure your body temperature (definitely not OK). The obvious question is, do you consent to all of this? While it's easy to say that one wouldn't consent to giving away personal vital signs, many of us already do with devices intended to track our health. More than that, the little bits of data we give out might be

connected later down the road to satisfy new uses, ones we may or may not like.

”The more devices we connect with, in clothing, in shoes, in our cars and homes, the more difficult it becomes to give genuine and meaningful consent. End user agreements are alradyineffective and confusing. We can’t keep up with what’s already in place, not to mention in the future, and so consent and privacy as we’ve come to understand them are increasingly outdated concepts. Society must engage with these issues, as individually it’s very hard to take them on,” Oppermann says.

It is also very easy to imagine malign applications and services intended to restrict and harm human beings, like state surveillance to control citizens, or terrorist attacks designed to degrade or downright destroy systems deployed in societies, or cybercriminals threatening to release sensitive information about individuals unless they pay a ransom. As the COVID-19 pandemic was unleashed on the world and people – including politicians, military personnel and corporate staff–started working from home, remote presence technology suddenly created a huge number of new cyber attack surfaces. And as we put zero energy devices into building materials or clothing and have everything talk to everything else, the vulnerabilities will only increase.

But, even if we may have little chance of imagining all the consequences of having data harvested and utilized at this exponential rate, we do have the possibility to lay down rules, says Oppermann.

”Civil democratic society can say, look, here’s a set of principles that everyone must abide by, like you must never reveal the location of a child, or divulge anyone’s religious or sexual preference and so on. However technology is employed, these are the principles that must be followed. But we must be forward-looking and anticipatory in our conversations about society.”

The challenges in creating a trustworthy 6G are multidisciplinary, spanning technology, regulation, techno-economics, politics and ethics. ”Trust is a must in 6G,” agrees associate professor **Mika Ylianttila** who leads a research group focusing on network security and softwarization at the Centre for Wireless Communications, University of Oulu.

”There are many examples of popular applications people download to their mobile phones, which they cannot truly trust, and where all their personal data can end up when they give their consent in order to use the application. Typically the user data is uploaded to a cloud service, and stored and processed further and in many cases sold to third parties, of which the users may not have the slightest idea. Without more sophisticated ways of ensuring trust, security and privacy, there will be even more challenges in the future, as more services and technologies emerge where user data can be collected and utilized. Distributed ledger and blockchain technologies are one potential way to increase trust in the network, but also other considerations are required,” Ylianttila explains.

## A human in the loop

How to keep up with development, then? The answer is putting people in the center of technology, or insuring there’s always a human in the loop–if we’re smart. Artificial intelligence is already doing the easy stuff for us automatically and moving to more and more complicated tasks, but we need to decide what technology can and should do for us.

”For instance, deploying lethal autonomous weapons is an extreme example of automated technology. Another would be the automatic deployment of a COVID-19 vaccine that AI has deemed sufficiently effective. We obviously have to have standards to deal with issues like these and others,” Oppermann says.

Oppermann stresses that the conversations around data, technology and security are urgent. We have a chance to describe the world we want to live in, but we can’t choose all the good stuff and ignore the bad. 2030 isn’t the end point: we will have an extra billion people on the planet during that decade, and in the 2050’s another billion people on top of that. Meanwhile, we need to figure out how to feed everyone and how to, say, fight off infection as we are running out of effective antibiotics. To think that we could revert to a life where people won’t survive minor cuts is horrifying, but something we absolutely need to think about, says Oppermann.

”We can model RNA interactions and gene folding and we can do some things that are pretty damn amazing. The important thing is to realize is that we don’t do them because they are cool. We do them because we have to. We must rely on digital services that are increasingly vulnerable and that is why we need some pretty good standards,” Oppermann says.

Not because it’s interesting, not because it’s cool: because it’s survival.

***Janne-Pekka Manninen***

**Read more:**
*urn.fi/URN:ISBN:9789526226804*

# CAN DIGITALISATION MAKE OUR HEALTHCARE SUSTAINABLE?

***Our healthcare is struggling with sustainability challenges. If the global healthcare system were a nation, it would be the 5th biggest greenhouse gas producer in the world. On top of that, the healthcare system is a significant contributor to toxicity and waste production due to disposable materials and the high use of chemicals. The healthcare system also contributes to social sustainability, as not everyone has equal access to services.***

At the global scale, health inequalities are striking, and even in the Finnish or European context, they are a major. Moreover, all nations are struggling with the rise of healthcare costs. The costs of healthcare have been rising and are predicted to continue doing so, reaching levels which are not sustainable anywhere.

> ***We need to develop education models for future-proofing our health professionals and invest in the digital skills of all people – young and old, abled and disabled.***

Digitalisation is seen as one important mechanism to tackle sustainability challenges in healthcare. Data-driven decision-making can help us understand the contributors to health and make informed decisions that are not only better for individuals but also for society and the planet.

European efforts to make health data available and accessible through European Health Data Space show us a vision where data will guide us to getting healthier. By 2030, European citizens will have better access to their personal health data and can use that to better understand their health status and the services available to them. However, to get the best impact from health data, we need to ensure that the people working in healthcare and health-related professions, as well as the citizens, have the competencies to fully embrace this vision of data-driven healthcare. This means we need to develop education models for future-proofing our health professionals and invest in the digital skills of all people – young and old, abled and disabled.

The University of Oulu is building strategic competence in technologies that can make these visions a reality. Visions of future wireless communication systems, advanced sensing, and intelligent software solutions are all elements that can be designed to pave the road towards more sustainable healthcare. With the 6GESS – 6G-Enabled Sustainable Society profiling effort – the University of Oulu guides the visionary technology work with a sustainability focus.

Finland is a forerunner in digital health data solutions. We have a history of successfully building national infrastructures for health data and a long tradition of using the data. These experiences and competence are valued in the global context. Our efforts in exploring digital health as the enabler of sustainable societies will ensure we can continue creating impact also in the future.

## About the Writer

**Professor Minna Isomursu is the theme leader of citizen-centred health data solutions at the University of Oulu's 6G-Enabled Sustainable Society (6GESS) profiling area. Her work focuses on leveraging digitalisation to enhance healthcare sustainability and accessibility, contributing significantly to the field through research and strategic leadership.**

Previously published in 6G WAVES

## MONITORING AND DIAGNOSING SOLUTIONS FOR

# FUTURE WIRELESS HOSPITALS

***Interest in portable medical diagnosis and monitoring systems has grown dramatically in scientific circles and in the mainstream media. The attention is partially driven by the portable devices' potential to address well-acknowledged concerns such as overburdened healthcare in growing cities, assistance for an ageing population, and equality in rural health care. Portable medical monitoring also supports diagnosis and medical treatments in hospitals and can be used for diagnosis in exceptional situations like pandemics when hospital visits are limited.***

Recently, researchers have turned their attention to new microwave-based techniques that can be used for various medical monitoring and diagnosis applications. These techniques give new promise to developing portable, low-power, low-cost diagnostic devices.

"In cases of serious physical illnesses, like a stroke, which can result in severe disability or even death, prompt diagnosis is needed. For example, if we could confirm a stroke already while the patient is in the ambulance, the treatment could begin sooner, and the patient's chances of survival would dramatically improve. Also, detecting blood clots early is critical for avoiding major thrombosis. Currently, all the detection methods we use – magnetic resonance imaging (MRI), computer tomography (CT), and ultrasound – require a hospital visit. Patients with suspected blood clots in rural locations may travel for hours to undergo blood clot verification. Therefore, there is an obvious need for portable blood clot detecting instruments," says **Mariella Särestöniemi**, a postdoctoral researcher at the University of Oulu who works in the 6G-enabled sustainable society (6GESS) project as a Docent in WBAN radio channel modelling for medical diagnosis and monitoring.

Another timely and significant research area Särestöniemi reveals is tumour detection using portable devices. Microwave-based brain tumour detection techniques are of interest to researchers because they would allow portable tumour diagnosis equipment to be utilized as a preliminary diagnosis approach in remote locations. Because microwaves can permeate the entire head, microwave-based techniques can be used to image the brain through the skull. The method is based on detecting changes in signal propagation caused by heterogeneous tissue.

Detecting breast tumours has also been studied intensively for years. Recently, there's been renewed interest in devel-

oping a self-monitoring vest for microwave-based breast cancer diagnosis. With easily accessible devices, we may be able to reach women who decline in participate in routine screenings like mammography due to distance or fear of pain.

## How are body abnormalities detected using radio channel analysis?

Abnormalities like tumours, blood clots, or haemorrhages can be detected using radio channel analysis because their dielectric properties (e.g., relative permittivity and conductivity) differ from those of the surrounding tissues. Tumour detection, for example, is predicated on the notion that tumours have significantly greater relative permittivity values than surrounding tissues. Consequently, dielectric properties cause differences in propagation time, and power loss as the signal passes through the anomalous areas.

Intelligent channel analysis detects and localises anomalies by analysing radio channel characteristics between many antennas situated in the area where irregularities are presumed to be present and comparing them to reference data. With sensitive receivers, changes in radio channel data can be noticed, and the data can be evaluated in a server computer using AI-based algorithms. AI is employed to obtain an extensive reference data set to determine which changes in channel responses are attributable to variances in the physical parameters of the area under study and which are due to tumours of varying sizes.

One suggested approach for realising medical monitoring systems and remote healthcare is to merge Wireless Body Area Networks (WBAN) and 5G/6G connection so that WBAN captures in-body sensor data, which is then communicated to a hospital, for example, via 5G/6G networks. WBAN standard IEEE802.15.6 includes e.g., the UWB frequency band 3.1-10.6 GHz, a strong alternative for in-body, on-body, and off-body communications.

The 6G-enabled sustainable society (6GESS) programme capitalises on the 6G Flagship's technological expertise to develop the scientific framework for a data-driven, hyper-connected future society in which digital eHealth and future energy systems are intertwined. 6GESS investigates new technologies to help make healthcare and energy systems more democratic and efficient in the future. It will also help healthcare and energy providers as well as citizens become more involved in developing and using data-driven and digitised solutions.

**Researchers delved through several online databases recipes to create a 'brain phantom,' a mimic brain with the dielectric properties of a real brain. Concoctions with dielectric properties resembling genuine tumours were also made. Both liquid and 3D brain phantoms (with tumours in them) were inserted into a real human skull.**

6GESS
UNIVERSITY OF OULU

**The 6G-enabled sustainable society (6GESS) programme capitalises on 6G Flagship's technological expertise to develop the scientific framework for a data-driven, hyper-connected future society in which digital eHealth and future energy systems are intertwined.**

**6GESS is a collaborative endeavour of four faculties: Medicine, ITEE, Technology, and Oulu Business School. 6GESS works closely with the OuluHealth ecosystem, the Oulu University Hospital, and the Future Hospital 2030 project.**

**Read more:**
*6gflagship.com/6gess*

Previously published in 6G WAVES

# 6G WHITE PAPER ON VALIDATION AND TRIALS FOR VERTICALS TOWARDS 2030'S

***The research community is increasingly absorbed in exploring and developing technology enablers for 6G including radio components as well as network architectures of the future. It has become clear that one solution fits all is no longer feasible as innovation for new business models, introduction of novel use cases and vertical specific key performance indicators (KPIs) diversify the future wireless. Therefore, an analysis of real life systems is needed to offer concise views on most probable use cases, KPIs, regulatory aspects, and legislative changes as well as methodologies to implement them. At the same time, the UN SDGs and how to measure the effect towards the SDGs with a given system design are still very much open challenges.***

Based on 6G drivers, megatrends as well as assessment of the most opportunity-rich verticals with revenue expansion potential, the 16-person expert group that wrote the White Paper on Validation and Trials for Verticals towards 2030's selected seven vertical businesses and future software-based testing areas for discussion: industry 4.0, future mobility, eHealth, energy, finance and banking, public safety, and agribusiness. Early on in the writing process, the team of experts recognized that the different verticals require a very different set of capabilities from the wireless communication system stemming from the expected use cases within the verticals. "As our KPI table indicates, the selected verticals require a quite diverse set of KPIs," says **Prof. Ari Pouttu**, who led the white paper work. "They may lead to market adoption with vertical specific service providers who have thorough understanding of the needs, dynamics and the business of a vertical thus having a position of being able to provide optimized solutions for its customers."

This is also evident from the NTT DoCoMo white paper, which suggests that starting with 5G but fully flourishing with 6G, we shall have new vertical-specific markets appearing. Whereas a new cellular generation emerges every ten years and traditional value markets emerge every twenty years, the speed in the transformation of verticals is changing through digitalization. The potential technical KPIs under

6G umbrella are currently under discussion, mainly in the scientific community, with respect to the envisaged usage of future systems, cost implications, business cases, and technical feasibility. So, for the time being, no KPIs are agreed. ITU-R WP5D has initiated the development of a report on the future technology trends towards 2030 and beyond, which will later lead to agreed technical KPIs at the global level.

The white paper also introduces a roadmap which was conceived in conjunction with the idea of gradually transforming the 5G test network (5GTN) at the University of Oulu to 6G test network (6GTN) as we move towards 2030's. "The roadmap presents both expected technology developments needed and the most opportunity rich verticals," Pouttu says. "It also points out the regulatory and legislative changes required as we move towards the expected new business model innovations."

In the 6G era, it is expected that the peak data rates required will begin to approach the Tbit/s regime indoors, which will require huge available bandwidths. Examples of such applications could be 16K video resolution in 360° with a refresh rate of 240 Hz for a "true immersion" experience or holographic displays. This will necessitate a spectrum use beyond millimeterwave (mmW), giving rise to (sub-) terahertz (THz) communications. However, a large portion of the verticals' data traffic will be measurement-based or actuation-related small data, which in many cases, requires extreme low latency, because many processes aspire to 1,000–2,000 Hz control loops, necessitating over-the-air latencies in the 100 µs domain to allow time for computation and decision making as well.

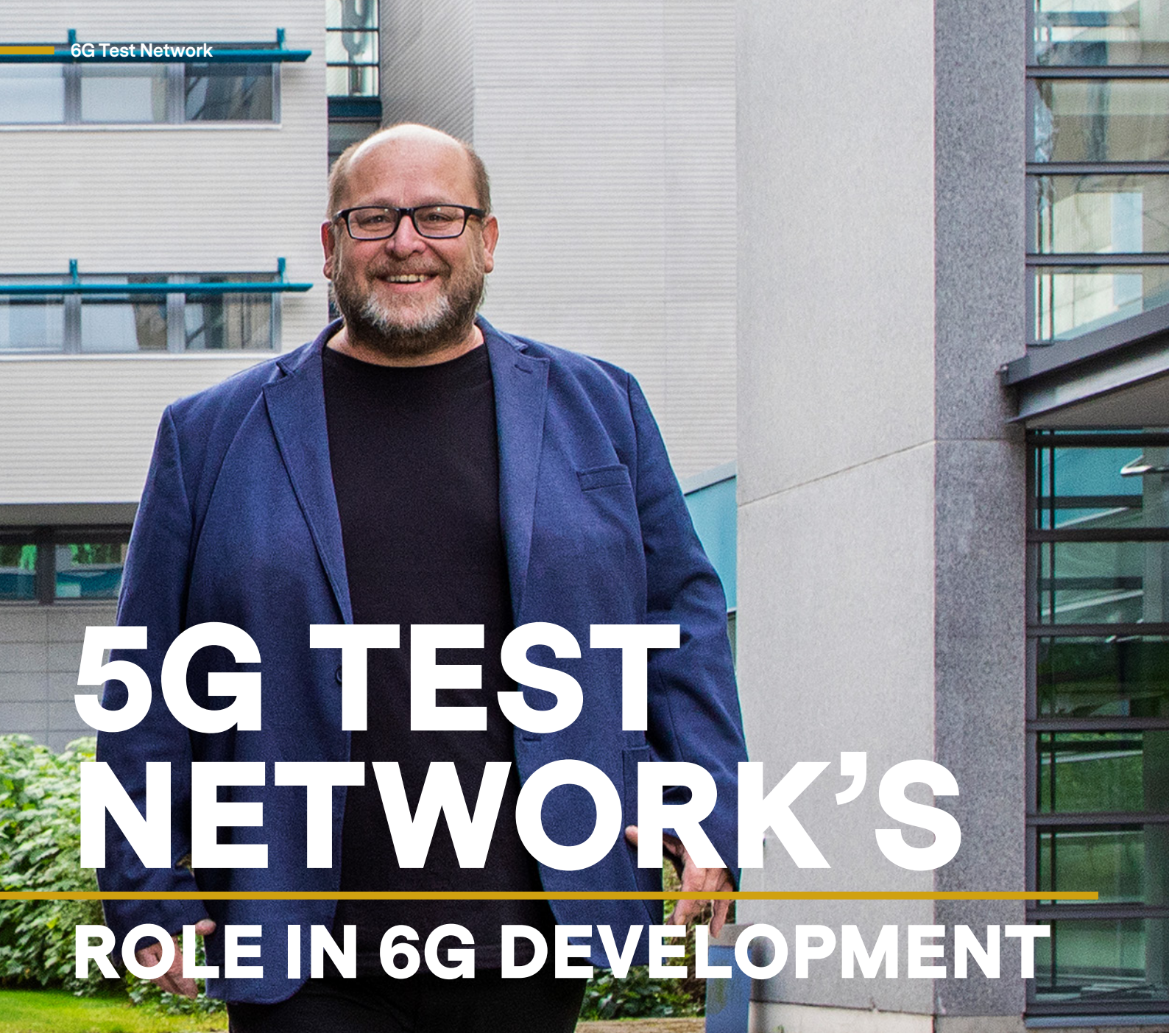
At the same time, the reliability requirement (which is the opposite of low latency) in many industrial, automotive, or health applications is expected to be of the order of 1–10-9. Even more challengingly, industrial devices and processes, future haptic applications, and future multi-stream holographic applications require timing synchronization to set requirements for transmission jitter of less than a microsecond. Many verticals will also need a multitude of extremely inexpensive sensors or actuators that are transmit-only or receive-only devices, hence requiring the granting of free access, because either the uplink or downlink is missing to reduce the cost.

To address the fact that different vertical industries may also differ considerably in their working environments, it may be worthwhile to define testing environments, which are individual to a certain industry type. "Thus, the goal should be to create a flexible and portable testing solution," Pouttu says. "With this, it will become possible to evaluate new testing ranges regarding their compliance with the reference testing system, and the compliance with given performance criteria (KPIs) can thus be evaluated by various neutral bodies." Only by taking this approach, will the industry-required certification of 6G industrial components become possible. And, only with such a certification, will the technology be adopted inside critical environments.

**Read more:**
*urn.fi/URN:ISBN:9789526226811*

| Vertical | Link Data Rate | Latency | Link Budget | Jitter | Density | Energy Efficiency | Reliability | Capacity | Mobility |
|---|---|---|---|---|---|---|---|---|---|
| Industry mMTC | < 1 Mbps | < 100 ms | + 10 dB | 100 µs | 100/m$^3$ | High | 1-10$^{-6}$ | < 10 Gbps | 240 km/h |
| Industry eURLLC | < 5 Mbps | < 100 µs | + 20 dB | < 1 µs | 10/m$^3$ | Nominal | 1-10$^{-9}$ | < 100 Mbps | 240 km/h |
| Mobility | < 10 Gbps | < 100 µs | + 20 dB | 100 µs | 100/m$^3$ | Nominal | 1-10$^{-7}$ | 1 Tbps | 1200 km/h |
| eHealth | < 1 Gbps | < 1 ms | + 10 dB | 100 µs | 1/m$^3$ | High | 1-10$^{-9}$ | < 10 Gbps | 240 km/h |
| Energy | < 1 Mbps | < 500 µs | + 40 dB | < 1 µs | 10/m$^3$ | Nominal | 1-10$^{-6}$ | < 100 Mbps | N/A |
| Finance | < 1 Gbps | < 10 ms | varies | N/A | 1/m$^3$ | High | 1-10$^{-9}$ | < 10 Gbps | Low |
| Public Safety | < 1 Gbps | < 1 ms | + 20 dB | 100 µs | 1/m$^3$ | Nominal | 1-10$^{-7}$ | < 10 Gbps | 240 km/h |
| Agri-business | 100 Mbps | < 10 ms | + 40 dB | 100 µs | 100/km$^2$ | Nominal | 1-10$^{-7}$ | 1 Gbps | 240 km/h |

**Some Key Performance Indicators for verticals.**



# 5G TEST NETWORK'S ROLE IN 6G DEVELOPMENT

***In the first Waves magazine, we highlighted the 5G Test Network (5GTN) as a key component of the 6G Flagship initiative. Further exploration was done in 2020, as detailed in the 6G White Paper on Validation and Trials for Verticals towards the 2030s[1]. We emphasised the importance of validation and trial activities, especially in addressing the requirements of vertical business sectors. The focus was on mmWave and sub-terahertz technologies.***

## Pathways to 6G

We now identify three prongs towards the realisation of 6G: 1) the evolutionary 3GPP path, 2) the O-RAN path, and 3) the disruptive 6G path.

The first involves aligning research with 3GPP standards to facilitate immediate testing, development, and innovation. This includes applications in health, energy, industry, critical communications, and vehicular sectors, leveraging mid-band frequencies (6-15 GHz) for compatibility with 4G/5G, offering up to 100 Gbps data rates, and improving latency and jitter.

The second prong, especially popular in the US, focuses on the softwarization of networks, including O-RAN and open-source solutions. It explores energy efficiency, protocol softwarization, and performance metrics like stability, latency, and jitter control.

[1] Pouttu, A. (Ed.). (2020). 6G White Paper on Validation and Trials for Verticals towards the 2030s. 6G Research Visions, No. 4. University of Oulu.

The third path ventures into disruptive 6G technologies, integrating sensing and imaging into radio systems and achieving terabits-per-second data rates and ultra-low latency. This enables advanced applications such as holographic communications, real-time digital twins, new industrial controls, cableless data centres, and in-chip radios.

## Funding and Collaborations Driving 6G Forward

Achieving our goals necessitates worldwide collaboration in research and substantial funding for network components. Fortunately, national support is available, with the Research Council of Finland allocating over €2 million for network investments. Additionally, through the Smart Networks and Services Joint Undertaking (SNS-JU), the EU Commission supports projects like 6G-XR, 6G-Sandbox, CONVERGE and SUNRISE-6G, which aim to create pan-European federated test platforms. These platforms leverage existing infrastructures to explore new 6G use cases within a larger system. The Business Finland 6G Bridge programme further enables the development of the network and 6G applications. Projects such as EMETA focus on metaverse solutions, EWARE-6G on energy-efficient networks, and 6GTNF on next-generation network innovations.

> ***Committed to continuous innovation, we do not stop at 6G.***

As these activities are project-oriented, a tool for the longer-term sustainability of the research Infrastructures is needed. European Strategy Forum for Research Infrastructures (ESFRI) has accepted SLICES-RI (an effort to build a pan-European research facility currently with 15 member states and 25 research institutions in ICT, including, e.g. high-performance computing, AI/ML, wireless) to its roadmap. Eventually, when operational, the SLICES-RI should allow funding to run the federated platforms as one until the 2040s.

## The Significance of 6G for Future Generations

I have been researching wireless cellular communications for nearly 30 years. The questions have been, "Why do we need 4G as we have 3G," "Why do we need 5G as we have 4G," and now (obviously) "Why do we need 6G as we have 5G?".

There are always innovators and visionaries who take advantage of new capabilities to create something unprecedented. For 6G, these may include holographic real-time photo-realistic metaverses with early application in remote conferencing but extending later to real-life copies of cities or businesses. Also, more down to earth, we have taken as a driver for 6G development the United Nations sustainable development goals (UN SDGs), meaning, e.g. to connect the unconnected and looking at sustainability in terms of social, economic, and environmental sustainability. This means supporting businesses around the world in generating services that are sustainable and also taking a look at the ICT sector's own footprint. For instance, we at 6G Flagship develop energy-aware network solutions and applications that can run year-on-year on renewables.

Since the 1980s, the University of Oulu has played a pivotal role in advancing wireless technologies, particularly since pioneering the 3G system. With over 600 experts, our ICT faculty spans the entire wireless ICT development spectrum. Significant national investments in ICT, notably the 6G Flagship programme, highlight our leadership. The Oulu region's vibrant ICT sector, bolstered by a strong Nokia R&D presence and its sole European factory in Oulu, fosters a dynamic ecosystem. Committed to continuous innovation, we do not stop at 6G.

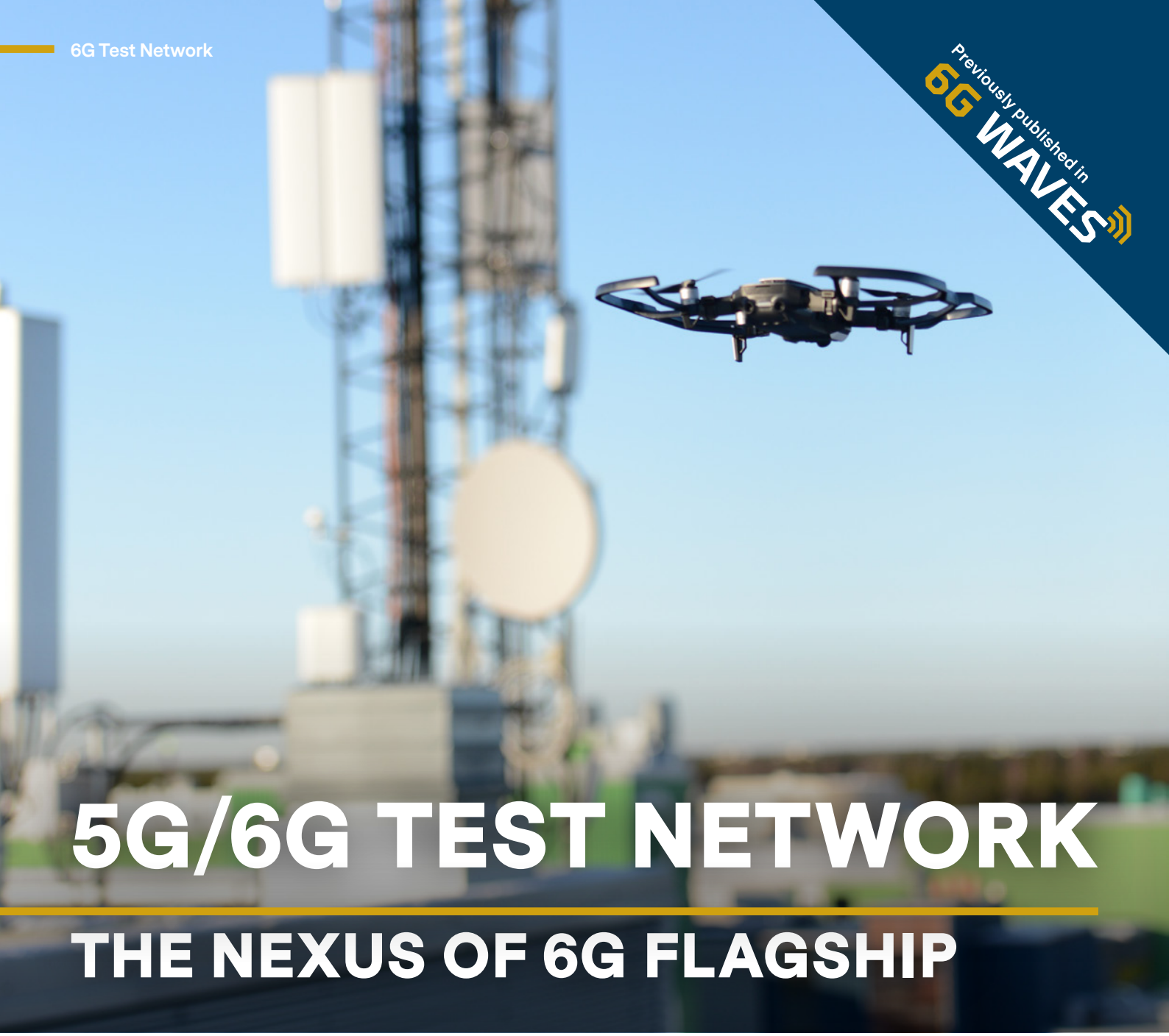
### About the Writer

**Ari Pouttu is a professor in Dependable Wireless Communications. He has scientific, engineering and management experience in fields such as synchronization, interference suppression, coding, modulation, and multiple access. He has been involved in cellular system designs since 3G (FP4 FRAMES).**

**The projects under his command have resulted in system designs for positioning, defence, radar systems, and energy. Furthermore, case studies are being performed for media, sports, maritime and the future hospital.**

**Currently, Pouttu serves as Vice Director of 6G Flagship programme. He also leads 5G Test Network research activities and the strategic research area, which develops solutions for business verticals such as industry, health, energy and automotive.**

Previously published in 6G WAVES



# 5G/6G TEST NETWORK

## THE NEXUS OF 6G FLAGSHIP

***The nexus of 6G Flagship programme is the rapidly evolving, open 5G Test Network (5GTN), which first introduced its advanced network functions to researchers and developers in 2015. As a focal point of connectivity, it simultaneously links test beds, novel devices and applications; theory and practice; as well as research and business. Bolstering 6G Flagship's research vision, the test network combines the development of future wireless technologies with new business models and new regulatory propositions and thus enables the creation of completely new application and service concepts based on them.***

The 5GTN team led by professor **Ari Pouttu** operates the network, which is built on major cellular network components provided by 6G Flagship's co-creator Nokia, and manages the more than 1 000 dedicated SIM cards, 2500 sensors, one of worlds largest indoor positioning systems, computation resources and state-of-the-art measurement equipment, that are available for trials, demonstrations and training – free of charge.

Unique in its diversity and structure, 5GTN provides access to multiple interfaces in advanced radio access networks (RAN), cloud-based virtualized core network controlled by SDN technology, and related service core network for applications. It offers several parallel 3GPP RAN technologies including NB-IoT, LTE-M, 4G-LTE (macros and picos), 5G NR macros as well as 5G proof of concept (PoC) on mmWaves (26-28 GHz). Recently, the architecture was complemented by 300 GHz radios supporting IEEE 802.15.3d. Also non-3GPP RANs, including WiFi, Bluetooth, and LoRa, are integrated in the platform. Open Air Interface (OAI) capable devices and core networks are also integral part of 5GTN. At the same time, in addition to normal smart phones, IoT sen-

sors, pre-commercial non-phone centric end-user devices as well as data storage and networking devices are available as well as support for processing needs arising from vertical businesses especially related to mobile edge computing, IoT services and sensor management.

As a research platform, 5GTN is especially suitable for research on verticals, which will be driving the way future wireless networks are developing both from technical and application characteristics perspectives. "We emphasize piloting and testing in various verticals," Pouttu says. "Our current focus areas are Industry and manufacturing, port and logistics as well as hospitals and health. We are also extending our capabilities in automotive and traffic, which are gaining increasing interest in the research community. Currently we are making our smart car 5G and beyond enabled and we plan to demonstrate connected autonomous driving with tests expected on border crossings between Finland and Sweden."

***We emphasize piloting and testing in various verticals.***

The team also integrates promising new technology components to 5G Test Network, including e.g. lidar-based asset tracking and drone based new services, to increase flexibility. The latest hardware acquisitions, on the other hand, support 5GTN's cloud-based radio architectural research, multi-mode radio interface integration and radio positioning, both indoor and outdoor as well as full 5G standalone core, which boosts 5GTN as an ideal open environment for testing end-to-end systems. "We would like to offer our research partners globally a flexible environment for international test cases covering use cases that are also global," Pouttu says.

For companies, 5GTN is an easily accessible integration framework where they can build and test technological and service-related solutions, and increase their expertise in developing, modelling and validating new concepts. The platform boosts research for challenging concepts never thought before and lowers the threshold and cost of innovation. Especially start-ups and SMEs benefit of the zero-cost option. If a user requires additional assistance or expert support to conduct experiments, compensation is considered on a case by case basis. Naturally, the platform also constitutes an excellent platform for any Horizon Europe collaboration.

5GTN offers a controlled environment for companies' service development. "We can use slicing or sandboxing to isolate experiments from each other," Pouttu says. "In addition, partners can run sensitive software also from their own computing resources that are connected to the wireless test platform over a VPN. Data from the experiments is handled confidentially if requested."

The roadmap for developing 5GTN towards 6GTN, was defined in 2018 and development has begun with full speed thanks to public infrastructure funding and collaboration with leading industry. The roadmap includes several critical steps, Pouttu confirms, starting with the introduction of 6G flavored TeraHertz proof of concept devices into the network. Full use of virtualization and cloud technology are included in the near-future targets of the upcoming 6GTN. As a result, the network becomes extra-secure and elastic with QoS and scalable resource pools for services designed to allow high-availability, high bandwidth and low latency for services. "This kind of capability is of critical importance when a test environment is built that can address the requirements stemming from different vertical needs," Pouttu says. "Slicing with dynamic resource allocation will be possible according to use, which requires intensive research and a solid infrastructure for algorithm validation to ensure network performance in all scenarios."

To address the fact that different vertical industries may have considerable differences in their working environments, it may be worthwhile to define testing environments, "golden references", which are specific to a certain industry type. So, the goal is be to create a flexible and portable testing solution. With this approach, it becomes possible to evaluate new testing ranges regarding their compliance to the reference testing system and by that the compliance to the given performance criteria can be evaluated by different neutral bodies. "Only by taking this approach the industry required certification of 6G-industrial components becomes possible," Pouttu states. "And only with such a certification will the technology be adopted inside critical environments."

Currently, THz range solutions are already being tested in the test network. Future updates will expand the research of materials, devices, waveforms, signal processing or distributed data driven network control paradigms. Improved capabilities in the next few years will furthermore support research of future radio interface, and RF assuming mmWave/THz high-capacity backhaul and fronthaul with MIMO antennas enabling adaptive beamforming. "With the addition of 6G flavoured capabilities, our test network will become an even more powerful nexus for our own innovation and co-creation especially with companies, academic partners and public sector," Pouttu says. "We can't wait to demonstrate selected vertical use cases together with our partners in the near future."

Previously published in 6G WAVES

# EXTREME ULTRA RELIABLE LOW LATENCY COMMUNICATION REVOLUTIONIZES SYSTEM PERFORMANCE

***Finland and South Korea are two countries with strong footprints in technology, particularly in wireless communications. After contributing to the world's first commercial success of 5G, the countries are now jointly developing future IoT connectivity for demanding industrial settings.***

Since April 2020, Electronics and Telecommunications Research Institute (ETRI) in South Korea and University of Oulu in Finland have collaborated on a joint project to build a long-term vision of next-generation Ultra Reliable Low Latency Communications (URLLC) services, focusing on specific use cases and key technical requirements.

Due to the growing demands from various verticals, especially Industry 4.0, it is crucial to evolve URLLC beyond 1ms latency and reliability of 99.999%. "Current 5G URLLC technology has inherent limitations to fully support future services in the view of data rate, connectivity, and latency," says Dr. **Hyun Kyu (HK) Chung**, project coordinator at ETRI. "These shortcomings emerge due to the mostly independent operation of three novel service scenarios in 5G: enhanced mobile broadband (eMBB) targeting broadband users; massive machine type communications (mMTC) targeting large numbers of IoT devices; and URLLC targeting communications with strict performance guarantees. Therefore, future 6G systems will need to integrate multiple, or even all, of the service scenarios, and must evolve to push the current limits to support an integrated but efficient framework."

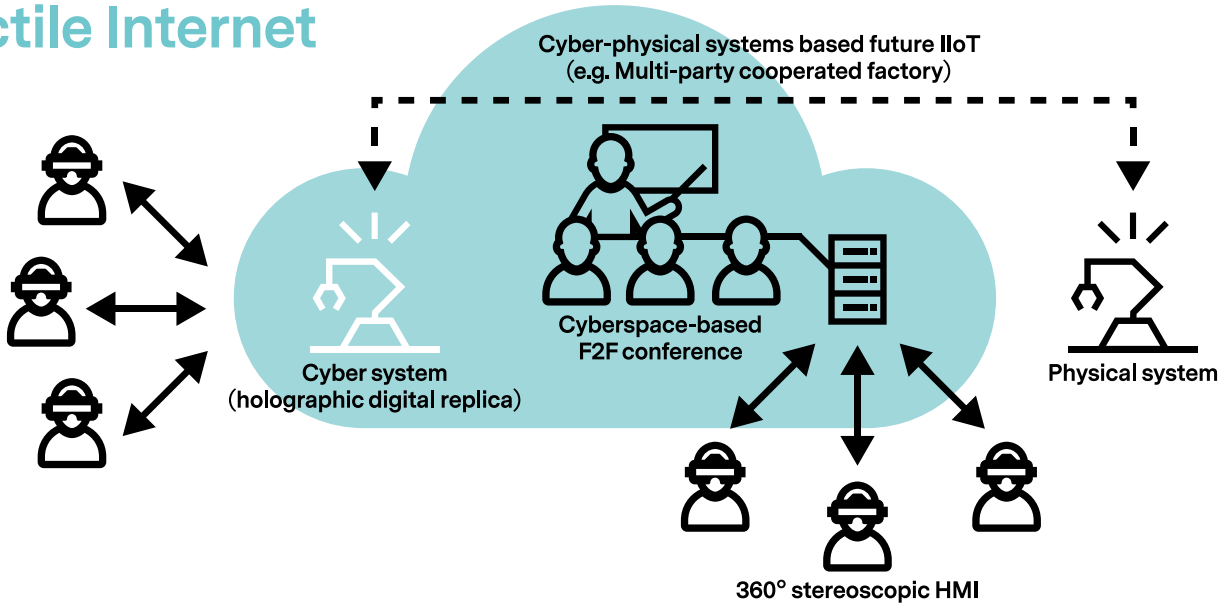
The joint work began with the question of identifying the evolution of URLLC from 5G to 6G and recognizing the areas where a clear disruption is needed. "We are now proposing new service classes such as broadband URLLC, scalable and extreme URLLC and investigating candidate enabling technologies," says Adjunct Professor **Nurul Huda Mahmood**, project coordinator in 6G Flagship. "Out of the many interesting open research questions on next generation URLLC, we have identified two core technology topics for joint research work - adaptive polar coding and position-aided predictive radio resource management - both of which are relatively novel topics with huge potential gain in improving the system performance."

Adaptive polar coding is a low-complexity coding scheme that is expected to ensure highly reliable transmissions that can easily adapt to the random fluctuations of the wireless channels. On the other hand, position-aided predictive radio resource management algorithms will utilize the location information of the devices and advanced predictive techniques to ensure high data rates with high reliability and low latency.

Tactile Internet, as a key driver for URLLC evolution, is an illustrative example of applications of these core technologies, which can enable various applications for example in Industry 4.0 use cases including digital twins and other human machine interface (HMI) applications.

A vast array of IoT devices collecting real-time data through robust wireless connectivity allows the digital twins to dynamically update and change along with their physical counterparts, collectively known as cyber-physical systems (CPS). A CPS-based Tactile Internet opens doors to a wide range of novel applications. For example, experts equipped with wearables and other HMI-enabled devices may remotely operate physical systems from distant locations, diagnose and repair them in case of failures, and make informed and rational production plans based on accurate predictions powered by advanced artificial intelligence algorithms. Furthermore, multiple experts located in different locations may seamlessly interact with the digital twins to virtually imple-

# Tactile Internet




ment and test new features before they are deployed in the real physical systems.

The Cyberspace-based tactile internet use cases, on the other hand, comprise of humans wearing wearables and interacting with virtual spaces implemented in the network, where the users feel as if they were present in a real place of interest directly interacting with its surroundings. One example is a face-to-face (F2F) conference where remote attendees feel as if they were in a conference room where they can look at any direction. The ongoing COVID-19 pandemic has further highlighted the demand for such applications.

The development of Tactile Internet based service scenarios in now ongoing and the project partners aim to validate them in real test network deployments at ETRI and University of Oulu that are already pushing the limits of current standards. "In practice, ETRI's state-of-the-art Industrial IoT Testbed, which is based on the latest 3GPP 5G release, shows that it is almost impossible to achieve end-to-end latency less than the minimum end-to-end latency required for some use cases in factory automation in recent 5G standard using the current 5G implementation," says Dr. **Jaesheung (Jason) Shin** who is a principal engineer at ETRI and the leader for the Test and Validation work package. "This motivates the development of an extreme URLLC service mode, which was suggested for the industrial use of 6G in a recent WWRF meeting and could be referred to in terms of our joint test network demonstrations in the future."

Considering the track-records and prior success stories in 5G adoption of ETRI and University of Oulu, this effort is expected to truly showcase how cross-continental collaboration promotes innovative research with high societal impact.

**ETRI**

**Electronics and Telecommunications Research Institute**

- National AI Research Institute, established in 1976
- Groundbreaking ICT innovator focusing on research, development and distribution of industrial core technologies in the field of Information, Communications, Electronics, Broadcasting and Convergence technologies
- Recent R&D achievements include Deepview – Visual intelligence source technology platform; Time Controlled Tactile Optical Access (TIC-TOC) – 25Gbps-class tactile Internet technology; and UHD mobile broadcasting technology
- ~ 2260 employees
- 2632 patent applications (domestic and international, 2019)
- 683 adopted standards contributions (domestic and international, 2019)

**Watch ETRI's video:**
*https://youtu.be/gsT_vvAfVbA*

# SUSTAINABILITY AT THE HEART OF 6G INNOVATION

***Sustainability was identified as the critical driver for 6G R&D in the world's first white paper published by the 6G Flagship in 2019. The white paper resulted from a stakeholder workshop at the 6G Summit in Levi in 2019. A follow-up white paper, published by the 6G Flagship in 2020, built a connection between UN SDGs and 6G. 6G Flagship's Director of Sustainability and Regulation, Marja Matinmikko-Blue, sums up where we are now.***

"The good news is that sustainability is included in all major agendas for 6G. A big milestone was reached in 2023 when the International Telecommunication Union Radiocommunication sector (ITU-R) published a globally agreed vision for 6G in its IMT-2030 framework recommendation," Matinmikko-Blue rejoices.

## Bridging Sustainability with 6G Development

A new element in the global 6G framework is to have four overarching design principles for 6G. These are sustainability, connecting the unconnected, ubiquitous intelligence, and security and resilience. "Incorporating sustainability, with its environmental, social, and economic facets, into the global 6G framework presented its challenges. However, we succeeded through persistent dialogue and collaboration," Matinmikko-Blue shares about the practical hurdles. The global 6G definition work is set to proceed with defining requirements.

According to Matinmikko-Blue, one of the hurdles in 6G R&D is the integration of sustainability as a core driver at the individual level. There's a need for crafting and implementing sustain-

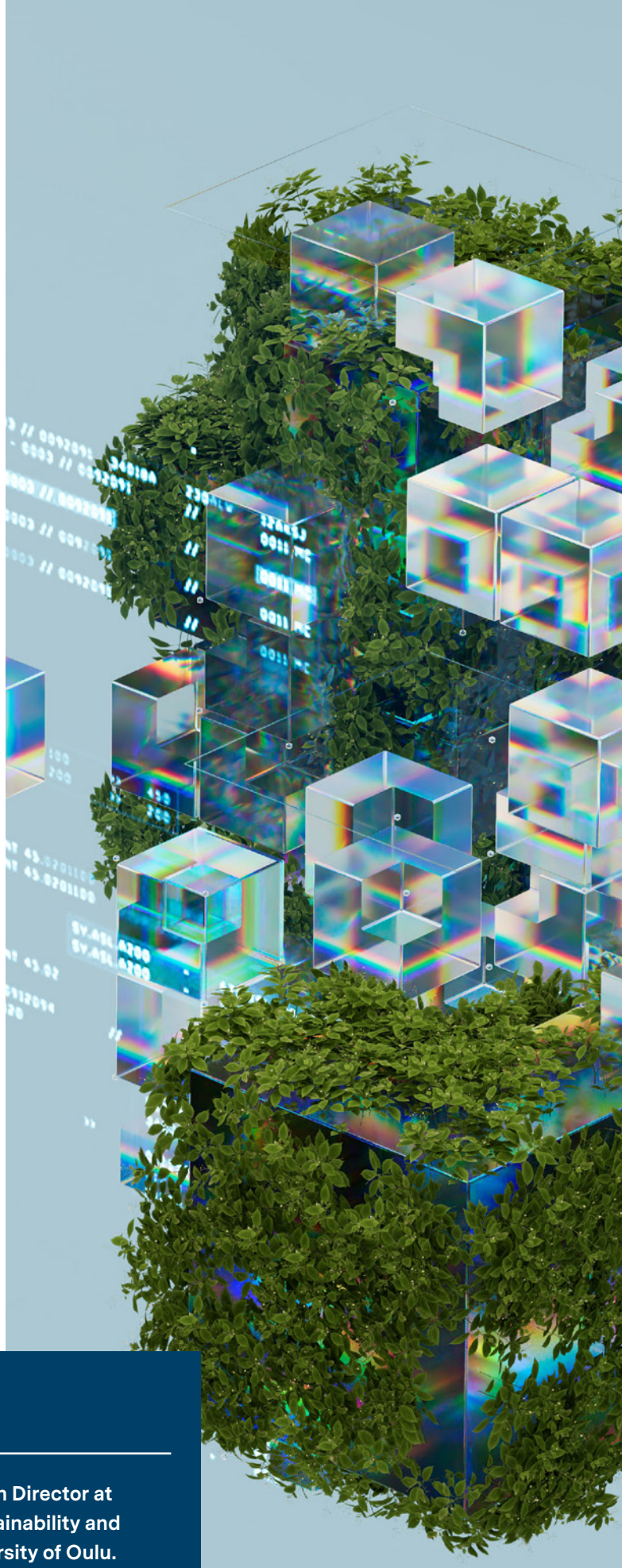
ability frameworks, including concepts, principles, indicators, and methodologies, within 6G development to achieve sustainable 6G solutions and utilise 6G to enhance overall sustainability. “This effort demands collaboration among various stakeholders and disciplines. Research initiatives are already exploring environmental, social, and economic dimensions of sustainability, advancing our comprehension of their impacts in the 6G sphere,” Matinmikko-Blue notes.

6G Flagship’s multi-disciplinary research agenda continues to cover business, regulation, technology and sustainability perspectives. “We published *The Changing World of Mobile Communications*, a book on the business of 6G including regulation and technology perspectives,” Matinmikko-Blue highlights the research approach taken in 6G Flagship.

## Fostering Multi-Stakeholder Collaboration in 6G Innovation

Multi-stakeholder collaboration between industry, academia and regulation has been a successful mode of operation in 6G Flagship. “I would like to see more researchers being active at the intersection of industry, academia and regulatory fora and conducting research that brings science-based knowledge to the decision-making tables,” Matinmikko-Blue urges. “This requires knowing and respecting the ways of working of the regulatory fora, which are quite different from the academic domain.”

“Academic research must enhance its interaction with regulation and businesses for tangible impact – especially in my favourite topic, spectrum management,” Matinmikko-Blue exemplifies. This issue is increasingly relevant today as the debate over the 6G spectrum gains momentum. “We should build on the insights from over a decade ago with cognitive radio technology to prevent a disconnect between academic research and advancements in regulation and industry within the 6G spectrum context,” Matinmikko-Blue advises. “This principle also applies to sustainability. Success lies in collaboration and leveraging solutions that other fields have already discovered,” Matinmikko-Blue adds in conclusion.




### About the Writer

**Marja Matinmikko-Blue** is Research Director at Infotech Oulu and Director of Sustainability and Regulation at 6G Flagship at University of Oulu. She also holds Adjunct Professor position in Spectrum Management.

# CARING OF SPECTRUM SHARING

***Marja Matinmikko-Blue** lives and breathes spectrum management. She realized very early on that wireless communications researchers must make assumptions on spectrum use but very few are aware of the reality of spectrum management. So she decided to bridge the gap between research and real life which led her to complete not only one but two doctoral theses in parallel with her contributions to spectrum regulation.*

For Matinmikko-Blue, the complexity of spectrum use is visible in latest developments. "Contentious 5G spectrum debates have resulted in divergent regulation between countries in terms of who gets to deploy 5G networks," Matinmikko-Blue says. "For example, the 3.5 GHz band awards and rules differ not only globally but even from one European Union country to another."

At the same time, the process lacks transparency. "One important group of people pretty much omitted in the 5G discussions are those living in the countryside," Matinmikko-Blue says. "They will not benefit from 5G if networks are not accessible to them."

However, with the adoption of 5G, local licensing is starting to become a reality, which allows different stakeholders to deploy their own 5G networks in specific premises. "When we started to talk about local spectrum licensing and operator models five years ago, the opposition was very strong," she says. "During the last few months, local licensing has become possible in several countries which promotes innovative location-specific solutions for instance in factories and ports."

In ten years from now, Matinmikko-Blue would like to see more flexibility and less confrontation. "We should realize that in the societal level it is not sustainable to let the spectrum use continue to be inefficient," Matinmikko-Blue says. "Valuable spectrum is largely under-utilized because of the


way it is allocated. Existing spectrum users should stop selfishly defending their rights, and spectrum sharing should be the new norm in 2030."

Matinmikko-Blue stresses that sustainability in all forms should be taken seriously. It is imperative to perceive spectrum as a natural resource, which must be managed and used in a sustainable manner. In line with this approach, Matinmikko-Blue initiated the development of a White Paper on the connection between 6G and United Nations' Sustainable Development Goals (UN SDGs). The outcome of the expert group will be published in spring 2020. "Efficient use of spectrum is a major design criteria in the development of any new wireless system, but efficient use of spectrum across wireless systems as a whole, is not yet a design criteria taken seriously at the societal level," she says. "The development and deployment of new wireless systems should not be postponed by incumbent technology claiming overstated protection needs."

Her strong message on spectrum management relies on 15 years of solid multidisciplinary research and wide international collaboration with industry and regulators. "I guess you can call it a passion," Matinmikko-Blue concludes. "At least it's a topic I discuss every day at home with my husband whom I brought home from an ITU meeting."

Previously published in 6G WAVES

# SUSTAINABILITY MUST BE TAKEN SERIOUSLY

***6G Flagship appointed Dr. Marja Matinmikko-Blue Director of Sustainability and Regulation in October 2021. The appointment not only formalises the importance of sustainability and regulation in the long-term 6G research, development, and innovation (RDI) but also urges to act now.***

Being a researcher, Dr. Marja Matinmikko-Blue's approach on sustainability builds on firmly established principles and practical impact. "I see sustainability as the big goal and sustainable development as the actions needed to achieve the goal," she explains. "What sustainability means to me comes from the decades' old definitions – the principle of ensuring that our actions today do not limit the range of economic, social, and environmental options open to future generations. Therefore, there is no need to reinvent the definitions, but we should instead focus on the ways to bring sustainability into reality in our day-to-day research, development and use of information and communication technologies (ICTs)."

Right after her appointment, Matinmikko-Blue hosted two webinars on ICT and sustainability – a panel on ICT sector's own sustainability impact and another panel on ICT's enabling role in future sustainable society. The panellists represented different stakeholder perspectives of academia, industry, and regulation. Similar topics were discussed in both panels but from different points of view covering especially the role of regulation and standards, societal, economic, and environmental sustainability, and connection to UN SDG framework, and the stakeholders' views differ. "Reaching long-term compromises requires proper stakeholder man-

agement so that relevant voices are heard, not forgetting the academia," she stresses.

## Promise of sustainable 6G

Joint 6G vision building led by 6G Flagship has identified sustainability as a key driver for 6G already in 2019. "Now 6G vision building is taking more concrete steps but sustainability seems to be ignored," Matinmikko-Blue laments. "Researchers struggle to figure out what sustainability means in the context of their own research, which is where I want to contribute," she continues. "If designed intelligently, 6G can decrease the environmental footprint of the telecommunications sector. Currently limiting the inevitable growth has dominated the discussion."

Yet, the ICT sector has the potential to enable new applications that will help other sectors to fight major sustainability challenges, including the climate change. There are great expectations for 6G to boost global economic growth, create new business models and enable the technologies needed to reach global sustainability goals. "We need to set the goals high together with relevant stakeholders," Matinmikko-Blue urges. "We cannot wait until 2030 and 6G and we should not only stress ICT's enabling role. There is so much that must be accomplished within the ICT sector itself in the coming years including indicators and measurement methods for the sustainability of ICT and making real data available for the research community to develop new innovative solutions. For me the continuing demand for more and more mobile data contradicts the sustainability principle and new indicators are needed to assess nations' forerunner position in mobile communications instead of total consumed mobile data."

## Good for humanity

Matinmikko-Blue's appointment also covers regulation, which is a key tool towards sustainable solutions. "In science, regulation is often about managing complex systems according to a set of rules and trends, and in a legal context it is related to official rules," Matinmikko-Blue says. "ICT sector and specifically telecommunications are highly regulated. It is important to understand this complexity in the development of future solutions to be able to have real impact."

Matinmikko-Blue's own research topic, spectrum management, cannot be addressed without considering related regulations. "New innovative sharing-based spectrum access approaches have remained as an academic exercise to a large extent, not adopted widely in regulation," she notes. "Also, new regulations related to sustainability aspects are needed and their impact on the sector is unknown."

How should regulations change towards 2030 is a topic to address. And why should academia act? "My approach has been to emphasize expertise and inter-disciplinarity – neither of which is truly accomplished without stakeholder collaboration," Matinmikko-Blue underlines. "It is easy to get lost in opinions and details to promote one stakeholder's interest and forget the bigger goal. In an industry that is often steered by the short-term goals of individual stakeholders, I attempt to guide long-term outcomes that are good for humanity. We are all impacted by telecommunications development, and it is important that future deployments are ubiquitous, sustainable, and affordable to all."

Matinmikko-Blue has been a regular speaker in different forums, not afraid to bring up topics that differ from the mainstream such as promoting spectrum sharing and introducing new local 5G operator models. In her new role as Director, Sustainability and Regulation of the 6G Flagship, Matinmikko-Blue says she can officially spend her days on sustainability and regulatory issues in the context of mobile communications and more broadly ICT. "I took a cross-disciplinary approach 20 years ago when I realized that the development of new wireless solutions was heavily influenced by the underlying regulation and business aspects," she says. "It has not been a straight-forward path, but I have not regretted it. After all, research is collaboration with stakeholders, and we should do everything in our sector towards the big goal of sustainability."

**Read more:**
*6gflagship.com/news/6g-flagship-appoints-dr-matinmikko-blue-director-sustainability-and-regulation*


# WIRELESS INFRASTRUCTURES ARE ENABLING REAL-WORLD AI

***Wireless infrastructures are bringing artificial intelligence applications to the physical world. The impacts of the ongoing ultra-densification of wireless communications were foreseen nearly a century ago by Nikola Tesla. In an interview with Collier's Weekly on January 30, 1926, he expressed a vision: "When wireless is perfectly applied, the whole Earth will be converted into a huge brain, which, in fact, it is, all things being particles of a real and rhythmic whole."***

This prediction astonishingly mirrors today's advancements in radio technologies and the integration of distributed artificial intelligence with the physical world, a research challenge that we investigate within the 6G Flagship.

Recent developments in artificial intelligence have been propelled by the vast amount of data, including images and textual content, available from the internet. Integrating AI with physical reality could, in the long run, enable robots to perform regular household chores, from loading washing machines to making beds. We anticipate seeing innovations in this category by the early 2030s to assist us in everyday life.

When higher frequency bands are used for communications, radios can be used as sensors in addition to transmitting data. They work without illumination and can supplement and occasionally even replace cameras. The sensing

modalities range from use as radars to channel analysers. With antenna arrays, radio energy can be directed precisely, enabling effective sensing strategies. Computer vision and radio communications face similar hurdles, suggesting that a unified development of solutions could lead to their seamless integration.

Intelligent ubiquitous wireless-vision systems in our environment could improve traffic safety, for example, by providing the capability to see cross-traffic behind corners. The same communication radio-based sensing technology could be enhanced to detect medical emergencies such as ventricular fibrillation.

Our research aims at fulfilling Nikola Tesla's vision and beyond. The bottlenecks we address include sensing, machine learning, and energy dissipation. Faithful 3-D modelling provides a digital twin that is a virtual replica of the real environment. In the virtual domain, artificial intelligence can, via trial and error, simulate combined sensing and communication, as well as learn action strategies that can be safely taken into reality.

We have built a multi-modal sensing laboratory as an experimentation environment to bridge between real and virtual representations. Efforts are underway to add humans to the simulations and experiments. Deep reinforcement learning is a promising method for handling the immense state space of the real world.

Cooper's law, which states that the capacity of wireless communications doubles every 30 months, has held true since the first transmissions by Marconi across the Atlantic Ocean. Still, most of the increases have come from the reduced cell sizes and transmission distances. This development will scale current networks into ultradense scenarios where millions of devices should work autonomously, self-sufficiently and coordinatedly.

The challenges of scaling distributed intelligence include the extensive collection of representative data from real-world measurements using radios and other sensors and the energy efficiency of the vast number of nodes that need self-sufficiency.

***The convergence of computer vision and communications allow us to bring artificial intelligence solutions to the physical world in applications beyond what is envisioned today.***

The energy consumption of current AI methods largely depends on the general matrix operations that dominate deep-learning algorithms. Currently, we're in discussions about showcasing the energy efficiency of our error-resilient, low-voltage matrix multiplication method to a supercomputer operator. While the solution was initially developed for MIMO baseband processors, it also applies to machine learning.

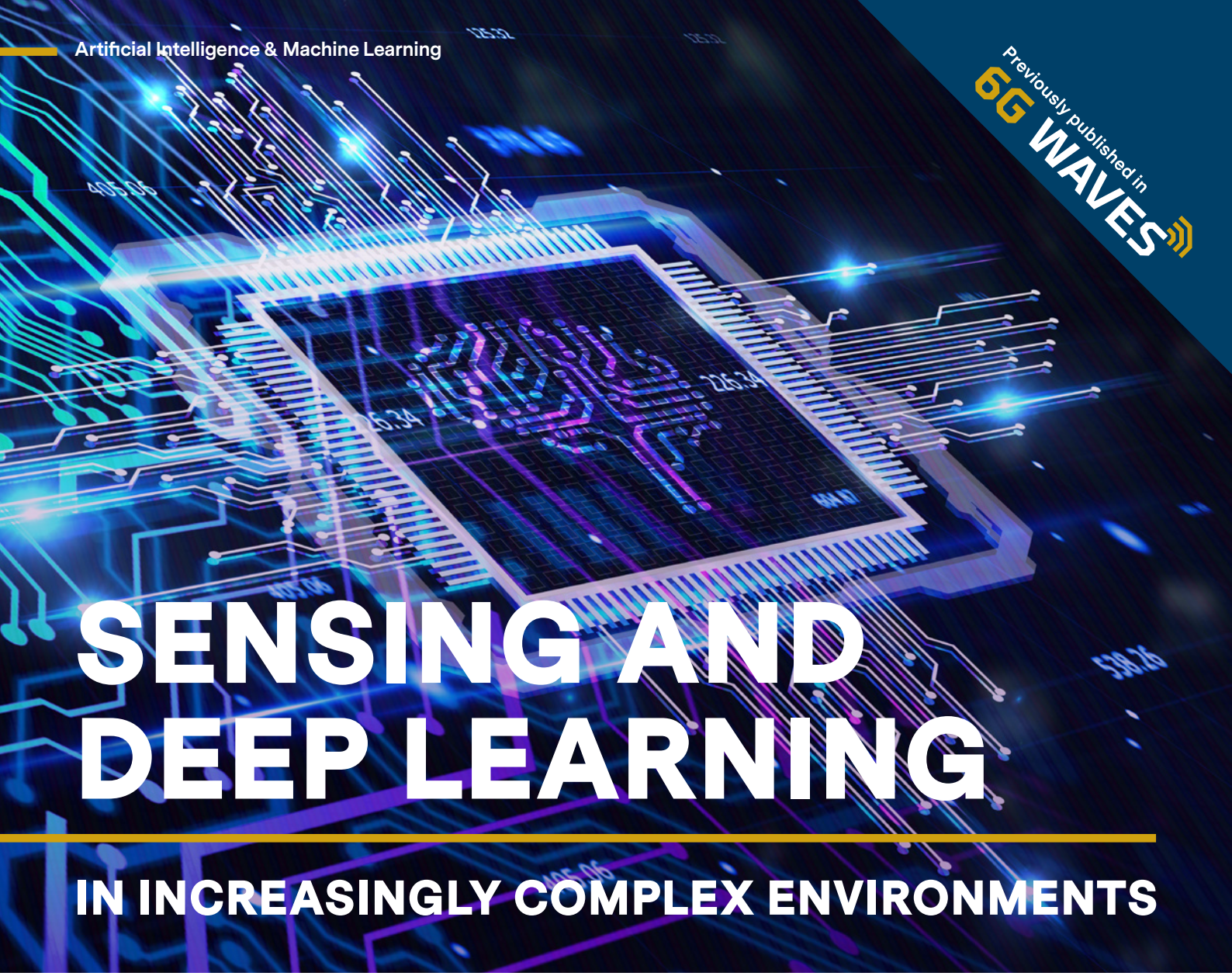
We lead the convergence of spatial AI and wireless communications from a visionary approach where multimodal sensing and 3D modelling converge, underpinned by robust partnerships and state-of-the-art experimental infrastructure. This fusion of technology and collaboration allows us to create innovative solutions for real-world applications beyond what is envisioned today.

## About the Writers

**Associate Professor Miguel Bordallo López works at the University of Oulu's 6G Flagship. His work focuses on the convergence of computer vision and telecommunications, developing multimodal sensing and distributed intelligence methods enabled by 6G technology.**

**Olli Silvén is a former Professor and Lead of Center for Machine Vision and Signal Analysis (CMVS) at the University of Oulu.**

Previously published in 6G WAVES



# SENSING AND DEEP LEARNING

## IN INCREASINGLY COMPLEX ENVIRONMENTS

***As we prepare for the future data-driven society in 6G, AI solutions and sensing intersect with wireless connectivity. In Praneeth Susarla's research, an antenna adopts the role of a sensor that transmits and receives radio signals. He aims to efficiently integrate sensor functionalities such as MIMO and massive MIMO using the framework of reinforcement learning over radio beamforming communications.***

"Integrated artificial intelligence like reinforcement learning with millimeter wave (mmWave) radio beamforming has high massive potential in parallel with the development of millimeter wave radios for sensing besides communications," Susarla underlines.

Now, he is developing a learning framework using Reinforcement Learning that can perform beamforming in an online manner under generic channel conditions. He is also contributing to the development of using mmWave radios for sensing besides communications in 5G and beyond networks. This involves integrating learning-based activity detection algorithms with 5G and 6G radio hardware.

"Using radios for sensing besides communications could have a significant impact in the society and can provide good business opportunities in the future," Susarla says. "This enhancement of radio capabilities can be well integrated with other sensors such as camera and Lidar. It can also be disruptive in many applications such as human activity detection, vital sign monitoring, and advanced analytics based on people's presence."

### Mastering our arbitrary 3D environment

While deep learning has been successfully used to solve various 2D computer vision problems, the major challenge of computer vision is that our surrounding world is essentially three-dimensional. It consists of an unorganized set of arbitrarily shaped and positioned 3D objects with appearance that can change drastically due to geometric and photometric variations such as 3D rotations, shading and partial occlusions.

Nowadays 3D computer vision combines methods from conventional geometric vision and modern deep learning.

"Our research covers various aspects of 3D imaging, where cameras are used for acquiring 3D information from the environment," Prof. **Janne Heikkilä** describes. "For example, we have carried out pioneering work on geometric camera calibration and published one of the standard algorithms for RGB cameras that has been used extensively both in industry and academia."

The team's recent works include, for example, RGBD (+depth) camera calibration, a SLAM system called DT-SLAM, and methods for dealing with motion blur in mobile photography.

"One research problem that we are currently investigating, is how to extract depth information from a single RGB image," Heikkilä says. "Another ongoing research line aims to the development of novel view synthesis methods that enable rendering images of 3D environment from arbitrary viewpoints based on a small set of reference images."

***This is exciting as it means we can do more processing with less energy consumption.***

The methods that Heikkilä and his team develop are generic and they can be used in various applications where 3D perception, localization, mapping, and navigation are needed. Key application areas include, for example, mobile imaging, augmented and virtual reality, and robotics.

## Cutting the energy demands

With the nearly endless amount of possible application areas, one key challenge arises. The training and inference of deep convolutional neural networks, as the major machine learning technique, requires tremendous energy supplies. Cutting the energy demands saves huge amounts of energy and environmental costs and calls for improved solutions - across layers.

In his research, **Mehdi Safarpour** combines techniques from the transistor level up to architecture and algorithm levels as he attacks the problem of energy efficiency in digital accelerators, through a holistic approach. He targets the problem of tremendous increase in energy demands of emerging technologies especially in deep neural networks and massive MIMO scenarios.

"As an 6G-oriented example, take massive MIMO antennas. With the increase in number of antennas of a MIMO application, the number of arithmetic operations increases dramatically," Safarpour asserts.

Most of the algorithms for MIMO heavily involve matrix computations, which happen to be the most compute intensive parts of MIMO algorithms. "We have created a low-power solution, which is specific for general matrix operations," Safarpour says. "According to our experiments, the energy for matrix computations can be reduced 50% without any performance loss. We perceive that our solution can be incorporated in any other applications which require lots of matrix operation and which are restricted in power or energy budget."

He is now working on reducing power through reducing voltage. "We have developed a couple of solutions that enable reducing voltage of e.g., a GPU or an FPGA device that is running a computationally intensive algorithm without affecting the end results," Safarpour says. "This is exciting as it means we can do more processing with less energy consumption. We have demonstrated two times higher energy efficiency with trivial trade-offs using commercial FPGAs."

However, reducing voltage leads to errors in computations. To tackle this challenge, Safarpour and colleagues have developed a method that can detect and tackle those hardware errors and make the system recover from failure. "We have shown 50% savings in common matrix applications by experimentation on a FPGA device with ~ZERO decrease in reliability or system performance," Safarpour summarizes.

The developed methods apply widely to challenges in machine learning accelerators and communication systems and include numerous benefits. They are easy and cheap to implement regarding the time investment and they can be integrated with even High-Level-Synthesis tools.

At the same time, the methods produce multiple folds power consumption savings on the FPGA and ASIC that are used for computations of MIMO and deep learning algorithms. They also increase in reliability of their processing platforms. "Even if the voltage is not intended to be scaled down, our low overhead method adds to reliability of computations," Safarpour says. "This can for instance be applied to satellite communications."

Futhermore, the methods relax thermal issues of the FPGAs, e.g., in base-stations, by operating in Inverse Temperature Dependence region. "We have been able to show how heat enables faster clocking at lower voltages and our method is cable of exploiting that," Safarpour concludes. And with smaller cell sizes in the future, leading to a massive rise in the number of base stations, this may well be a winning solution.

Previously published in 6G WAVES

# AI-ASSISTED DETECTION OF BIOSIGNALS AND HUMAN EMOTIONS

***Fundamental methodology research on autonomous learning can benefit most, if not all, computer vision tasks. With the aid of autonomous learning, we can automatically design a contextual-aware neural network for different perceived data given specific computer vision tasks.***

"Although wireless communication and machine vision focus on different forms of signals, we can use machine learning to advance specific tasks, e.g., to automize or optimize processes, and to facilitate human interactions," professor **Guoying Zhao** and professor (Tenure Track) **Xiaobai Li** note.

The experts study Emotion AI including the recognition and analysis of facial (micro)-expressions, emotional (micro)-gestures and for non-typical emotions, which are directly related with emotion understanding and can facilitate education, psychotherapy, remote services, and autonomous driving, to mention a few.

"Facial micro-expression analysis is important for understanding human's hidden or suppressed emotions, and facial action unit (AU) is the smallest element of facial movements," the experts note. Moreover, body gesture and micro-gesture analysis and recognition are also crucial for emotional status recognition. Multi-channel information fusion has been investigated for a complete emotion understanding system.

The team aims to improve understanding of emotions that do not belong to the most general or typical classes, e.g., happy, sad, anger, etc., but are commonly encountered in our daily life and are practically essential in application scenarios. Such non-typical emotions include boredom, confusion, interest, shame, nervousness and confidence, Li notes.

## Solutions for self-monitoring and early screening of diseases

Remote physiological signal measurements carry immense potential for numerous applications in remote heathcare, e.g., self-monitoring of heart functions, early screening of heart disease, and so on. Hence, they are a crucial tool for remote heart rate measurements, heart rate variability measurements and respiration measurements and can lead to massive cost savings in healthcare services. One example application case is remote atrial fibrillation detection from just face video analysis with the collaboration with the cardiologists in the University hospital.

With advanced computer vision and machine learning technology, the experts look for solutions to interconnected challenges such as: how to counter the influence of human motions and lighting variations when measuring heart rate from facial videos; how to deal with low intensity and improve micro-expression recognition accuracy and; how to relieve the problem of insufficient and imbalanced data for micro-gesture analysis.

Multimodal learning and fusion have been deeply explored in the group. In practice, multimodality fusion can take place on various levels. It includes fusion at the sensor level, i.e., data recorded with multiple sensors (RGB, NIR, depth, or 4D cameras, bio-sensors), fusion at the feature level, i.e., different feature clues such as depth and texture, multi-view faces, etc., and also fusion at the decision level, i.e., collaborative classification and voting of parallel modules.

"With 6G technology and the concept of IoT, we can explore ideas to combine cameras with other kinds of sensors for distributed learning and fusion, for tasks such as safety of driving, or home healthcare monitoring," Zhao says. "When combined, multimodal fusion and autonomous learning can lead to more robust and efficient machine learning solutions in various fields and in forms of software, services, or smart products with emotional intelligence and self-learning towards 6G."

## Vision-based assistive medical diagnosis

In the current and future video-capable and communication devices, the integration of assistive diagnosis applications based on computer vision is going to play an increasingly important role as it will be integrated in all types of Tele-Health strategies.

Professor (Tenure Track) **Miguel Bordallo López** adopts a multidisciplinary approach at the intersection of AI-assisted primary healthcare and real-time computer vision and signal analysis. "Our research is likely to enable new applications and methods in several related fields which are not traditionally studied jointly, such as digital and public health, computer vision, computing and communication architectures."

His research aims at laying the foundations to produce novel solutions for vision-based assistive diagnosis in primary healthcare, bringing the technology into practical applicability and potentially changing the way that medical and healthcare are performed.

"Camera-based assistive medical diagnosis assistance is an emerging topic of interest as it provides a remote alternative to traditional primary healthcare, since it does not necessarily require personal visits to the health centers and allows continuous monitoring," Bordallo López says. "Computer vision and AI can leverage remote and mobile video data, and they can assist in providing unobtrusive and objective information in a patient's condition."

To give an example, up to 30 medically relevant symptoms or conditions can be detected or at least assessed objectively using computer vision methods and facial images. At the same time, analyzing the signals of complementary modalities such as radio signals, such as the ones used in 5G/6G communication, provide for privacy preserving alternative sources of information.

"Although many advanced computer vision based healthcare and medical diagnosis methods have been demonstrated, their actual implementations as embedded or remote solutions, if existing, are still far from being useful," Bordallo López notes. "The problem derives from the implementation challenges arising from explainability, real time computations, communication capabilities and cost issues."

## Challenges of distributed and embedded 5G/6G devices

The real challenge is finding how we could enable the use of computer vision for medical diagnosis using camera-based devices such as mobile phones, or remote video connections e.g. video-conference services, both including communication capabilities.

"A particular problem that we are trying to tackle now is the use of radio signals produced by 5G/6G devices, jointly for communication and sensing, so we could obtain data about location, activity and biosignals, such as vital signs, of a patient in an unobtrusive and privacy preserving way," Bordallo López notes. "These would enable a wide range of applications with cooperative systems that are integrated with other devices as well."

The applicable implementation of these methods deals fundamentally with multiple distributed and embedded devices that need to communicate and process large amounts of data with low latencies in a very energy efficient way - a challenge, which is at the core of 6G research. In addition, effective applications need to deal with multiple sources of heterogenous data that is retrieved from different locations and that must be combined in real-time.

It is important to embrace the challenges and particularities that derive from real world scenarios, conditions and devices, so that the solutions become truly applicable. He and his colleagues use video to extract and classify biosignals (such as respiration or pulse) and respiratory or circulatory danger signs (chest indrawing, asymmetries) from regular videos obtained with hand-held devices or remote video-conference services - a cost-effective solution that can have wide global impact.

"We are trying to create self-assessment video-based mobile apps for the pre-diagnosis of stroke, even before visiting the hospitals," Bordallo López explains. "We are also bringing real-time video analysis based on mobile devices to remote areas in small and middle-income countries, enabling point-of-care assistive diagnosis to, for instance, child pneumonia."

# THE (SUB-)THZ HORIZON

***6G Waves sat down with Professor Aarno Pärssinen and Assistant Professor Nuutti Tervo to chart the strides towards radios at new frequency ranges and ultra-high bandwidths, enabling future communications and sensing.***

## What is the goal to achieve in the next two years?

For the past few years, one of our main efforts has been to develop a full-scale functional 300 GHz RF receiver and get it measured and tested. This work has progressed steadily with many successes. We have published many world-class publications that push the boundaries of the used integrated circuit technologies beyond traditional limits.

Now, the final effort is to put together the existing building blocks for a functional receiver and get it measured with real communication signals. While we've had good progress, there is still work to finalise this goal. Testing extremely wideband systems in sub-THz frequencies is challenging and requires the efforts of many experts in our team. We have already proven high-quality signal reception capabilities in some of the parts.

In other research topics, we'll continue our research, focusing on three main themes: materials, key hardware building blocks, and system-level concepts and platforms. To remind you, the 6G is not a system of one-frequency band. We're actively engaged in research spanning from centimeter-wave frequencies and beyond towards the THz regime. For instance, we continually innovate to challenge conventional notions in transceiver architectures. These groundbreaking ideas will be implemented in current and forthcoming industry-related projects.

## What must be done to achieve the goals?

Hard work by innovative minds and a significant team effort! The research requires collaboration from tens of people, especially in areas that aim for real-life demonstrations and physical components and devices. Developing a functional transceiver contains plenty of steps, from early system specifications and novel ideas to remarkable design and circuit innovation efforts, intense collaboration among many people to interface the building blocks, deep knowledge of manufacturing and materials, and finally, plenty of time, hard work, and bright thinking in the laboratory to make everything work

smoothly to get something measured. And one must not forget things that we consider routine, like verification. There is no way out from traditional engineering efforts needed to support the novel ideas.

> *The role of academia should be to look further into the horizon to pave the way for the next technical innovations, which can sometimes go much beyond 6G.*

### Has your 6G vision remained the same, or has it changed?

We will continue solving the most challenging RF and hardware problems from different perspectives. The focus has been on very high data rates, but that should be achieved with commercially feasible efforts to be able to also enable business in the area. In this phase, we also look beyond 6G systems while the industry is, piece-by-piece, advancing the current technologies. The role of academia should be to look further into the horizon to pave the way for the next technical innovations, which can sometimes go much beyond 6G. Those are valuable part to carry on when we know better what 6G will eventually be.

### What will 6G mean in everyday life in the 2030s?

Great question. It is certain that in 2030 we will have faster communication systems than today. What this means for regular consumers depends on what the industry is putting forward toward feasible products and, on the other hand, what killer applications 6G will generate. For example, sensing solutions using wireless infrastructure or using the same radio hardware is one functionality that has the potential to create applications that have been envisioned and even more applications that we couldn't imagine but that will be enabled unintentionally.

### For whom and for what 6G is being developed?

We want to see 6G developed mostly for people to enhance their lives. Of course, plenty of breakthroughs also happen in sectors that regular consumers may not notice, like in the industry, factory automation, autonomous machines, and so on, where highly reliable and fast wireless systems are needed.

Success in the wireless industry and related fields relies on high-quality, high-risk research. This truth drives continuous research efforts. The world won't wait for Finland; complacency is not an option. Active engagement is essential for impact. Long-term research builds expertise vital for short-term industry success.

### Why is 6G Flagship among the top 6G research groups in the field?

At the University of Oulu, we have made wireless solutions for decades. That knowledge and expertise is not something one builds in a day. Also, industrial experience in the team broadens the view and provides competencies beyond the traditional academic scope. Competition is getting tougher, however. Hard work, fresh mind and international collaboration are the keys to staying at the crest of innovation.

## About the Writers

**Professor Aarno Pärssinen at the University of Oulu specialises in RF system and circuit design for wireless communications and sensing. With extensive experience in both industry and academia, he has contributed to over 200 publications, holds numerous patents and is the recipient of the EuMC microwave prize. He is one of the original contributors of Bluetooth Low Energy technology..**

**Nuutti Tervo is an Assistant Professor at the University of Oulu, focusing on RF, signal processing, and wireless communications. Recognised for his contributions, including over 65 publications and several patents, he has been awarded the Young Scientist Award and the EuMC Microwave Prize.**

Previously published in 6G WAVES

# WOOD-BASED ELECTRONICS FOR SUSTAINABLE 6G?

***The amount of electronics in the world is growing. It is important to study how we could made electronics more sensibly and more sustainably in comparison with the current production method. What will new technology do and what it will be used for? These aspects determine how devices should be manufactured and what they could be made of.***

The interfaces between communications technology and materials technology are interesting, and wood-based electronics are an important line of investigation, especially in a country like Finland where forest industry represents one fifth of the export of goods. Predictions of what kinds of applications wood-based electronics could be used for would be premature, but radio lenses that direct the signals of a radio transmitter have already been made of nanocellulose.

Key guiding factors in the manufacture of electronics are the temperature of manufacture and the use of energy. Temperatures are being brought down and in many situations production at room temperature is already possible. Different materials are optimised for the intended use of specific electronics: sustainability, recyclability, availability, environmental friendliness, and naturally also the price, which is affected by procurement, transport, and processing. The new manufacturing methods are significantly linked with printable electronics, which is going strong in the Oulu area. Production of wood-based electronics is one part of the development of printed electronics. Radio lens is a central part of the production of new technology at the intersection of radio technology and printed electronics.

“We are now making a 6G radio device for demonstrating data communications that is as fast as possible. In 6G the frequency of the signal is 300 gigahertz, and the wavelength is such that the size of the antenna need not exceed one millimetre,” says postdoctoral researcher **Sami Myllymäki** of the Microelectronics Research Unit.

Aiming the signal toward the antenna of the receiver is a crucial point where radio lenses are needed. A lens focuses the radiation and increases the distance between the transmitter and receiver, thereby extending the range.

“For example, cameras also have lenses because they give a sharp picture. Similarly, in a radio the goal is high-quality signal transmission, which requires an accurate radio environment image. Radio lens is a central part of producing new technology,” explains Myllymäki, who is specialised in radio technology and new materials.

One aim of 6G is to bring much greater speed to radio devices. A hope for the future is to transfer volumes of data that massively exceed what was previously possible almost without delay and, of course, very reliably. This will be made possible by raising the frequency. Consequently, the requirements for the computational capacity of the data to be transmitted will also vastly increase.

“The computational power and high frequency steer equipment solutions in a direction that imposes high demands on a silicon-based microprocessor, and the speed of a transistor in the amplifiers is pushed to the extreme. On the other hand, it is not feasible to replace silicon with a more expensive material, which should be considered when innovating something new,” Myllymäki ponders.

The semiconductor industry uses plastics, ceramics, and metals. With respect to materials, consideration is given to what is used now, and what new materials might replace them. Silicon is the key material, and any new materials will be

compared to it. A new material must naturally be better than the current ones in performance, but also in other respects.

"Traditionally in electronics the aim has been to fit things into a small space, which means that they are tightly integrated. This has been done by utilising materials with high permittivity. In 6G, it is not essential to squeeze things into a smaller space. For purposes of integration, small size in the new materials has largely reached its sensible limit," Myllymäki points out.

## Radio lenses out of nanocellulose

If we calculate the share of electronics in the overall consumption of plastic in the world, it is quite small. Therefore, wood-based electronics alone will not bring us a new way to utilise the forest industry, but it is definitely one of the possibilities for the future.

"The search is on for raw materials that replace plastic. Environmental friendliness is an important, perhaps even the most important reason. Nanocellulose is a natural, interesting substitute material. In addition, the recycling is easier when the material is water soluble," Myllymäki says, adding that the material is also brittle, but nevertheless a potential option.

"Nanocellulose has many benefits: it is a light, mechanically strong material, with a low loss structure for electricity, and the material is easy available. Lightness and low loss are important. Loss of signal in the material needs to be made low. The best of materials can be 99% air and then the proportion of loss is infinitesimal. We can already print a material that is similar to air for research purposes - which means that it is extremely light. However, it is also brittle," Myllymäki notes.

Nanocellulose is used in different ways in the production of components: mould casting technology, printing technology, and 3D printing. It is a great bonding agent in materials and it forms a printable surface. When we go to materials with low permittivity, they start to be so porous that they do not have a contiguous surface for an electrical conductor. Cellulose makes these suitable for printing and gives a necessary support structure. They are formed out of nanotube structures, which means that much air is mixed in. Sami Myllymäki explains the matter enthusiastically, even though a water soluble and brittle electronic component sounds like a strange starting point, to say the least.

"As researchers we are looking for positive possibilities. We must not get bogged down with problematic issues. I also believe that the market will decide, which means that a protective surface material can be developed for lenses, which means that they are durable enough, and water solubility is not an obstacle to use, but it is a significant advantage at the recycling stage."

The multidisciplinary character of the University of Oulu is showing its strength once again when developers of new electronics from the same place acquire tailor-made nanocellulose as a handicraft produce from northern Finland. The mass comes from the Fibre and Particle Engineering research unit, which aims to promote the implementation of circularity and bioeconomy with the help of materials research.

## Reflecting surfaces and smart dust

Sami Myllymäki is specialised in radio technology and microelectronics which is a great combination for 6G research.

"I have an engineer's identity and I am a link person between different topic areas and their researchers."

Both 5G and 6G are taking us to a heavy radio infrastructure and powerful computational requirements.

"And then there are IoT devices that can link to the internet. A single, exceedingly small device is sufficient for producing certain information, for example, measuring temperature. Structural electronics are developing at the same time; devices and materials are functional on their own, electronics is integrated into them already in the manufacturing phase," Myllymäki says.

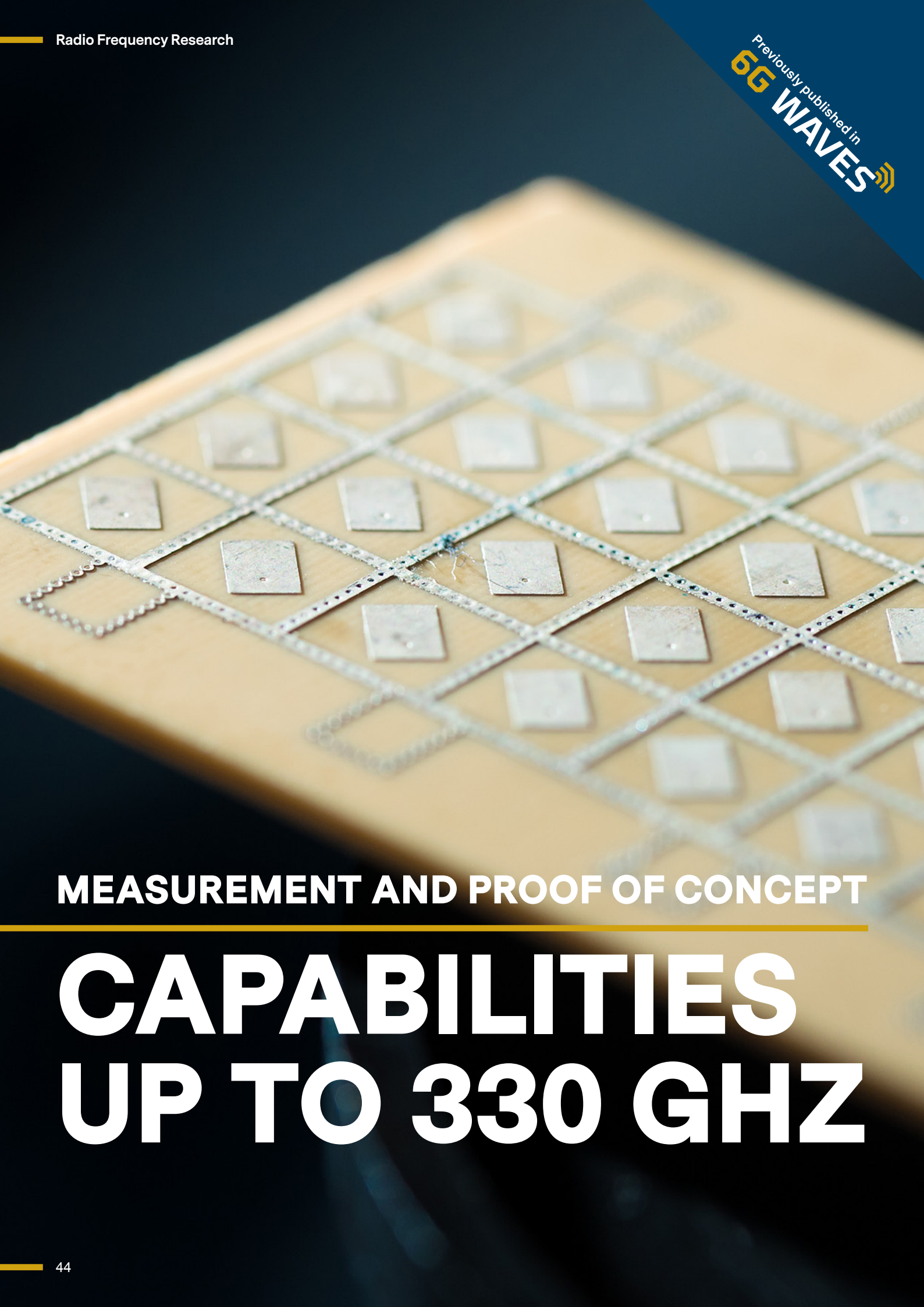
An interesting example are reflecting surfaces that are needed to help the propagation of signals as wireless data communications expands in the built environment. What could they be like? From this we can move to large-sized materials of printable electronics. The material needs to be electronically adjustable, or controllable. When radio devices are used to point a signal at a surface, it needs to be capable of directing it to the desired target. So, researching new materials and developing directing lenses are also centrally also linked with the large surfaces of the built environment and the highly promising area of intelligent reflecting surfaces.

The next interest for Myllymäki, in addition to reflective surfaces, is to consider extremely fine smart dust, or devices that might be made in the future that are so small that they are like tiny particles.

"We researchers offer alternatives. It is not possible to move to anything new if it has not first been developed. Experimental culture must be maintained. We can do that when we think about how 6G works. Researched knowledge beats guesswork every time," Myllymäki concludes.

**Read more:**
*6gflagship.com/news/wood-based-electronics-for-sustainable-6g*

Previously published in 6G WAVES



## MEASUREMENT AND PROOF OF CONCEPT

# CAPABILITIES UP TO 330 GHZ

***6G Flagship's radio frequency (RF) experts create proof of concept (PoC) platforms where the research outputs of the group members are integrated, seamlessly. The group focuses on two main PoC categories - technology or component demonstrations, and platform demonstrators – which integrate multiple standard and PoC components.***

Previously, the RF group has created a complete 5G mmWave radio unit for wireless backhauling purposes. Now, a new mmWave radio platform is under development. "For 6G purposes, we are currently developing measurement and PoC capabilities up to 330 GHz," says Dr. **Marko Leinonen** who leads experimental radio research in the RF laboratory.

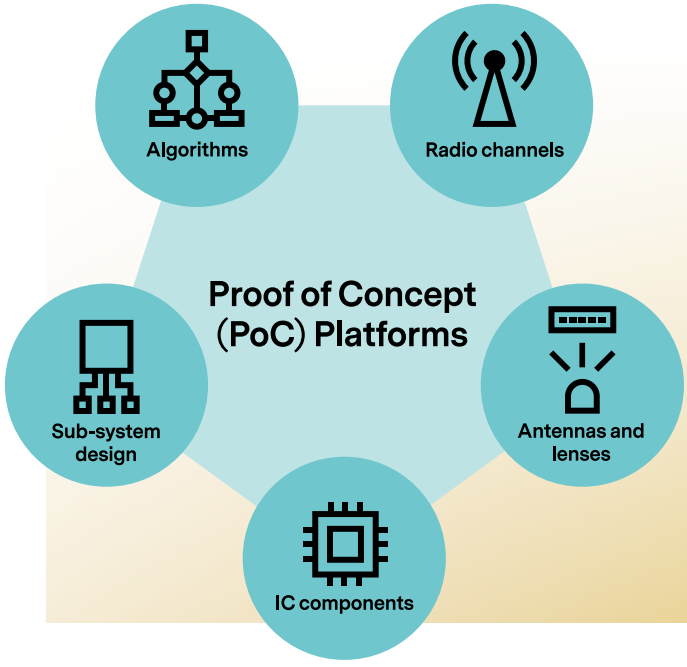
A successful PoC platform requires effective teamwork between multiple researchers and organisations due to the complex interactions between used technologies. "The complete radio platform requires integration of radio frequency components, antennas, printed circuit boards and controlling software into one system, which have similar functionalities as radios used in base or mobile stations," Leinonen says. "We have successfully demonstrated multiple 5G antennas as individual antenna elements and integrated into the complete arrays. We have also developed complete 5G mmWave radio platforms with electrical beam steering, and with the same platform, we have evaluated several interference mitigation methods. The RF IC design team has developed and measured several world leading designs which can be implemented into the larger radio platforms, as well."

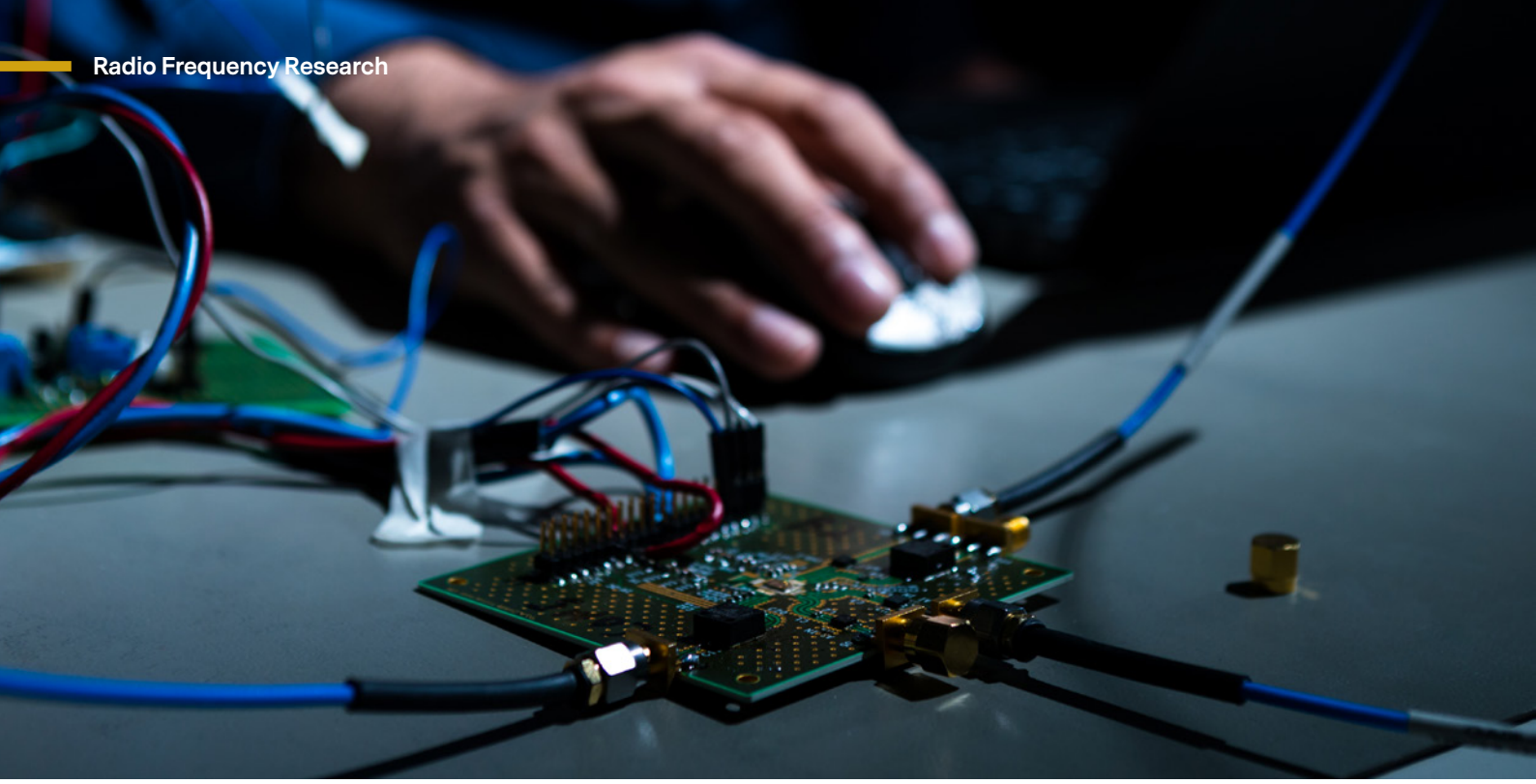
With its unique skillset, the group combines innovative component design, system analysis and measurements leading to verified solutions. "An efficient and parallel usage of multiple electronic computer-aided design tools is an essential success factor for any high performing radio frequency circuit and antenna design," Leinonen says. "We have state-of-the-art measurement equipment in our radio laboratory which are crucial for the evaluations and measurements of the designed radio components."

A closer look at five experts' intertwined expertise areas illustrates some of the major research and development challenges that the experts are now solving.

## Integrated Circuit (IC) design

The mmWave and THz RF receiver integrated circuits that **Sumit Pratap Singh** designs and develops will be implemented and integrated into the 6G radios." A major goal of the RF group is to design a complete 6G transceiver, and the designed low noise amplifiers and downconverters are some of the main building blocks at the receiver side," Singh says. "By implementing these blocks and then combing them with components such as antenna and phase shifters, a phased array receiver will be designed to meet the criterion of ultra-high-speed transceiver for future 6G radio system."





As his most promising achievement, Singh names "breaking the barrier by achieving the good power gain beyond half of maximum frequency of oscillation (Fmax) over wide bandwidth with decent noise performance." The results have been published in the benchmarking paper on low-noise amplifier (LNA) design at sub-terahertz , presented in the 2021 IEEE Radio Frequency Integrated Circuits Symposium (RFIC). This takes the RF group significantly closer to the target of implementing/completing a THz transceiver for 6G communication using exiting process technologies with limited speed at THz frequency range.

## Antenna design

Antennas are essential components to demonstrate anything over-the-air since no radio link can work without antennas. In the modern communication systems, antennas are not only converters of conducted signals to radiated ones, but they also operate as frequency- and spatial-domain filters, impedance matching elements, mechanical supports, and may conduct heat away from the transceiver IC.

In comparison with previous mobile generations, the higher frequency in 6G sets increased demands on antennas. "Antenna gain must compensate for limited transceiver performance and reduced antenna reception area," says Dr. **Markus Berg**, who conducts 6G antenna research in the RF group.

High gain results in a narrow radiation beam, which in turn causes need for dynamic beam steering in the case of a mobile user. However, high gain antennas have typically fixed radiation beams achieved by electrically large dielectric lens structures. "Developing a high gain beam steering antenna for 6G is a challenging task," Berg says. "A possible solution is to develop hybrid antennas combining lenses with phased arrays to enable beam steering and high gain."

## Sub-system development

The next level of RF design after individual components is integrate them to functioning sub-systems. **Mikko Hietanen** researches and develops the millimeter wave RFIC-frontend. His work is limited by the performance of the used semiconductor process and the requirement of simplicity of the design. "Designing amplifiers at technology limits forces the designer to work with as simple circuits as possible to maximize performance," Hietanen says. "Hence, the technology dictates the level of sophistication."

The sub-system development as such follows the same principles as any system development. "We design standalone blocks, combine them together, and fine-tune the sub-system for optimum performance," Hietanen says.

In absence of 6G system and corresponding radio signal, the group uses 5G new radio signals for the design validation purposes. "Showcasing performance with real-world signals proves the end result without leaving open questions about modeling accuracy or mistakes in simulations," Hietanen confirms. "As a result, prototypes are benchmarked as close as possible to product level in terms of functionality in early phases of development."

## Channel models

The measurement capability for above 100 GHz frequencies is now developing and measurement data is accumulating from different sources, including our own. "We are getting more insights into interactions of radio waves and various

materials, and their frequency dependency," says Dr. **Pekka Kyösti**, who focuses on radio propagation measurements, estimation, and channel modelling in the RF group. "The accumulated measurements begin to provide a limited statistical view on transmission loss and multi-path characteristics in considered environments and frequencies."

Radio channel and propagation studies are enablers for other fields of research and development. Hence the progression of propagation research advances real-life 6G adoption indirectly. "Radio channel measurements at above 100 GHz frequencies are typically very slow to conduct due to high gain requirement of measurement antennas," Kyösti says. "The measurement-based knowledge is still in its infancy and most combinations of frequency, environment and deployment still need to be measured."

> ***With real-life experiments, we can learn how our technical solution has impact on the big picture. This is very motivating, and at the same time, it is very educative.***

In a recent journal article "How many beams does sub-THz channel support", the team introduced three methods to approximate the number of beams building on data from real indoor measurements performed at 140 GHz. The initial 6G channel models will be extensions of measured propagation data. "The use of such stored channel models is highly realistic and provides a good basis for evaluations on PoC platforms," Kyösti says.

## Radio algorithms

Early on, the RF team took the decision to develop a radio PoC platforms instead of using commercial options. "When I started working around my topic many years ago, there were no commercial mmWave phased array platforms available," says **Nuutti Tervo** who creates spatial linearization concepts of phased array transmitters. "If I would have waited for those to be mature enough, my research would have been very limited. As we are jointly developing the PoC, we get to decide together what we should include in the design to support and solve our specific research problems. And with the novel approaches, we can have scientific impact in early phase."

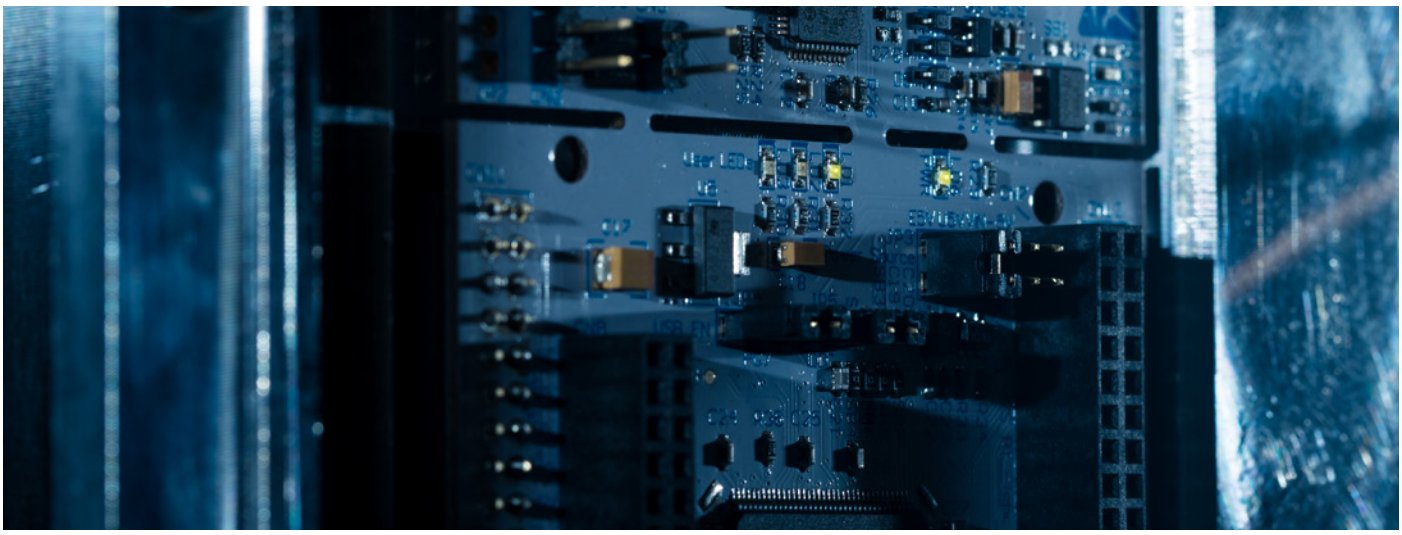
For his own research, Tervo needed a real phased array transmitter. RF and especially power amplifiers have a very fundamental problem - a nonlinear nature of behavior, and this problem is clearly visible with power amplifiers at the region where their power efficiency is the highest. "In my own research, I look for ways how an antenna array can beamform its nonidealities," Tervo says. "In phased antenna arrays, we have learned that the linearization can be designed in the array level. Basically, it means that the individual elements can compensate for each other over-the-air for linearization purpose."

PoC development thus has importance on multiple levels of research and development. "We really are depending on each other to get the research done," Tervo says. "With real-life experiments, we can learn how our technical solution has impact on the big picture. This is very motivating, and at the same time, it is very educative. You learn to think outside of the box which may lead to solutions that others are omitting. And we have good results in the end."

**Read more:**

*ieeexplore.ieee.org/document/9490435*

*ieeexplore.ieee.org/document/9563241*



## INNOVATION UNDER THE NORTHERN LIGHTS

# WHY CHOOSE FINLAND, OULU AND THE 6G FLAGSHIP?


### Happiest Country in the World

Finland has been ranked the world's happiest country for six years in a row. It is a land where world-class research and innovation thrive; where life is safe and easy. The crime rate is low, the social safety net is strong, the air is clean and pollution-free, and the water is safe to drink straight from the tap.

Finland has excellent public services and a strong economy. Children attend school free, and municipal childcare and universal healthcare are available to all residents. 6G Flagship employees receive occupational healthcare. And the University of Oulu has a special Spouse Programme, which helps the whole family to adjust to the Finnish society.

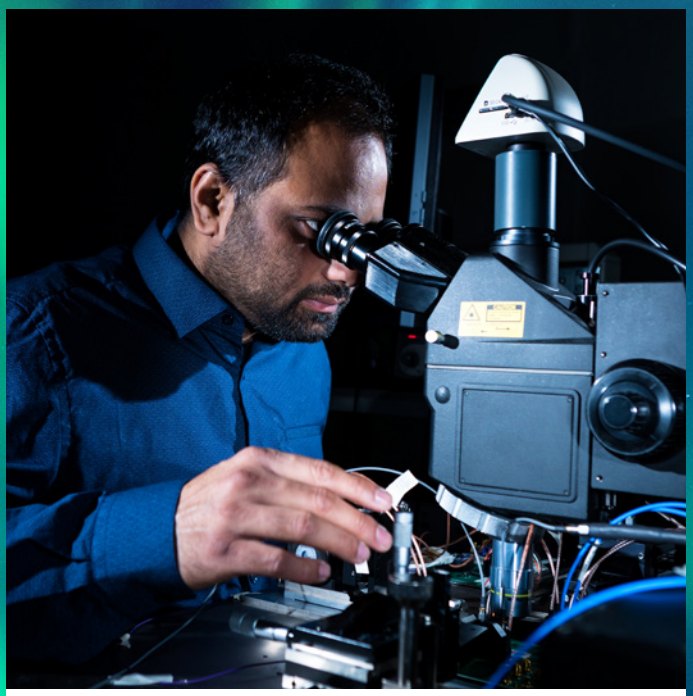
### High Tech Up North

The city of Oulu is the home of 6G Flagship. The city is located in northern Finland, which is widely regarded as one of the world's safest and most stable regions. With only 250 000 residents, Oulu is quite compact, but it is also very smart! A whopping one third of the residents has a university degree.

Oulu is a major high-tech hub, with 50 years of experience in ICT and related operations – technologies used by almost 3 billion people every day. The university of Oulu has a long history with telecommunications technology, and particularly wireless telecommunications research. It has been a strength of the university since the 1st G in the 1980s.

*The big pro of Oulu is an optimal life-work balance, I think it's one of the best - better than Stockholm, better than Helsinki. Why? Life is so easy and simple. You don't have to commute. My gym, my supermarket, my house, my office are within half an hour's walk. I don't have to drive, I just bike to work. To me this is unbeatable.*

**Professor Mehdi Bennis**




## Compact City – World-class Research

The university is home to the world's first 6G research programme, 6G Flagship, where top innovators and leading experts work passionately to build a data-driven, sustainable future society.

Professor **Mehdi Bennis**, one of the world's most highly cited researchers and and a Professor at 6G Flagship, summed Oulu's appeal to world-class researchers perfectly: "The big pro of Oulu is an optimal life-work balance, I think it's one of the best - better than Stockholm, better than Helsinki. Why? Life is so easy and simple. You don't have to commute. My gym, my supermarket, my house, my office are within half an hour's walk. I don't have to drive, I just bike to work. To me this is unbeatable."

## Join the crew of trailblazers in 6G

6G Flagship is continually looking for new talents. We offer positions for doctoral and post-doctoral researchers in four research areas:

- **Wireless Connectivity**
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Are you the trailblazer we are looking for? Apply to one of our four research areas and help us shape the future of wireless communication!

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# 6G FLAGSHIP IN NUMBERS

## MAY 2018 - DECEMBER 2023

### Staff

**525**
experts in 2023

**55**
Nationalities

64% International

### Doctoral Degrees

**109**
Doctoral degrees

**318 081**
Doctoral thesis downloads*

### Company Collaboration

**442**
Company collaborators

48% International

### Investments & Funding

**457**
Research projects (external funding)

**121**
Companies investing in research portfolio

## Publications

**3 042**
**Peer-reviewed publications / Journal and conference articles**

**76% Joint publications with collaborators**

**67% Joint international publications**

**12% Joint publications with companies**

## 6G Waves

**334 483**
**Total downloads***

## 6G White Papers

**164 212**
**2019 White Paper downloads***

**920 250**
**2020 White Papers downloads***

**1 084 462**
**Total White Paper downloads***

* Number of downloads in University of Oulu repositories *jultika.oulu.fi* and *oulurepo.oulu.fi*

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**ISSN 2670-2029 (print) | ISBN 978-952-62-4032-9 (print) | ISSN 2670-2088 (online) | ISBN 978-952-62-4033-6 (online)**